R. Sundararaj *Editor*

Science of Wood Degradation and its Protection

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ISBN 978-981-16-8796-9 ISBN 978-981-16-8797-6 (eBook)
https://doi.org/10.1007/978-981-16-8797-6

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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About the Editor

R. Sundararaj has 35 years of research experience in the field of protection of wood from bio-deterioration, forest entomology, integrated pest management with special reference to sandalwood and Whitefly taxonomy. He obtained his M.Sc. (Zoology) from Madurai Kamaraj University and his M.Phil. and Ph.D. from the University of Madras, Chennai. He has published more than 250 scientific papers in renowned international and Indian journals. He has guided 11 students for Ph.D. degree and three postdoctoral fellows. Dr. R. Sundararaj is Fellow of the Royal Entomological Society, London, UK, Fellow of the Entomological Society of India, New Delhi, and Fellow of the Applied Zoologists Association of India. He is the recipient of several awards notably Guru Vandhana Appreciation award from Rotary Bangalore South and Karnataka Civil Defense Corps and Rao Sahib Dr. T.-V. Ramakrishna Ayyar Memorial Award from Dr. B. Vasantharaj David Foundation, Chennai. Recently he co-authored the book *Handbook of Whiteflies*. Presently he is serving as Scientist G and Head, Forest Protection Division of the Institute of Wood Science and Technology, Bangalore, an institute under the umbrella of Indian Council of Forestry Research and Education, under the Ministry of Environment, Forest and Climate Change, Government of India.

Wood Degradation, Challenges, and Mitigation

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Contents

Abstract

Wood is an ancient material used in the development of human civilization. It is the first material used by the human kind for its protection and survival that further came into use as material for shelter preparation and food preparation, as fuel wood. Since then the wood has become an integral part of day-to-day life of

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_1

mankind. This renewable and recyclable material however forms material of food, shelter and reproduction for many other organisms too. In this chapter we have discussed about the joint action of major organisms, which are dependent on wood for their survival and also the environmental factors in the process of wood degradation. Such degradation of wood and wooden products results in enormous economic loss, and it has a negative impact on the present era of global warming, as carbon locked in the wood is released in the process of degradation. Consequently, the possibility of mitigating wood degradation is also discussed.

Keywords

Wood degradation · Fungus · Bacteria · Insects · Marine borers · Wood protection

1.1 Introduction

Wood is a natural organic material composite of cellulose fibres produced by the growth of trees. The trees are an integral part of life, which have furnished with two of life's essentials, food and oxygen for all dependent creatures. Forests contain an extraordinary variety of living organisms both in the trees themselves and in the flora and insect fauna which they support. From birth till death and after that also a tree and its wood support an enormous amount of species (Erwin, 1982). Wood is the internal, lignified part of the stem, branches and roots. They are the traditional material used next to stone by primeval man to exploit food and explore new frontiers. Since time immemorial it has been one of the basic materials that have been naturally and abundantly available for use to mankind; in peace and war, in industry and farming and also has become a part of day-to-day activity (Youngs, 2009; Obadoyin, 2018) like primarily as a fuel or as a construction material to make houses, tools, weapons, furniture, packaging, artworks and paper. Since it is a biologically derived multipurpose raw material it demands low processing and in turn provides high economic returns along with a high strength-to-weight ratio, appealing aesthetic properties, ease of construction, the ability to be repaired and cost-effectiveness. It is also a renewable resource, and its production is much less energy-intense than that of other construction materials, such as steel, aluminium or concrete (Mindess, 2007).

Despite the passage of several millennia and advent of various modern construction materials such as cement, metals, alloys, rubber, plastic, perspex and fibre reinforced polymer, timber has retained its status as a pristine structural material due to its many virtues such as light weight, high strength, non-corrosiveness, non-magnetic nature and fidelity to be shaped, bent or joined (Borges et al., 2009). It is a material, which is highly valued in industrial sectors such as paper, panel wood, construction, furniture and the packaging. However, this marvellous material is more or less susceptible to various forms of degradation which acts as the limiting factor for the utilization of wood for various aspects. Wood is impaired by abiotic factors such as sunlight, temperature and weathering, and it, being an organic material, is also susceptible to various bio-deteriorating organisms viz., microbes such as fungus (McCarthy et al., 2009) and bacteria (Edlund & Nilsson, 1998), insects such as termites (Scheffrahn, 1991), beetles and marine borers (Tsunoda, 1990; Highley, 1999). The timber and trees being affected by these abiotic and biotic factors is part of the biological process in forests. However, when it comes to utilization it causes huge economic loss. The resulting degradation forms major threats to wood both in standing tree as well as in the service life of economically valuable wood.

1.2 Basic Anatomy and Cell Structure of Wood

The tree/shrub or bole is composed of concentric cylindrical layers, namely, outer bark, inner bark, vascular cambium, sapwood, heartwood and the pith throughout its length and breadth (Fig. 1.1a, b). The outer bark is made up of cells that provide mechanical protection to the living tissues of trees and also help to check the water loss due to evaporation. The inner bark or phloem is the tissue through which carbohydrates and amino acids produced in leaves translocate throughout the other parts of the tree. The growth layer (vascular cambium) is the layer between the bark and the wood, which produces these tissues each year, i.e., it divides to produce phloem cells on the outside and the needle-shaped sapwood (xylem) cells towards inside. The active, living wood is the sapwood that conducts the water (or sap) from the roots to the leaves and the heartwood is the core of dark-coloured wood in the middle of the trees as they age. The pith, at the centre of the trunk, is the remnant of early growth before the wood was formed (Morris, 1998; Wiedenhoeft, 2012).

Each year, the tree forms new cells, arranged in concentric circles called annual rings or annual growth rings, which are restricted to the spring and summer months

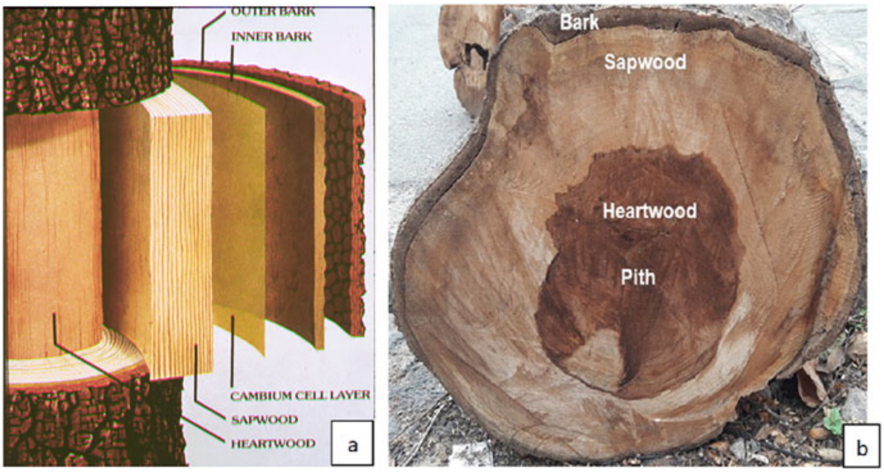

Fig. 1.1 (**a**) Transverse section of wood truck (Source: Morris, 1998) and (**b**) Cross section of tree trunk

Fig. 1.2 Cross section of (**a**) dicot (Teak) showing annual rings and (**b**) monocot (Black palm) without annual rings

of the year. These annual rings show the amount of wood produced during one growing season. Growth rings are more or less distinct in trees depending on the degree of cell differentiation within an individual growth ring. One year of growth is therefore represented by a ring consisting of a light part and a dark part which are prominently seen on the transverse surface. The outermost ring or layer of secondary xylem cells adjacent to the cambium is the most recently formed. The cells formed at the beginning of the growth are called early wood and cells formed in the latter portion of the growing season are called late wood. These growth layers are visibly distinct due to difference in cell size and cell wall thickness in soft woods and ring-porous hardwoods, whereas in diffuse porous hardwood the annual rings are not so clear, exceptions are laurel, mango, champ etc. The tracheid of softwood undergoes a transition from thin walled wide laminated earlywood cell to thicker walled, narrow laminated latewood cell. In the ring-porous woods the vessel size decreases substantially from early wood to late wood (Eaton & Hale, 1993; Wiedenhoeft, 2012). The arrangement of vascular bundles of monocot differs by having scattered arrangement, whereas dicot trees have ring arrangement (Fig. 1.2a, b).

1.2.1 Cellular Structures of Wood

Wood is composed of complex cellular structures of various shapes and sizes which perform different functions in living trees. All woods can be grouped into two general classes:

a. Softwoods: trees with needle like leaves—gymnosperms (mostly conifers) e.g. fir, pine and deodar.

Table 1.1 Cell types in hardwoods and softwoods (Source: Eaton & Hale, 1993)

Axial cells	Transverse cells
Hardwoods	
Vessel element	Ray parenchyma cell
Tracheid	Ray epithelial cell
Fibre	
Fibre tracheid	
Libiform fibre	
Axial parenchyma cell	
Epithelial cell	
Softwoods	
Tracheid	Ray tracheid
Axial parenchyma cell	Ray parenchyma cell
Epithelial cell	Ray epithelial cell

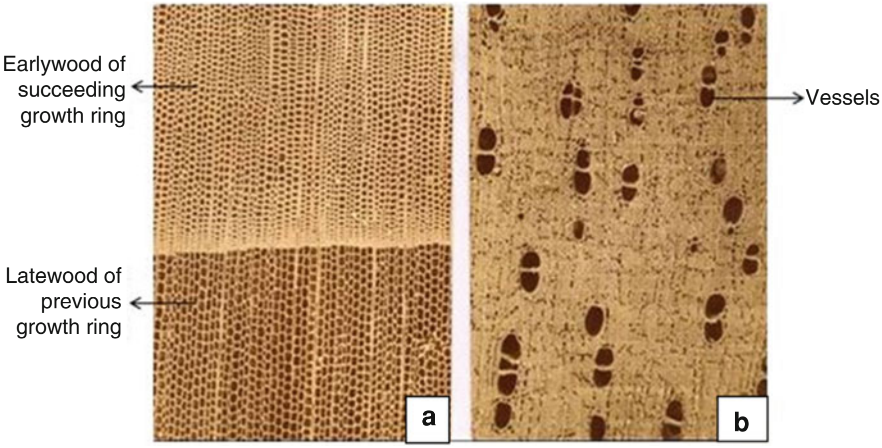

Fig. 1.3 (**a**) Non-porous wood (Softwood); (**b**) Porous wood (Hardwood)

b. Hardwoods: broad-leaved trees—angiosperms (flowering plants) e.g. teak, mango and sandalwood.

Major types of elements in wood are parenchyma cell, fibre and tracheid or vessel element. The cell types are different in soft wood and hardwood (Table 1.1). In softwoods the bulk of the wood is composed of small, regular fibrous cells called tracheids and complete absence of pores or vessels (Fig. 1.3a). These serve the combined purpose of conducting sap from the roots to the leaves and giving strength to the wood, whereas in hardwoods fibres (Fig. 1.3b), pores (vessels), axial parenchyma and ray parenchyma cells are present. In hardwood the mechanical support/ strength is contributed by fibres and conduction of sap from the roots to the leaves are by pores/vessels. In both cases food is stored in ray parenchyma cells and transported from core or pith to bark radially.

1.2.1.1 Hardwoods

Fibres

Fibres are the major elements that provide mechanical support to hardwood. They include libriform fibre and fibre tracheid. Libriform fibres are long, finely tapering narrow cells with small pits, whereas fibre tracheids are also elongated cells but shorter than libriform fibres, less pointed ends and reduced bordered pits.

Vessels

The specialized water conducting cells of hardwood are vessels; they are perforated and composed of wide cylindrical cells stacked upon one another. This perforation may be simple perforation plate with no obstructions across vessels or may be scalariform perforation (ladder like) or reticulate (network) or foraminate perforation. The vessels can be arranged in a different pattern. If the early wood vessels are larger than late wood vessels, it is called *Ring porous wood* e.g. teak (Fig. 1.4a). Thus, the growth ring can be visibly distinct because of sharp change in vessel diameter. In contrast, if all the vessels are uniform in size and scattered, it is referred to as *Diffuse porous wood* e.g. semul (Fig. 1.4b). In the sapwood, vessels conduct water and in heartwood they may be occluded with tyloses, coloured or white chalky deposits. Tyloses are the parenchyma cell membranes blown in to the vessel element lumens which cause blockage in vessels partially or completely (Fig. 1.5a). The formation of tyloses may also be the response to transition from sapwood to heartwood, fungal wound or insect attack and also due to drought. It may be filled with resins, gums or pigments.

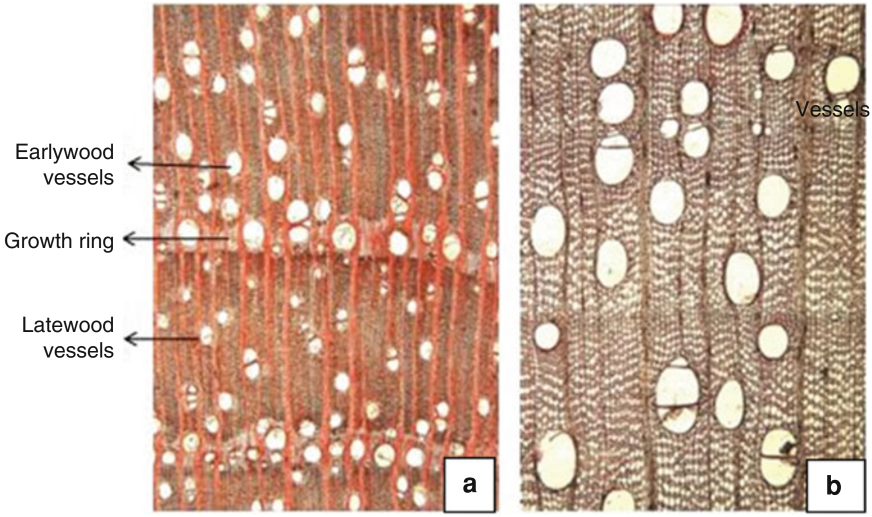

Fig. 1.4 (**a**) Ring-porous wood (Teak wood); (**b**) Diffuse-porous wood (Semul)

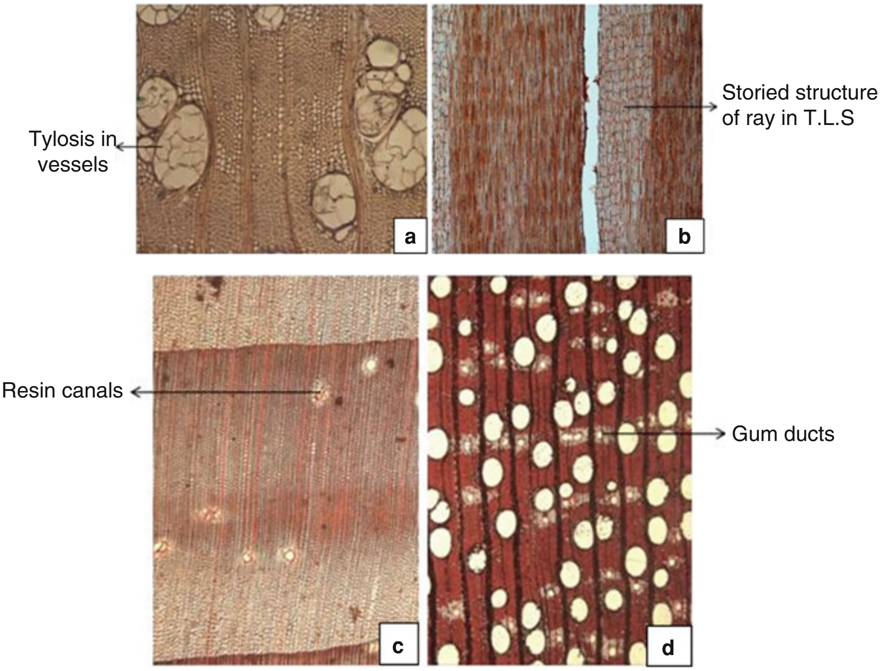

Fig. 1.5 (**a**) Tyloses; (**b**) Ripple mark; (**c**) Intercellular canals in a soft wood (resin canals)—Pine and (**d**) hardwood (gum ducts)—Gurjan

Axial Parenchyma

They are parenchyma cells arranged in bands running more or less at right angles to the rays or as a sheath surrounding vessels or scattered, it may be associated with vessels (paratracheal) or not associated with vessels (apotracheal).

Ray Parenchyma

Composed of only parenchyma cells and occur as uniseriate or multiseriate. These ray cells are divided into two categories based on forms; upright—found at upper and lower margins of the ray with smaller cell size and procumbent—found in remainder of the ray with longest diameter.

1.2.1.2 Soft Wood

Tracheids

They are longer cells, comprise most (90%) of the volume portion of softwood and serve both mechanical and conductive function. The late wood tracheid largely provides strength, which are thick walled with small lumen, whereas early wood tracheid provides water conducting and nutrient transfer function. The pits of tracheids are bordered, exist between adjacent tracheids, between ray parenchyma and tracheids and between tracheids and ray tracheids.

Axial and Ray Parenchyma

Axial parenchyma cells are absent or sometimes rare in softwoods but never as abundant as hardwood which stacked one on top of other to form parenchyma strand. They are smaller in size with simple pits. Ray parenchyma cells are rectangular in shape and are primarily involved in synthesis, storage and lateral transport of bio-chemicals.

1.2.1.3 Ripple Marks

Timbers of some of the families of hardwoods may possess some form of stored structure in elements of vessels, parenchyma, rays and fibres which will be helpful in diagnosis of the timber when viewed in tangential or radial sections (Fig. 1.5b).

1.2.1.4 Intercellular Canals

These are long tubular cavities which run either vertically or in horizontal direction, which do not possess any wall of their own. These canals serve as repositories for various kinds of gum, resins and mucilage canals. These are found in few hardwoods and are of great help in identifying the woods. Resin canals (Fig. 1.5c) or ducts (Fig. 1.5d) are voids or spaces in the wood but are not cells. Specialized parenchyma cells that function in resin production surround resin canals (Higuchi, 1985; Eaton & Hale, 1993; Wiedenhoeft & Miller, 2002; Wiedenhoeft, 2012).

1.2.2 Chemical Composition of Wood Cell Wall

Cell wall of the wood is structurally complex (Fig. 1.6) which consists of three main regions: the middle lamella, the primary wall and the secondary wall. Each of these regions is composed of three basic structural materials; cellulose as framework substance, hemicelluloses as matrix and encrusting materials, typically pectin in primary walls and lignin in secondary walls with minor amounts of extractives and inorganics. Cellulose exists in the form of microfibrils and is associated with the matrix and encrusting substances (Panshin & de Zeeuw, 1980; Higuchi, 1985).

1.2.2.1 Cellulose

Cellulose is a linear polymer of D-anhydroglycopyranose units linked by β-(1 $\rightarrow$ 4)-glycosidic bonds. The building block for cellulose is actually repeating units of a two sugar unit—cellobiose (Fig. 1.7). The number of glucose molecules per cellulose (the degree of polymerization) range from 8000 to 10,000. It has the tendency to form intra- and intermolecular hydrogen bonds. These cellulose molecules are arranged in an orderly manner into structures about 10–25 nm width called microfibrils.

1.2.2.2 Hemicellulose

Hemicellulose is a relatively short, branched homo- and heteropolymer of sugars, and its derivatives are D-xylopyranose, D-glucopyranose, D-galactopyranose, L-arabinofuranose, D-mannopyranose, D-glucopyranosyluronic acid and

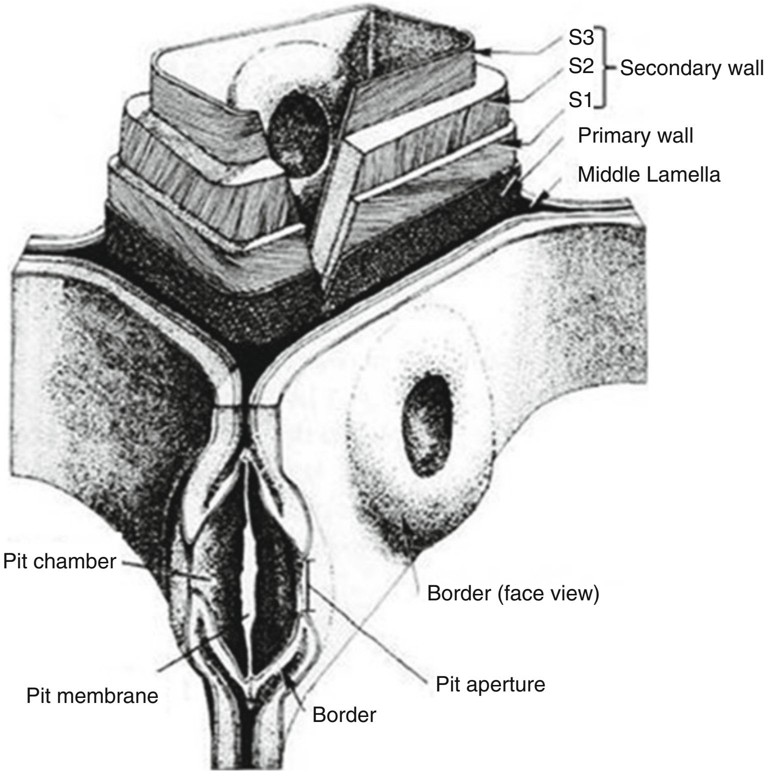

Fig. 1.6 Cell wall showing all the layers of the cell wall including the structural details of a bordered pit (Source: Wiedenhoeft, 2012)

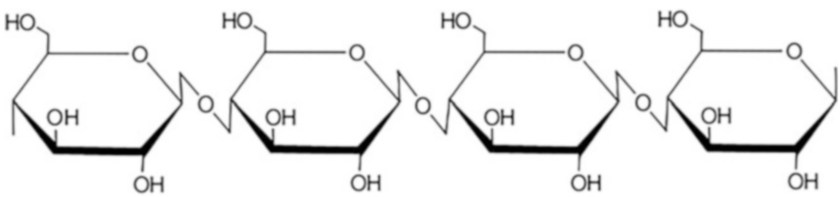

Fig. 1.7 Partial structure of Cellulose

D-galactopyranosyluronic acid (Fig. 1.8). It is associated with the cellulose and contributes to the structural component of the tree. It contains more than one type of sugars, and based on types of sugars, they are referred to as galactoglucomanan, arabinoglucuronoxylan, arabinogalactan, glucuronoxylan, glucomannan etc.

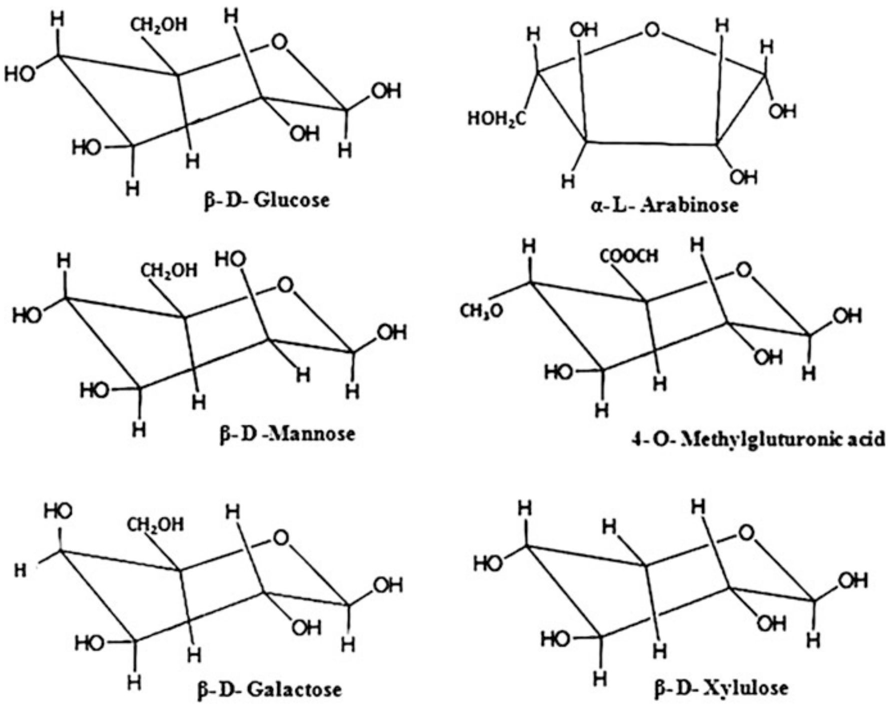

Fig. 1.8 Sugar monomers of Hemicellulose

1.2.2.3 Minor Polysaccharides

A small amount of pectin and starch is found in both hardwood and softwoods. Pectin is a polysaccharide polymer made up of repeating units of D-galacturonic acid linked α-(1 → 4), located in the border pits between wood cells and in the middle lamella. Starch is the principal reserve polysaccharide in plants. It normally occurs as granules and is composed of D-glucopyra-nose units linked α-(1 → 4) (amylose) or α-(1 → 4) with branches about every 25 glucopyranosyl units at α-(1 → 6) (amylopectin). Amylose occurs as a helix structure in the solid state due to the alpha-configuration in the polymer, and amylopectin is a highly branched structure.

1.2.2.4 Lignin

Lignin is complex polymer of polypropane units (Fig. 1.9).The precursors of lignin biosynthesis are *p*-coumaryl alcohol, a minor precursor for both softwood and hardwood, coniferyl alcohol and sinapyl alcohol, a predominate precursor of softwood lignin and hardwood lignin respectively. Lignin does not have a single repeating unit of the hemicelluloses like cellulose does; but instead consists of a complex arrangement of substituted phenolic units (Fig. 1.10). Lignin is distributed throughout the secondarycell wall, with the maximum concentration in the middle lamella (Higuchi, 1985; Eaton & Hale, 1993; Rowell et al., 2005).

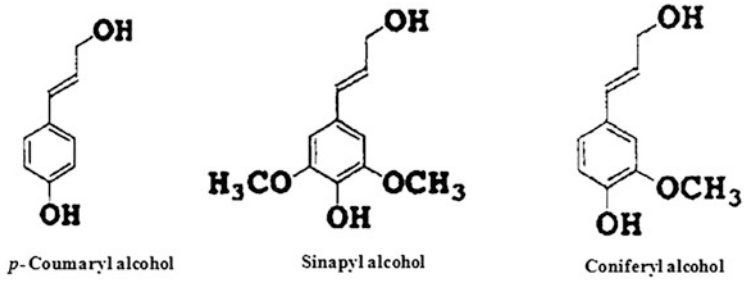

Fig. 1.9 Lignin precursor blocks

1.3 Wood: Structure and Composition as a Source of Food

In softwoods as well as in hardwoods, the core of the truck is divided into sapwood and heartwood. Adjacent to bark is the sapwood that primarily forms an active conductive portion of the stem and involved in storage and synthesis of biochemicals. Starch and lipids are the primary storage forms of photosynthate and are stored in parenchyma cells of sapwood. Due to the presence of these non-structural materials, the woods are attracted by bio-deteriorating agents like fungi and insects. Though essential minerals like nitrogen are scare in wood, the wood rotting fungi are efficient enough to get them from the environment (air, damp soil, etc.). Sapwood is protected from outside by bark layer, but once the bark is damaged or removed due to external factors like scorching sunlight, chemicals and termite attack, the tree becomes prone to the damage by bio-deterioration. Added to the high moisture content along with starch and soluble carbohydrates, it is highly susceptible to invasion by sapwood staining fungi, moulds and insects. Heartwood is formed by long-term storage of extractives or secondary metabolites, only the parenchyma cells and certain fibres are retained from sapwood for the function of storage and translocating nutrients. The central zone of the trunk is deposited with oils, gums, resins, tannins and aromatic compounds. This imparts a characteristic colour to the heartwood, which gets intensified due to oxidation of phenolic compounds. These substances along with lower permeability to water and oxygen increase the natural durability of the wood and resistance towards bio-degrading agents. Older the tree, higher the concentration of extractives deposited in each successive annual ring. Also, least durable heartwood is located in the centre of the tree, which is susceptible to the wood rotting fungi and insect borers (Eaton & Hale, 1993; Morris, 1998; Wiedenhoeft, 2012).

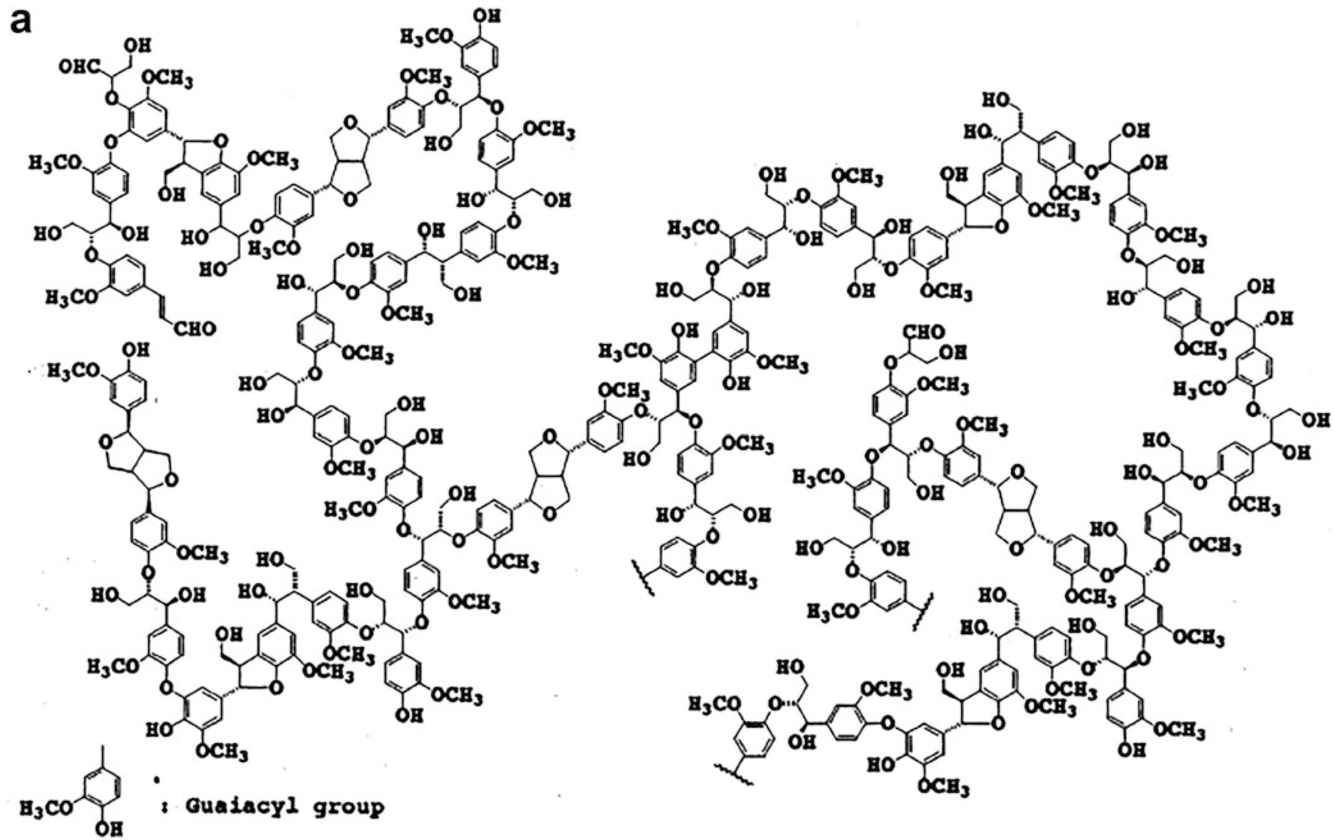

Fig. 1.10 (**a**) A structure model of conifer lignin (guaiacyl lignin) and (**b**) hardwood lignin (guaiacyl- sygrinyl lignin) (Source: Higuchi, 2002)

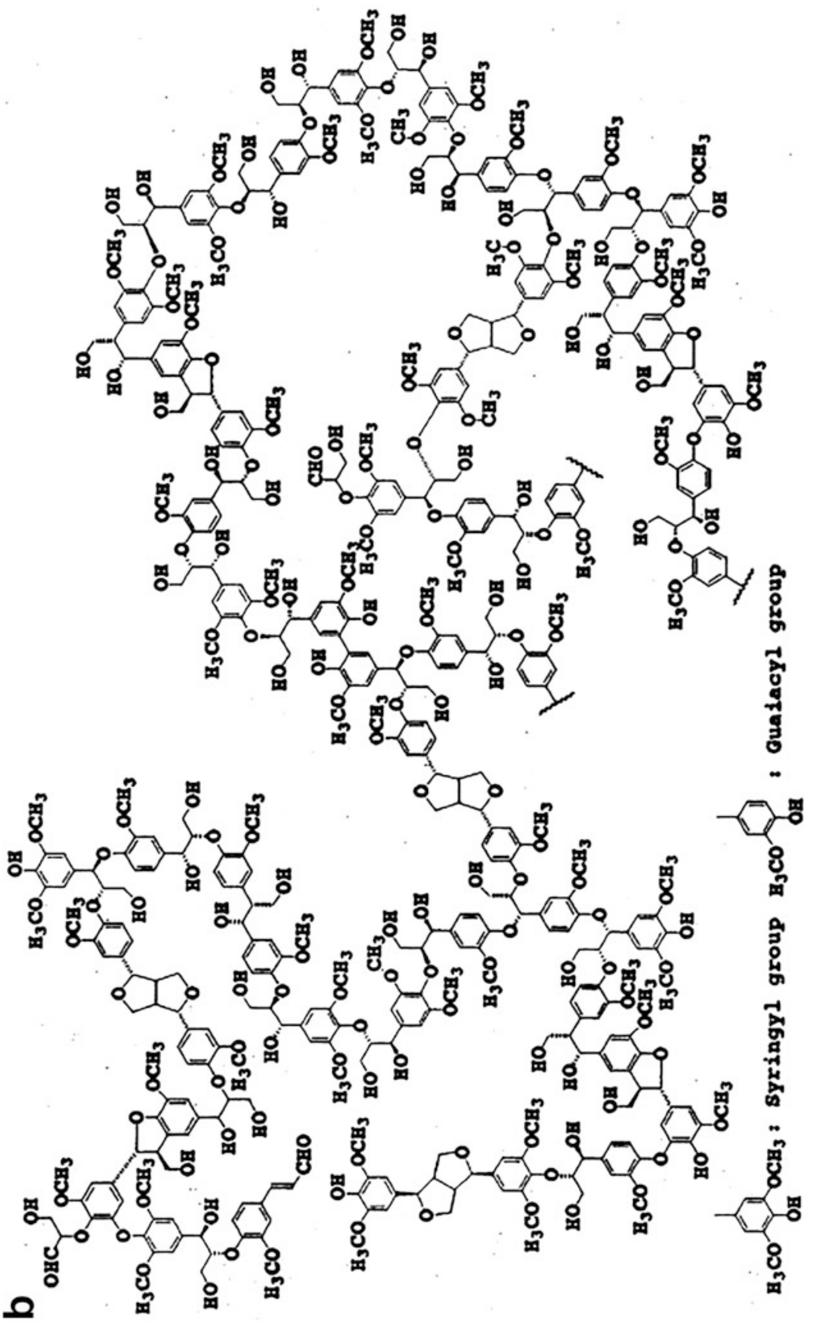

Fig. 1.10 (continued)

1.4 Wood Degradation

According to Swift et al. (1979), wood decomposition is a multifaceted process that involves combined effect of biotic and abiotic influences, as well as the mechanical and chemical properties of the wood itself (Harmon et al., 1986). In various types of wood decomposition climate is a very important factor, especially in the early stages of decomposition (Meentemeyer, 1978) where unfavourable (dry and cold) weather conditions result in the wear and tear of the wood (Couteaux et al., 1995). Accordingly wood degradation is classified into *Abiotic* and *biotic* type of wood degradation.

Woody debris is an important primary structural and functional component of forest ecosystems supporting a large proportion of the forest's biodiversity (Harmon et al., 1986). Decomposition of wood affects (Fig. 1.11a, b) soil development, reduces erosion, stores carbon, nutrients and water, which serves as a germination site for the forest vegetation, and also serves as a major habitat or substrate for numerous vertebrates, invertebrates, vascular plants, fungi, bryophytes and lichens (Samuelsson et al., 1994). Many microbes/fungi/insects inhabit the dead wood and carry out important ecological functions by accelerating rates of wood decomposition (Zhong & Schowalter, 1989) allowing nutrient export from decomposing wood (Swift, 1977) to the surrounding which results in the many physical and chemical changes in the wood (Lambert et al., 1980). In contrast, this wood inhabiting organism, along with adverse environmental conditions, will have a menacing effect on the structural and functional integrity of the economically valuable wood species (Fig. 1.12a, b).

1.4.1 Types of Wood Degradation

1.4.1.1 Degradation of Wood by Abiotic Factors

The abiotic factors such as thermal, radiation, water, sand, drying along with non-weathering factor such as chemicals will cause (Fig. 1.13) the degradation of

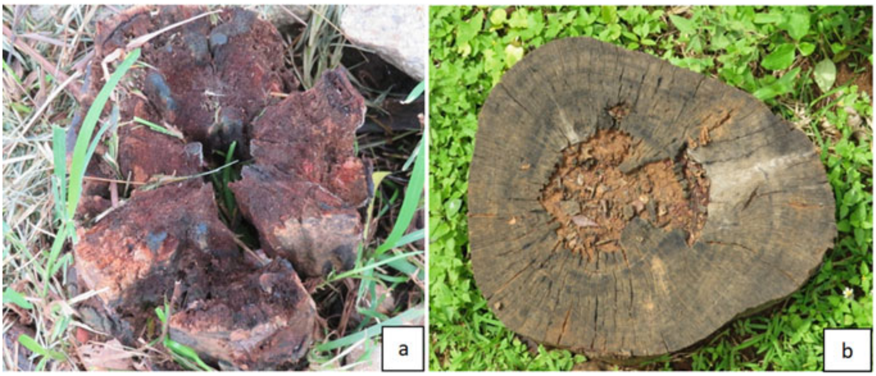

Fig. 1.11 Degradation of stump of trunk in forest ecosystems (**a**) Sandalwood and (**b**) Silver oak

Fig. 1.12 Combined degradation action of abiotic and biotic factors on (**a**) fallen tree and (**b**) wood in usage

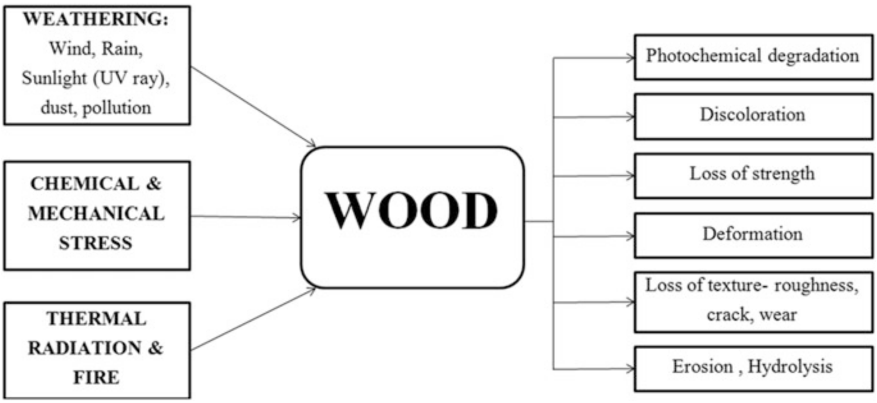

Fig. 1.13 Abiotic factors causing degradation on wood

wood (Williams, 2005). The thermal factor may cause fire, darkening and loss of strength in wood, radiation is likely to cause wood discolouration, action of water results in photo-catalysis of lignin (Pandey, 2005), presence of sand where wood is put to use will result in the fibrillation and roughening of wood, extensive drying is likely to cause cracks and surface wear. Chemical action on wood, which is directly proportionate to intensity of the chemical type and concentration of the aggressive chemical will cause fibrillation, roughening, colour changes and decrease in strength in wood. All this factors are work together to create combined effect of wood degradation and that type of wood degradation is termed as weathering (Cogulet et al., 2018).

Weathering

Weathering is a combined effect of chemical, mechanical and light factors (Müller et al., 2003). It is a complex process, involving surface changes in wood when exposed to sunlight, rain, freeze-thaw, alternating thermal loading and wind (Williams, 2005). They primarily cause surface effect, do not particularly affect the mechanical properties of wood and thus mainly of concern with regard to the appearance of the wood (Mindess, 2007).

The ultraviolet (UV) portion of sunlight reacts with lignin exposed at the wood surface and causes a slow deterioration of the lignin (Pandey, 2005). As a result, the lignin-rich lamella zones around the wood fibres degrade, the fibre-to-fibre bonding at the wood surface will be greatly reduced on which both physical/mechanical forces collectively act creating an internal stress resulting from cyclic swell/shrink, freeze-thaw and diurnal thermal loadings, combined with the external forces from rain and/or wind, resulting in an on-going erosion of the wood fibres from the wood surface (Kirker & Winandy, 2014). As lignin gets degraded, wood changes its colour to grey from yellow or brown and this process is called as *photochemical degradation of wood* (Feist & Hon, 1984; Williams, 2005). Post lignin degradation, its cellulose and hemicelluloses in the wood are exposed (George et al., 2005) which appear grey-white under visual spectrum, hence the lignin-degraded wood is grey in colour. Cellulose and hemicellulose's capacity to absorb more moisture reduces the efficiency of extractives. The entry of water during rain or other process into wood extractives results in leaching out of extractives from the wood as most of the extractives are water-soluble (Kirker & Winandy, 2014). Due to degradation of lignin, UV light further penetrates deeper and enhances moisture absorption/desorption (Evans et al., 1992).

Unlike lignin, carbohydrate-rich wood fibre is relatively resistant to UV rays (Norrstrom, 1969), but they readily absorb moisture in wet or humid conditions, which promotes swelling and in dry condition, shrinkage occurs. Due to cycles of shrinking and swelling as the wood is dried and re-wetted and sometimes due to cyclic freezing and thawing, the surface fibres may loosen and wear away, leading to a very slow surface erosion (Mindess, 2007). When the wood surface shrinks or swells, the external mechanical forces of rain and/or wind can eventually erode these degraded wood fibres from the wood surface (Teacă et al., 2013).

Exposure to Chemicals and Mechanical Factors

Degradation by chemical and mechanical manner results in swelling and shrinkage of wood, which decreases strength and also stiffness of the wood. As moisture content increases, durability is affected and wood coatings can be compromised (Carll & Wiedenhoeft, 2009). The term mechanical degradation is to be used cautiously as wood does not degrade mechanically but due to unrealistic heavy static loads placed on wood resulting in creeping of wood along with faulty designing aspects (Green et al., 1991). Chemical degradation of wood takes place due to the corrosion of metal which was used in joints, comes in contact with wet wood and termed as chemical rot (Baker, 1974). Using some harsh chemicals on wood surface will also result in the discoloration and degradation of wood (Williams, 2010).

Thermal Degradation and Fire

Wood is a highly flammable material and used as a source of fuel for at least 500,000 years. Thermal effects on wood properties are more significant. At temperatures above 100 °C, various chemical bonds of extractive, carbohydrate and lignin begin to break leading to increase in the weight loss (wood pyrolysis). If wood is heated or cooled below about 65 °C fairly, the changes in properties are reversible. However, if wood is exposed to higher temperatures for long periods of time, the wood itself will degrade due to acid hydrolysis of the cellulose. There will be a loss not only in strength but also in mass. This effect is more marked in hardwoods than in softwoods. The loss in properties is also greater at higher moisture contents (Dietenberger & Hasburgh, 2016; Mindess, 2007).

1.4.1.2 Degradation by Biotic Factors

Even though different species of wood possess different degree of resistance against biological pest, all will deteriorate under an appropriate condition. The principle wood degrading pests are fungi, bacteria, insects and marine organisms. These organisms get nourished from wood by getting basic requirements of food, oxygen, moisture and warmth. A fungal attack can be prevented by maintaining moisture content and keeping wood in dry condition, but some insects infest on dry wood and even fully submerged wood can be attacked by marine organisms (Mindess, 2007). Thus preventing wood deterioration from biological agents is a burdensome procedure, and clearly different techniques of preservation are to be adapted for different types of exposure.

Bacterial Attack

Bacterial degradation of wood is a very slow process and only carried out by cellulolytic bacteria, which have the capacity to degrade wood substances. These early colonizers attack and destroy only the non-lignified wood components (Singh & Dawson, 1998); especially in water-logged and aquatic conditions, wood is rapidly colonized by bacteria (Eriksson et al., 1990). Bacterial attack on wood causes the softening of the surface layers and excessive shrinkage on drying and wood attacked by bacteria is called wet wood. Bacterial wood degradation mostly takes place in woods which are lower in density, toughness and compression strength but with higher permeability to preservatives. Hence wood species such as poplar, willow and white fir are more susceptible to bacterial degradation and that too this decay happens mostly in the heart wood portion. Bacterial wood decay may not be very prominent, but in combination with fungal wood decay, it can cause fast degradation of wood (Kim & Singh, 1996; Schemidt & Liese, 1994; Singh & Wakeling, 1997).

Fungal Decay

Fungi are eukaryotic chemoheterophic organisms, which grow on dead and living organic material for energy and carbon source. Parasitic fungi draw nutrients from living trees and sometimes even cause disease to them, saprophytic fungi attack dead wood and woods in logs. The vegetative part of the fungi brings about invasion and colonization of wood through apical growth of hyphae. They secrete an enzyme which de-polymerizes the long-chain cellulose molecules and the lignin structure, eventually softening and weakening the wood. Sometimes the fruiting bodies are visible like deadwood conks and mushrooms and from which the reproductive spores are produced and disseminated. Wood decaying fungi belong to higher fungi, here sporulation is induced in damp condition and spore are non-motile thus insects and wind forms the major agents for dispersion. Fungi enter the wood of a standing tree in the form of spores through wounds of the tree branches or roots, under favourable conditions these spores germinate and grow gradually degrading the wood both structurally and chemically (Mindess, 2007). Among fungi, mostly ascomycetes group causes soft rot/stain while basidiomycetes fungi cause white rot and brown rotting.

The carbon-to-nitrogen ratio in components of wood is high (350:1 to 1250:1), whereas fungal mycelium requires greater nitrogen content. Thus wood decay fungi conserve and recycle their cellular nitrogen by diffusion of soluble nitrogen (organic and inorganic) into wood from the external environment through bacteria (King et al., 1980) or through atmospheric nitrogen fixation by nitrogen-fixing bacteria (Levy et al., 1974). Hence, an increased amount of nitrogen in wood above 0.3% positively affects the growth and activity of the majority of fungi. For example, wood-staining fungi primarily colonize parenchyma cells of wood with the highest content of nitrogen, or parasitic fungi attack just the wood of live trees with a permanently increased content of nitrogen (Eaton & Hale, 1993; Reinprecht, 2016). Most wood decay fungi are mesophilic and grow at 10–40 °C temperature with an optimum of 20–32 °C. The temperature plays important role in enzyme activity and growth of the fungi; wood decaying fungi are active between 18–35 °C, staining fungi at 18–29 °C and moulds at 27–37 °C (Kollmann & Côté Jr, 1968).

Insects

Wood is subjected to infestation by wood damaging insects on standing live and dead trees, wood in storage, processed wood and various products made of wood. Wood is primarily food for xylophagous insects, but can also be used as a place to live. These insects may target leaves, barks, sapwood, heartwood and even roots. Some insects generate the feeding mark on the diseased or weakened wood and thus reducing its quality. Abiotic factors like temperature, relative humidity and flow of air, sunlight or even electromagnetic field are also playing an important role in the activity and development of these wood deteriorating insects. The wood inhabiting insects depend mainly for the source of organic and inorganic substances necessary for their development (sugars, starch, fats, proteins, nitrogen substances, vitamins, salts, etc.) found in consumed wood. They can be attracted to living trees or to stored and processed wood by attractants; primary attractants are volatile chemical substances released from bark, leaves, needles or wood (e.g. monoterpenes) and secondary attractants are chemical substances biosynthesized by insects by which they mutually communicate upon the invasion of trees and harvested wood (e.g. aggregation pheromones, sexual pheromones) (Harborne, 1988; Reinprecht, 2016).

Some type of insects can infest wood when they are freshly felled with the bark intact as they lay the eggs in the crevices of the bark. These are called as insect infesting green timber. Larvae hatched from egg feed on both sapwood and heartwood and deeply penetrate by gallery systems. In some cases, they will be living in symbiotic association with fungi and their symbiotic partners always need moisture that will be high in case of green and freshly felled timber to survive, such as pinhole borers, longhorn borers and flat headed borers. Some insects like powder post beetles and termites, carpenter bee and ants can attack partially dried timber or completely dried timbers (Eaton & Hale, 1993; Reinprecht, 2016).

Marine Borers

In aquatic regimes of India, which include mangrove habitats, marine borers are the major agents of wood deterioration. Monetary losses caused by marine woodborers in India alone may range from Rs. 300 to Rs. 3000 per annum (Karande & Chongdar, 2001). All structural materials including wood in marine condition are affected by many marine bio-fouling groups, viz., micro-fouler i.e., biofilms comprised of bacteria, diatoms, algae and fungi that exert 1–2% frictional drag; soft macro-fouler (mostly macro-algae) that cause another ~10% loss and hard macro-fouler, i.e., bryozoans, tubeworms, barnacles, mussels, etc. that further exert up to 40% burden to the owner of any marine structure deployed (Marechal & Hellio, 2009). In addition, wood in particular is also infested by several primary agencies, i.e., wood boring organisms responsible for the degradation of wood in sea and mainly include crustaceans of the families Limnoriidae, Sphaeromatidae and Cheluridae and bivalves of the families Teredinidae and Pholadidae (Cragg et al., 1999; Brink et al., 2019). As marine transportation accounts for 90% exchange of global goods, the undesired phenomenon of bio-fouling of artefact is essential in maintaining good operational effectiveness of marine structures and to prevent heavy economic losses and these facts call for the management of marine bio-fouling on marine structures (Mouzouras, 1989; Vinagre et al., 2020).

1.5 Chemistry of Wood Degradation

Bio-deteriorating agents like bacteria, fungi, insects and marine borers decompose the wood structural component primarily by means of enzymatic reactions. But these enzymes are generally too larger than cell wall capillaries and also due to paracrystallinity of cellulose, the complexity of the hemicellulose coating ofcellulose microfibrils and the interpenetration and encapsulation of polysaccharide components by lignin restricts the free entry of the enzyme inside the cell wall (Cowling & Brown, 1969; Cragg et al., 2015). Thus, smaller degradative agents like

Table 1.2 Agents of biochemical degradation of cellulose

Enzymes/inorganic substances	Catalysed reaction
Cellulose	
exo-1,4-*β*-Glucanase	Attacks *β*-(1 → 4)-glycosidic bonds at non-reducing ends of cellulose giving cellobiose or glucose
1,4-*β*-Glucosidase	Hydrolysis of cellobiose and water soluble cellodextrines to glucose
Free radical (OH^-/ H_2O_2)	Decompose cellulose by oxidation reactions
Hemicellulose	
endo-1,4-*β*-Xylanase	Randomly hydrolyses 1,4 glycoside bonds of xylanes to produce oligosaccharides, xylobiose and xylose
1,4-*β*-Xylosidase	Hydrolysis of xylobiose and xylane oligosaccharides, to xylose
Acetyl (xylane)esterase	Hydrolysis splitting-off of acetic acid from xylanes
endo-1,4-*β*-Mannanase	Randomly hydrolyses 1,4 glycoside linkage of mannanes to produce oligosaccharides, mannobiose and mannose
1,4-*β*-Mannosidase	Hydrolysis of mannobiose, and mannane oligosaccharides to mannose
β-D-Galactanases	Degrade D-Galactans and L-arabino-D-galactans. It attack 1. 4-*β*-D-galactoyl linkage to produce D-galactose and galactose oligosaccharides or attack 1.3- *β*- galactosyl bond to produces 1,3 and 1.6 linked *β*-D-galactose oligosaccharides.
Lignin	
Lignin peroxidase	Involved in cleavage of Cα–Cβ bonds, Cβ–Cγ bonds, oxidative cleave of aromatic rings and $C\gamma$–C_1 bonds etc.
Mn^{2+} peroxidase	Oxidizes phenol units of lignin to phenoxy radical by Mn^{3+}
Laccase	Oxidizes phenol units of lignin to phenoxy radical

metal ions, free radicals and some low molecular organic substances cooperate with the enzymes for the degradation (Eaton & Hale, 1993). The degradation of lignocellulose is carried out by the combined action of celluloytic, hydrolytic, oxidative and oxido-reductive enzymes (Higuchi, 1985); the list of enzymes and mode of action are tabulated in Table 1.2.

White rot and soft rot fungi have a complex set of enzymes for degradation of lignin cellulose than brown rot fungi. In case of white rot fungi the enzymes of specific importance in lignin degradation are primarily oxidative, which are laccase, lignin peroxidase, manganese peroxidase, versatile peroxidase and the dye-decolourizing peroxidases. Brown rot fungi lack peroxidase enzymes for lignin depolymerization, but can degrade lignin non-enzymatically by producing free radical-Fenton reagents system (Goodell et al., 2020) which causes lignin to depolymerize and then re-polymerize as small, discrete irregular masses, separate from the cellulose (Goodell, 2020) and thus opening the cell wall for further degradation. These low molecular substances easily penetrate even between the micelles of crystalline cellulose and decompose it by oxidation reactions (Goodell, 2003).

Biochemical degradation of hemicelluloses in the cell walls of wood can occur either without simultaneous decomposition of their other macromolecular components (e.g. it takes place before decompositionof cellulose), or it takes place together with the decomposition of cellulose or also of lignin. The xylanolytic complex of enzymes is present in several bacteria and wood decaying fungi and affects xylanes in the hardwoods. It includes: endo-1,4-β-xylanase, 1,4-β-D-xylosidase, α-D-glucuronidase, α-l-arabinofuranosidase and acetylxylanesterase. The mannanolytic complex of enzymes decomposes mannanes (galactoglucosomannanes and glucomannanes) in softwoods, in case of hardwoods, endo-1,4-β-mannanase attacks the frame of mannanes while producing oligomers, β-mannosidase, β-glucosidase and α-galactosidase, by which oligomer sugars hydrolyse to monosaccharides (i.e. to mannose, glucose and galactose). Oxalic acid of brown-rot fungi can be involved first in the degradation of the side chains of the hemicelluloses, thus providing entrance to arabinose and galactose, and then depolymerize the main hemicellulose chain, or also amorphous cellulose (Green et al., 1991; Reinprecht, 2016).

Fungi are more efficient in the breakdown of lignin than bacteria, in which de-lignification is slower and more limited (Sigoillot et al., 2012). In case of insects, it is the combination of mechanical digestion with the enzymatic action that maximizes lignocellulose degradation. For example, in case of termites, the cellulolytic process starts in the foregut as the wood fragments cut by the mandibles are further triturated into smaller particles by the muscular gizzard. The endogenous enzymes secreted by the salivary glands into the foregut primarily endoglucanases initiates cellulose hydrolysis. The high concentration of endoglucanases in the midgut, breaks down the cellulose fibres and the synergistic action of β-glucosidases prevents product inhibition by reducing cellobiose accumulation (Brune, 2014). Finally, the protistan flagellates (lower termites) or bacteria (higher termites) in the hindgut produce the three principal types of cellulases viz., endoglucanases, exoglucanases, and β-glucosidases as well as hemicellulases (Talia & Arneodo, 2018).

The complex structures of various secondary metabolites or extractives are highly stable substances, which provide the durability of the wood against many microbes and insects. The disintegration of aromatic products by microbes is governed by the principle that these compounds are utilized as a source of food and energy (Higuchi, 1985). Flavanoids are readily degraded by hydrolytic removal of acyl groups and hydrolysis of glycosidic moieties by various microbes. Isoflavanoids i.e., isoflavanones and isoflavones are considered as pre-infectional inhibitors and phytoalexins against fungal pathogens. Thus, degradation of these compounds are regarded as detoxification process by fungal strains (Van Etten et al., 1982). Likewise, Lapachol belonging to quinone family is degraded through oxidative cleavage by microbes (Otten & Rosazza, 1983). In case of insects, these complex substances are degraded by the help of gut microbiotas and contribute in deterioration of wood.

1.6 Mitigation of Wood Degradation

1.6.1 Use of Natural Durable Wood

The timber resources of the world play an important role in the economic development of both wood-producing and importing regions (Wong et al., 2005). Timber, being a biological material, is susceptible to bio-deterioration by a variety of the timber dependent organisms, and hence the need to protect the wood for preventing heavy economic losses constitutes a major challenge. These timbers differ remarkably in performance when exposed to bio-degradating agents, some timber species also poses opposition to these bio-deteriorating agents and provides good structural material for many purposes. Some wood species need rapid conversion and drying after felling if the hazards of spoilage and decay are to be avoided, whereas other species like teak will last for decades (Fig. 1.14a, b) even in areas of high decay risk. This ability of the heartwood of any wood species to resist degradation or it is the inherent resistance of a timber species to decay, insect, and marine borer attack is called natural durability (Sen-Sarma et al., 1975). As per the definition 'natural durability' is an inherent ability of timber to resist deterioration by weathering and abrasion or to withstand attack by wood destroying organisms such as bacteria, fungi, insects and marine borers without preservative treatment (Eaton & Hale, 1993).

Durability is one of the key performance factors used to assess the suitability of a timber species for a specific application. For example, wood is resistance to high relative humidity and different chemicals and conditions that adversely affect steel and concrete, such as corrosive salts, dilute acids, industrial stack gases and sea air made wood as material of choice in non-residential structural applications such as cooling towers and industrial buildings used for chemical storage. Thus, natural durability of wood plays an important part as the knowledge on the natural resistance

Fig. 1.14 Natural durable teak (*Tectonagrandis*) of age 780 (**a**) and 362 (**b**) year old maintained in IWST museum, Bangalore

of woods enables users for making rational and judicious use of wood. Information on durability is also necessary to determine the suitability of species for untreated exterior use and to assess the need for preservative treatment (Haslett & Young, 1990).

1.6.1.1 Factors Contributing to the Resistance of Wood Against Degradation

Durability or natural resistance is extremely variable and the factors responsible for the difference in durability are numerous and diverse, some of them relating to conditioning within the wood and others within the circumstances attaining its use (Behr et al., 1972). Harris (1961) stated that timber reputed to be termite resistant in one area might fail when exposed to different termite species from other areas. Even the individual trees of the same species may differ considerably in their decay resistance. Observed differences may be due to genetic factors (Scheffer & Hopp, 1949) or possibly due to silviculture systems (Edmonson, 1947) although Cambell and Clark (1960) reported no correlation between the locality and durability. It is therefore important that local information about the performance of wood species is sought, prior to specifying its use in other localities or in other decay risk situations (Eaton & Hale, 1993).

Natural durability can also vary within the tree, especially in species with very durable heartwood. In many species, inner heartwood shows less resistance than outer heartwood, outer heartwood is less durable from the base of the tree upward, while the opposite occurs with inner heartwood (Scheffer & Cowling, 1966).

Durability of wood directly related to the extractives laid in heartwood. Thus wood species of darker wood are more durable than moderate/pale coloured species. These extractives are considered as important decay resistance to fungi, range of insects (Rudman & Gay, 1963) and to marine borers (Bultman, 1976), since they act as toxicants or repellents to the micro-organisms and insects. Most of the extractives include hydrolysable tannins, lignans, coumarins, alkaloids, terpenoids, steroids, flavonoids, and condensed tannins, etc., which vary from species to species and also between trees of same species (Eaton & Hale, 1993; Reinprecht, 2016).

Flavonoid provides protection against ultravioletradiation, pathogens, and herbivores (Harborne & Williams, 2000) and is classified into flavanones, flavones, chalcones, dihydroflavonols, flavonols, aurones, flavan-3-ols, flavan-3,4-diols, anthocyanidins, iso-flavonoids and neoflavonoids. It protects heartwood against fungal decay mainly from white-rot and brown-rot fungi by fungicidal activity and free radical scavengers (antioxidant) (Schultz & Nicholas, 2000; Gupta & Prakash, 2009).

The naphthoquinone plays a key role in the resistance of teak against fungal attackand tectoquinone have strong anti-termitic activity and is assumed to be the origin of the resistance of teak wood against termites (Haupt et al., 2003; Kokutse et al., 2006). Condensed tannins are natural preservatives and antifungal agents, found in high concentrations in the bark and wood in some tree species (Zucker, 1983), which act as inhibitors of enzymes like cellulases and lignases produced by decay fungi by complexing and blocking their action (Nascimento et al., 2013).

Silica, when present in sufficiently large quantity makes the wood resistant to marine borers provided the wood has compact texture. Bozkurt and Erdin (1989) reported that wood species with high silica and calcium crystal contents shows high blunt effects and will be resistant to marine borers. For example wood species *Pterocarpus soyauxii* also contain calcium oxalate contents which accounts for their natural durability under marine conditions (Sen et al., 2009). In Teak wood, the silica content is variable up to 1.4% and in *Dryobalanops* spp. silica content of 0.12 to 0.91 is reported and that is responsible for blunt effects. But there are some exceptions also such as *Shorea* spp. This will contain abundant amount of silica in the ray tissue but found to be non-resistant to marine borers (Chudnoff, 1984). In addition, these woods are reported as more dense wood hence it would have been difficult for marine borers to file denser woods as marine borers grind wood materials while using it for food (Berkel, 1970).

1.6.1.2 Natural Durability of Timbers and Their Role in Mitigating Climate Change

Climate change is one of the major issues which our generation is facing and is the result of human activity, at present the current global average temperature is 0.85 °C higher than it was in the late nineteenth century. Increased carbon emission is considered as the major reason for the climate change. Therefore, as a fact the line of combat also falls in the line of carbon emission reduction and minimization. Utilization of wood is one of the simplest, most effective and one and only way to mitigate the carbon emission as it minimizes carbon emission to nature and by removing the carbon and store it for long time. It is reported that on an average, a typical tree absorbs, the equivalent of 1 ton of CO_2 for every cubic metre growth through photosynthesis, while producing the equivalent of 0.7 ton of oxygen (Nath, 2017). Timber formed by the trees is the longer and major sinks of carbon, 1.8 tonnes of carbon dioxide is taken from the atmosphere and gets 'locked' for the life of the wood. This carbon stored in wood returns to the atmosphere only when wood gets degraded by the action of weathering and bio-deteriorating agent's intervention.

Utilization of wood species, which cannot with stand the bio-deterioration for long time, is not suggested as that allows the faster returns of carbon to the environment rather than saving it for long time hence promoting the right tree is important. Use of naturally durable timbers for the major construction is one of the best ways to ensure carbon locking for longer duration and thus safe guarding the ecosystem as these structural purpose timbers reduces the overall carbon footprint by up to 75%.

However, the question remained, are naturally durable timber species of India holding high amounts of carbon in their woods. To obtain answer we reviewed literature, which are on these particular aspects. We got data on carbon content of Indian grown tree species and compared the same with the natural durability data of those species. An analysis on the carbon content of 18 Indian grown tree species with their natural durability revealed a significant variation in the carbon content of wood species with more carbon store in class I timbers (48%) followed by in class II timbers (46%) and class III timbers (43%) (Fig. 1.15).

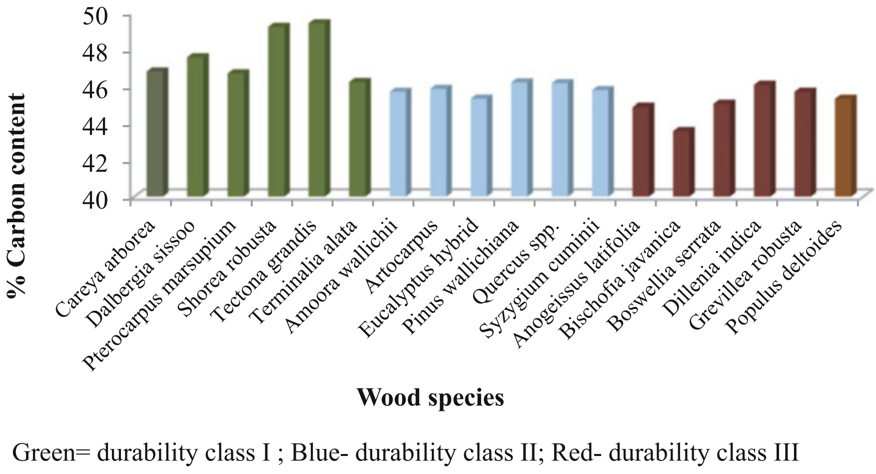

Fig. 1.15 Percentage carbon content stored in woods of three durability classes

Teak is a tree well known in the Indian subcontinent and synonymous with durability. A natural durability data shows that the teak is a class one timber and carbon content data represented by literature reveal that teak also locks high amount of carbon in its stem i.e. 49.4%. At any age of the tree, the main bole will have an average of 62% of total carbon sequestered by the tree. Review of literature also revealed that on contrary to popular belief, mature forests have been found in many cases to sequester far less CO_2 than previously thought. A typical 21-year-old teak tree will have stored 1037 kg of carbon and removed 3801 Kg of CO_2 from the atmosphere just by growing (Grant, 2008).

In the present era, it is well-accepted fact that forests can no longer be used in the same way as they have been in the past. Hence, with the new policies and political choices, the forest products and services must be assured in such a way that the survival and services of the forests can be secured. Timber is one of the most important raw materials extracted from natural forests and using them in manner under which biological agents such as fungi or borers can lead to waste of wood may result in deforestation and a whole set of problems. This can be prevented to a large extent by using naturally durable timbers which will last for long without any wood preservative treatment.

1.6.2 Use of Wood Preservatives

Chemical preservatives are toxic substances which are targeted to inhibit the activity and viability of the biodeteriorating organism and increase the shelf life of wood and timber, hence these substance are known as 'wood preservatives'. They can be bactericides (against bacteria), fungicides (against fungi), insecticides (against insects), fire retardants (against fire), anti-weathering and anti-corrosive agents

Fig. 1.16 Chair (**a**) and handicraft (**b**) made from naturally durable timber *Tectona grandis*

(against atmospheric and aggressive chemical effects). The quality of chemical protection of wood depends upon (1) the sufficientefficiency, distribution and stability of the preservative in the wood and (2) the minimal risk of the preservative to people and the environment. More ofthese factors are directly influenced as well as by the wood structure (dimension, porosity, permeability, etc.), the application properties of the preservative and the technology using of the preservative (Reinprecht, 2016).

For instance wooden products from durable timbers like teak (Fig 1.16a, b) and any preservative-treated wood both will last for years, but the natural hazard of preservative won't be there in naturally durable species. Especially in a country like India where wood after main use will be used for secondary use such as fuel wood, the hazardous effect of preservative-treated wood will be doubled as burning makes treated wood unacceptable and releases the preservative chemicals in the ash and smoke particulates (TRADA, 2005). Preservatives used to protect biodegradable materials are often noxious (Table 1.3) and are rarely themselves renewable. Many countries have banned the production and trading of several wood preservatives due to their adverse effect on humans and environment. One such is pentachlorophenol, and its salts and esters are banned in seven countries like Austria, India, Indonesia, New Zealand, Sweden and Switzerland due to its high toxicity to humans and animals, whereas a severe restriction in the use of these preservatives is implemented in members of European Union (EU), Belize and China (Intergovernmental Negotiating Committee, 2001). Creosote, another preservative that was widely used worldwide, was banned by the Environmental Protection Agency (The

Table 1.3 Advantages and risks associated with the wood treatments

Type of preservative	Advantages	Risks
Water based preservatives		
Chromated copper arsenates (CCA)	Low cost, anti-corrosive	Toxic and carcinogenic
Alkaline copper quaternary	Health and environment friendly	Increased corrosion of the metal in contact with wood
Copper azole	Health and environment friendly. Effective in smaller quantities	Increased corrosion of the metal in contact with wood
Borate preservatives	Low cost	Leachability with contact of water; copper chrome boron (CCB) leaches less, but more toxic
Sodium silicate-based preservatives		Easily washes away. Low penetrability
Bifenthrin spray preservatives		Low penetrability
Organic solvent based preservatives or oil-based preservatives		
Cole-tar creosote	Useful in large rough applications such as rail-road sleepers	Affects the aesthetics of the wood and not suitable for internal applications. Highly toxic as a pungent.
Linseed oil	Natural product	Less biological action
Light organic solvent preservatives (LOSP)	Clear non-viscous liquid, leaves no stains or shine on wood	Contains volatile organic compounds
Pentachlorophenol		Highly toxic

New York Times, 1984) and in 2003 EU Biocidal Products Regulation (BPR) placed restrictions on the type of products and on where wood treated with creosote can be used (NFU, 2021). Worldwide use of chromated copper arsenates is banned by Environmental Protection Agency in 2003 (Chen & Olsen, 2016). Treated timber is not innocuously biodegradable as untreated timber, which is one of the big advantages of using naturally durable wood so there won't be not be any long-term disposal problems.

1.7 Conclusion

Wood is a biological material, which is remarkably durable if it is properly maintained. However, they are also subject to decay due to a number of biological factors such as bacteria, fungi, insects and molluscs, and also due to non-biological factors such as weathering, wetting and drying, chemical exposure and atmospheric contaminants. Understanding the biology of wood allows to protect them by cost-effective and environmental friendly method, through the use of natural durable wood species, less environmental toxicant preservatives and by other means of treatment. If deforestation is the problem to be addressed, avoiding natural durable timber is not the way. Instead it can be answered by design adaptation to minimize the degradation or to restrict the use of durable renewable timbers for structural components and use of less durable renewable timber for other interior components. We always need to keep in mind that natural durability is a significant factor in forest conservation. The long lifespan of timber, in particular, can substantially reduce the depletion of forest resources. This also increases the profitability of forest logging. Therefore, promoting naturally durable wood should be of prime importance not only to the timber industry but also to forest services.

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Wood Decay by Fungi: Challenges and Prevention

2

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_2

Abstract

India's forest tree cover is increasing at a very slow pace. It is not sufficient enough to fulfill large population demand, and in coming years, it is expected to increase. Major part of the usable wood is destroyed by the pest and pathogen. They become active in suitable environmental conditions. The significance of wood decay and the associated fungi are discussed.

Keywords

Bacterial decay · Brown rot · White rot · Soft rot · Sap stain · Decay fungi · Decay resistance · Wood storage · Wood preservatives · Decay detection · Ultrasonic waves

2.1 Introduction

Wood has been used in the construction of houses, ships, weapons, various tools and other things for centuries (Koziróg et al., 2016). It is a versatile raw material and the only renewable construction material. Wood has quite variable properties and is used in construction for many purposes. Manufacturing of wood products requires the input of very little external energy as compared to other construction material. All construction materials except wood have a single ecocycle that involves reuse. This can help reducing the greenhouse gases emission (Anonymous/Swedishwood.com).

India's forest and tree cover stands at 24.56% of total land area, and is increasing at a very slow pace. At present, India's forest and tree cover has increased by 1%, equivalent to 3097 square miles (sq. mi) as compared to the previous survey of 2017. The top five states where the maximum forest cover has increased are Andhra Pradesh, Karnataka, Kerala, Odisha and Telangana. However, in Mizoram, Nagaland, Arunachal Pradesh, Tripura and Meghalaya forest cover has decreased (India State Forest Report, 2019).

The population's large demand for wood and fuel wood is met from trees growing outside the forest such as tree plantations, farms, and private lands (India State Forest Report, 2017, 2019; India: Wood and Wood Products Update, 2019). According to government estimate, the total growing stock of India's forest and trees outside recorded forest areas (TOF) at 5822 mcm, of which 4218 mcm is inside the forests and 1603 mcm outside. There is an increase of 54 mcm of total growing stock, as compared to the previous assessment. Out of this increase in growing stock, there is an increase of 23 mcm inside the forest and 31 mcm outside the forest area. Some of major timber species available in forests and trees outside forests include *Shorea robusta* (Sal), *Tectona grandis* (Teak), *Mangifera indica* (Mango), *Cocos nucifera*

(Coconut), Eucalyptus (Safeda) and *Areca catechu* (Areca Palm), *Melia dubia* in plains & *Cedrus deodara* (Deodar) and *Pinus roxburghii* (Pine) in hills (India State Forest Report, 2017, 2019). Other domestic species preferred by the Indian manufacturers but in low stock include *Acacia arabica* (Gum tree) and *Dalbergiasissoo* (Rosewood). Due to heavy demand, logs dominate Indian imports. Adding all categories, the total estimated wood consumption (excluding fuelwood) in India comes to about 69 mcm per year. This may be a gross underestimation, considering that a large share of wood markets, especially panel and plywood, and furniture markets, are fairly unorganized, and no official estimates are available for the same (Shrivastava & Saxena, 2017; India: Wood and Wood Products Update, 2019).

According to Planning Commission of India, the demand for timber in India is estimated to increase from 58 mcm in 2005 to 153 mcm in 2020. But, its domestic supply was expected to increase from 29 mcm to 60 mcm between 2005 and 2020 leaving a large gap between domestic supply and demand. Production of timber in India is only 0.7 cu.m/ha/year as compared to world average of 2.1 cu.m/ha/year. Domestic supply of timber is mainly from forest plantations. Between 2010–2011 and 2011–2012, India's import of wood increased from $1.70 bn to $2.58 bn (Ganeshan, 2014).

2.2 Wood Properties

When wood is used as a raw material in the manufacture of more refined wood products, the performance characteristics may be more related to factors in the manufacturing process than to the intrinsic qualities of the natural wood (Wilcox, 1978). As an organic substrate, wood is, however, liable to degradation to microbial agencies causing significant losses. There are several parameters on which wood is checked for durability such as strength, stiffness, hardness, finish retention, treatability with preservatives, resistance to shrinkage/swelling, warping checking, weathering decay, photo-degradation, colour changes and insect attack (Wiemann, 2010).

2.3 Wood Decay

Microorganisms can degrade wood under varied environmental conditions. However, while some wood-degrading organisms, such as soft rot fungi, can tolerate a wide range of temperature, humidity and pH conditions, and attack a variety of wood substrates, others have a limited tolerance (Eriksson et al., 1990; Eaton & Hale, 1993; Kim & Singh, 2000; Hunt, 2012). In comparison to soft rot fungi, white rot and brown rot fungi are sensitive to harsh environmental conditions and prefer to grow in optimum. Carbon and nutrient recycling are import aspects of degradation. Most of the degradation is carried out by fungi (Singh & Butcher, 1991; Schmidt et al., 1995). However, fungi are not solely involved in degradation but bacteria also carry out the degradation process and important in community interaction with fungi (Petrenko, 1969; Kim & Singh, 2000). Wood decay by bacteria and fungi involves degradation of cellulose, hemicellulose and lignin. This leads to aesthetic deterioration of the surface (peeling, delamination, discolouration) which leads to reduced strength, hardness (Daniel et al., 1987; Gaylarde & Morton, 1999; Blanchette, 2000; Fazio et al., 2010; Koziróg et al., 2016). However, properly maintained and treated wood can last for several years.

2.3.1 Bacterial Decay

Bacteria are omnipresent; that is why they utilize a vast range of resources. So, it is not uncommon to find bacteria on living and dead trees and harvested timbers. Bacteria are very efficient when it comes to degrade the wood cellulose but some has been reported to degrade lignin containing cell walls (Janusz et al., 2017). Primarily they are involved in pectin degradation (Abbott & Boraston, 2008). Bacteria are more tolerant towards toxic/recalcitrant substances as compared to their fungal counterpart. This property enables them to utilize heartwood extractives (Nilsson et al., 1992) and wood preservatives such as copper chrome arsenate, pentachlorophenol which are used to protect the wood against the decay fungi under suitable conditions (Clausen, 1996, 2006). They can also degrade preservative-treated wood exposed in service under a range of conditions, such as in contact with soil (Singh et al., 1994) and as part of cooling towers (Singh et al., 1992).

In aquatic environments or under other conditions of water saturation, wood is rapidly colonized by bacteria, usually in a matter of a few days (Eriksson et al., 1990). These early colonizers attack and destroy only the non-lignified wood components (Blanchette et al., 1990; Singh & Dawson, 1998). Although wood decayed by fungi such as soft rot may superficially resemble that decayed by bacteria, the patterns of bacterial wood decay are different from those produced by most decay fungi.

Based primarily on ultra-structural descriptions of the micromorphology of the patterns produced during cell wall degradation, three different forms of bacterial decay are recognized: tunnelling, erosion and cavitation. Tunnelling bacteria (TB) require the presence of oxygen for their activity and can penetrate all areas of wood cell walls, including highly lignified middle lamellae (Kim & Singh, 2000). Tunnelling bacteria can also degrade a range of lignocellulosic substrates with high lignin content (Singh & Butcher, 1991; Daniel & Nilsson, 1998) and lignin-rich outer S2 wall in compression wood (Singh, 1997a, b). Stripy (striated) erosion—In this type of attack bacteria present in the lumen of wood cells degrade the wall by producing troughs into it; the troughs are parallel with cellulose microfibrils (Kim & Singh, 2000). Conical erosion—Erosion bacteria also degrade wood in a way that produce conical or inverted V-shaped erosion troughs. Erosion bacteria (EB) can tolerate conditions with extremely low levels of oxygen (Singh et al., 1990). Wooden objects placed under water are attacked by anoxic erosion bacteria (Donaldson & Singh, 1990; Blanchette et al. 1991a, b; Kim & Singh, 1994, 2000;

Blanchette, 1995; Kim et al. 1996a, b; Björdal et al., 1999; Björdal, 2000; Singh et al., 2003, 2016; Hoffmann et al., 2004; Schmitt et al., 2005; Klaassen, 2008; Singh, 2012; Rehbein et al., 2013; Cha et al., 2014). Bacterial cavitation—Cavities are very small, but later enlarge in a fashion that keeps their characteristic diamond shape, reflecting the precise manner in which bacterial colonies establish themselves and grow as the wood decay progresses. As the decay becomes more severe, adjoining cavities often coalesce, and as a result cavities of varied forms are produced (Singh et al., 2016).

In presence of adequate oxygen and moisture mixed soft rot and bacterial degradation is found. This can be seen in preservative-treated timbers are attacked by Erosion Bacteria (EB) and Tunneling Bacteria (TB) and in timbers placed in cooling towers are attacked by TB and soft rot fungi (Singh et al., 1992). They can degrade preservative-treated wood exposed in service under a range of conditions, such as in contact with soil (Singh et al., 1994) and as part of cooling towers (Singh et al., 1992, 2016). With a combination of Light Microscopy and Transmission Electron Microscopy, difference between bacterial decay and fungal decay can be ascertained even in advanced stages where cell wall integrity may be essentially lost and bacteria may no longer be present in extensively degraded wood tissue regions (Schwarze, 2007).

Evaluating conditions that support bacterial attacks on wood and degradation of cell walls can be helpful in developing protection strategies for enhancing the service life of wooden products (Singh, 2012; Singh et al., 2016). Bacteria like *Pseudomonas* sp., *Bacillus polymyxa* and *Clostridium* sp. produce cellulases and pectinases that alter wood permeability by opening up the crystalline structure of cellulose microfibrils (Boutelje & Bravery, 1968). As discussed above, Bacteria are often able to tolerate wood preservatives at retention levels usually employed to prevent fungal attack (Shields, 1969). For example, bacterial decay has been observed in CCA-treated wood (Greaves, 1968). Some members of *Bacillus* spp. and *Pseudomonas* spp. have the ability to attack wood treated with oil borne preservatives, such as copper naphthenate and pentachlorophenol, and both genera of bacteria are more resistant to copper than are decay fungi (Clausen, 1996). Because these bacteria are more resistant to preservatives, their enzyme systems allow them to derive nutrients present in the wood cell wall while simultaneously opening the crystalline structure for advance diffusion of cellulolytic enzymes to pave the way for invasion by fungi. Non-spore-forming *Pseudomonas* spp. is commonly replaced with spore-forming *Bacillus* spp. in the biological succession of species in wood. Increasing quantities of preservative hardly change the overall bacterial flora. Rather, under those circumstances, the flora is naturally supplemented with an increased number of cellulolytic bacteria. High loadings of preservatives also indirectly enhance the bacterial population by excluding fungal competitors (Shields, 1969; Clausen, 1996, 2006).

2.3.2 Fungal Decay

2.3.2.1 White Rot

Fungi producing this type of wood decay mostly belong to Basidiomycetes and rarely Ascomycetes (e.g. *Daldinia concentrica*, *Xylaria polymorpha* and *Sarcoxylon compunctum)*. They comprise almost 93% of the decay fungi (Ryvarden & Gilbertson, 1994). They are common in nature. They are particularly active in forest ecosystems, bringing about extensive decay of stumps and debris left over from tree harvest. Hardwood species are more susceptible to white rot attack than softwood species, and untreated timbers are more readily attacked than preservative-treated timbers. White rot fungi can degrade all components of wood cell walls, including lignin; some species are specialized to primarily degrade lignin and hemicellulose, with cellulose largely unattacked (Blanchette et al., 1990; Eriksson et al., 1990). Wood cell walls can be degraded at a considerable distance from fungal hyphae. White rot has been classified by macroscopic characteristics into white-pocket (Fig. 2.1), white-mottled, and white stringy, the different types being affected by the fungal species, wood species, and ecological conditions (Schwarze & Fink, 1998). In the simultaneous white rot, carbohydrates and lignin are almost uniformly degraded at the same time and at a similar rate during all decay stages. Typical fungi with simultaneous white rot are *Flavodon flavus, Fomes fomentarius, Ganoderma applanatum, Phellinus gilvus, Phellinus igniarius, Phellinus robustus, Schizophyllum commune, Trametes hirsuta* and *T. versicolor* in standing trees and stored hardwoods (Blanchette, 1984a). Wood decayed by *F. fomentarius*,

Fig. 2.1 White pocket rot in timber

T. versicolor and some other fungi show black demarcation lines or zone lines (Schmidt, 2006). Lignin and hemicelluloses degradation run faster at least in early stages of attack by *Heterobasidion annosum* (root rot in conifers), *Xylobolus subpileatus* (heart rot in Oaks) and *Ganoderma applanatum* (butt and root rot in hardwoods). This results in relatively higher accumulation cellulose into the tissue. That is why wood decayed by white rot fungi appears "bleached". Bleaching of wood is also caused by many simultaneous degraders. Further fungi showing successive white rot are *Bjerkandera adusta, Hymenochaete rubiginosa, Irpex consors, Inonotus dryophilus, Merulius tremellosus, Phellinus cayophylli* and *Phellinus senex*. Some *Ganoderma* species caused within a wood tissue as well white pocket rot as simultaneous rot, or, depending on the wood species, white pocket rot in birch and oak and simultaneous rot in poplar (Blanchette, 1984a; Dill & Kraepelin, 1986; Otjen & Blanchette, 1986). The micromorphology is variable depending upon host and wood cell wall types attacked (Daniel & Nilsson, 1998) and in some situations the cavity formation is reminiscent of soft rot attack.

Many white rot fungi, e.g., *Heterobasidion annosum* (Hartig, 1874), *Fomes fomentarius, Ganoderma* species, and *Trametes versicolor* cause black spots of manganese dioxide deposits in the attacked wood (Blanchette, 1984b; Eriksson et al., 1990; Daniel & Bergman, 1997). Manganese deposits may occur in connection with lignin degradation by manganese peroxidase. *Physisporinus vitreus*, isolated from cooling-tower wood (Schmidt et al., 1996) exhibited these manganese deposits predominantly in the slime layer and in the inner S2 beneath a hypha shown by TEM/EDX spectra (Schmidt, 2006).

2.3.2.2 Brown Rot

Brown rot fungi also belong to the class Basidiomycetes, which metabolize cellulose and hemicelluloses of the woody cell wall by non-enzymatic and enzymatic action and leave the lignin almost intact that is why it appears brown in colour (Fig. 2.2). Some brown rot fungi also belong to the Ascomycetes (Rayner & Boddy, 1988). They are only about 7% of total rot fungi (Eriksson et al., 1990; Ryvarden & Gilbertson, 1994). This may be due to their preference over conifers, but also occur in other environments, such as various soils (Wakeling & Singh, 1993). These fungi can attack both untreated and preservative treated wood, but prefer untreated wood. One of the most characteristic features of brown rot attack is that cellulose is rapidly depolymerized even in the early stages of decay. Thus strength losses due to brown rot attack can be enormous even when the wood appears sound. Loss of birefringence from decaying wood cell walls even in early stages is a useful diagnostic feature of brown rot attack (Eaton & Hale, 1993; Wilcox, 1993; Zabel & Morrell, 1992). The degradation of wood cell walls is diffuse (Highley et al., 1985). During decay, polysaccharides are extensively depolymerized and removed, and lignin can also be modified, although lignin residues largely remain (Blanchette et al., 1990). In some cases, lignin may be removed to a limited extent. Although degraded cell walls are highly porous, the original form of the cells often remains unchanged. The degraded wood appears brown largely due to the presence of lignin. Brown rot fungi do not produce lignin-degrading enzymes. There is however reports of lignin peroxidase and manganese peroxidase in some brown rot fungi, and lignin

Fig. 2.2 Brown rot in timber

loss or metabolization by brown rot fungi have been reported. Particularly in later stages of decay, the highly lignified middle lamella/primary walls were observed to undergo attack (Schmidt, 2006). Laccase activity has been found in *Coniophora puteana* (Lee et al., 2004), and in *Gloeophyllum trabeum* and *Oligoporus placenta* (Goodell, 2003). Brown rot occurs in standing trees (e.g. *Laetiporus sulphureus*), felled and processed wood as well as in sapwood and heartwood (e.g. *Fomitopsis rosea, Gloeophyllum striatum*). Brown rot fungi colonize the wood via the rays and spread in the longitudinal tissue through pits and by means of microhyphae. They grow inside the cell lumina and there in close contact with the tertiary wall. Cubical cracks on brown rotted wood are a typical macroscopic feature. Microscopically, brown rot decay can easily be distinguished from other fungal attacks and bacterial decay from a combination of features, including loss of birefringence, absence of erosion troughs and cavities and near-normal morphological appearance of degraded wood cells (Schmidt, 2006).

2.3.2.3 Soft Rot

Certain Ascomycetes cause soft rot of the wood. These fungi are most common in soils, but can occur in other environments. Soft rot fungi are particularly active under conditions that discourage the activity of white and brown rot fungi, e.g., high preservative loading and high moisture content (Kim & Singh, 2000). Soft rot fungi often are present with wood-degrading bacteria (Santhakumaran & Singh, 1992; Singh et al., 1992; Singh & Wakeling, 1993, 1996, 1997; Wang & Worall, 1992). The attack of soft rot fungi on gymnosperm wood results in the formation of cavities (Fig. 2.3) in the secondary wall, which appear as voids in transverse sections (Kim & Singh, 2000). In longitudinal profiles these cavities appear oriented parallel to cellulose microfibrils (Bailey & Vestal, 1937; Nilsson, 1976). Individual cavities

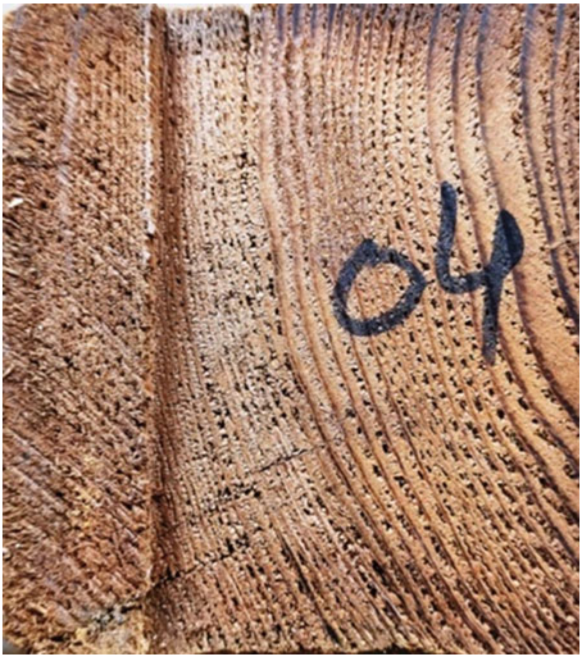

Fig. 2.3 Cavity formation due to soft rot fungi (cooling tower wood)

are conical and diamond-shaped or elongated with pointed ends. Extensive degradation results in the widening of cavities, which may also coalesce. These features are unique to cavity-forming soft rot attacks and can be used to distinguish this form of attack from bacterial attacks and other fungal attacks. Cell wall erosion is the most common form of wood decay by soft rot fungi in angiosperms (Blanchette et al., 1990; Eriksson et al., 1990; Eaton & Hale, 1993). In the erosion type of attack, although cellulose and hemicellulose can be extensively degraded, lignin is modified only to a certain extent, and microscopic observations show lignin present in degraded areas (Nilsson et al., 1989). Secondary walls can be extensively degraded, but there is little or no degradation of middle lamella. Soft rot erosion can be distinguished from other fungal attacks and most bacterial attacks, with the exception of bacterial erosion. Stripy or striated appearance of the bacterial eroded wall distinguishes this attack from soft rot erosion. However, in the advanced stages of degradation these decay patterns can be difficult to distinguish as the bacterial erosion troughs coalesce and the wood cell wall loses its striated appearance (Kim & Singh, 2000; Singh et al., 2019).

2.3.3 Stains (Sap Stain)

Blue stain (synonymous sap stain) is a blue, grey or black, radially striped wood discolouration of sapwood (Fig. 2.4), which can be caused by about 100 to 250 fungi belonging to the Ascomycetes and Deuteromycetes (Käärik, 1980). These fungi colonize the parenchymatous tissues of freshly felled timber. These varieties of pigmented fungi cause a permanent discolouration of the sapwood which may penetrate throughout the wood. These sap-stain fungi can be economically damaging because they discolour the wood and lower its value, leading to revenue loss (Florence et al., 1996). It is also called blue-stain. The most common colourations are black, grey, brown or blue, each colour showing different intensities depending on the fungi which cause the stain. Blue stain occurs in conifers, particularly in pine, but also in spruce, fir and larch, in hardwoods, like beech and birch, and in tropical woods. The stain may be superficial or penetrate deeply into the wood. In heartwood species, only the sapwood discolours, since blue-stain fungi live mainly on the content of the parenchyma cells. The hyphae are brown coloured due to melanin (Zink & Fengel, 1989) and relatively thick. Hyphae penetrate into stem wood from cross sections or radially through bark fissures and move via the medullary rays. For log colonization, moisture loss in the felled tree of 10–15% is sufficient. Blue stain occurs during seasoning or transportation of green lumber before the wood is dried and is enhanced at relative humidities above 90% (Seifert, 1999).

Seifert (1999) and others differentiated three groups of blue-stain fungi: – *Ceratocystis*, *Ophiostoma* and *Ceratocystiopsis* species (Upadhyay, 1981; Perry, 1991; Gibbs, 1999), – black yeasts such as *Hormonemadematioides, Aureobasidium pullulans, Rhinocladiella atrovirens* and *Phialophora* species, – dark molds such as *Alternaria alternata*, *Cladosporium sphaerospermum* and *C. cladosporioides*. The

Fig. 2.4 Sap stain of the poplar

majority of species identified are members of the Ophiostomataceae. Mostly isolated species is *Sphaeropsis sapinea* (syn. Diplodia pinea). Ophiostomatoid genera include: *Ophiostoma*, *Leptographium*, *Pesotum* and *Sporothix*. Some of the Ophiostomataceae members are *Leptographium truncatum*, *Leptographium procerum*, *Ophiostomaips*, *Ophiostomapiceae* conifer form, *Ophiostomapiliferum*, *Ophiostoma pluriannulatum*, *Ophiostoma querci* (syn. *O. piceae* hardwood form), *Ophiostoma coronate, Ophiostoma stenocerus, Ophiostoma floccosum, Ophiostoma huntii, Trichoderma* and *Gliocladium* species. *Trichoderma* spp. are among the most important in this respect - especially in softwoods such as pine (Thwaites et al., 2005).

Blue stain of sawn timber (secondary blue stain) is caused e.g., by *Cladosporium* species (moisture optimum 50–100%) and *Strasseria geniculata* (Butin, 1995) in sawn timber that is not completely dry or badly stacked in timber yards (Schumacher et al., 2003). Blue stain (moisture optimum 30–80%) results frequently from *A. pullulans* and *Sclerophoma pithyophila* on timber that has been converted into products, was painted and re-imbibe moisture while in service, like wooden façades, window frames, garage doors and garden furniture (Schmidt, 2006). Through decays of the coating in window wood e.g., by nails or due to inappropriate window construction, water is taken up, distributes in the wood and cannot evaporate through the coat layer. Fungi start growing and their mycelia, spore masses or perithecia cause the paint layer to flake off with further moisture increase (Sell, 1968). Hyphae of *A. pullulans* can grow through alkyd paints (Sharpe & Dickinson, 1992). Colonized wood shows excessive uptake of solutions, so that spot-shaped colour differences develop after painting. Air-borne blue stain means the spread of blue-stain fungi by wind or rain, insect blue stain is due to fungi, which are associated with bark beetles (Solheim, 1992).

Sapstain has proved difficult to control. To control sapstain fungi, synthetic fungicides have been used but they do not give reliable results even after 3 months (Florence et al., 1996). Furthermore, use of these synthetic fungicides on a large scale can cause some environmental and health concerns. Biological control of sap stain fungi has been studied extensively. Isolates of *Trichoderma* spp., *T. harzianum* and *Trichothecium roseum* can control sapstain besides the standard fungicide treatments. They are good for the internal tissues of debarked logs than the fungicide. The second approach is based on inhibition of the sapstain causing fungi by secondary metabolites produced by plants or microorganisms. Massoialactone, produced by various fungi including *Trichoderma* spp., has good anti-sapstain activity (Vanneste et al., 2002). Essential oils which have high levels of oxygenated monoterpenes and Oxygenated alcohol or phenolic monoterpenes are also effective against sapstain fungi (Hill et al., 1997; Vanneste, 1996).

2.3.4 Molds

Molds are also ascomycetous fungi and do not form fruit bodies over the wood surface (Fig. 2.5). They develop in humid conditions. Molds form non-permanent

Fig. 2.5 Mold growth on poplar (photo credit: Dr. Akhato Sumi)

colour stains on wood that can be easily brushed off. The colour is dependent on the type of mold. Green colour may be due to *Penicilium* spp., *Aspergillus* spp. or *Trichderma* spp., *Alternaria alternata* is responsible for grey colouration and black is due to *Aspergillus niger*. They do not cause mechanical alteration in wood. A good way to protect wood is to keep it away from humid conditions.

2.3.5 Wood Decay Under Wet Conditions

When wood cells are saturated or filled with water, one factor that becomes limiting to the activity of wood-degrading microorganisms is the oxygen supply. Under such conditions wood is degraded slowly, as the fast degrading Basidiomycetes, such as white rot or brown rot fungi which can actively degrade wood in most terrestrial environments (Eriksson et al., 1990), cannot degrade wood or their activity becomes highly restricted. The rate and extent of degradation depends on the conditions of exposure and the presence of toxic extractives and preservatives in the wood. Little oxygen is present in wood that is excessively wet or saturated with water or buried deep in sediments. Studies have shown that bacteria, sometimes together with soft rot fungi, play a major role in the degradation of wood in these situations (Blanchette & Hoffmann, 1993; Kim & Singh, 1994; Kim et al. 1996a, b). Because soft rot fungi and bacteria are slow degraders as compared to white and brown rot fungi, wood degradation under these conditions is slower. It is therefore not surprising that some archaeological woods recovered from ocean waters or sediments have survived for hundreds and even thousands of years (Kim & Singh, 2000). Much of the work on degradation of wood in wet environments has been devoted to examining archaeological woods because of their historical importance and a concern for their satisfactory preservation. Less attention has been given to wood that may be exposed to such conditions in service, e.g. timbers in foundation piles, cooling towers and retaining walls. Information available on the decay micromorphology of buried archaeological woods suggests that bacteria and soft rot are their main degraders as the oxygen limiting conditions of burial exclude fast degrading Basidiomycetes (Blanchette & Hoffmann, 1993; Riess & Daniel, 1997; Schmitt & Hoffmann, 1998; Kim & Singh, 1999).

2.3.6 Factors Affecting Decay

Factors governing initiation and progress of microbial degradation of wood may be external or internal; the latter is inherent in the wood (Bakshi, 1976).

2.3.6.1 External Factors

Source of Infection

Source of infection is usually an infected wood. Whenever sound wood is kept in contact with infected wood, the infection spreads via fungal hypahe without forming any spores. In service, wood will not decay if kept air dry as in case of home furniture. Soil contains mycelia and spores of decay fungi. If wood is kept in contact with moist soil the chances of infection are very high. Even when there is no contact between sound wood and infected materials, the space between them can be bridged by airborne spores (Bakshi, 1976; Schmidt, 2006).

Moisture

The development of fungi on wood is largely controlled by the moisture content. Water is taken up from the substrate wood, the soil, from masonry etc. Altogether the moisture content of wood is the most important factor for wood degradation by fungi and thus also for wood protection. Moisture in wood exists in two different forms: Bound or hygroscopic water occurs within the cell wall mainly in the cellulose and hemicelluloses and to smaller extent in the lignin. Free or capillary water in liquid form is located in the cell lumen as well as in other holes and cavities of the wood tissue (e.g. Siau, 1984; Smith & Shortle, 1991). Fungi only need a moderate amount of water for growth. In absence of sufficient water they can remain dormant for years and become active when sufficient moisture is available. About 35% to 50% moisture is required for wood rotting fungi to flourish, the actual moisture content depending on the species of fungi and the kind of wood. Fungal spores do not germinate readily on wood that has moisture content below the fibre saturation point, commonly reached at around 25% to 30%. Once established, fungi produce certain amount of moisture by the chemical decomposition of the wood enabling further propagation (Kim & Singh, 2000; Schmidt, 2006; Gonzalez & Morrell, 2012; Zelinka et al., 2020).

Oxygen

The air is most important factor in controlling the susceptibility of wood to decay. Oxygen is needed for the various reactions occurring in wood fungi, such as degradation of lignin, oxidative polymerization of phenols, and melanin synthesis in blue-stain fungi and other fungi (Schmidt, 2006). Under conditions of completely filled spaces of wood with water, the air supply is cut off and growth is stopped. However, soft-rot fungi are an exception among the wood decay fungi. They exhibit lower a requirement for oxygen and can also live in water-filled wood tissue like in sprinkled cooling-tower wood with about 200% moisture content, because the cooling-tower water is enriched with the necessary O_2 by the spraying effect of the dripping water (Reid & Seifert, 1982; Highley et al., 1983; Kim & Singh, 2000; Schmidt, 2006; Gonzalez & Morrell, 2012; Zelinka et al., 2020).

Temperature

At a certain temperature range, enzyme activity runs two to four times faster by increasing the temperature of about 10 °C (Q10 value). Frequently, the optimum lies, depending on the species between 20 and 40 °C. Psychrophilic fungi have their optimum below 20 °C, mesophilic species between 20 and 40 °C and thermophilic species over 40 °C. Thermotolerant fungi, e.g., *Phanerochaete chrysosporium* and other fungi growing in wood chip piles, prefer the mesophilic range, tolerate however still 50 °C. The maximum for mycelial growth and wood decay by most wood fungi is often at 40–50 °C, because then the protein (enzyme) denaturing by heat takes effect (Jennings & Lysek, 1999; Schmidt, 2006).

Other Factors

The pH value influences germination of spores, mycelial growth, enzyme activity (wood degradation), and fruit body formation. The optimum for wood fungi is often in slightly acid environment of pH 5–6 and for wood bacteria at pH 7. Basidiomycetes have an optimum range of pH 4–6 and a total span of about 2.5–9 (Thornqvist et al., 1987). Ascomycetes, particularly soft-rot fungi, may tolerate more alkaline substrates to about pH 11. Thus, the pH values from 3.3 to 6.4 in the wood capillary water of living trees and in aqueous extracts of wood and bark samples from trees of the temperate zones and from trading timbers (Sandermann & Rothkamm, 1959; Rayner & Boddy, 1988; Fengel & Wegener, 1989; Landi & Staccioli, 1992; Roffael et al., 1992a, b) correspond with the pH demands of wood fungi. Organic acids are produced by fungal growth, thereby increasing wood acidity. This may be a factor in the corrosion of metal fittings in contact with the wood. Treatment of wood with nitrogenous materials stimulates growth of wood-rotting fungi, and contamination of wood by urine or manure can increase susceptibility to decay (Schmidt, 2006).

At first sight, light might have no significance for fungi, because fungi are carbon-heterotrophic. A requirement for light occurs particularly with respect to the initiation of reproduction and the ripening of the fruit bodies. Light is the signal that the mycelium has reached the (irradiated) surface, where there the spores can be produced in an environment suitable for spore release (Jennings & Lysek, 1999). Fungi may also use the direction from which the light is coming to orientate themselves (Jennings & Lysek, 1999). During the primordium growth of Basidiomycetes, the stipe grows towards the light source.

2.3.6.2 Internal Factors

Wood provides a suitable substrate for fungus growth, and the cellulose, lignin and other components of the cell walls and wood tissues provide suitable food. Some species of wood are more naturally durable because they contain substances toxic to fungi, and the heartwood of these will only be attacked by certain fungi. It can be generally assumed, however, that no wood is entirely immune to attack if placed in conditions favourable to fungal growth, allowing for some variation in the susceptibility to decay of different kinds of wood. It is possible to eliminate the food supply by treating it with certain substances toxic to fungi but harmless to men and animals. This is the basis of wood preservative treatment (Bakshi, 1976; Schmidt, 2006; Verbist et al., 2019).

2.4 Evaluation of Decay Resistance

Wood durability (Natural Durability) is based on the presence of accessory compounds, whereby it concerns numerous compounds from different chemical classes (Fengel & Wegener, 1989; Obst, 1998). They are produced in the living tree during transition from the sapwood to the heartwood and are deposited in the heartwood (Taylor et al., 2002). Thus only the heartwood exhibits natural durability, while the sapwood of all wood species is only little or not durable. Indian standard uses four classes based on durability tests namely, I (very resistant), II (resistant), III (moderately resistant) and IV (non- resistant) based on weight loss of wood in laboratory tests (Bakshi, 1976). For each species, outer and inner heartwoods are tested. Soil Block (Fig. 2.6) and Kohl Flask methods are employed to evaluate decay resistance.

2.4.1 Fungi Used as per the Bureau of Indian Standard (BIS)

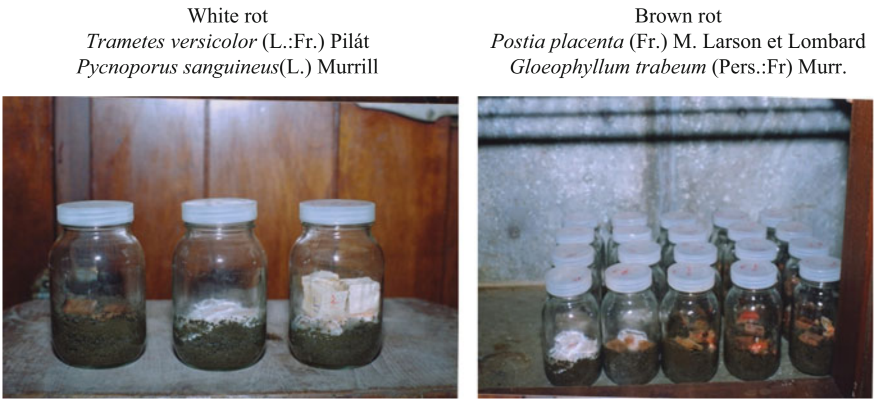

Fig. 2.6 Evaluation of decay by Soil Block method (Photo credit: Dr. N.S.K. Harsh)

2.4.2 Decay and Field Resistance of Some Indian Timbers

Some of the Indian timbers species with their durability class are tabulated in Table 2.1.

2.5 Chemistry of Decay

Decay fungi degrade modulus of rupture (MOR) and modulus of elasticity (MOE) of plywood with modest weight loss (Wei-hong et al., 2005). During early incipient decay of wood, small changes in the chemical composition of wood can result in measurable reduction in strength before measurable weight loss has occurred (Schmidt et al., 1978; Wilcox, 1978; Imamura, 1993; Winandy & Morrell, 1993; Kim et al. 1996a, b; Curling et al., 2001, 2002). Many techniques have applied to assess wood decay, such as weight loss (Carneiro et al., 2009), strength and modulus loss (Yu et al., 2011), microscope techniques (Schwarze, 2007), X-ray diffraction analysis (Li et al., 2011), molecular weight changes (Wang et al., 2013), thermogravimetric analysis (Popescu et al., 2010), Fourier transform infrared spectrum (Popescu et al., 2011), 13C solid-state nuclear magnetic resonance (Tomak et al., 2013), stress wave non-destructive testing (Yang et al., 2017) and many more. Ultrasound sonic detection is discussed later in this chapter.

2.6 Decay in Storage and Service and Its Control

Decay in living trees proceeds inside out, while in dead or fallen trees it proceeds from outside to inside. When tree with preexisting decay is felled, the infection continues to grow depending on the species and moisture conditions while some species become inactive (Bakshi, 1976). Fungi are most active in hot and humid condition and very less active or almost inactive during winters. So, winter is considered best time for felling in plains but in hills best time for felling is summers and spring.

2.6.1 Decay After Felling

It is recommended that after felling logs should be transported as soon as possible to the storage yard. In case of delay the cut ends should be treated with a preservative, followed by an end-coating to control drying checks (Puri & Taneja, 1967).

2.6.2 Decay in Storage

Logs need to be stored at conditions that minimize the growth of fungi, bacteria and insects. There are two general methods for storing logs: dry storage and wet storage.

Table 2.1 Decay and field resistance of some Indian timbers

Sl. No.	Tree species	Common name/ trade name	Decay class of heart wood		Durability class in field testing	Reference
			Outer	Inner		
1.	*Abies pindrow*	Fir	–	–	III	Masani (1961), Das et al. (1965), Purushotham et al. (1973), Tewari (1978)
2.	*Acacia arabica*	Babul	–	–	III	Masani (1961), Das et al. (1965), Purushotham et al. (1968)
3.	*Acacia auriculiformis*	Assam teak	I	–	–	Nagaveni and Ananthapadmanabha (1991), Remadevi and Raja (2007)
4.	*Acacia catechu*	Khair	–	–	I	Masani (1961), Das et al. (1965), Tewari (1978)
5.	*Acacia nilotica*	Babul	II–III	III	III	Bakshi (1976), Tewari (1978)
6.	*Acacia nilotica*	Babul	II–III	III	III	Bakshi (1976)
7.	*Acer* sp.	Maple	IV	IV	III	Masani (1961), Bakshi (1967), Bakshi (1976)
8.	*Acrocarpus fraxinifolius*	Mundani	III–IV	III–IV	III	Tewari (1978), Nagaveni et al. (2011)
9.	*Adina cordifolia*	Haldu	III	III	III	Masani (1961), Purushotham et al. (1968), Bakshi (1976), Tewari (1978)
10.	*Albizia chinensis*	Siris	III	II–III	III	Bakshi (1976)
11.	*Albizia odoratissima*	Kala Siris	I	I–II	I	Bakshi (1967, 1976), Masani (1961), Das et al. (1965), Purushotham et al. (1973), Puri and Khan (1970), Tewari (1978)
12.	*Albizia procera*	Safed siris	I–II	II–III	II	Das et al. (1965), Bakshi (1967, 1976), Purushotham et al. (1973), Tewari (1978)
13.	*Amoora walichii*	Amari	II–III	–	II	Masani (1961), Das et al. (1965), Bakshi (1976), Tewari (1978)
14.	*Anogeissus latifolia*	Axlewood	III	II–III	III	Tewari (1978)
15.	*Aphanamixis polystachya*	Pitraj	II	–	I	Das et al. (1965), Bakshi (1967, 1976), Tewari (1978)
16.	*Artocarpus lakkcha*	Lakooch	I	–	I	Das et al. (1965), Bakshi (1967, 1976), Masani (1961), Tewari (1978)

(continued)

Table 2.1 (continued)

Sl. No.	Tree species	Common name/ trade name	Decay class of heart wood		Durability class in field testing	Reference
			Outer	Inner		
17.	*Bambusa arundinacea*	Bamboo	–	–		Das et al. (1965)
18.	*Bambusa nutans*	Bamboo	–	–	III	Das et al. (1965)
19.	*Bassia latifolia*	Mahua	–	–	I	Masani (1961), Das et al. (1965)
20.	*Bombax ceiba*	Semul	IV	IV	III	Bakshi (1976), Masani (1961), Tewari (1978)
21.	*Boswellia serrata*	Salai	IV	IV	III	Masani (1961), Das et al. (1965), Tewari (1978), Bakshi (1976)
22.	*Bridela retusa*	Kasi	I–II	II	II	Masani (1961), Das et al. (1965), Puri and Khan (1970), Bakshi (1967, 1976), Purushotham et al. (1973)
23.	*Cassia fistula*	Amaltas	I	I	I	Bakshi (1976), Masani (1961), Bakshi (1967, 1976)
24.	*Casuarina junghuhniana*	Casuarina	IV	IV	–	Bakshi (1976)
25.	*Chukrasia velutina*	Chickrassy	III	III–IV	III	Masani (1961), Bakshi (1967, 1976)
26.	*Dalbergia latifolia*	Rosewood	I	I	I	Bakshi (1976)
27.	*Dalbergia sissoo*	Shisham	I	I–II	I–II	Masani (1961), Bakshi (1967, 1976), Tewari (1978), Scheffer and Morrell (1998)
28.	*Dillenia indica*	Dillenia	III	III	III	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), Tewari (1978), Scheffer and Morrell (1998)
29.	*Diospyros melanoxylon*	Ebony	IV	IV	III	Tewari (1978), Scheffer and Morrell (1998)
30.	*Dipterocarpus turbinatus*	Gurjan	II	–	III	Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), Scheffer and Morrell (1998)
31.	*Dryobalanus aromatic*	Kapoor	I	–	–	Nagaveni et al. (2011)
32.	*Dysoxylum malabaricum*	White Cedar	–	–	I	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998)
33.	*Elaeocarpus tuberculatus*	Rudrakh	–	–	III	Rao et al. (1982)

34.	*Eriolaena candollei*	Salmon wood	–	–	I	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998);
35.	*Eucalyptus camaldulensis*	Eucalyptus	–	–	I	Dobriyal and Indra Dev (1992)
36.	*Eucalyptus citriodora*	Lemon-scented gun	–	–	III	Dobriyal and Indra Dev (1992)
37.	*Eucalyptus globulus*	Blue gum	–	–	II	Tewari (1978), Scheffer and Morrell (1998)
38.	*Eucalyptus grandis*	Eucalyptus	–	–	I	Dobriyal and Indra Dev (1992)
39.	*Eucalyptus hybrid*	Eucalyptus	–	–	II	Indra Dev and Chauhan (2004)
40.	*Eugenia jambolina*	Jaman	–	–	II	Das et al. (1965)
41.	*Ficus benghalensis*	Fig	–	–	III	BIS-401 (1982)
42.	*Garuga pinnata*	Garuga	–	–	I	BIS-401 (1982)
43.	*Gluta tavayana*	Gluta	–	–	I	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998)
44.	*Gmelina arborea*	Gamari	III	III	I	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)
45.	*Grewia tiilifolia*	Dhaman	I–II	II–III	III	Bakshi (1976)
46.	*Hardwickia binata*	Anjan (piney)	I	I	I	Masani (1961), Das et al. (1965), Bakshi (1976), Puri and Khan (1970), Tewari (1978), BIS-01 (1982), Scheffer and Morrell (1998)
47.	*Heritiera minor*	Sundri	–	–	I	BIS-401 (1982)
48.	*Hevea brasiliensis*	Rubber wood	III	III	III	Ananthapadmanabha et al. (1990), Indra Dev and Chauhan (2004), Remadevi and Raja (2007), Shanbhag and Sundararaj (2013a, b)
49.	*Hopea cordifolia*	Hopea	–	–	I	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)
50.	*Juglans regia*	Walnut	IV	IV	III	Masani (1961), Bakshi (1967, 1976), BIS-401 (1982)
51.	*Lagerstromia lanceolata*	Benteak	II	II	I	Purushotham et al. (1973), Bakshi (1976)

(continued)

Table 2.1 (continued)

Sl. No.	Tree species	Common name/ trade name	Decay class of heart wood		Durability class in field testing	Reference
			Outer	Inner		
52.	*Lagerstromia parviflora*	Lendi	I–II	III	III	Masani (1961), Das et al. (1965), Bakshi (1976), Tewari (1978), Scheffer and Morrell (1998)
53.	*Lagerstromia speciosa*	Jarul	I–III	II–III	II	Bakshi (1976)
54.	*Madhuca latifolia*	Mahua	I	II	I	Puri and Khan (1970), Bakshi (1976), Tewari (1978), BIS-01 (1982), Scheffer and Morrell (1998)
55.	*Mangifera indica*	Mango	III	III	III	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), Rao et al. (1982), BIS-401 (1982), Scheffer and Morrell (1998)
56.	*Maniltoa polyandra*	Ping	III	–	III	Bakshi (1976)
57.	*Melia composita*	Malabar Neem	III	–	–	Bakshi (1967, 1976)
58.	*Mesua ferrea*	Mesua	I	I	I	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), BIS-401 (1982), Jain and Narayan (1998)
59.	*Michelia champaca*	Champ	III	II–III	III	Bakshi (1976)
60.	*Morus alba*	Mulberry	–	–	III	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998)
61.	*Ougeinia oojeinensis*	Sandan	II	I	I	Masani (1961), Das et al. (1965), Bakshi (1967
62.	*Palaquium ellipiticum*	Pali	II–III	III	II	Bakshi (1967, 1976), BIS-401 (1982)
63.	*Pinus roxburghii*	Chir	III	–	III	Das et al. (1965), Purushotham et al. (1968), Bakshi (1976), Tewari (1978), BIS- 401 (1982), Scheffer and Morrell (1998)
64.	*Pinus walichiana*	Kail	I–IV	III–IV	III	Bakshi (1976)
65.	*Populus deltoides*	Poplar	–	–	III	BIS-401 (2001)
66.	*Prosopis chilensis*	Babul	–	–	II	Indra Dev and Chauhan (2004)
67.	*Pterocarpus marsupium*	Bijasal	I	I–II	I	Masani (1961), Bakshi (1976), Tewari (1978), Scheffer and Morrell (1998)

68.	*Quercus lamellosa*	Indian oak	–	–	II	Tewari (1978), Scheffer and Morrell (1998), BIS:401 (2001)
69.	*Quercus lineata*	Indian oak-	–	–	II	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)
70.	*Schima wallichi*	Chilauni	III	–	III	Bakshi (1976)
71.	*Schleichera oleosa*	Kusum	–	–	III	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)
72.	*Shorea robusta*	Sal	I	I–II	I	Masani (1961), Bakshi (1967, 1976)
73.	*Sonneratia apetala*	Keora	–	–	II	BIS-401 (1982)
74.	*Soymida febrifuga*	Rohini	–	–	I	Das et al. (1965), BIS-401 (1982)
75.	*Tectona grandis*	Teak	III	III	I	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Jain and Narayan (1998), Scheffer and Morrell (1998), Muthukrishnan et al. (2004)
76.	*Terminalia allata*	Laurel	II–III	III–IV	II	Bakshi (1976)
77.	*Terminalia bellirica*	Bahera	III–IV	III–IV	III	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)
78.	*Terminalia paniculata*	Kindal	I	I	III	Purushotham et al. (1973), Bakshi (1976)
79.	*Toona ciliata*	Toon	I–III	II–IV	III	Bakshi (1976)
80.	*Vitex altissima*	Milla	–	–	I	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Balasundaran et al. (1985), Scheffer and Morrell (1998)
81.	*Xylia xylocarpa*	Irul	I	I	I	Masani (1961), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998)

Source: Bakshi (1976) and Sundararaj et al. (2015)

Precautions must be taken with each storage method to ensure defect-free timber. Fungi and insects are inactive at under conditions of wet storage with low levels of oxygen. On the other hand, many types of bacteria can grow in wood under wet, anaerobic conditions, but not at subfreezing temperatures. In dry storage, the end coating should be thick enough to cover all wood pores, cracks, and irregularities on the surface, yet viscous enough so that it neither cracks excessively. It is good practice to treat the log ends with chemical fungicide before end coating to prevent sapwood staining and rot fungi. Wood-boring insects carry spores and hyphae of sapwood-staining fungi and decay fungi into the logs, even though areas with attached bark, logs may need to be sprayed with a mixture of chemicals that control both insects and fungi. Prompt sawing of freshly cut logs is the easiest way to control chemical sapwood stains because treating the logs with fungicides that prevent blue stain will not be effective (Simpson & Ward, 2001; Rietz, 1978; Anonymous; Lutze, 2014).

It has been observed that logs sent to timber depot are not maintained properly. They are dumped on ground that does not have concrete floor, usually for months and sometimes even for years until they are completely decayed (Fig. 2.7). The soil absorbs enough moisture during rain that provides suitable conditions to fungal spores surviving in soil. Rain increases the moisture content of the logs to 20% or more, fungi may grow very easily under these conditions and cause stain and decay. Some of the saprophytes like *Schizophyllum commune* and *Trametes hirsuta* can fruit within 3 months on fallen log if conditions are suitable.

Ideal storage areas should be open, well drained, and kept free of weeds and debris that restrict air movement along the surface of the ground, harbour fungi and insects, and create a hazard when dry. The ground, particularly along runways for lumber-handling equipment, should be surfaced with gravel, crushed rock, asphalt, or concrete. To minimize fungal and insect attacks on stored lumber, air-drying yards

Fig. 2.7 A poorly maintained timber depot

should be kept sanitary and as open as possible to air circulation. Open sheds should be well maintained, with an ample roof overhang to prevent wetting from rain. In areas where termites or water-conducting fungi may be troublesome, stock to be held for long periods should be set on foundations high enough to be inspected from beneath (Rietz, 1978; Lutze, 2014).

2.6.3 Decay in Service

Wood may be used outdoors or indoors. Most of the fungi cannot grow below 20% moisture. Seasoned wood is most suitable for interior use. There is no reliable method to remove already established decay into the wood. To keep wood continuously dry, adequate measures should be taken like moisture proofing, ventilation or use of treated and durable wood where timber is liable to wetting. Treatment should be done with oil-based preservatives containing water repellants (FAO, 1986).

For the exterior, durable timbers and preservative-treated wood should be used as it has high chances of decay. If necessary, chemical treatment of soil is recommended, like around poles (Bakshi, 1976). To prevent soft rot, resistant wood should be used and prior use, treatment with high quality preservative should be must.

The indoor wood decay fungi ("house-rot fungi") cause considerable economic damage in buildings. *Polyporus arcularius, Schizophyllum commune, Datronia mollis, Datronia caperata, Xylobolus frustulatus, Gloeophyllum striatum* and *Serpula lacrymans* are some of the indoor wood decay fungi. Pioneer colonizers are usually *Schizophyllum commune* which produce fruitbodies in the same season.

For prevention following preservatives can be used:

1. Water-based preservatives (boron, CFB, CC, CCA, CCB, CCF salts, quaternary ammonium compounds, quaternary ammonium-boron compounds, chromium-free copper compounds (Cu-HDO, Cu-quaternary ammonium, Cu-triazol))
2. Solvent-based preservatives (e.g., Al-HDO, pyrethroids)
3. Solvent-based and water-soluble preservatives (only insects, carbamates)
4. Coal tar oil distillates (creosotes)
5. Special compounds for wood-based composites (only fungi, inorganic boron compounds, K-fluorides, K-HDO)
   Source: Schmidt (2006)

2.6.4 Decay in Pulpwood

In India, timber species mainly used for pulpwood are Bamboos, Eucalyptus, Poplar, Casuarina, Subabul (*Leucaena* spp.), Ardu (*Ailanthus excels*) and Bakain (*Melia* spp.). The wood-based paper mills contribute 31%, agro-based 22% and recycled 47% (Ganeshan, 2014). Per capita consumption of paper in India is 9.3 kg as against the world average of 56.7 kg and by 2020 (https://www.careratings.com/upload/NewsFiles/Studies/Paper%20Industry%20Report%202018.pdf), it was estimated that the per capita consumption of paper will be 13 kg in India. Indian paper industry consumes eight million MT/annum of wood (~13 million cum/annum), and 90% requirement met through farm level plantations, https://events.risiinfo.com/asian-conference/sites/default/files/presentations/2016/Sanjay%20Singh_EN.pdf).

Principally two types of fungi are involved in deterioration of pulpwood: (1) staining and molding fungi (2) wood-decaying fungi. Staining and molding fungi are important in pulpwood primarily because they discolour wood. Their attack is concentrated in sapwood and in non-fibrous cells that are of little significance in supplying cellulose for pulp. Consequently, their effect on reduction of strength of wood usually is minor. Wood decay fungi, in advanced stages target cellulose and hemicelluloses which is main ingredient in paper making (Lindgren & Eslyn, 1961).

Lumbers are stored in large piles at paper mills which have to hold the stock in storage for several months resulting in stain and decay and also attacked by borers. In high rainfall areas, decay may be particularly severe in piles stacked directly on the ground. Pile may become completely too partially decayed that is directly in contact with soil (Lindgren & Eslyn, 1961; Bakshi, 1976).

2.6.5 Chip Deterioration

Traditionally wood chips have been digested chemically that are hazardous to environment and use conventional energy. Use of white rot fungi to digest wood chips is an eco-friendly method (Messner et al., 2003). This process of biopulping includes “selective white rot”. As in most cases of “selective white rot” and particularly in late stages of attack, cellulose is also degraded to some extent (Ander & Eriksson, 1976). As per Schmidt (2006), the term “preferential delignification” should be used. Biopulping is defined as the pretreatment of wood chips with selectively delignifying white rot fungi prior to mechanical or chemical pulping (Messner, 1998). In this process, mechanical pulp is produced from chips pretreated with a white rot fungi e.g. *Phanerochaete chrysosporium* (Ander & Eriksson, 1975). The fungi produce lignin peroxidase (Tien & Kirk, 1983) that helps to degrade lignin of the wood chips.

Biopulping successfully reduces chemicals and manufacturing and energy costs. When biopulped chips are used to produce mechanical pulp, energy for typically improves 20% to 40% (Hunt et al., 2004). Biopulping can reduce 20% of the total pulping time necessary for achieving pulp and paper properties comparable to those from controls (Chen et al., 1999).

Despite the massive amount of money and work devoted to biopulping, a sweeping success seems however vague. Some common difficulties involved are (Schmidt, 2006):

- It is generally difficult to scale-up small-sized laboratory experiments with fungal pure cultures via medium-sized rotating fermenters with controlled aeration and temperature to the final aim of obtaining the same result in chip silos or even in large-sized chip piles under natural outdoor conditions.

- During controlled biopulping, the different white rot fungi may be grown on wood chips for 10 to 15 days. In a wood chip pile, available nutrients, humidity and temperature are, however, favourable to contamination by many fungi. Most common are *Trichoderma* species, of which some excrete antibiotics against other fungi.
- Uneven distribution of the inoculum, unsuitable or uneven oxygen and carbon dioxide amounts, unfavourable or uneven wood moisture content, and increase of the temperature to 50 °C or even to the incineration point where most of the wood decay fungi fail to survive.

2.7 Pruning

Forest trees and trees outside forest are pruned to produce high-class timber; trees in urban areas are pruned for safety reasons and along motorways and power-lines for clearance. Each cut causes a wound, which leads in the exposed wood to discolouration and decay. Pruning is usually done during the dormant season. Injuries should be avoided in hardwoods during the dormant stage and in spruce from late summer to winter due to different wound reactions (Lenz & Oswald, 1971; Armstrong et al., 1981; Dujesiefken et al., 1991; Schmitt & Liese, 1992). Pruning should be clean and perpendicular to avoid any retention of water. There should be no stubs or remnants of the branch as they serve as infection courts for the wood decay fungi. Decay fungi can enter into the main trunk via these stubs. Usually wood preservatives are used for the treatment of the wound. However, it is important to check the toxicity of the chemical. Treatment with wood preservative can lead to discolouration up to few inches into the tree. The open wound or exposed wood after pruning can be treated with Chaubatiya paste (Kaith et al., 2011). Cavities can be filled with polyurethane foam (Dujesiefken & Kowol, 1991). Traffic wounds on street trees should be covered by black plastic wraps, which promote the development of a surface callus overgrowing the wound area.

2.8 Tree Rot by Decay Fungi

There is a broad spectrum of decay fungi affecting trees. The broad spectrum fungi belong to various clades. Earlier they were collectively known as Aphyllophorales which is now an obsolete order (Kirk et al., 2008). General term used for rot fungi is still polypores (Seehann, 1971). However, there are numerous rot fungi that strictly do not follow specific pore pattern. They mostly belong to corticioid fungi.

India has various climatic zones in which different wood decay fungi are found. A minimum estimated could be 1000–1200 species (Kumar, 2017). Many of such fungi have been reported to cause damage to the living tree, felled and stored wood, wood in use and to wood in indoor use. Fungi live as saprophytes or parasites. As parasite they cause multiple diseases in different plant parts, such as leaves, bark, stem and root. Though all the diseases are harmful to the plant and pose severe threat to plant/tree, diseases of bark and trunk are directly related to damage of usable timber. Few species have greater economic importance due to their severe damage. There are several fungi which damage the standing trees and timber extensively in the Indian subcontinent.

Major root rot pathogens include *Armillaria mellea* (Fig. 2.8), *Ganoderma lucidum* (Fig. 2.9), *Heterobasidion annosum* (Fig. 2.10) and *Inonotus shoreae*. Butt and Heart rot pathogens—*Ganoderma applanatum* (Fig. 2.11), *Hymenochaete rubiginosa* (Fig. 2.12), *Phellinus caryophylli* (Fig. 2.13), *P. senex* (Fig. 2.14), *P. gilvus* (Fig. 2.15), *P. badius, P. pachphloeus* (Fig. 2.16), *P. rimosus, Fomes fomentarius* (Fig. 2.17), *Xylobolus subpileatus* (Fig. 2.18). Sap wood rot and saprophyte—*Trametes versicolor* (Fig. 2.19), *T. hirsuta* (Fig. 2.20), *T. lactinea, Bjerkandera adusta, Trichaptum biforme* (Fig. 2.21), *Daedalea dickinsii, D. quercina, D. flavida* (Fig. 2.22), *Phanerochaete chrysosporium, Gloeophyllum sepiarium* (Fig. 2.23), *G. striatum* (Fig. 2.24), *Coriolopsis telfarii, Schizophyllum*

Fig. 2.8 *Armillaria mellea*, a root rot pathogen of deciduous and coniferous trees

Fig. 2.9 *Ganoderma lucidum*, a serious root rot pathogen of angiospermic trees

Fig. 2.10 *Heterobasidion annosum*, a root rot pathogen of conifers

Fig. 2.11 *Ganoderma applanatum*, a serious butt and root rot pathogen of angiospermic trees

Fig. 2.12 *Hymenochaete rubiginosa*, a heart rot pathogen of Sal, also grow as opportunistic saprophyte

Fig. 2.13 *Phellinus caryophylli*, a heart rot pathogen of angiospermic trees

Fig. 2.14 *Phellinus senex*, a heart rot pathogen of angiospermic trees

Fig. 2.15 *Phellinus gilvus*, a root and butt rot pathogen of angiosperms, mostly saprophyte

Fig. 2.16 *Phellinus pachyphloeus*, a heart rot pathogen of major angiospermic trees

Fig. 2.17 *Fomes fomentarius*, a heart rot pathogen of oaks

Fig. 2.18 *Xylobolus subpileatus*, cause heart rot on oaks

Fig. 2.19 *Trametes versicolor*, mostly saprophytic, causes rot of sapwood in oaks

Fig. 2.20 *Trametes hirsuta*, mostly saprophytic, causes rot of sapwood

Fig. 2.21 *Trichaptum biforme*, saprophyte on oaks

Fig. 2.22 *Daedalea flavida*, saprophyte on variety of woods

Fig. 2.23 *Gloeophyllum sepiarium*, saprophyte on conifers, Fir and cedar

Fig. 2.24 *Gloeophyllum striatum*, saprophyte on pine

commune (Fig. 2.25), *Hexagonia tenuis, Earliella scabrosa* (Fig. 2.26)*, Flavodon flavus* (Fig. 2.27)*, Hymenochaete tabacina, Pycnoporus sanguineus* (Fig. 2.28)*, Rigidoporus lineatus, Stereum hirsutum* (Fig. 2.29)*, Stereum sanguinoloentum, Daldinia concentrica, Junghuhnia* sp.*, Peniophora gigantea, Merulius* sp.*, Spongipellis obtusus, Irpex consors, Tapinella panuoides.* Rhizome rot—*Serpula similis* (Fig. 2.30), Canker and bark rot- *Xylaria polymorpha* (Fig. 2.31).

Decay does not start overnight. It may take several years to show its symptoms and remain undetected for many years. Usually, a fungal fruit body is an indicator of decay, but by the time fruit bodies are produced the fungus has already established itself into the core, as fruit body formation is an energy cumbersome process. We usually get to know about it when the tree is broken, thrown by the wind, or felled when a visible indicator is absent.

Fig. 2.25 *Schizophyllum commune*, saprophyte on variety of woods

Fig. 2.26 *Earliella scabrosa*, saprophyte on poplar

Fig. 2.27 *Flavodon flavus*, saprophyte on variety of woods

Fig. 2.28 *Pycnoporus sanguineus*, saprophyte on variety of woods

Fungi can attack any tree irrespective of its age. As soon as heart wood formation takes place they become liable to be attacked by heart rot fungi. Most of fungal pathogens are wound parasite. Weakened trees may be more susceptible to fungi (weakness parasites). Rot fungi may also enter via dead stubs (Schmidt et al., 1986). Fungi either penetrate via the roots (root rots) or the stem (stem rots). Root-decay Basidiomycetes such as *Armillaria* species, *Heterobasidion annosum*, *Ganoderma lucidum* and *Inonotus shoreae* attack roots of the trees via root to root contact. Fungi attack the heartwood (heart rots) and effect thus a considerable strength and volume reduction of the tree xylem, e.g. *Phellinus badius* and *Phellinus pini* (Figs. 2.32 and 2.33). They cause either brown or white rot in the process of their succession. Tree decay fungi have great economic importance, since a great part of the wood body can be devaluated, and felling of infected trees may be necessary. After felling, wind

Fig. 2.29 *Stereum hirsutum*, on deciduous and coniferous wood

Fig. 2.30 *Serpula similis*, cause of rhizome rot in bamboo, also grow as saprophyte

throw, or death of the tree, some fungi continue growth as saprobes in the wood for several years, and then however usually die, that is, typically they do not endanger structural timber. Fungal fruitbodies may be annual or perennial.

Among the different causes responsible for loss to the standing crop in the plantation, decay is by far the most important. In an assessment of Sal forests in India, about 73% trees exhibited decay resulting in 10% loss of timber (Bakshi et al., 1963). No such latest data is available to us now. Tree becomes liable to be infected by decay fungi as soon as heart wood is formed. Heartwood is usually protected by sap wood and bark but whenever there is injury/wound, the heartwood gets exposed to pathogens. It establishes itself by these openings in heartwood as heart rot which becomes progressive with age. Heart rot may not be detected as it does not affect the vigour of the tree. Tree continues to grow and may present all the outward

Fig. 2.31 *Xylaria polymorpha*, sap wood and bark rot of angiosperms

Fig. 2.32 Heart rot in Khair by *Phellinus badius*

appearance of a healthy tree. The volume of the decay increases in the tree and in the stand with age. Furthermore, diseased trees constitute a source of infection to healthy trees. Therefore, it is important to detect decay before a major part of the log gets decayed and to protect from heavy losses. Heart rots can be detected either from external symptoms or through direct probing. External indicators include sporophores, punk knots, swollen knots, swollen boles and external injuries (Bakshi, 1976).

Fig. 2.33 Heart rot/decay in deodar (*Phellinus pini*)

2.9 Ecological Significance of Decay Fungi in Forest Ecosystem

Decay fungi regulate diversity of vegetation in forest by making dominant species victims of their own success. Fungi spread quickly between closely packed plants of the same species, preventing them from dominating and enabling a wider range of species to flourish. In this process they directly modulate the availability of resources other than themselves for several other functional groups (Harley, 1971; Jones et al., 1994; Krajick, 2001; Moore et al., 2004). Wood decaying fungi break down and release nutrients from the large volumes of plant remains that accumulate in the forest (O'Dell et al., 1996). They have a crucial role in decomposition of biomass, comprising wood and other lignocelluloses, which is a necessary part of the natural nutrient cycle: during photosynthesis, wood and O_2 are formed from CO_2 and H_2O by means of light. In counterpart, the wood becomes degraded by fungi to CO_2, H_2O and energy for fungal metabolism (Schmidt, 2006). In forests of the earth, about 400 billion tons of CO_2 are bound. Without fungal degradation of the biomass, the CO_2 supply of the atmosphere necessary for photosynthesis would be used up in 20–30 years, photosynthesis would grind to a halt, and the earth would be overfilled with non-decaying biomass (Schlegel, 1992).

Standing and fallen decaying trees support a high species-rich environment and play an important role in the formation of ecological niches (Odling-Smee et al., 2003). Coarse woody debris (CWD) or coarse woody habitat (CWH) refers to fallen dead trees and the remains of large branches on the ground in forests and in rivers or wetlands (Harmon et al., 1986; Bull et al., 1997; Burris & Haney, 2005; Crow et al., 2002). They provide a food source for a wide range of invertebrates including Collembola, mites and nematodes (Shaw, 1992), and gain nutrition in turn from living or dead animals as well as plants.

Some of the studies recognizing deadwood as main source of resources of living organisms include small mammals (Maser et al., 1978), forest-floor vertebrates (Butts & McComb, 2000), soil macro-arthropods (Jabin et al., 2004), insects in polypores (Jonsell & Nordlander, 2002), coleoptera (Kappes & Topp, 2004) and gastropods (Kappes, 2005).

Though wood decaying fungi support a web of organisms, they themselves are part of biodiversity too. The number of fungi increases as the number of substrate increases (Sippola & Renvall, 1999; Humphrey et al., 2000). So, reduction in dead wood can result also in the reduction of wood decaying fungi. According to Siitonen (2001), 90% reduction in dead wood can result in 50% loss of wood decaying fungi. This can also be understood as a large number of CWD may allow more room for large fungal individuals to develop. Many wood decaying fungi require certain size and age of wood for fruiting. Relationships between CWD size and the number of fungal species might to some extent be dependent on the age of the part of the tree concerned, as size is partly related to age. Age involves factors such as the formation of heartwood and the initiation of heart rot while the wood was still standing (Lonsdale et al., 2008). Size of the CWD is also related to the moisture as larger logs can retain more moisture thus allow more time for colonization of various species with different requirements (Ódor et al., 2006). So, for forest ecological point of view, wide range of CWD (both low and high turnover of CWD) is needed in order to conserve species of varying requirements (Lonsdale et al., 2008).

2.10 Assessment of Tree Decay

2.10.1 Visual Tree Assessment

The objective of tree assessment is to identify the part of the tree (whole tree, large branch or small branch) most likely to fail and prescribe works which reduce the risk of harm caused by the failure to an acceptable level (Tamang et al., 2018). The earliest nondestructive evaluation of trees is the visual inspection of the tree condition (growth, foliation, wilt and decay) and occurrence of wounds, resin excretion, necrosis, canker or fruit bodies. Visual inspection is also applied for lumber, poles and wood in indoor use. Fruit bodies might serve to identify the causal agent. This visual inspection is by definition neither objective nor sure. Olfactory detection is done by the use of sniffer dogs that detect dry rot (Koch, 1991), molds and termites (Zabel & Morrell, 1992).

2.10.2 State of Urban Trees

"Tree abuse" is a real issue in India. General public lack sensitivity towards trees. Though, the traditional practices promote conservation of trees. Yet most of the people are ignorant towards tree health. Trees growing under continuous stress deserve special attention. Maltreatment of trees is not always done with any malicious intent but due to lack of tree sense. Some of the most common visible tree abuse in the society include: (1) soil compaction: Human activity in the parks and pavements resulting soil compaction that makes soil hard enough not to percolate rain water rather it run off towards slope. It creates moisture stress culminating into wilting and top dying. (2) Root girdling due to soil compaction and hardpan around the roots result in strangling of main roots. (3) Space around the trees along the roadsides and footpaths covered with concrete, tiles, coal tar, etc. leaving no or little breathing space for roots and for percolation of water, culminating in asphyxiation and moisture stress to the roots. (3) Tarring of surface killing a tree, (4) Concreting of basal area, (5) Nailing- it is common practice to nail the tree for various uses. It creates wound perfect for the pathogen that may result in heart rot or wilt, (6) Construction activities (roads, drainage) around tree base – it does an irreparable damage to the roots. The construction injuries causes succumbing a tree, (7) Intentional and unintentional girdling of trees- very common practice to get rid of undesired tree, (8) Girdling by tied fence wires, (9) bad lopping, (10) blazing, (11) unattended iron guard left even after trees getting good growth caused injury to stem thus opening wounds for heart rot fungi/borers, (12) litter around trees, (13) landfill over basal area, (14) due to soil compaction, water does not absorb this create dampening conditions ideal for fungi, and (15) burning of litter/waste near tree base, causes injury to the tree creating perfect place for fungal entry. All these malpractices can be minimized in the people through education for the larger interest of the community.

2.10.3 Detection of Decay Defect in Standing Trees by Use of Ultrasonic Waves

Presence of defects deteriorates quality of tree trunk which can be assessed up to a limit on the basis of external indicators such as broken or loose branches, trunks or branches with missing bark, leaning trees and other root problems, weak branch connections, cracks and splits, dead wood, evidence of significant decay etc. The integrity of such decayed trees are always doubtful and may be dangerous not only to the property loss but also for human life. A tree usually decays from the inside out, eventually forming a cavity, but sound wood is also added to the outside of the tree as it grows. Tree with sound outer wood shells may be relatively safe, but this depends upon the ratio of sound wood to decayed wood, and other defects that might be present. Therefore, need to identify and assess the extent of damage from wood decay either caused by fungi or bacteria in the wood of living trees through suitable non- destructive testing techniques which will be helpful to take timely precautions for the safety of the tree through suitable treatments. There are a numbers of non- destructive testing techniques (X-ray and computer tomography (CT), neutron radiography, magnetic resonance (MR), vibration (sonic and ultrasonic techniques) etc.) in use based on different concepts. But all these testing cannot be used for defect detection of tree in the field conditions because some of these are either not economical, hazardous to health or instrument transportation problems from one site to other site.

Ultrasonic testing technique is one among them which can be used for quality (strength/centre hollowness) assessment of a standing tree's trunk. This technique has several advantages over traditional testing such as less time consuming, reliable results, easy to transport instruments at inspection site and also simpler and economic than other techniques. Because the propagation of stress waves is basically a mechanical phenomenon, therefore these are frequently used to detect internal defects in wood. Other sonic technique is also employed sounding a tree by striking it with a tool can detect advanced decay or hollows inside the trunk, but this method is not effective on large thick-barked trees. Early hidden defects (hollowness and multiple cracks in the tree trunk) detection may be of a prime importance to the forest management for prescribing silvicultural treatment and maintaining a healthy forest and also important to the industries in term of making accurate quality assessment timber (log).

Forest Research Institute, Dehardun has developed an ultrasonic technique to detect the location and magnitude of the deterioration (hollowness) inside of the main tree trunks for different girths which will help either to take timely precautions for the safety of the valuable tree by giving suitable and effective treatment for conservation of trees or to get good yield (timber) for utilization purposes. This will also be helpful in urban forestry management, State Forest Departments and for other agencies to take timely decision for removal of hazardous trees which are located at prime locations for the safety of life.

Acoustics and ultrasonic techniques are one of the non-destructive testing techniques have proven to be an effective tool for detecting and estimating deterioration in tree stems and wood structural members. These techniques are simpler and economic than imaging techniques. Because the propagation of stress waves is basically a mechanical phenomenon, therefore these are frequently used for quality (properties) assessment and internal defects detection in wood. Ultrasonic technique has been used in many applications, e.g. tree quality evaluation in various forestry species (Mattheck & Bethge, 1993; Wang et al., 2001; Elizabeth & Smiley, 2004). Acoustic tomography for the decay detection in standing trees (Wang et al., 2007; Lin et al. (2000, 2008). Poles and timber (Biagi et al., 1994). ARBOTOM impulse tomography has been used to evaluate decay activity of a fungi as well e.g. *Phellinus pini* (Tarasiuk et al., 2007). Besides these, some techniques are employed for condition assessment of wood structures in service (Ross & Pellerin, 1994; Machado, 2000; Sandoz & Benoit, 2002). Ultrasound method is helpful in grading of construction timber (Sandoz, 1989). Ultrasonic properties, such as ultrasonic velocity and elastic constant are greatly affected by the grain directions and grain angles (Suzuki & Sasaki, 1990; Mishiro, 1996).

2.10.3.1 Principle of Ultrasonic

The principle behind determination of hollowness using stress waves is that the sound waves are longitudinal waves and require a medium to travel. They travel at different velocities in different mediums. Stress wave propagation in wood is a dynamic process and it is directly related to physical and mechanical properties of wood. High frequency sound also called ultrasonic waves when allowed to transmit from one point to another through the tree trunk in radial direction, they travel through the woody material and time of travel is recorded with the help of equipment to evaluate the sound velocity in the woody medium. Any air gap (hollowness) in the path of ultrasonic waves would make the waves travel at different velocity through it. These velocity changes due to change in medium of travel are modeled after numerous experimentations to design ultrasonic equipment for determination of hollowness in tree trunks. By measuring wave transmission through a tree in radial direction, the internal condition of the tree can be fairly accurately estimated (Fig. 2.34).

2.10.3.2 Methodology

At DBH, the girth of tree trunk is measured using measuring tape. Peripheral division of the girth is done into 6 or 8 segments for transducers. Trunks of girth less than or equal to 120 cm are divided into 6 segments and those of girth more than 120 cm are divided into 8 segments. At these segment points, bark is drilled up to wood in order to provide location for transducers. With the help of vernier scale, liner distances between each pair of segments points and the time of travel within the wood medium is recorded from ultrasonic concrete tester.

The lines in Figs. 2.35 and 2.36 represent the direction of travel of ultrasonic waves (Fig. 2.37) through the wood. For bigger girth trunks (>120 cm), 8 points detection is recommended as it covers larger portion of the trunk and waves can detect even a small fissure.

Distance and Time are fed in to the Software and it will elucidate the presence or absence of defects in log.

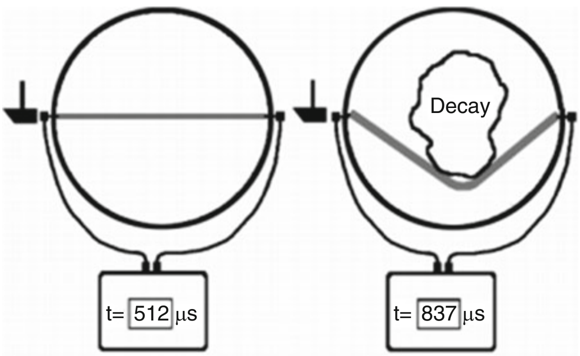

Fig. 2.34 Concept of stress wave for detection of hollowness

Fig. 2.35 Six points detection

Fig. 2.36 Eight points detection

2.10.3.3 Colours and Their Indication

Colours	Remarks
Dark red	Presence of hollowness
Light red/pink colour	Decay is started/hollowness just initiated
Plain light brown colour without red colour	Absence of hollowness

Fig. 2.37 Ultrasonic equipment

Fig. 2.38 Measure girth of standing tree

2.10.3.4 Detection Procedure

As mentioned in methodology, 6 points or 8 points marking and drilling will be done up to the trunk based on the girth size of tree, then silica gel is applied in the drilled portion in order to get uniform wave transmission. All the drilled holes will be numbered properly and distance between all the combination may be noted like 1–2, 1–3, 1–4, 1–5, 1–6, 2–3, 2–4, 2–5, 2–6, 2–1 and so on; similarly, note the wave length passing time of all the combination point. At least we need three to four people to execute the works as shown in Fig. 2.38 and 2.39. Drilled hole will be plugged with honey wax once the experiment is over. Ultrasonic equipment will be properly charged and placed in the stool or leveled platform surface to get accurate

Fig. 2.39 Measurement of time and distance through ultrasonic

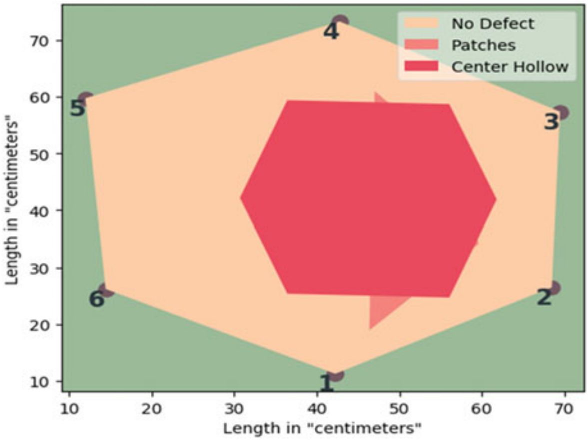

Fig. 2.40 Software output showing the presence of decay

results. Finally, feed the distance and timing data in the decay detection software to know the presence or absence of decay in a standing tree (Fig. 2.40).

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Wounding of Trees: The Precursor of Wood Decay

3

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https://doi.org/10.1007/978-981-16-8797-6_3

Abstract

Wound or injury is the precursor for inducing wood decay in a living tree as the first and the best level of defence, the bark is damaged in the process of wounding or injuries. Microorganisms, mainly fungi, enter trees through wounds or injuries and such trees are susceptible to wood-feeding insects. These wounds or injuries act as infection court and start the processes that can lead to decay, which is a major cause of damage to trees. The wounds or injuries are usually caused by different abiotic and biotic factors such as fire, weather, insects, birds, small or large animals and anthropogenic activities. This chapter highlights the concept of tree decay, agents causing wounds on trees, impacts of wounds or injuries in living trees, trees' response to wounding caused by various factors and possible preventing measures to save the economically important wood-yielding tree species.

Keywords

Lopping · Pruning · Tree decay · Decay indicators · Heartwood-rot · Stem canker · Hollowness

3.1 Introduction

Tree is a woody perennial plant, typically having a single stem or trunk growing to a considerable height and bearing lateral branches at some distance from the ground. Trees are well known for providing several tangible and intangible benefits such as timber for construction; fire wood for cooking and heating; fruit for food; shade, shelter and habitat to other living forms including wildlife; supply oxygen; atmospheric CO_2 assimilation and become active part of global climate control; and stabilizes oil and control erosion, thereby significantly contributing to the ecological services. Tree stems are compartmented into networks of living cells (the symplast includes outer wood, inner bark, and the cambium) and networks of dead cells (the apoplast includes vessels and fibres in hardwoods as well as tracheids in softwoods). The trunk of a tree is composed of both sapwood as outer part, which is primarily involved in conduction of sap, and heartwood as inner core giving mechanical strength. The bark is the outermost thick covering of the sapwood made up of dead tissues and is one of the most important parts, which protects the tree from all forms of injuries and entry of degrading agents. Wood decay in living trees is a major problem causing loss of wood products and product quality and it damages wood in service and creates hazards for people and property (Shortle & Dudzik, 2012). The causal agents of wood decay are macro-fungi often seen fruiting on living trees in the forest that have basal logging scars (home-sites and in public places (Shortle & Dudzik, 2012).

3.1.1 Tree Decay

Tree decay is a form of tissue damage due to either injury or wound to the tree stand in forests, man-made plantations, seed production areas or seed stands, seed orchards, parks, avenue trees in cities, etc. Besides its ecological importance, tree decay is looked more importantly in economic terms as it is one of the most significant factors responsible for the loss to the standing trees in plantations. Tree decay in urban landscapes is an important cause of tree hazard too that it creates major mechanical defects in the tree form which most likely lead to increased physical failures of either the whole tree or its branches. While many biotic and abiotic factors are involved in the decay processes, the primary factor responsible for decay is the wound or injuries which make the trees susceptible to diseases/ infections caused by pathogenic fungi and bacteria. The tree diseases, among many, that mostly affect the timber part are stem decay and root rot. The former one involves the decay of the central core of the living tree i.e., heartwood and is termed as heartwood-rot. As the decay occurs in the heartwood, the tree is not killed outright, but it continues to grow and may exhibit all the external appearance of a healthy tree owing to some sort of physical strength offered by the relatively less affected living sap wood region. Therefore, a considerable volume of standing timber is getting destroyed by the heartwood-rot. In aged plantations, the trees having advanced heart-rot diseases exhibit certain signs usually known as decay indicators, which include cankers, open wounds, swollen knots, swollen bole, punk knots, branch stub and rotten branches, sporophores or fruiting bodies of fungi, early forking, resin flow(Figs. 3.1a–c and 3.2a–c), etc. (Thomas & Thomas, 1954; Boyce, 1961; Bakshi et al., 1963; Mohanan, 1994; Mohan & Palanisamy, 2018).

The causal agents of wood decay are macro-fungi called as heartwood-rot fungi, which most often manifest with protruding fruiting bodies on living trees in forests, plantations, and urban areas. The wood decay in living trees usually commences with wounds or injuries caused by various biotic and abiotic factors. There are two basic types of wounds or injuries that often develop due to decay of the living trees viz., the stub and the scar. Stubs usually occur when tree tops and branches are died or broken on account of growth suppression, diseases, physical damages, etc. The stub protruding from the stem delays wound closure and allows the decay process to proceed for many years. Tree decay has been subjected to research and investigations since the work of Robert Hartig more than 100 years ago (Merril et al., 1975). The presence of wounds is large enough to expose the heartwood, which allows the entry of heartwood-rot fungi, which in turn directly results in decay (Boyce, 1961; Merril & Shigo, 1979; Shigo, 1974; Shortle, 1979; Manion & Zobel, 1979).

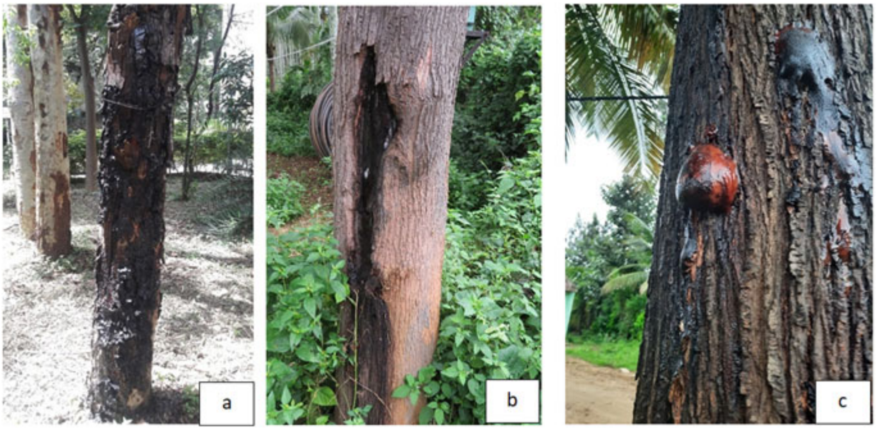

Fig. 3.1 Resin or gum flow due to injuries from the trunk of trees; (**a**) *Eucalyptus tereticornis*, (**b**) and (**c**) *Grevillea robusta*

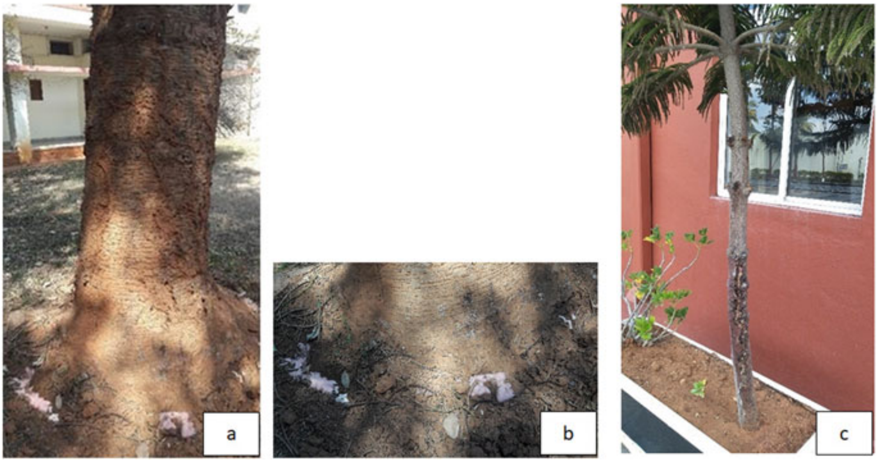

Fig. 3.2 Resin or gum flow due to injuries in *Araucaria heterophylla* (**a**) and (**b**) from root; (**c**) from stem

The subject of decay associated with wounds or injuries of living hardwood trees has been reviewed over the past half a century and many reports are available (Shigo, 1974, 1984; Shigo & Hillis, 1973; Shigo & Berry, 1975; Shigo & Marx, 1977; Boddy & Rayner, 1983). The studies have shown that colonization by microorganisms including bacteria as well as non-hymenomycetes and hymenomycetes fungi can also occur in parts of the tree other than heartwood. In India, Bakshi (1957a, b) initiated the studies on heartwood-rot in natural stands and made a quantitative account of heartwood-rot in sal (*Shorea robusta*) and khair (*Acacia catechu*) forests (Bakshi et al., 1963). Decay of standing trees in natural forests in Kerala was studied by Mohanan (1994) who commented that often the decay induced by wounds or injuries cannot be cured completely by any means. Hence, the progress of decay in injured trees belongs to intensively managed forests, urban avenues, etc., can be brought to a limit by providing proper care for trees from physical damages of natural and anthropogenic pressures.

This chapter discusses tree decay problems, various causative agents responsible for causing injury or wounds on trees, effect of wounds or injuries in living trees, trees' response to wounding caused by different factors, and possible preventive measures to save the economically important wood-yielding tree species.

3.1.2 Concept of Tree Decay

Decay of wood in a healthy living tree is a wound/injury-induced process, as in the process of wounding, the bark of the tree, the first and best level of defence of a tree, is damaged. Tree wounds are usually caused by different abiotic and biotic factors such as fire, weather, insects, birds, small/large animals, and anthropogenic activities. This allows the entry of bio-deteriorating agents, mainly fungi, to enter the trees through wounds or injuries during conducive environmental conditions (Shortle & Dudzik, 2012). Many earlier studies showed that wood decay in standing trees is most often caused by decay fungi and the decay causes substantial reduction in timber quality and its merchantable value, making it unfit for the intended use. Among the different microbes, fungi constitute the major group of microorganisms that cause decay of wood. In the decay processes, there are three basic types of host–pathogen interactions identified viz. (1) obligate pathogens that interact only with live tree cells, (2) facultative pathogens that interact with both live and dead tissues in trees and (3) obligate saprophytes that act only on dead tissue in trees. All these pathogenic and saprophytic organisms are responsible for causing decay on live or dead trees (Shortle & Dudzik, 2012).

3.2 Agents Causing Wounds or Injuries on Living Trees

Tree wounds are common and the causes include, broken branches; impacts, abrasions and scrapes; animal damage; insect attack; fire; human activities, etc. Wound or injury usually breaks the bark and damages the conducting tissues of the sapwoods in the tree trunk. Wounds or injuries also expose the inside of the tree to organisms, primarily bacteria and fungi that may infect and cause discoloration and decay of the wood. Decay can result in structurally weakened tree stems and can shorten the life of it. Details of different agents causing wound or injury on living trees are highlighted below:

3.2.1 Tree Damage due to Human Activities

Trees grown in urban and sub-urban areas are more likely to have wounds or injuries and decay than trees in natural/planted forests because of human interventions in the growth advancement of trees. Trees are often wounded by careless use of yard equipment like lawn mowers, weed whips, and other trimming equipment. These injuries cut through important vascular tissue just inside the bark tissue of the tree, which can lead to wood decay and ultimately death of trees. Often shade trees in avenues/homestead are routinely pruned for their appropriate use such as eliminating crowded branches and reducing tree size to prevent crowding, avoiding street wires, and preventing obstruction of views, etc. (Harris, 1992). Also, mechanical damages like improper cutting or lopping of branches and nailing on trunk cause the same kind of wood decay problem to the trees. Improper electric wire or TV cabling can also result in damage to the tree and the creation of a living hazard. Trenching next to trees is likely to cause damages to major roots. Ripping or tearing tree roots with a backhoe or other implement/equipment will leave large open wounds or may shatter roots, preventing the formation of new roots. Hence, when tree roots are to be cut, it should be done cleanly so as to make no major injuries or wounds to the root system. Changes in soil grade can also seriously injure the trees. About 90% of the tree's root system lies within the upper 18 in. of the soil. Covering tree roots with as little as 3 in. of soil can cause damage by suffocating roots. Hence, it is very essential to allow for air movement and drainage (Harris, 1992).

3.2.2 Tree Damage due to Animals

Animals like squirrels, rabbits, and porcupines can cause serious wounds or injuries that damage and kill trees. These animals feed on different parts of tree such as roots, bark tissues, tender leaves, fruits, and nuts. Effects of the tree damage by animals include tree girdling, scarring, deforming, brooming, stunting, and callus ridge formation (Source: https://www.tfsweb.tamu.edu). The disease causing organisms (especially canker and wood decay fungi) as well as insects used to get attracted to the wounds or injuries and accelerate the damages to the trees.

3.2.3 Tree Damage due to Insects

Insects can cause several types of wounds. Some insects bore directly into the main stem and branches. Others feed on the bark tissues, young shoots and leaves. Wood-boring insects bore deep into the wood and can structurally weaken the wood or introduce disease causing other organisms that can severely damage or even kill the entire tree (Potter & Potter, 2016). The wounds or injuries can act as infection court for entry of disease causing organisms (canker and wood decay fungi).

3.2.4 Tree Damage due to Fungi

Tree injuries or wounds occurring due to many factors (mechanical damage, human activities, fungi, insect pests, and animals) are the infection court for the entry of decay causing fungal organisms (Gauthier et al., 2015). Fungi play an important role in damage of living or dead trees. The action of fungi on dead wood/tree is most often looked at ecological point of view rather than a problem, because fungi are considered as one of the important primary colonizers of dead wood/tree in natural environment making it amenable to degradation leading to recycling. Hence, fungi play an important ecological role. However, in intensively managed forests like tree plantations, the fungi cause potential damages leading to death of the tree. Wood-decay fungi spread through wood as microscopic strands called hyphae, which begin as either germinating spores or bits of hyphae carried to the wound or injury by insects.

3.2.4.1 Heartwood-Rot Fungi

Decay is the most important single factor responsible for considerable loss to the standing tree in natural forests and plantations. Research on tree decay has been carried out by Robert Hartig more than 100 years ago (Merril et al., 1975). Decay in standing trees mostly originates by saprophytic growth in dead heartwood. Presence of wounds is large enough to expose the heartwood that allows entry of heart-rot fungi leading to decay (Boyce, 1961; Merril & Shigo, 1979; Shigo, 1974; Shortle, 1979; Manion & Zobel, 1979).The pathogen enters through wound or injury and causes heartwood-rot.

Stem decays are an important cause of potential damages to trees by creating defects that increase the likelihood of physical failure of tree stands. Such diseases are traditionally grouped into heartwood-rot and sapwood-rot. Traditionally, decays in stems are grouped into heartwood-rots i.e., “any decay that becomes progressive in the central dead wood of a living tree”, and sapwood-rots i.e., “decays primarily of the sapwood”. Heartwood-rot is the major factor for loss in sawn timber, accounting to 80% of the total loss (Hepting & Jemison, 1958). Bakshi et al. (1963) reported 73% of decayed trees in the stands of Sal forests (*Shorea robusta*) in Uttar Pradesh resulting in 10% loss of timber. Mohanan (1994) studied decay of standing trees in natural forests in Kerala state and recorded various external decay indicators for predication of decay and heartwood-rot problems on various tree species. Similarly, heartwood-rot disease incidence to the tune of 50% due to *Phellinus badius*, a wound parasite in Khair (*Acacia catechu*), has been reported by Bakshi (1956).

Heartwood-rot disease mostly arises by the invasion of the fungi capable of decomposing and utilizing cellulose and lignin. These fungi generally form prominent fruit bodies from which air-borne spores are liberated and invade the host plants or other trees frequently through wounds or injuries. There are many fungi causing decay in the heartwood of standing trees. These fungi mostly belong to Hymenomycetes of which the Polyporaceae are important. Heartwood-rot in tropical acacias has been reported from India (Mehrotra et al., 1996) and Sabah, Peninsular Malaysia, (Sudin et al. 1993; Ito & Nanis, 1997). The studies revealed that stem defect is closely associated with branch stub infections, wounds, and forking of the trees (Lee et al., 1988; Ito, 1991; Sudin et al. 1993). *Phellinus noxius*is is reported as a causal organism for heartwood-rot disease from Peninsular Malaysia together with many other fungi viz., *Phellinus pachyphloeus*, *Tinctoporellus epimiltinus* and *Rigidoporus hypobrunneus* (Lee & Maziah, 1993; Lee & Noraini Sikin, 1999), while *Trametes palustris* is reported from India (Mehrotra et al., 1996). Common heartwood-rot fungi occurring in Indian forests are *Phellinus caryophylli*, *Hymenochaete rubiginosa*, and *Phellinus fastuosus* on sal, *Phellinus badius* on khair, *Phellinus pini* on blue pine, *Pheniophora luna* on deodar, *Phellinus pachyphoeus* on poplars, *Phellinus lividus* and *Polporus zonalis* on teak, and *Phellinus caryophylli* on sandal (Bakshi, 1957a; Bakshi et al., 1963; Bakshi & Singh, 1970). In central India, heartwood-rot in hard wood species has been studied in detail by Jamaluddin et al. (1985); Soni et al. (1989); Harsh and Tiwari (1995) and Harsh et al. (2000).

Heartwood-rot disease occurs in many hardwoods and all deciduous species especially found in *Bombax malabaricum* (Simal), *Terminalia termentosa* (Asna), *Dalbergia sissoo* (Sissoo), *Pinus roxburghii* (Salla), *Castenopsis indica* (Katus), *Schima wallichii* (Chilaune), and *Quercus glauca* (oak) in Nepal (Sinclair & Lyon, 2005; Jha & Tripathi, 2012; Aryal & Budhathoki, 2013; Acharya & Parmar, 2016). Jamaluddin et al. (1985) recorded incidence of heartwood-rot due to *Phellinus* sp. in *Pithecellobium dulce* and *Acacia leucophloea* from road side and agriculture land plantations of Jabalpur Forest Division, Madhya Pradesh. Soni et al. (1989) recorded incidence of trunk-rot due to *Phellinus pachyphloeus* in *Thespesia populnea* from road side plantation of Coimbatore Forest Division, Tamil Nadu. Verma et al. (2008) recorded rare fructification of *Phellinus pachyphloeus* causing heartwood-rot in *Anogeissus latifolia* from East Raipur Division, Chhattisgarh and the same pathogen causing heartwood-rot in *Shorea robusta* from Jashpur, Chhattisgarh state. Wood decay pathogens cause high-scale mortality of *Terminalia* species in Yellapur division of Uttara Kannada district in the Central Western Ghats, Karnataka state (Ranjan, 2006). Among various diseases, root-rot and heartwood-rot happen to cause huge loss in standing trees (Old et al., 2000). Suryanarayana (2012) recorded mortality up to 71% in *Terminalia alata* in Yellapur division, Karnataka state due to heartwood-rot problem.

Heartwood-rot problem is common in relatively aged plantations and the intensity as well as the extent of decay depended upon various factors such as stand composition, age, degree of biotic and abiotic interference, and site factors. Usually, trees affected with heartwood-rot exhibit almost all the outward appearances of healthy growth, which often result in faulty marking of trees for timber extraction. However, trees affected with heartwood-rot may also exhibit certain external visible signs of decay which are called as decay indicators (Mohanan, 1994). In tropical forests white-rot fungi dominate over brown-rot fungi (Cunningam, 1965; Ryvarden & Johansen, 1980) causing decay problems in many tree species.

Decay and heartwood-rot caused by basidiomycetous fungi on different tree species have been reported by many researchers. Bakshi (1976) reported heartwood-rot in teak caused by *Ganoderma appalanatum* and *Polyporus rubidus*.

Mohanan (1994) reported that only a few fungi were responsible for causing heartwood-rot disease of standing trees, while many of them caused decay of small branches and twigs (sapwood-rot). A total of 44 fungi belonging to 18 genera were identified as associated with decay of various tree species and the nature of decay caused by them was ascertained. Most of the fungal species had a wide host range and they were widely distributed in the semi-evergreen, evergreen and wet-evergreen forests of Kerala. Altogether 35 fungi were identified as white-rot (sapwood-rot) affecting various tree species. Ten species of *Phellinus* cause white-rot in different tree species and among these *P. troyanus*, *P. fustuosus*, *P. gilvus*, and *P. rimosus* are the most widely encountered ones. *Polyporus auriculiformis*, *Tramates scabrosa*, and *Lenzites* spp. are the other common white-rot fungi encountered in the natural forests of Kerala. The fungi like *Microporus affinis*, *M. xanthopus*, *Coriolopsis* spp., *Flavidon flavus*, etc. that caused mainly white-rot of branches and twigs were also common, and nine fungi viz., four species of *Fomitopsis*, three species of *Rigidaporus* and one species each of *Hexagonia*, and *Pyrofomes* caused brown-rot of various tree species in Kerala state (Mohanan, 1994).

3.2.4.2 Heartwood-Rot Disease in Sal

Heartwood-rot of sal in India is caused by *Hymenochaete rubiginosa*, *Phellinus caryophylli*, *P. fastuosus*, *Daedalia cubensis*, *D. sulcata*, and *Coriolopsis* sp. (Bagchee, 1954, 1959, 1961). Jamaluddin et al. (1985) studied heartwood-rot in sal forests of Madhya Pradesh and Chhattisgarh states and reported a timber loss of 2.0% to 11.5% in high sal forest and 5.5% to 15.5% in coppice sal forest. Dead branches, branch stubs, and knots constitute important wounds or infection courts, and 70–80% infections in sal occur through branch stubs and sporophores (fruiting bodies) are the indicator of decay in majority of cases (Bakshi et al., 1963).

3.2.4.3 Heartwood-Rot Disease in Teak

Decay caused by *Perenniporia tephropora* and *Rigidoporus lineatus* in dry coppice teak forests in Gujarat, Maharashtra, and Madhya Pradesh has been reported by Bakshi et al. (1972), Jamaluddin et al. (1985), and Soni et al. (2010). Large-scale dying in coppice teak has been noticed in many places of Madhya Pradesh (Prasad & Jamaluddin., 1989). 50% incidence of heartwood-rot in teak was found in the western part of Gujarat, (Singh & Tewari, 1970; Singh et al., 1973) and 38% to 88% incidence was found in Madhya Pradesh state forests (Harsh & Tiwari, 1995).

Mohan and Palanisamy (2018) investigated the damage and decay indicators in different teak plantations of Cauvery canal bank areas in Thanjavur, Tiruvarur, and Nagapattinam forest divisions of Tamil Nadu state forest. In all the teak plantations surveyed, stem canker, punk knot, hollowness and top broken symptoms were very common (Figs. 3.3 and 3.4). Maximum incidence of stem canker (39%) was recorded in a 30-year-old plantation at Neyvasal (Thanjavur) and minimum (35%) at Vadavar (Tiruvarur). In Nagapattinam forest division, maximum incidence of stem canker was 46% in 15-year and 24% in 30-year-old plantations. Maximum incidence of hollowness (26%) was recorded at Vadavar (Tiruvarur division) followed by (20%) Neyvasal (Thanjavur division) and (12%) in Kondathur Vaikal

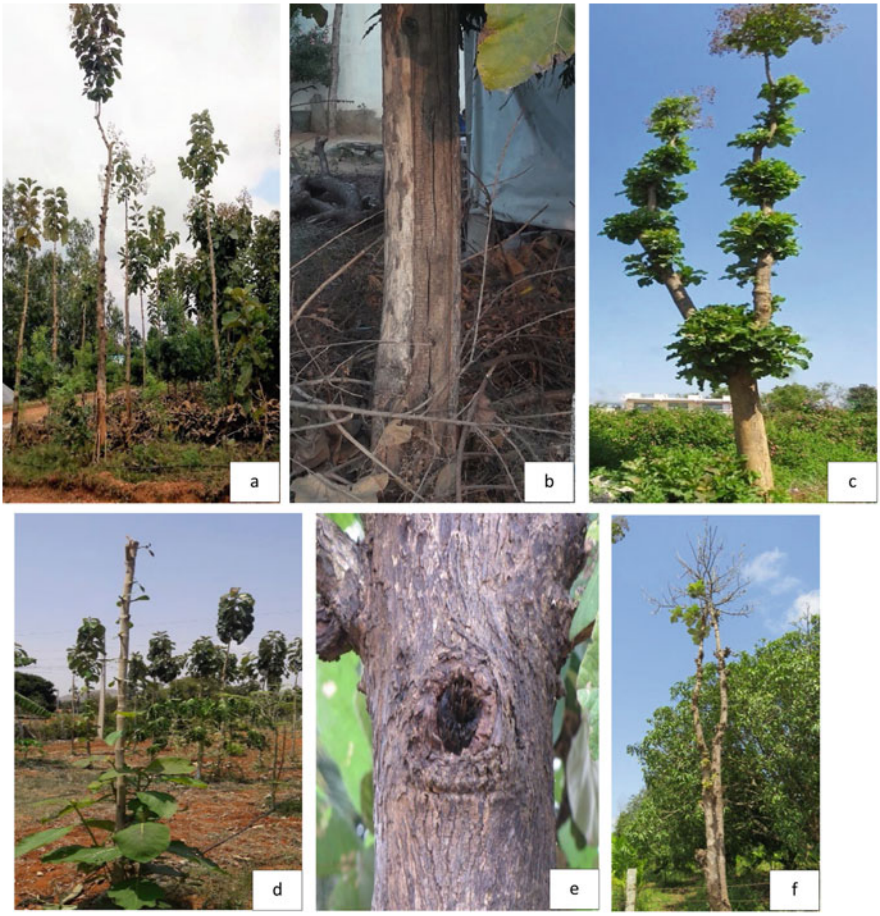

Fig. 3.3 Impact of pruning in *Tectona grandis,* (**a**) Formation of stem canker and crookedness; (**b**) Development of crack in the trunk; (**c**) Top breaking and stem forking; (**d**) Top breaking by wind; (**e**) Formation of branch stub and hollowness; (**f**) Verge of dying and stag-headed appearance

(Nagapattinam division) in 30-year-old plantations. Occurrence of decay causing basidiomycetous fungus, *Trametes* sp. is observed in the decay portion of the teak stem in 30-year-old plantation at Neyvasal of Thanjavur division and the decay causing fungus, *Ganoderma* sp. is recorded at the stem base of teak trees in these plantations.

Pruning or lopping and mechanical injuries induced cankers (Fig. 3.3a), crack in the stem (Fig. 3.3b), top breaking and stem forking (Fig. 3.3c), top breaking by wind (Fig. 3.3d), branch stub and hollowness (Fig. 3.3e), verge of dying and stag-head appearance (Fig. 3.3f), development of hollowness (Fig. 3.4a), stem canker formation (Fig. 3.4b), development of heartwood-rot causing fungus *Trametes* sp. from the trunk (Fig. 3.4c) and death of trees (Fig. 3.4d). The harvested teak woods were with

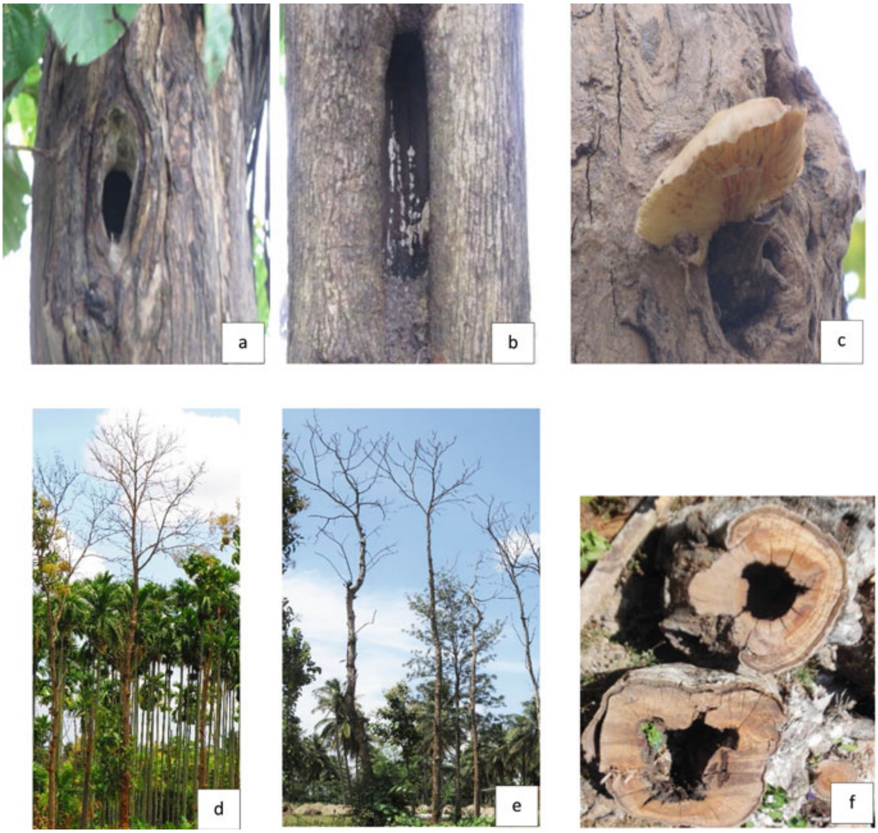

Fig. 3.4 Impact of mechanical damage in *Tectona grandis*, (**a**) and (**b**) Hollowness and stem canker formation; (**c**) Development of heartwood-rot disease causing fungus *Trametes* sp. from the trunk; (**d**) and (**e**) Dead teak trees due to severe pruning; (**f**) Hollowness in the extracted woods

hollowness (Fig. 3.4d) as the wound or injury portions act as infection court for the development of pathogenic organisms and their prolonged actions resulted in hollowness. It is concluded that the nature and position of the decay indicators exhibited by the trees, especially hollowness, stem canker and open wound of the bole, rotten branches, etc. of the infection courts of the decay in standing trees are due to injuries or wounds caused by biotic (human and domestic animals activities) and abiotic factors (cyclonic wind, fire etc.).

3.2.4.4 Impact of Wounds/Mechanical Damage in Some Important Trees

Sandalwood trees suffered due to forest fire scars led to dead branches and branch stubs in south Seoni forest division of Madhya Pradesh caused the infection of heartwood- rot fungus (Soni et al., 2010. The injury induced symptoms in sandalwood include formation of bulging, canker, stem forking and punk dots (Fig. 3.5a, b), cracks in the exposed sapwood (Fig. 3.5c), development of hollowness

Fig. 3.5 Impact of mechanical damage in *Santalum album*: (**a**) Formation of canker, hollowness and stem forking; (**b**) Formation of bulging and hollowness from the tree trunk; (**c**) Development of cracks due to weathering; (**d**) Development of hollowness due to heartwood-rot; (**e**) Hollowness in the extracted woods

(Fig. 3.5d), and loss of heartwood in the extracted wood (Fig. 3.5e). Different kinds of response were observed due to mechanical injuries in living trees. Nailing of living trees in urban environment affecting the health of the trees (Fig. 3.6a–c); tying of nylon wire on Jamun (*Syzygium cumini*) leading to compression in the tied part of the trunk (Fig. 3.6d); tying of iron wire on Eucalyptus leading to death of the tree (Fig. 3.6e, f); formation of stem canker and excessive hollowness (Fig. 3.7a), top dying and stag headed appearance (Fig. 3.7b), huge bulging and decay on the collar region (Fig. 3.7c) and huge bulging structure as healing of wound which withers in the trunk (Fig. 3.7d) in *Azadirachta indica* (neem); formation of bulging structure on the tree trunk and healing of the wound of pruning in the trunk of *Swietenia mahagoni* (mahogany) (Fig. 3.8a); in *Melia dubia* (Fig. 3.8b); wound induced abnormal swelling/bulging and hollowness (Fig. 3.8c) in the trunk of *Psidium guajava;* stem canker, swelling/bulging and hollowness (Fig. 3.9a, b) in the trunk

Fig. 3.6 Damage of tree trunk due to human activities, (**a**) and (**b**) Hammering of iron nail on the tree trunk of *Delonix regia;* (**c**) Hammering of iron nail on the tree trunk of *Grevillea robusta*; (**d**) and (**e**) Tying of nylon rope leading to compression in the tied part of the trunk of Jamun (*Syzygium cumini*); (**f**) Tying of iron rope or chain leading to compression in the tied part of the trunk resulting in death of *Eucalyptus* sp.

of *Artocarpus heterophyllus* (Jack Fruit) trees. The wound induced cumulative bio-deterioration often lead development of notable hollowness in living tree (Fig. 3.10a–d) as well as in extracted wood (Fig. 3.10e). The trees with internal hollowness are found very prone to wind (Fig. 3.11a, b).

3.3 Fire

Fire also causes injuries or wounds in living trees of many species results in scar mark on the affected part and damaged trees tend to die more easily after a fire. In sandal wood trees, fire scars are the most favoured infection courts or wounds of heartwood severely affect the heart wood (Soni et al., 2010). Though such trees may continue to live for some time, yet heartwood may not be available for extraction. In Central India, these factors are considered as the cause of decline of sandalwood trees and most of the mature sandalwood trees observed to die with canker and heartwood-rot problems (Soni et al., 2010).

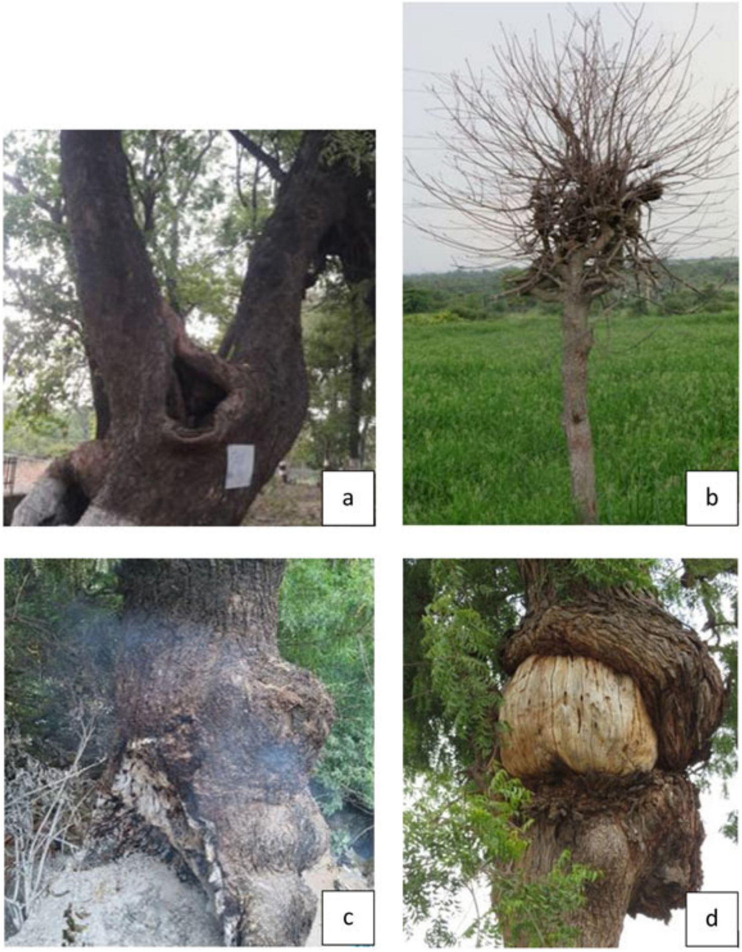

Fig. 3.7 Impact of injuries in *Azadirachta indica* (Neem: (**a**) Formation of stem canker and excessive hollowness. (**b**) Top dying and stag-headed appearance due to pruning/lopping. (**c**) Formation of huge bulging and decay on the collar region. (**d**) Formation of huge bulging structure as healing of wound which withers in the trunk

3.4 Climatic Factors

Climate change could alter the frequency and intensity of many disturbance factors in forests or tree plantations such as conducive environment for microbial activities, insect outbreaks, invasive species, wildfires, extreme temperature and storms. These disturbances can reduce forest productivity by affecting the health of tree species.

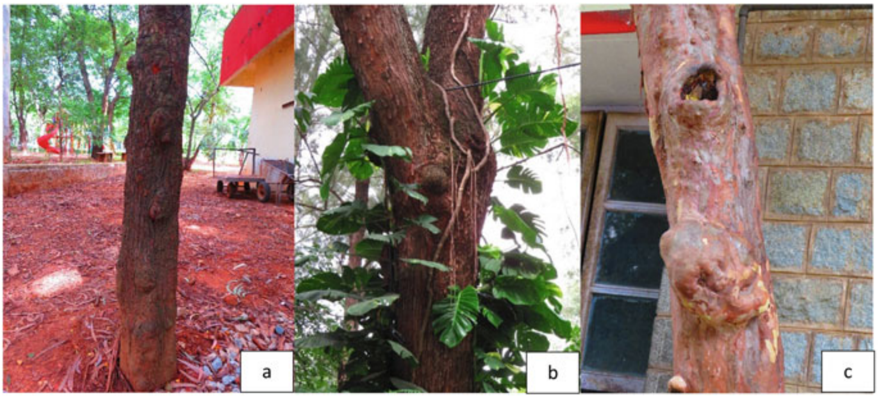

Fig. 3.8 (**a**) Healing of the wound of pruning by swelling or bulging in *Swietenia mahagoni* (Mahogany) tree; (**b**) Wound healing by formation of excessive bulging in *Melia dubia* tree; (**c**) Wound-induced abnormal swelling/bulging on stem and hollowness problem in *Psidium guajava* tree

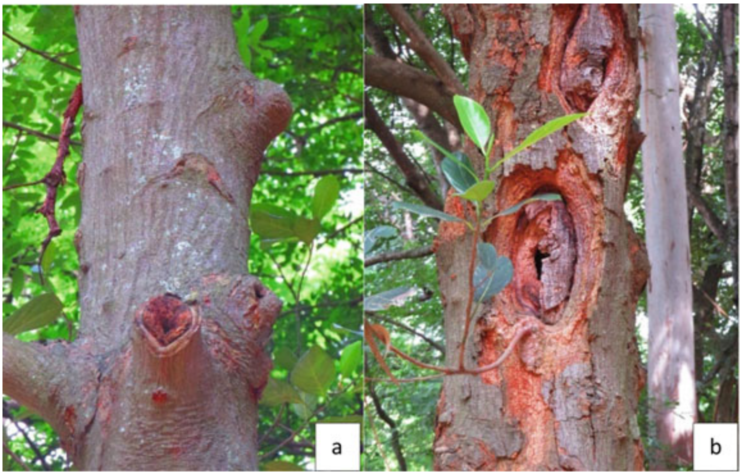

Fig. 3.9 (**a**, **b**) Wounding/mechanical damage-induced stem canker, swelling/bulging, and hollowness from the trunk of *Artocarpus heterophyllus* (Jack Fruit) trees

3.4.1 Cyclonic Storms

Naturally occurring events, such as cyclonic storms like high winds also cause wounds or injuries on living trees. The cyclonic storm injury or wound on living trees causing broken tops and branches leads to the slow progress of decay in exposed wood and this is very common in coastal as well as nearby coastal areas where the cyclonic storms are high during monsoon seasons (Fig. 3.12).

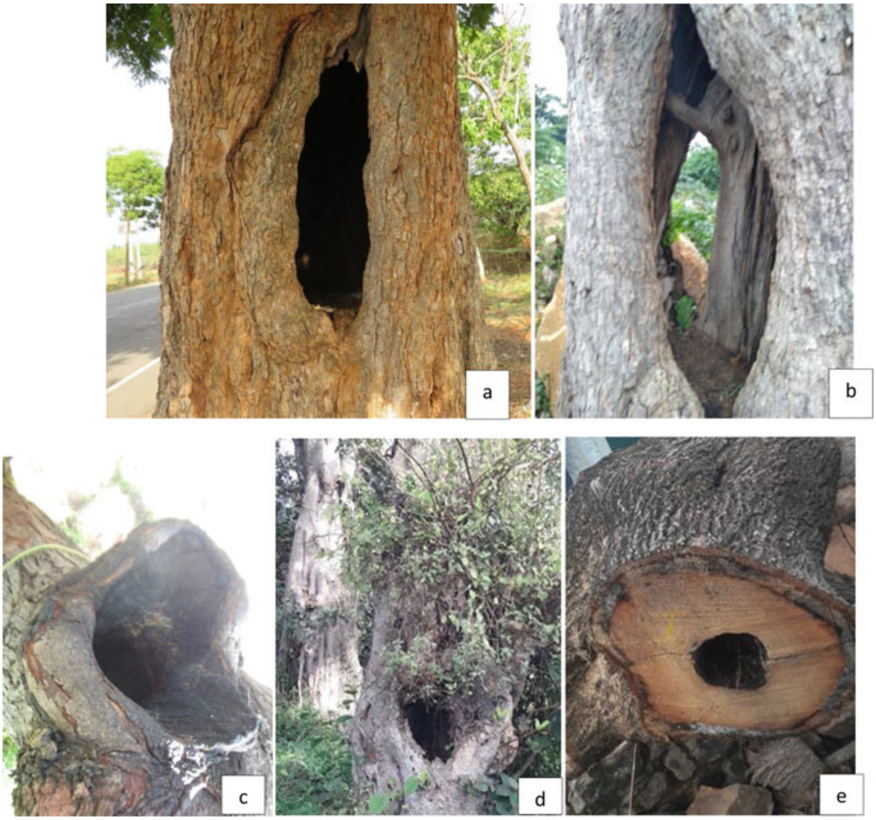

Fig. 3.10 Wounding/mechanical damage-induced decay causing hollowness, (**a**, **b**) in *Tamarindus indica*; (**c**) in *Samanea saman*; (**d**) in *Ficus* sp.; (**e**) hollowness in the extracted wood of *Grevillea robusta*

3.4.2 Temperature Stress

Many woody plants, especially tropical and subtropical trees are sensitive to extreme temperature conditions and may become injured. Shade trees can also be injured by sudden and large increases or decreases in temperature, especially when the climate changes far exceed the normal range for that season of the year. A sudden increase or decrease in temperature during the winter may cause premature flushing of foliage or a decrease in hardiness. The buds or emerging foliage are often killed when the temperature again returns to its normal range. Sudden decreases in temperature can cause injury or wound even when temperatures do not reach below freezing.

Fig. 3.11 Internal hollowness-induced breakage of trees: (**a**) *Santalum album* and (**b**) *Broussonetia papyrifera*

Fig. 3.12 Effect of cyclone in trees causing branch-break and injuries

3.5 Tree Response to Wounding or Injury

Trees respond to wounding or injury in two ways such as compartmentalization and development of barrier zones (Shigo, 1986).

3.5.1 Compartmentalization

When a tree is wounded or injured due to different factors, the injured tissue is not repaired and does not heal. Eventually the tree covers the wound or injured surface by forming specialized “callus” tissue around the edges of the wound. After wounding, new wood growing around the wound and forms a protective boundary preventing the infection or decay from spreading into the new tissue. Thus, the tree responds to the injury by “compartmentalizing” or isolating the older, injured tissue with the gradual growth of new, healthy tissue (Shigo, 1986).

3.5.2 Barrier Zones

Not only do trees try to close the damaged tissue from the outside, they also make the existing wood surrounding the wound unsuitable for spread of decay organisms. Although these processes are not well understood, the tree tries to avoid further injury by setting chemical and physical boundaries around the infected cells, reacting to the pathogen and confining the damage (Shigo, 1986). If the tree is fast and effective with its boundary-setting mechanisms, the infection remains localized and does not spread. However, if the boundary-setting mechanisms are not effective, the infection will spread. Most vigorous or actively growing trees are fairly successful in coping with decay-spreading mechanisms (Shigo, 1986).

3.5.3 Disfiguring the Shape of Tree due to Pruning/Lopping

In general, most of the trees grow straight when there is no mechanical damages like pruning or lopping of branches. Pruning is observed to have profound effect in the shape and form of a tree. *Thespesia populnea* is observed to grow straight up when there is no damage like lopping, cutting, or pruning of branches (Fig. 3.13a). But due to mechanical damage in the form of pruning and lopping the branches, the tree is affected and takes different shape and form (crooked stem) (Fig. 3.13b–d). *Swietenia mahagoni* is found to grow straight in the absence of any human interventions like pruning/mechanical damage (Fig. 3.14a). Similarly, *Muntingea calabura* (Singapore Cherry), which is commonly known as umbrella tree, grows straight up in the absence of any pruning (Fig. 3.14b), but it takes umbrella shape when it is pruned for the purpose of getting convenient shade for parking vehicles and maintaining landscape (Fig. 3.15a, b). Extreme pruning alone or coupled with mechanical damage often leads to death of the trees (Fig. 3.16a, b).

Fig. 3.13 Growth of *Thespesia populnea*, (**a**) Straight growth when there is no damage like pruning or cutting of branches; (**b**) Takes different shape (crooked stem and branches) due to pruning/mechanical damage; (**c**, **d**) Takes umbrella-like shape due to lopping of the branches

3.6 Tree Wounds or Injuries: Preventive Measures and Care

3.6.1 Prevention of Tree Wounds or Injuries

There are different ways and means to prevent tree wounds or injuries. The best way to care for tree wounds or injuries is to prevent them from happening. Proper tree planting and maintenance free from injury or wounds due to mechanical damage at any stage of growth of the trees are the keys to keep them healthy and safe (Mooter & Kuhns, 1991).

Fig. 3.14 Straight growth of trees without pruning or lopping: (**a**) Mahagony (*Swietenia mahagoni*) and (**b**) Singapore Cherry (*Muntingea calabura*)

Fig. 3.15 Growth of a Singapore Cherry (*Muntingea calabura*): (**a**, **b**) Takes umbrella-like shape due to lopping or pruning of the branches for the purpose of shade and landscape

3.6.2 Proper Selection and Planting

The most important steps involved in injury prevention are proper site selection, soil working, placement, and time of planting of the tree saplings mostly during rainy

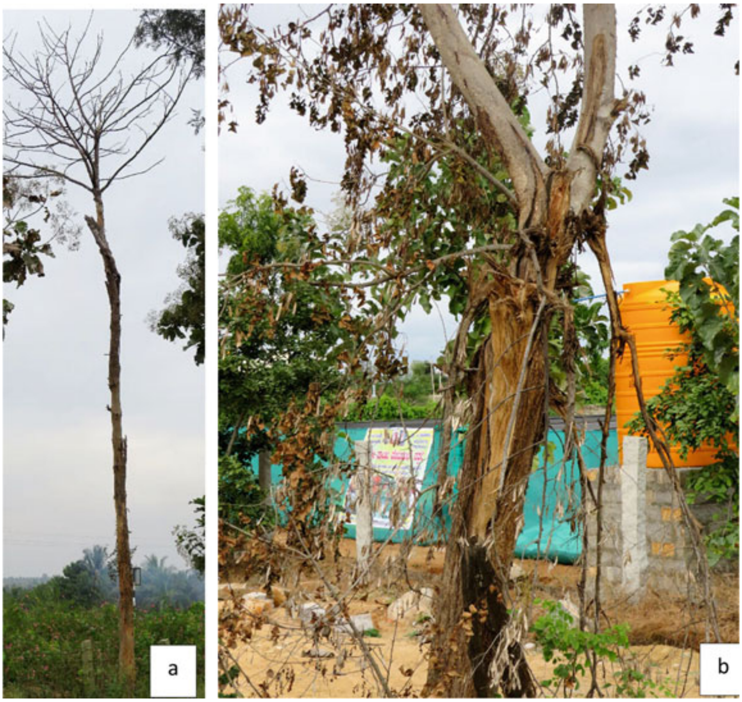

Fig. 3.16 Death of trees due to (**a**) prunning (**b**) mechanical damage

season. Site preparation before tree saplings planting is also very essential (Mooter & Kuhns, 1991).

3.6.3 Mulching

Mulching is an important maintenance practice for protecting trees from moisture and temperature stress. Properly applied mulch will increase growth rates, prevent basal damage, and conserve soil moisture. There are different kinds of organic materials such as wood chips, bark or some other natural materials used as mulch. Avoid using rocks or plastic sheeting. Rocks cause soil compaction, and plastic sheeting suffocates root systems. Woven weed barrier fabric can be effective at reducing weed competition and does allow moisture and oxygen to enter the soil. It does not, however, add organic matter to the soil or reduce compaction like natural mulch. Mulch should be spread a foot or more from the base of the tree in all directions. Mulch can be placed directly on grass when mulching established trees (Mooter & Kuhns, 1991).

3.6.4 Watering

Moisture is very critical to all living organisms including trees, but too much moisture can also cause serious damage. Newly planted trees should be watered once per week in the absence of rainfall. Established trees should receive 1 in. of water every 10 to 14 days. These amounts are in addition to the water that a surrounding grass lawn would need. Therefore, a new tree with a grass lawn competing with it may need 2 in. or more of water a week to thrive. Daily watering causes a lack of soil oxygen, smothering roots, and can reduce the number of deep roots. Instead, larger amounts of water should be applied once or twice a week. Do not inject water "deep" into the soil and most tree roots are not very deep, and deep roots will receive water if enough is applied to the soil surface. Tree roots extend away from the tree at least as far as the tree is tall and in most cases much farther. Therefore, it is usually beneficial to water the entire yard to water a tree. (Mooter & Kuhns, 1991).

3.6.5 Fertilizing

In general, trees get nutrients from the soil. Hence, trees should be fertilized only when necessary. If the plant growth is adequate and steady, leaf parts appear healthy, and there has been no major disturbance around the tree, no fertilization is needed. When fertilizing is necessary, slow release, balanced, granular fertilizer or soil-applied liquids should be distributed over the tree's entire root zone. Application of fertilizer through holes augured into the soil or with fertilizer spikes is not recommended. Routine trunk injections of fertilizers into healthy trees are also not recommended (Mooter & Kuhns, 1991).

3.6.6 Pruning

Pruning is an essential phenomenon in horticultural crops for getting more leaves, flowers, and fruits, as the case may be in an accessible height. However, the longevity of such plants are reduced depending upon on the level of pruning, as they become very susceptible to decay fungi and wood feeding insects (Mooter & Kuhns, 1991). Pruning is also essential in trees grown in landscapes as well as in urban environment. But, wood- or timber-yielding long rotation tree species should not be pruned or lopped. Because, due to pruning the tree parts get wounds or injuries and they act as the entry point of microbes particularly decay fungi as well as wood damaging insects and they cause damage to sapwood as well as heartwood in the entire life of the tree. The following are some of the important considerations when pruning or lopping dealing with wounds or injuries to minimize tree damage (Mooter & Kuhns, 1991).

3.6.6.1 Natural Target Pruning

Pruning in unavoidable situations is important to make final cuts at the proper location. Cuts should be made from just outside the branch bark ridge (readily visible on most species) to just outside the swollen branch base or branch collar. A cut between these “natural target” points removes all branch tissue but does not cut into trunk wood. Leaving stubs will lead to unwanted sprouting and decay of the remaining stem tissue. Cuts made too close (flush cuts) leave much larger wounds than proper cuts and can cause dieback of the surrounding cambium. As a result, flush cut wounds do not heal properly, causing major damage to the trunk from which the tree may not recover (Mooter & Kuhns, 1991).

3.6.6.2 Maintenance of Pruning

Pruning or lopping of trees can be done only in unavoidable circumstances which may include safety, removal of dead or injured branches, correction of a structural defect, or interference with utility lines. Removal of healthy branches to “thin” a crown or for similar reasons is never necessary (Mooter & Kuhns, 1991).

3.6.6.3 Topping

Topping or cutting of tree or its branches and crown is not a good arboricultural practice, and it should not be used for healthy tree maintenance. Topping or cutting of tree leads to formation of larger wounds or injuries, and these injuries and wounds act as infection court for the entry of insects and wood damaging fungi and cause severe damage to the wood. In some instances, as in the case of severe storm damage, topping can be done to get a few more years of life for the tree prior to its removal (Mooter & Kuhns, 1991).

3.7 Compartmentalization of Decay in Trees (CODIT)

It describes the reactions that take place in a tree in response to wounding. In general, when a tree is injured or wounded, it sets up protective mechanism against the invasion of decay organisms like fungi and other insects. The vessels near the wound are plugged with gums, resins, and chemicals that resist the spread of decay. The living tissues outside of the injured or wounded area of the tree will then begin to form a callus layer in an attempt to close the wound (Mooter & Kuhns, 1991).

3.8 Wound Dressing

Scars, particularly at the base of the tree, are caused by removal or death of bark. Exposed wood surfaces crack open as the wood dries and insects then bore into the exposed wood. The time needed to close the wound depends on the size of the scar and the growth rate of the tree. Many earlier studies and reports revealed that tree wound dressings do not prevent decay on trees (Collins, 1934; Marshall, 1950;

Shigo & Wilson, 1977; Mercer, 1979, 1982; Bonnemann, 1979; Dooley, 1980), and are of limited benefit for wound closure (Neely, 1970; Mcquilkin, 1950; Young & Tilford, 1937). Shigo and Shortle (1984) used different materials for wound dressing of many trees and reported that no material prevented decay. If pruning cuts are made properly, there is no need for a wound dressing (Shigo, 1982a, b). If pruning cuts are made improperly and damage occurs, wound dressings will not help and the damaged trees die ultimately. Additionally the chemicals mainly fungicides used in wound dressing cause soil pollution and thereby affecting the soil health.

3.9 Management of Heartwood-Rot

Losses due to heartwood-rot may be prevented or reduced through management and silvicultural practices (Bakshi, 1957a; Jamaluddin et al., 1997). Injury or wound due to frost and suppression may be prevented by canopy adjustment as applied in uniform or selection system. Fire protection measures in dry and moist Sal forest are important to prevent the fire damage. The stand management can be practiced by timely thinning and improvement felling of deformed, crooked, injured or wounded, diseased or dead trees. The pathological rotation age should be worked out when decay becomes significant with age, the crop should be felled at that age in order to obtain maximum return of sound wood.

3.10 Conclusion

Trees are vital, they give us oxygen, store carbon, stabilize the soil and provide key ecosystem services. Like any other living thing, trees suffer differently due to wounds/injuries. Trees in urban areas are likely to receive more wounds or injuries due to human activities such as tying of iron rope or chain, hammering nail to the tree trunks and branches, and other mechanical damages like cutting or pruning or lopping branches. Woody plants are unable to heal the damaged tissues, as well as the injuries make the tree more susceptible to diseases and pests. Thus injuries in trees demonstrably decrease the carbon sequestration potential of trees and loss of wood, and in extreme cases the tree succumbs. Hence, any mechanical damages in the living trees particularly in wood yielding trees to be avoided. Here we suggest an awareness programme about the consequences of mechanical damages to the woody plants among different people including school and college children with the concept of "Let Trees Grow on their Own". This is of particular importance for obtaining the key ecosystem services of trees in the present era of progressing urbanization and climate change.

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Economically Important Wood Feeding Insects: Their Diversity, Damage and Diagnostics

4

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Contents

Abstract

Wood feeding insects are the economically important group of arthropods that cause severe damage to the agricultural, horticultural crops and forest trees. These primarily belong to the orders Coleoptera, Hymenoptera, Lepidoptera and Blattodea of class Insecta under phylum Arthropoda. The larvae of wood feeding

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_4

insects are the most damaging stages that feed on the internal tissues of wood and make tunnels and galleries inside the stem of a tree or a plant. As a result the xylem and phloem tissues of the plant get disrupted and the branches dry and die subsequently. The economic losses due to these wood boring insects are huge and enormous in various parts of the world. The morphological identification and species diagnostic characters are very important especially for the major groups of wood feeding insects to detect and strategize the management options to curb the losses. So, the present chapter deals with the major wood feeding insects, their species diversity, nature of damage and the diagnostic characters.

Keywords

Wood borers · Coleoptera · Hymenoptera · Lepidoptera · Diversity · Damage · Distinguishing characters

4.1 Introduction

Insects are the predominant group of animal kingdom that belong to class Insecta under phylum Arthropoda and subphylum Hexapoda. The insects are economically important mainly for their harmful and beneficial effects. Harmful insects mainly include pests of agricultural, horticultural and forest crops/trees. The larval and adult forms of insect species that destroy and feed on wood are known as wood borers. The insect borers cause serious damage to the hardwood and softwood of the trees and are becoming major pests in the tropical, subtropical and temperate regions of the world (Nair, 2007; Wylie & Speight, 2012). Most of the species are serious pests of agricultural and horticultural crops inflicting huge loss in terms of production and productivity. The larval forms that attack wood are generally referred as woodworms.

The wood boring or feeding insects are one of the most destructive pests of forest trees, ornamental, agricultural, horticultural plants/trees, wooden poles and furniture. Their larvae are the most damaging stage that feed under the bark, into the sap wood and result in tunneling inside the trunk portion of the tree thus leading to the death of trees. The wood feeding larvae destroy the conductive tissues and deprive the tree from water and nutrient flow resulting in wilting and subsequent dying of the plants. Initially the damage starts with the stem girdling, then the die-back of branches followed by wilting and death of the plants. In addition to the direct damage inflicted by these wood feeding insects, they also pave way for secondary infestation by pathogens at the infestation points of the tree or plant.

Stress conditions like drought, injuries and sun scald weaken the trees and make them more susceptible to the borer infestation (Muilenburg & Herms, 2012). It has been reported that most of the times the adult borers are guided by the volatiles emitted from the stressed trees or plants for their oviposition. The wood feeding insects are the most detrimental group of pests at most of the times; the damage will be evident at a very advanced stage of plant deterioration, during which the management practices become futile. The wood feeding insects are found to infest the living trees, the freshly felled or dying trees, trunks or logs. Many a species infest the dead wood of household furniture too thus causing huge damage to the house constructions.

4.2 Economic Importance of Wood Feeding Insects

Wood feeding insects mainly infest the forest trees, which are valuable economically, socially and environmentally that accrued huge benefits for human well-being. The total forest cover on the globe is estimated to be about 4060 million hectares (FAO, 2020), of which highest per cent of forest area (about 46%) falls in tropical zone (approximately 1870 million hectares). The forests are characterized by diverse plant species both in terms of species richness and abundance that nurtures unique faunal diversity including wildlife. So, protection of these forest trees is of utmost importance in the direction of conservation of biological resources that are in turn linked with the human well-being.

Among all the wood feeding insects, the wood borers belonging to Coleoptera are the major group that causes significant economic losses. The invasions of phytophagous insect species into newer areas or regions are of serious concern that causes serious ecological losses. Among the invasions of the insect pests, wood borers constitute a significant proportion (Haack, 2001, 2006; Work et al., 2005; Mattson et al., 2007) resulting in huge yield losses. The enhanced rate of invasions of bark beetles and pinhole borers belonging to Scolytinae and Platypodinae of Curculionidae has drawn much attention in this regard (Wood, 1977, 1982, 2007; Wood & Bright, 1992). The quarantine inspections at ports revealed that beetles are the major intercepted organisms accounting to nearly 93% of all insects. The introduction of Asian longhorn beetle belonging to Cerambycidae in the U.S. during 1996 has resulted in urban resource losses to the tune of ~$669 billion (Nowak et al., 2001). The reports have shown that the beetle is capable of infesting more than 100 different tree species with more preference towards poplars, aspens, cottonwoods, maples and willows, and invasions have been found in Ohio, New York, New Jersey, Massachusetts and Illinois. The emerald ash borer, *Agrilus planipennis*, belonging to Buprestidae of Coleoptera has infested millions of ash trees in the U.S. and Canada since its first detection on ash trees in southeastern Michigan and neighbouring Ontario, Canada, in 2002 (Haack et al., 2002). The infestation has resulted in $280 billion loss to the ash industry in North America alone.

Of the several natural destructive forces, wood feeding insects are one of the major factors that inflict direct and indirect damage to the agricultural, horticultural crops and forest trees. In particular, the wood boring insects are the major pests of the forest trees that determine the structure and function of the forest ecosystem. So, understanding the types of wood feeding insects, their nature of damage, biological information and taxonomic identification is crucial for the management. Hence, the information on various aspects of major wood feeding insects is presented in this chapter.

The wood feeding insects of major orders viz., Coleoptera, Hymenoptera, Lepidoptera and Blattodea are discussed here order wise.

4.3 Important Groups of Wood Feeding Insects

The major groups of wood feeding insects are listed below (Table 4.1).

Table 4.1 List of important groups of wood feeding insects (order wise)

Sl. No.	Order	Common name	Family
1.	Coleoptera	(a) Longhorn beetles or longicorn beetles	Cerambycidae
		(b) Jewel beetles or metallic wood boring beetles	Buprestidae
		(c) Bark beetles (Scolytinae) and pin-hole borers (Platypodinae)	Curculionidae
		(d) Death-watch beetles	Ptinidae
		(e) Powderpost beetles and false powderpost beetles	Bostrichidae
		(f) False blister beetles	Oedemeridae
2.	Hymenoptera	(g) Carpenter bees	Apidae
		(h) Carpenter ants	Formicidae
		(i) Saw flies	Tenthridinidae
		(j) Horntails	Siricidae
		(k) Wood wasps	Anaxyelidae Xiphydriidae
3.	Lepidoptera	(l) Clearwing moths	Sesiidae
		(m) Wood moths/goat moths/carpenter moths	Cossidae
4.	Blattodea	(a) Termites	Mastotermitidae Hodotermitidae Termopsidae Kalotermitidae Rhinotermitidae Serritermitidae

4.3.1 Coleopteran Wood Feeding Insects

Coleoptera is one of the largest orders of class Insecta consisting of beetles and weevils representing around 40% of the known insect species. The wood feeding insects of Coleoptera belong to suborder Polyphaga and include the longhorn beetles (Cerambycidae), jewel beetles (Buprestidae), bark beetles and pin-hole borers (Curculionidae), the powderpost beetles and the dunnage beetle (Bostrichidae), the wharf borer (Oedemeridae), ship timber beetles (Lymexylidae), the furniture beetle (Ptinidae), timberworms (Brentidae), and ironclad beetles (Zopheridae). The size of the wood feeding insects vary greatly among different groups, where the longhorn beetles and jewel beetles are larger, measuring up to 50 mm, while powderpost beetles and death watch beetles of Anobiinae, Ptinine and Bostrichidae are smaller, measuring less than 5 mm. Similarly the shape of the borers also varies greatly. The larvae of these beetles are the most damaging stages and are called as woodworms.

The major coleopteran wood borers are discussed hereunder as per their economic importance.

4.3.1.1 Longhorn Beetles

Systematic Position

Class: Insecta

Order: Coleoptera

Suborder: Polyphaga

Superfamily: Chrysomeloidea

Family: Cerambycidae

Subfamilies: Most species subfamilies are Cerambycinae, Lamiinae followed by Prioninae

The longhorn beetles also known as longicorns, capricorns, round-headed borers, timber beetles, goat beetles or sawyer beetles vary from 2.5 mm to 17 cm in size. The distinguishing features of these beetles are the presence of long antennae and antennal sockets. The adult beetles are short living and feed on flower's pollen and nectar, fungal spores and sap of trees. After mating, the adults oviposit eggs under bark or in crevices inside the wood. The hatched larva looks generally white, yellowish white or pale orange in colour. The body is stout and segmented. The larva feeds on the tissues and form tunnels in the wood with its powerful mandibles. The pupation takes place inside the tree and adult emerges out either in summer or pre-monsoon or south west monsoon, and post-monsoon seasons depending upon the species. The longhorn beetles generally have 1 year life cycle where the larval period is the longest and hence the damage becomes more pronounced.

The longhorn beetles or longicorn beetles are the serious pests of several forest trees, agricultural and horticultural crops, exclusively phytophagous and their larvae feed on the internal wood of living or dead plants (Ślipiński & Escalona, 2016). These beetles cause enormous damage to live, dead and dying trees of several forest and horticultural crops like mango, citrus, cashew, apple, etc. The identification of the borer species by their morphological characters and understanding its nature of damage and biology of the respective species are the prerequisites in formulating an effective management strategies.

Species Diversity

The longhorn beetles belong to Cerambycidae, which is one of the largest families comprising about 35,000 described species under 4000 genera worldwide (Švácha & Lawrence, 2014; Wang, 2017). Ślipiński et al. (2011) reported Cerambycidae as one of the largest families of beetles in existence consisting of 34,490 extant species under 4959 genera within the Chrysomeloidea Latreille superfamily.

The longhorn beetles mainly belong to subfamilies Cerambycinae, Lamiinae and Prioninae, of which subfamilies Lamiinae and Cerambycinae are speciose covering nearly 90% of all longhorn beetles. Around 60% of the global fauna of longhorn beetles is distributed within the Oriental or Neotropical regions (Rossa & Goczal, 2021).

Nature of Damage

The larvae known as round-headed borers are the most damaging stage, which bore into the stem portion of the tree as soon as they hatch from the eggs laid on the bark and cause damage to the wood by tunneling inside. During the process of tunneling, the larva cut the holes to outside through which the frass containing faeces and the sawdust is thrown out. The tunnels usually assume round shape in accordance with the larval head shape. This tunneling widens as the larval instars progress and also lead to satellite tunnels thus resulting in drying of the branches due to disruption of phloem and xylem tissues. As the damage goes unnoticed, eventually the entire tree succumbs to death. The damage is more pronounced in live trees, occasionally to wood in buildings. For example, *Hylotrupes bajulus* causes problem indoors.

Besides direct damage, the longhorn beetles also serve as vectors of deadly plant pathogens like fungi and nematodes (Jankowiak & Rossa, 2007; Akbulut & Stamps, 2012). The beetles of this family lay their eggs in cracks or crevices in the bark or on the surface of rough surface timbers. The larvae are woodborers causing extensive tunneling in the inner soft wood. Mature larvae are large varying from 1/2 to 3–4 in. long and the rear portion of the head is partly drawn into the body so that only the mandibles and other mouthparts are easily seen.

Diagnostic Characters

1. *Diagnostic features of adults*

The longhorn or longicorn adult beetles can be distinguished by following characters:

(a) The adult beetles possess a long and jointed antennae, which are often as long as or longer than the beetle's body and the antennal sockets are located on low tubercles on the head.
(b) Body usually cylindrical, often with bright colourful patterns

(c) Pronotum distinct with or without lateral spines and carinae
(d) Tarsi pseudotetramerous and the tarsal claws are divaricate.

Note: Few species of longhorn beetles may have shorter antennae but invariably possess the tubercules whereas other beetles (other than longhorn beetles) having long antennae can be distinguished by absence of the tubercules.

2. *Diagnostic Characters of three Subfamilies, Lamiinae, Cerambycinae and Prioninae* (Adopted from Gahan, 1906; Ślipiński & Escalona, 2013; Sangamesh, 2015; Wang, 2017):

Prioninae can be distinguished with the following morphological characters:
(a) Maxillae possess a very small or obsolete inner lobe
(b) Prothorax with marginated sides
(c) Pronotum with lateral spine and/or carinae, often dentate or setose
(d) Procoxae strongly transverse with large exposed trochantins
(e) Mesonotum without a striated stridulatory area
(f) Protibiae often expanded and serrate along external edge

Lamiinae possess the following distinguishing characters:
(a) Head vertical
(b) Genal margin in the head directed posteriorly
(c) Maxillary palpi is pointed at the apex
(d) Protibiae usually grooved on inner side and mesotibiae grooved externally that aid in antennal cleaning

Cerambycinae can be distinguished with the following distinguishing characters:
(a) Antennae placed very close to eyes
(b) Mesonotum with an undivided stridulatory plate
(c) Mandibles without pubescence on inner margin
(d) Pro-coxae not angulated on outer side.

3. *Diagnostic features of larva*:
   (a) Larvae straight, creamy white, with or without very small thoracic legs.
   (b) The larval body is straight (not 'C' shaped), taper gradually from anterior to posterior
   (c) Head generally round, not flat, with dark, hardened and well-developed mandibles.

E.g. *Batocera rufomaculata* De Geer, *B. parryi* (Hope) *Cerosterna scabrator* (F.), *Aeolesthes* sp. *Dorysthenes rostratus* (F.), *Acanthophorus* sp. (Fig. 4.1a–f)

4.3.1.2 Jewel Beetles

Systematic Position

Order: Coleoptera
 Superfamily: Buprestoidea
 Family: Buprestidae

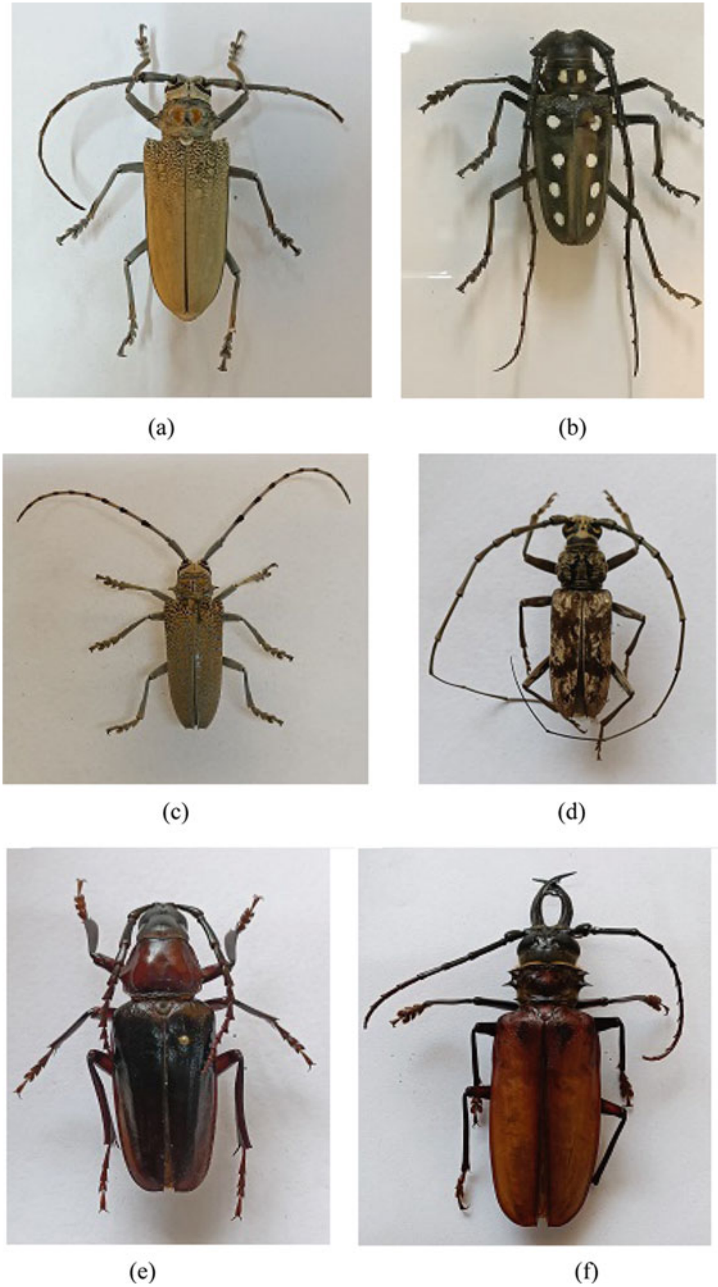

Fig. 4.1 (**a**–**f**) A few species of longhorn beetles belonging to Cerambycidae

The jewel beetles also known as metallic wood borers belonging to Buprestidae are usually shiny with their glossy iridescent colours. The iridescence exhibited is due to the structural coloration (where the cuticle texture selectively reflects specific light frequencies) and not because of the pigments present in exoskeleton. The adult beetles measure from 3 to 80 mm length. Larvae of this family are known as flat-headed borers. The jewel beetles may have one generation in a year (annual) or in 2 years (biennial).

Species Diversity

The family Buprestidae comprises 15,500 species under 775 genera. In addition, almost 100 fossil species have been described (Gbif.org; Bellamy, 2008). The beetles vary in their size ranging from 3 to 80 mm and shape from cylindrical or elongate to ovoid.

Nature of Damage

The larvae also known as flat-headed borers are the damaging stages and larvae bore through the roots, stems, logs and leaves of various types of plants, from grasses to trees. The larvae infest the live trees and fresh healthy wood. The larva makes tunnels inside the stem or trunk portion and the tunnels made tend to have almost the same shape as their thoraxes, approximately three times broader than the height assuming oval or 'D' shape. These can be easily distinguished from nearly rounded tunnels made by the round-headed borers of Cerambycidae. In buprestid larvae, the tunnels are often filled with frass in the softwood of the tree and appear oval in cross section and usually walls scarred with transverse lines. About ten species of these buprestid borers are reported to feed on spruce, fir and hemlock (Rose & Lindquist, 1985). A few species are serious pests of horticultural and forest trees resulting in complete drying and subsequent death of the plants. Emerald ash borer is reported to cause major economic damage.

Diagnostic Characters

1. Adults are brightly colored with metallic luster and hence are called metallic wood borers or jewel beetles.
2. The adult beetles appear slightly flattened and narrow.
3. The larvae are creamy white, apodous and flat headed.

E.g. *Sternocera* sp., *Chrysochroa* sp. (Fig. 4.2a, b), *Agrilus* sp.

The larvae of longhorn beetles (cerambycids) and jewel beetles (buprestids) are very difficult to identify in the field at the sites of infestation. So, the marks of identification once again emphasized for clear identification of the group.

Distinguishing Characters of Larvae of Cerambycids and Buprestids (Adopted from Duffy, 1968)

1. The larvae of both cerambycids and buprestids can be differentiated based on the shape of the head, where it is round in former (Fig. 4.3a) and flat in the latter (Fig. 4.3b).

Fig. 4.2 (**a**, **b**) Common Jewel beetle species belonging to Buprestidae

2. The larval bodies of the longhorn beetles taper less abruptly while the narrowing down of body segments after first two segments are clearly visible in buprestids.
3. The buprestids possess inverted 'V' marking on the first segment and hardened plate-like structure on dorsum and ventral side of the first segment behind the head portion, whereas the Cerambycids are devoid of plate-like structure on ventral surface.

Apart from these, one can distinguish the species based on the damage inflicted. The frass and saw dust thrown out through exit holes will be coarse and fibrous/shredded, mostly powder-like containing barrel-shaped pellets in case of Cerambycids and it will be highly packed frass, ringed sawdust-like containing pellets in case of Buprestids (Sreedevi & Verghese, 2014).

4.3.1.3 Bark Beetles and Pin-Hole Borers

Systematic Position

Order: Coleoptera

Superfamily: Bostrichoidea

Family: Curculionidae

Subfamilies: Scolytinae and Platypodinae

The bark beetles and pin-hole borers belong to the subfamilies, Scolytinae and Platypodinae of the family Curculionidae. The family comprises of "true" weevils (or "snout beetles") and one of the largest among the families of Coleoptera. These beetles can be identified by their snouts (characteristic feature of weevils) and geniculate antennae with small clubs. The adult beetle size range from 1 to 40 mm and single generation of most of the species completes in 4 to 6 weeks. The bark

(a) (b)

Fig. 4.3 (**a**, **b**) Larvae of Cerambycidae and Buprestidae

beetles of the subfamily Scolytinae subsocial, brown to black, cylindrical to hemispherical, small to medium size and measure about 0.90–10.00 mm in length and largely adopt their shape in accordance with their wood-boring lifestyle. The species of Platypodinae are known as pinhole borers as they make very minute pinhead size holes in the trunk or wood (Jordal, 2014). Few species of these subfamilies are also known as ambrosia beetles as they cultivate or harbour the fungal gardens in their excavations in the wood. Almost all species of Platypodinae are recorded as ambrosia beetles that cultivate fungi. Certain species of Platypodinae like *Euplatypus* exhibit sexual dimorphism.

Species Diversity

The family Curculionidae comprises about 83,000 described species covering 6800 genera ("Curculionidae". *www.gbif.org*). The bark beetles belonging to the subfamily Scolytinae comprises 6000 species under 25 tribes and 225 genera worldwide (Wood & Bright, 1992). The pin-hole borers belonging to subfamily Platypodinae comprises more than 1400 species in 34 genera that mostly inhabit tropical and or subtropical regions (Wood & Bright, 1992).

Nature of Damage

The scolytid beetles generally are recognized as secondary pests as they cause damage in plants which are weakened due to other stress rather than healthy plants. During the periods of their outbreak, the beetles infest the healthy trees also and cause considerable damage (Maiti & Saha, 2004, 2009). Certain species of platypodine are important early decomposers of dead woody plants in wet tropics. Certain other species make tunnels deep into the sapwood or heartwood of a dead tree to cultivate the fungus that serve as food. Most of the species of Platypodinae are entirely dependent on the fungus they grow in the excavated tunnels, which is essential for larval development that assumed to possess steroid components in their fungal diet (Kok et al., 1970). The transmission of fungal spores or hyphae from one plant to other is facilitated by the specialized structures in the beetle integument as invaginated mycangia in the pronotum or in coxal cavities (Beaver, 1989).

Diagnostic Characters
The tunneling pattern in the bark and wood, excavation and throwing of the bored dust or frass determines the morphological variations of the bark beetles especially the declivity of the elytra in the posterior part of the abdomen. This is dependent on scraping and shoveling activity of the wood. Often the declivity of elytra is truncate and furnished with spines and teeth to enable the shoveling activity (Beeson, 1941).

Diagnostic Characters (Adopted from Maiti & Saha, 2004)
Scolytinae and Platypodinae can be distinguished by following characters:

1. The first tarsal segment generally not longer than the second or third segment in Scolytinae, whereas the first segment is longer and as long as next 2–5 segments combined together in Platypodinae.
2. Head narrower than pronotum and concealed when viewed from above in Scolytinae whereas it is as broad as pronotum in Platypodinae.
3. Antennal club with or without sutures in Scolytinae whereas antennal club without sutures in Platypodinae.
4. The lateral spines/denticles of protibiae usually socketed in Scolytinae while they are not socketed in Platypodinae.
5. Larvae are small, whitish, curved and apodous.
6. Mycangia are often found only in the females, and they may take very different shapes in different taxa and can sometimes be used as a taxonomic character.

E.g. *Xylosandrus compactus* (Eichhoff), *Xyleborus perforans* (Wollaston), *Euplatypus parallelus* (Fabricius) (Fig. 4.4a, b).

4.3.1.4 Deathwatch Beetles or Furniture Beetles
Systematic Position
Order: Coleoptera
Superfamily: Bostrichoidea
Family: Ptinidae
Subfamily: Anobiinae

The death watch beetles belong to subfamily Anobiinae of family Ptinidae. Anobiinae was treated as family rank earlier and is now a subfamily in recent classification (Ivan & Smetana, 2007; Bell & Philips, 2012). These beetles are

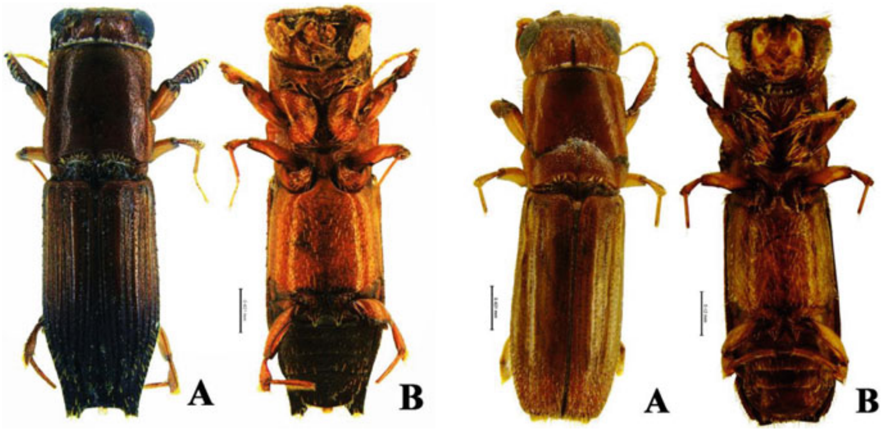

Fig. 4.4 Platypodine species, *Euplatypus parallelus* (**a**) Male; (**b**) Female (A-Dorsal view and B-Ventral view)

named as "Death watch beetles"because of a clicking noise made by each sex as a mating call for the potential mates. But the clicking noise has historically made to fear of impending death caused due to plague and sickness. These are also known as furniture beetles as the larva damages the furniture and house wood furnishings. Gahan (1946) has given an account on furniture beetles. The adult beetles are red-brown to dark brown in colour. The shape of the beetles vary in form, either cylindrical or oval shaped, a few can be narrow and elongate or nearly circular from the dorsal view. The beetles are poor fliers, small sized ranging from 1 to 9.5 mm in length and attacks several hard wood species in nature and mostly prefer the wood partially predigested by the fungi in indoors. These beetles are nocturnal, active during the nights, and are attracted to the light.

Species Diversity

There are around 2200 described species representing 220 genera in family Ptinidae worldwide (GBIF database). Ptinidae includes both spider beetles and deathwatch beetles where the latter belong to the subfamily Anobiinae. The species of Anobiinae are represented by 45 genera (Bouchard et al., 2017).

Nature of Damage

The beetles infest the softwood and seasoned wood as they can digest cellulose from the wood. The larvae bore into the wood causing excessive tunneling and damage to wooden furniture and house structures especially of old buildings. The death-watch beetles also damage flooring, joists, and other timber in housing structures and basements. The beetles usually infest wood that have been subjected to fungal decay. The tunnels made by the larvae are filled up with frass mixed up with chewed wood particles. The exit holes made by these beetle are round and the powder thrown out will be fine to coarse often with cigar-shaped pellets. The common species,

Fig. 4.5 Larva of *Anobium punctatum*

Anobium punctatum infest usually the seasoned sapwood timber and in most of the cases, exit holes are not visible on the trunk (Hickin, 1963). These beetles commonly infest seasoned sapwood and hardwood. They attack structural timber, lumber, cabinets, and furniture. Often, these beetles re-infest as the females are capable of laying eggs in the wood from which they emerged. Generally, the adult beetle lay its eggs on the exposed wood devoid of bark. The infestation in wooden structures and furniture goes unnoticed until the round adult emergence holes appear on the surface. The characteristic pellets found in the frass and the consistency of the frass aid in identification of the species infesting the wood.

Diagnostic Characters

1. The adult beetles are medium sized, reddish brown to dark brown covered with very fine yellowish hairs.
2. Head possess a prominent frontal protuberance and is concealed by the hood like pronotum and not visible from above.
3. Body is covered with fine yellow hairs and the elytra possess long striations with deep punctations.
4. Antennae 11 segmented, the last three segments of the antenna are longer forming an elongated club and lengthier than the remaining eight segments combined together (White, 1960, 1962). Antennae may be either serrate (saw-toothed) or pectinate (comb-shaped) in certain species.
5. The tibiae without spurs, tarsi 5-segmented, tarsal claws divaricate.

Larval Identification Features

1. The larva appears grayish white with spinules on first seven abdominal segments and absent on remaining three segments (Fig. 4.5).
2. The first six segments possess the transverse markings with two rows of spinules while the seventh segment possesses a single row of spinules.
3. Larva possesses a tubular projection or air tube on each spiracle, which is equal to the length of the spiracle.

Courtesy: M O'Donnell and A. Cline, Wood Boring Beetle Families, USDA APHIS PPQ, Bugwood.org.

E.g.: *Anobium punctatum* (De Geer) (furniture beetle), *Xestobium rufovillosum* (De Geer) (death-watch beetle), *Ptilinus pectinicornis* (Linnaeus) (fan-bearing wood-borer) and *Ernobius mollis* (Linnaeus) (pine bark anobiid or pine knot borer).

4.3.1.5 Powderpost Beetles

Systematic Position

Order: Coleoptera

Superfamily: Bostrichoidea

Family: Bostrichidae

Subfamily: Lyctinae

Powderpost beetles belong to the subfamily Lyctinae of family Bostrichidae. These beetles, along with other wood borers, deathwatch beetle, furniture beetle, spider beetles falls under superfamily Bostrichoidea that includes two important families, Bostrichidae and Ptinidae. The Bostrichidae family comprises of more than 700 species that includes several wood boring insects and storage pests in both tropics and temperate regions. The true powderpost beetles belong to Lyctinae, whereas fasle powderpost beetles belong to Bostrichidae.

Species Diversity

Lyctinae consists of two tribes, Lyctini and Trogoxylini, and comprises more than 70 species (Geerberg, 2008).

Nature of Damage

The adult beetles tunnel into the wood and often attack the deciduous trees. The larvae are the most damaging stage in the subfamily Lyctinae unlike other bostrichids (Liu et al., 2008). The larvae make minute tunnels in the stem portion and result in a very fine, powder like substance with which the timber quality deteriorates. The infested portion exhibit narrow tunnels and numerous holes on the surface. The larvae of these beetles reduce wood to a mass of very fine powder. The damage will not be evident until the emergence holes i.e. pinhole-sized openings, often called "shot holes" are visible (Fig. 4.6). Based on the species infesting the wood, the shot holes size varies and normally range in diameter of 0.8 to 3.5 mm. These beetles infest the large-pored hardwood of oak, ash hickory, mahogany and bamboo. The powder post beetles infestation is noticed in dried and seasoned wood, hardwood flooring, timbers, plywood, old wood antiques and wood articles causing serious damage (Akhter, 2005; Peters et al., 2002). The lyctid beetles mostly infest the sapwood. They chiefly feed on the starch and prefer to oviposit in the starch rich sapwood, which contains starch content more than 30% and also having good moisture content, above 10%. Many a times the lyctid beetle enters wood that is stored or cured and the infestation may start late. An active infestation will have borings in piles that are accumulated on the floor below or near the holes.

Diagnostic Characters

The adults are tiny ranging from 2 to 7.5 mm in length. They are flattened and reddish-brown to dark brown and black in colour. Larvae are white and cream

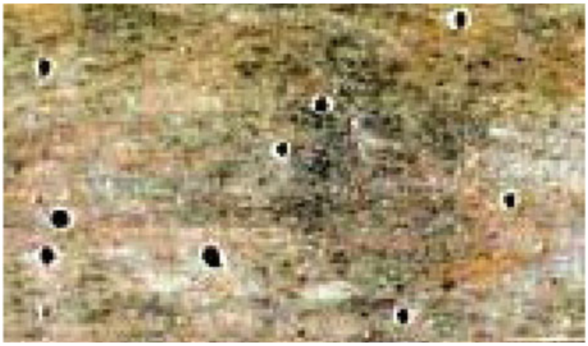

Fig. 4.6 Pin holes in the infested wood

coloured, shaped with dark brown heads. Larvae create tunnels in the wood and become pupae. As adults, they bore out through the wood, pushing a fine powdery dust out. The shape of their emergence holes is round, usually measuring 0.8–1.60 mm diameter while in Anobiids, it is 1.60–3.20 mm and bostrichids, 3.18–4.80 mm.

1. The powderpost beetles possess prominent head not covered by pronotum and head clearly visible from above.
2. The antennae 11 segmented with two-segmented terminal club.
3. The first abdominal segment longer than the rest of segments.
4. The tibiae with distinct spurs.
5. The larva of this group is white and c-shaped.

Distinguishing Features of Lyctids from Anobiids

1. The powderpost beetles (lyctids) can be easily distinguished from similar looking death watch beetles (anobiids) by visible head from above, where it is not visible in case of latter.
2. The larva of lyctids can also be differentiated with greatly enlarged posterior spiracle from the anobiid larva.
3. In case of severe infestations, fine powder is found in lyctids, whereas large amount of frass that is grainy is thrown out of the exit holes in anobiids (Hickin, 1963).

   E.g. *Lyctus* sp., *Acantholyctus* sp., *Lyctodon* sp., *Trogoxylon* sp., *Lyctoderma* sp.

4.3.1.6 False Powderpost Beetles

Systematic Position

Order: Coleoptera

Superfamily: Bostrichoidea

Family: Bostrichidae

The false powder post beetles are small- to large-sized beetles, elongate and cylindrical and are also known as auger beetles and horned powder post beetles.

Fig. 4.7 Larva of False powder post beetle (Courtesy: M O'Donnell and A. Cline, Wood Boring Beetle Families, USDA APHIS PPQ, Bugwood.org)

These beetles are larger in size than the true powder post beetles or lyctids and are brown to reddish brown or black. The bostrichids are found abundant in the tropics and several species bore into the dead, seasoned, or cured hardwoods or hardwood furniture. Like lyctids, these bostrichid beetles also prefer to feed on the starch in wood and prefer wood with good moisture content. These beetles complete their life cycle in 1 year.

Species Diversity

The bostrichids comprise more than 700 described species worldwide.

Nature of Damage

The bostrichids also tunnel into the softwood but differ from the lyctids and anobiids in adult beetles boring into the wood through "egg tunnels" prepared for egg laying as against the oviposition in surface cracks or pores observed in lyctids. The female oviposits in pores leading from the tunnels. The larvae attack both softwood and hardwood and make tunnels, which vary greatly in size and shape. The species mostly infest fresh wood and will not infest seasoned wood. The exit holes of false powder post beetles are larger and do not contain frass, but the galleries are filled with the frass. The frass is tightly packed unlike lyctids where it is loosely packed. The frass appears meal like and stick together without any pellet formation. The species mostly do not reinfest the wood after it is seasoned unlike true powder post beetles. Bamboo is the one most affected by these beetle species.

Diagnostic Characters

1. The head is deflexed and not visible from above, as the large prothorax covers the head and thus giving the beetle a humpbacked appearance (Fig. 4.7).
2. The thorax is noticeably roughened in most species.

3. The antennae are short but the bostrichids have 3 or 4 enlarged, sawtoothed, terminal segments, compared with 2 for the lyctids.
4. The first abdominal segment of bostrichids is equal in length to each of the other segments.
5. The tibiae have distinct spurs.
6. The larvae are curved and wrinkled.

Usually all lyctids, anobiids and bostrichids are generally termed as powder post beetles.

4.3.1.7 False Blister Beetles

Systematic Position

Order: Coleoptera

Superfamily: Tenebrionoidea

Family: Oedemeridae

The false blister beetles belonging to the family Oedemeridae of Coleoptera are common pollen feeding beetles. The larvae of most genera feed on decomposed wood and are primarily xylophagous except one species, wharf borer, *Nacerdes melanura,* whose larva feed on the live wood of the plants submerged in water. The adult insects are medium sized measuring around 10–12 mm in length, yellowish to reddish orange in colour, with a long slender body. The antennal size will be half of its body length. Each elytron contains three raised longitudinal lines, which is a characteristic feature of all species in the family Oedemeridae.

Species Diversity

The family consists of more than 1500 species represented by nearly 115 genera.

Nature of Damage

Only a single species, i.e. wharf borer of Oedemeridae, is observed to be a wood boring insect. The wharf borer is so called as the larval stages are associated with timber and pilings of wharves. Larvae typically bore into the wood and wood products associated with wooden shipyards and facilities. Larvae create extensive galleries in the wood. The female beetle usually lays eggs on fungus-attacked, damp and decaying timber. The eggs are creamy white in colour, slightly curved with tapered ends. The hatched out whitish larvae bore into the timber and feed on the rotten wood. The peculiar feature of this species is that the adult stage is a non-feeding stage and depend on energy reserves stored during the larval stage.

Diagnostic Characters

1. Body moderately convex and almost flattened.
2. Head prognathous with frontoclypeal suture absent.
3. Antennae 11 segmented and sometimes appear to have 12 segments in males of certain species.
4. Pronotum broad in the anterior or medial region and narrow posteriorly, lateral margin absent and evenly rounded.

Fig. 4.8 *Nacerdes melanura* (Linnaeus) (Courtesy: M. O'Donnell and A. Cline, Wood Boring Beetle Families, USDA APHIS PPQ, Bugwood.org)

5. Procoxal cavities are open, tarsal formula 5-5-4.
6. Abdomen consists of five sternites with complete and visible sutures.
7. Larva elongate, convex to subcylindrical with frontoclypeal suture almost always absent, labrum free, mandibles asymmetrical, thoracic terga with asperities present and abdominal terga bears raised ampullae with asperities, urogomphi is typically absent.

   E.g. *Nacerdes melanura* (Fig. 4.8)

Identification Characters of the Wharf Borer, *Nacerdes melanura*
1. The adult beetles have a distinct black band across the apex margin of both elytra.
2. Foretibiae possess single spur.
3. The distance between both eyes will be twice the length of an eye.

4.3.2 Hymenopteran Wood Feeding Insects

4.3.2.1 Carpenter Bees

Systematic Position

Order: Hymenoptera
  Suborder: Apocrita

Family: Apidae

Subfamily: Xylocopinae

Carpenter bees, belonging to family Xylocopinae, are beneficial as pollinators; however, they are also known to cause damage to wooden structures. Most species occur in the tropics or subtropics. Less than 10% extend into the temperate zones, reaching as far north as the steppes of Russia (Malyshev, 1931).

Species Diversity

The large carpenter bees of the genus *Xylocopa* include more than 730 species, which are grouped into 48 subgenera (Hurd & Moure, 1963).

Nature of Damage

The carpenter bees prefer unpainted, weathered wood, especially softer varieties such as redwood, cedar, cypress and pine for nesting. Painted or pressure-treated wood is least preferred for nesting. The carpenter bees are usually solitary and bore into the wood mainly for making nests and do not feed much on the wood but for chewing the nesting galleries in solid wood (Hurd & Moure, 1963). The adult bee cuts the wood surface and creates holes of size nearly half an inch for the nest. The galleries are formed to lay their eggs. The eggs are laid in the excavated galleries and covered with wooden fibre and saliva. At the farthest end of the entrance hole, the adult bees make a ball-shaped larval food made up of pollen, which is called as "egg chamber". The larva emerged from the last egg laid, i.e., near the entrance hole, matures first and exits as adult bee through entrance hole (Amburgey, 2008). The saw dust lying on the soil under the entrance hole signifies boring activity by the carpenter bee. Thus the carpenter bees do not consume the wood but drills holes that are perfectly round to make cells in the nest.

Diagnostic Characters

1. The adult bees are larger, more than 20 mm in size and have a constriction between the thorax and the abdomen, but are broad-waisted unlike wasps.
2. The jugal lobe of the hind wing is either absent or shorter than the submedian cell.
3. The forewing has three submarginal cells with second being triangular in shape.
4. Absence of the malar space i.e. the lower margin of the eye is placed in proximity with the base of the mandible.
5. Abdomen glossy and generally devoid of hairs.
6. The larvae are grub like without legs.

Carpenter bees are similar to bumble bees in size and appearance and are often confused with them. They are devoid of hairs on the abdomen, and the dorsum of the gaster is generally shiny black. Bumble bees, on the other hand, have dense hairs on the thorax and abdomen, are fuzzy in appearance and are yellow in colour (Reed & Landolt, 2019). E.g.: *Xylocopa* sp.

4.3.2.2 Carpenter Ants

Systematic Position

Order: Hymenoptera

Suborder: Apocrita

Family: Formicidae

Carpenter ants belong to the genus *Camponotus* and are known potential biocontrol agents of forest pests. However, they are known to cause serious damage to wooden structures (Chen et al., 2002). These ants are known to nest in fallen trees, logs and stumps. They are rarely found to nest in living trees. They generally prefer commercially important parts of trees, i.e., the lower part of the stem. Each nest may harbour as many as 3000 individuals (Seifert, 2017). They are sometimes found nesting on wood that is already infected by brown rot (Vele & Horak, 2019). It has also been found that over one-fourth of the trees that fall during windstorms are inhabited by these ants. The workers possess a strong formic acid odour and emit formic acid when they bite, which is painful.

Species Diversity

Carpenter ants belong to the family Formicidae that comprise around 900 species worldwide (Davis, 2008). They are represented by a single genus *Camponotus* consisting of around 1000 species.

Nature of Damage

Carpenter ants cause damage by boring into wood for creating and expanding nesting sites. Like carpenter bees, these ants also do not feed on the wood but make tunnels in the wood for nests especially in damp wood that ensures high moisture content for the survival of their progeny. They cause damage which may be as serious as or more serious than that caused by termites. Worker ants make galleries in sound wood. They make runways into adjacent wooden structures in order to make exit holes for foraging activities. The galleries formed are irregular in shape and are excavated into the softer portion of the wood, whereas the harder layers serve as walls of galleries (Hansen et al., 1993). Wooden structures weaken due to the boring activity of these ants (Hahn, 2018). Unlike termites they don't consume the wood, but chew it in order to make pathways and nests, leaving behind frass, which resembles sawdust (Davis, 2008).

Diagnostic Characters

The ants are very large (0.16–0.47 in. or 4–12 mm) and, depending on the species, they vary in colour from black, brown or red to yellow. They do not sting but can bite (Amburgey, 2008).

1. These ants are predominantly black with geniculate (elbowed) antennae.
2. Adults have a narrow constriction between the thorax and the abdomen with a single node petiole or pedicel separating the abdomen from the thorax.
3. Trochanter 1 or 2 jointed.
4. The larvae are grub like and lack legs.

Winged carpenter ants can be at times be confused with winged termites. The following characters help to easily distinguish ants from termites:

(a) The antennae are geniculate in ants, while it is moniliform in termites.
(b) The wings are dissimilar in size, forewings larger and hindwings smaller in ants, while both the wings are equal in size in termites.
(c) The constricted segment termed as narrow waist between thorax and abdomen is observed in ants, while it is a broad waist as abdomen joins broadly to thorax in termites.

E.g: *Camponotus compressus*—(Fab.)—a common species in the tropics, *Camponotus pennsylvanicus*—(DeGeer)—a common species in the US.

4.3.2.3 Sawflies

Systematic Position

Order: Hymenoptera
Suborder: Symphyta
Superfamily: Tenthredinoidea
Family: Tenthredinidae

Sawflies and Wood wasps belonging to the suborder Symphyta of the order Hymenoptera are structurally the most primitive insects within the order. The common name, sawflies, is derived from the saw-like ovipositor of the females, which is used to cut into plants to lay their eggs.

Species Diversity

Sawflies are spread across six families viz., Argidae, Blasticotomidae, Cimbicidae, Diprionidae, Pergidae and Tenthredinidae under the superfamily Tenthredinoidea, the largest superfamily in the suborder Symphyta with about 8400 described species under 800 genera worldwide found primarily in the family Tenthredinidae (Aguiar et al., 2013). The family Tenthredinidae comprises around 7500 species in 430 genera worldwide. Meicai and Haiyan (1998) reported 17 subfamilies and 66 tribes under the superfamily Tenthredinoidea.

Nature of Damage

These insects attack plants at various stages of development from very young seedlings to mature trees. The damage caused by these insects results in the death of living stems and shoots and reduction in wood quality due to boring and weakening of standing trees. In addition to these direct effects, borers may pave the way for secondary attack by wood rotting or staining fungi, thus hastening decay (Wagner et al., 1991). Female sawflies typically lay eggs on or inside plant tissue using a long, sclerotized ovipositor. The hatched larvae are mostly external leaf feeders while at the same time many are internal wood borers and stem borers. The members of Siricidae are all wood borers (Baine et al., 2020).

Diagnostic Characters

1. The adults lack a constriction between the thorax and the abdomen (normally known as 'wasp waist'), which is typical of the suborder Apocrita and the thorax broadly joins the abdomen.

2. Adult females possess a distinct ovipositor that looks and functions like a saw blade.
3. The adult possesses a medially narrowed pronotum and is devoid of the transverse mesonotal groove.
4. The legs possess a pair of protibial spurs.
5. The larvae are eruciform looking like lepidopteran caterpillars but can easily be distinguished from lepidopteran larvae by the presence of more than five pairs of prolegs and the absence of crochets. The larvae of sawflies usually have only one pair of ocelli.

   E.g.: *Diprion pini* (Linnaeus) (Pine sawfly)

4.3.2.4 Horntails

Systematic Position

Order: Hymenoptera
Suborder: Symphyta
Superfamily: Siricoidea
Family: Siricidae

The horntails are primitive solitary wasps and are a type of xylophagous saw fly. The wasps are moderately large, and the species in the genus *Sirex* is invasive in several parts of the world. The body is cylindrical, brown, blue or black in colour, often with yellow spots or bands. Generally the life cycle of horntails varies from one to several years and normally takes 2 years for complete development. In case of both the species, *Sirex gigas* and *S. cyaneus,* the life cycle extends over a period of 3 years from the egg to the adult stage. Rarely, the development gets retarded and the adult insects may not emerge from the timber until several years have elapsed. The siricid wasps are known to cause damage to the wood of pine trees.

Species Diversity

The family Siricidae comprises 122 species under 10 extant genera worldwide (Schiff et al., 2012).

Nature of Damage

Siricid wood wasps are of considerable economic importance in forestry and are often introduced in imported timber. They mostly attack dead and fallen trees and rarely infest healthy trees. The adult wasp usually lays eggs in the wood of dead or dying trees. Along with the eggs, it also inserts a symbiotic fungus, on which the larvae feed and live throughout their lives in trees. The eggs are laid during the summer from the end of June onwards, in a short oviposition hole in the outer layers of the wood. Initially the tiny larvae burrow tunnels in the wood running at almost right-angles to the oviposition holes, later they begin to burrow deeper into the wood and as the larvae develop they burrow towards the pith (Kajimura, 2000). At the time of pupation, the larvae migrate to just beneath the bark and pupates in a cocoon of silk and saw dust. The species *Sirex noctilio* attacks live host trees and causes serious damage to pine trees in North America, South America, South Africa, Australia and

New Zealand. The family includes two subfamilies, Siricinae and Tremecinae, wherein species of Siricinae such as *Sirex, Urocerus and Xeris* attack softwood, and of Tremecinae, such as *Tremex* sp., develop in hardwood.

Diagnostic Characters

1. Head is broad and eyes are small.
2. The thorax joins abdomen broadly without any constriction.
3. Both the male and female adults possess a short hornlike process at the end of the abdomen and hence the insect is named a horntail.
4. Larva elongate, devoid of legs and possesses a spine at the posterior end of the body. The horntail larvae look similar to bark beetle larvae but can easily be differentiated with elongate shape and spine at end of the body.
   Eg. *Sirex cyaneus* Fabricius, *Sirex noctilio* Fabricius and *Sirex juvencus* Linnaeus

4.3.2.5 Wood Wasps

Systematic Position

Order: Hymenoptera
  Suborder: Symphyta
  Superfamily: Siricoidea
  Families: Anaxyelidae, Xiphydriidae

The wood wasps belong largely to two families Anaxyelidae and Xiphydriidae. The family Anaxyelidae includes incense cedar wood wasps that bores into the cedar plants. The family Xiphydriidae include species that bores into the dead and dying trees or branches. Smith et al. (2011) reported six species in three genera of Xiphydriidae from Korea.

Species Diversity

Wood wasps belonging to Xiphydriidae comprise about 150 species under 28 genera distributed all over the world including North and South America, Australia, Europe and others (Jennings et al., 2007). Smith (1976) reported about 90 species in 22 recognized genera in 1976 and in a span of 30 years the number of species and genera have increased with more studies and discoveries.

Nature of Damage

The wood wasps belonging to the family Xiphydriidae are borers of dead trees and dying branches (Smith, 1976). They mainly bore into the dying or weakened trees. The species of this family cultivate fungus in tunnels and the larvae feed on the symbiotic fungi and grow. The recorded hosts of these species are elm, ash, oak, beech, birch, hawthorn, maple, apple, hickory, etc. (Smith, 1976). The wasps inhabit freshly cut logs and weakened or living trees, and feed on nutrient-deficient sapwood and heartwood (Haack and Slansky, 1987). The newly hatched larvae bore tunnels in the wood, where they eventually pupate and develop into adults.

The wood wasps belonging to the family Anaxyelidae bore into the living trees and cause damage to the wood. Wickman (1967) recorded the wood borer, *Syntexis libocedrii* as heavily infesting incense-cedars on a forest burn near Viola, California.

The species commonly known as incense-Cedar Wood wasp, was first described by Rohwer (1915) from the female. Adults range from 6 to 11 mm long, averaging 8 mm. Females lay eggs in the soft wood usually preferring smaller trees and young saplings, owing to the thinner bark that renders them more amenable for the insertion of the female's short ovipositor. The larva starts boring into the wood immediately after hatching. Larval galleries are almost always U-shaped, sometimes nearly circular. The larvae bore several inches into the sapwood of incense-cedar and form galleries.

Diagnostic Characters

1. The adults have a protruding spike from the dorsum of the last abdominal segment.
2. Adult females have a very long ovipositor in family Xiphydriidae and a short ovipositor in family Anaxyelidae.
3. The larva is white, cylindrical and not more than 15 mm long.
4. It has small posterior spines, and its head is recessed into the thorax.

Eg.: *Xiphydria camelus* (Linnaeus), *Syntexis libocedrii* Rohwer (Cedar wood wasp)

4.3.3 Lepidopteran Wood Feeding Insects

Lepidopterans usually include butterflies and moths where the body is clothed with scales and the wings are especially covered with flattened scales and hence the name Lepidoptera to the order. The wood boring insects of Lepidoptera mainly belong to the families, Sesiidae and Cossidae. A few species belonging to the family Xyloricitidae, commonly known as timber moths are also wood feeding insects where the larvae are the wood borers tunneling into the wood. In most species, larvae are arboreal, a few bore into the branches, tunnel under bark, a few bore into the flower heads. Major wood feeding lepidopteran insects are clearwing borers and carpenter worms/moths belonging to families Sesiidae and Cossidae respectively. The moths of Sesiidae resembles wasps and hornets in external appearance and behavior. These are active in daylight, unlike most other moths.

4.3.3.1 Clearwing Borers

Systematic Position

Order: Lepidoptera
Suborder: Ditrysia
Superfamily: Sesoidea
Family: Sesiidae

The clearwing moths are delicate, diurnal, swift flyers and resemble small wasps and hornets in both appearance and behaviour. The wings are long and narrow lacking scales. The group includes Ash/lilac borer, dogwood borer, peach tree borer, red oak borer, willow clearwing borer, banded ash clear wing and pine moth.

Species Diversity
Clearwing moths are small- to medium-sized moths distributed all over the world and comprises more than 1000 described species under 170 genera.

Nature of Damage
The female moths lay their eggs in crevices or broken bark of the trees and the hatched neonate larvae burrow into the bark and then to bore into the sapwood of the tree and start feeding on the inner contents. The larva makes tunnels in the trunk and the branches. Pine moths bore into the terminal and lateral shoots of the host tree, pine and cause extensive damage. The infestation often results in wilting of terminal shoots with subsequent dieback of crown and the entire branches of the plant. The branches become weak due to the infestation and are liable to be broken easily even with slight pressure of wind. The clearwing borers usually throw out the brown coloured sawdust like frass from the cracks and crevices of the bark. The frass is often mixed with oozing sap or gum in certain plant species. The infestation sites are marked by cankers, calluses or cracked bark. The feeding holes abandoned by woodpeckers and other birds are the indication of clearwing borer infestation. The already stressed or damaged plants are more liable for the clearwing borer attack. They mostly infest birch, fir, dogwood, lilac, ash, oak, poplar, rhododendron and ornamental *Prunus* species, including flowering peach, plums and cherries.

Diagnostic Characters (Adopted from Kristensen, 1999)
1. Mouth parts sucking type with a unscaled proboscis often reduced
2. Antennae gradually or sometimes abruptly clubbed and tip often hooked
3. Mesothorax larger
4. Ocelli present and large
5. Wing membrane devoid of microtrichia
6. Vein Rs unbranched in the hind wing and jugal lobe not markedly produced in the fore wing
7. Tympanal organs present at base of the abdomen

The larvae will be creamy white or dark tan coloured with thoracic and abdominal prolegs usually with final pair of legs at the tip of the abdomen.

E.g.: *Synanthedon* spp.

4.3.3.2 Carpenter Worms/Wood Moths

Systematic Position
Order: Lepidoptera
Suborder: Ditrysia
Superfamily: Cossoidea
Family: Cossidae

The carpenter worms are also known as goat moths as they emit bad smell. These are small- to large-sized bodied moths having long and narrow forewings. Usually, the abdomen extends beyond the hind wings. The life span is larger, sometimes single generation exceeding 4 years. The species of this family are mostly nocturnal and few Asian species are diurnal.

Species Diversity

The family Cossidae comprises about 700 described species under 113 genera worldwide.

Nature of Damage

The larvae of Cossidae tunnel into the heartwood of the living trees. These are the woodborers but sometimes tunnel into the soil and feed on external roots of the plants. Several species bore into the wood and make extensive galleries. The infestation of wood moths is often associated with oozing of the gum, commonly termed as 'bird's eyes'. The gum pockets further attracts fungus resulting in rotting of the wood. The larvae usually make 'J'-shaped tunnels of larger diameter. The excessive tunneling makes the trees weak and become vulnerable to wind damage. They usually attack oak, maples and elm trees. The larva overwinters in the tunnels and pupates in the associated chambers. When the adult emerges out the pupal skin extruded from the tunnel.

Diagnostic Characters

1. The mouth parts lack proboscis.
2. Antennae bipectinate in males and thread like in females.
3. Wings hyaline, media stem present and forked within discal cell.
4. Forewing with accessory cell, intercalary cell (loop formed by anastomosis of anal veins) present and about half the length of discal cell.
5. Abdomen extending well beyond hindwings.

E.g: *Prionoxystus robiniae*, *Acossus* spp., *Polyphagozerra coffeae, Dervishiya cadambae* (Fig. 4.9).

Fig. 4.9 *Dervishiya cadambae,* a pest of grape vine

4.3.4 Termites

Systematic Position
Order: Blattodea
Infraorder: Isoptera
Families: Mastotermitidae, Hodotermitidae, Termopsidae, Kalotermitidae, Thinotermitidae, Serritermitidae

Another group of wood feeding insects are termites that belong to the order Blattodea. The lower termites belonging to the six families are wood feeding insects. The lower termites have flagellates and prokaryotes in their hindgut which assist in cellulose digestion. The termites primarily feed on the wood and cause extensive damage to the trees and wood structures by hollowing the consumed portion. The termites usually consume fungus-infected wood, as it will be easy to digest the cellulose. They are eusocial insects living in groups.

Diagnostic Characters

1. The front and hind wing are equal and wings longer than the body.
2. Antennae moniliforme.

4.4 Conclusion

Among various biotic stresses, the wood boring insects are serious pests of several horticultural and forest trees resulting in huge economic losses. Major wood borers include beetles, bees, wasps, ants, sawflies, moths and termites. The insects belonging to order Coleoptera are the predominant and abundant group followed by hymenopteran insects. In Coleoptera, the longhorn beetles are the most destructive pests followed by bark beetles. An insight into the morphological features of immature and adult stages of different groups of insects helps in proper identification of borers, which is essential in developing suitable management strategies.

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Wood Degradation by Termites: Ecology, Economics and Protection

5

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Contents

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_5

Abstract

The significance of termites in the biodegradation of wood which is rich in lignocellulose is discussed. Members of Macrotermitinae (Termitidae), Rhinotermitidae and Kalotermitidae cause severe losses in forestry and construction structures. Being a complex aggregate of cellulose, hemicellulose and ligninocelluose, wood fulfils the termite's need for food. Once the wood is ingested, the involvement of midgut enzymes followed by the action of mutualistic symbionts in hind gut helps in the process of cellulose digestion. The annual cost estimated for termite damage and its prevention is in billions globally. To avoid these damages, it is recommended to use naturally durable timbers and resistant tree species against termite attack for major construction works. Adding to native pest termite species, the invasive termites are also becoming increasingly problematic in the regions of invasion. In natural forestry, colonies of pest species of termite can be controlled by poisoning the nest or mechanically removing the queen from the nest. In urban forestry, neonecotinoid insecticides have been widely used for management. In structures, combination of strategies such as wood preservatives, use of wood-plastic composites, insecticide baiting systems, pre- and post treatment of buildings is becoming increasingly important for successful management of termites.

Keywords

Biodegradation · Cellulose · Invasives · Preservatives · Termites · Wood feeding · Termiticides

5.1 Introduction

Principally, in terrestrial habitat, fungi, insects and bacteria are the organisms that degrade the wood. In temperate climate, fungi are the primary cause of damage to wood. In the tropics, the insects involved in biodegradation include termites and beetles to a greater extent, and carpenter ants and carpenter bees are lesser. It appears that in tropical and subtropical regions, termites are more important wood consumers than any other organism (Wood & Sands, 1978).

Termites are considered unwelcome guests at home as they cause damage to structures. But in their natural environment, termites are part of an entire ecological system, either in agricultural or forest habitat. Their role is to degrade dead trees into valuable organic matter. Although wood decomposition is affected by climate, the organisms involved play a vital role in wood degradation (Bradford et al., 2014).

A great diversity of organic material may provide diet for termites, which includes wood (sound or decaying) (Fig. 5.1a, b), herbaceous plants litter (Fig. 5.2), grass, nests constructed by other species of termites, fungi, dung (Fig. 5.3), lichen, carrion and even humus rich soil. Food preference of termites varies with species. They feed on grass, leaf mold, manure, algae, and soil. Some

Fig. 5.1 (**a**, **b**)Termites-mediated wood decomposition

termites cultivate fungi (Fig. 5.4a, b) as food for the colony. They cannot withstand harsh environments but thrive easily in conditions that are free from predators and other natural enemies like ants. Termites prefer locations that stay warm during cold season and cool during hot weather, and many species usually prefer to construct nests or colonies below ground. Termites are classified as subterranean, damp wood and dry wood termites based on the type of wood affected and the environment where the attack occurs. Out of the all known species of termites, 363 species are

Fig. 5.2 Termite feeding on Acacia leaves

Fig. 5.3 Elephant dung fully covered with termite sheathings'

considered to be significant pest species (Krishna et al., 2013), which was initially 80 pest species out of 2700 known termite species (Lee & Chung, 2003). Among these, subterranean termites alone accounted for 38 species with maximum of

Fig. 5.4 (**a**, **b**) Presence of "Fungus comb" inside the termite mound

Coptotermes having the highest number of species followed by *Macrotermes*, *Reticulitermes* and *Odontotermes* (Rust & Su, 2012).

Many termite species are identified as important pests in agricultural and forest plantations as well as in urban and rural areas inhabited by man (Fig. 5.5a–f). They construct mound in forest/plantation and from their workers forage for a long

Fig. 5.5 (**a**) Termite mound in young Eucalyptus plantation; (**b**, **c**) Drying of main stem act as a precursor of termite infestation due to wounds caused by mechanical injuries in growing tree which often lead to death of a tree; (**d**, **e**) In a healthy tree termites feeding only on the dried barks. (**f**) Termite infestation in a treated pole implanted in the soil

Fig. 5.5 (continued)

distance causing earthen sheeting on plants (Fig. 5.5a). However, complete death of such infested trees mainly attributed to previous mechanical damage which acts as precursor for termite infestation (Fig. 5.5b, c). In most cases where plants are healthy and sound, only bark is attacked (Fig. 5.5, d, e) which does not cause damage to hardwood. Coal tar treatment which is generally done to avoid infestation may not be long lasting, especially when the tree poles are used for supporting cables or for any other purpose (Fig. 5.5f). Further, they are serious economic threats to urban structures (Fig. 5.6a, b), valuable books (Fig. 5.7), manuscripts, paintings, organic materials (Fig. 5.8) and even inorganic materials like buried telephone and electrical cables (Henderson & Dunaway, 1999). Annual loss caused to grain crops alone in India ran into 220 million rupees (Roonwal, 1970).

In this review, the probable impairments produced by termites in natural and urban forestry, wood damage in structures, ecology and physiology of wood degradation, invasive termites, and economic loss attributed to termites injury and their protection are discussed.

Fig. 5.6 (**a**) Wooden structures in the house damaged by termites; (**b**) Auditorium floor damaged by termite infestation

5.2 Wood Degradation in Natural and Urban Forestry

Although many recent publications have questioned termites' role as a pest in the forest ecosystem system (Junqueira & Florencio, 2018), there is substantial evidence of termite damage in forest ecosystems, especially in implanted forest plantation.

Fig. 5.7 Books eaten by termites

Fig. 5.8 Coir mat eaten by termites

Termites devour nearly seven billion tons of biomass each year, majorly wood and other forest litter. The feeding galleries where termites live may become colony centres (Eggleton et al., 1996; Wardell, 1987). In addition to their ecological importance, termites are pests of forest plants. Species of Macrotermitinae, a fungus-growing sub-family of Termitidae, is reason for the majority of the tree mortality in African forests (Mitchell, 2002). In Australia, species such as *Neotermes insularis*, *Coptoterms acinaciformis and Porotermesadamsoni* are attributed to serious loss of timber in indigenous eucalypt forests and plantations of exotic pines (Greaves, 1959).

Seedlings and newly planted saplings are susceptible to attack during the first 6 to 9 months after planting. Mortalities range between 19 to 78% and may reach 100%. In Africa, *Coptotermes amanii* (Sjostedt) (East African subterranean termite) (Rhinotermitidae: Coptotermitinae) is a major contributor for severe injury to wooden structures and buildings. In the arid western parts of Africa, *Psammotermes allocerus* Silvestri (Rhinotermitidae: Psammotermitinae), a widespread termite, is known to infest buildings causing substantial damage to timber. *Macrotermes* and *Odontotermes* are the two termite genera that cause heaviest damage to the seasoned timbers in structures and in forest ecosystems. In coastal South Africa, the invasive species *Cryptotermes brevis* (Kalotermitidae) causes considerable damage.

In general, the termite damage in tropical forestry is severe on exotic species than on natives. In general, stressed trees are most vulnerable to attack (Nair & Varma, 1985). Dry-wood termites (Kalotermitidae) as pests are mostly restricted to humid tropics, live and feed in deadwood but occasionally damage living parts of mature trees. *Coptotermes* termites cause more widespread and significant damage to mature trees, mainly in Australia and Malaysia. Up to 100% loss predominantly by various Macrotermitinae (Termitidae) such as *Macrotermes*, *Microtermes*, and *Odontotermes*, was reported in young introduced trees such as Eucalyptus in Africa and India (Cowie et al., 1989).

Different degrees of damage and symptom manifestation often depend on the termite species involved. A tree may be attacked at any stage of growth, although young stages are generally susceptible. The common soil-covered foraging galleries or extensive soil sheets on the live trees results in the removal of bark and dead tissues (Harris, 1971; Rajagopal, 1982). Stressed trees due to moisture reduction (e.g. drought or inadequate watering, physical damage (e.g. mechanical or fire), diseases (e.g. microbial infection) etc., are succeptibe to termite damage than health trees (Nair & Varma, 1985; Sen-Sarma, 1986). The broken branches and wounds (e.g. physical damage or fire scars), particularly if subject to aggressive fungal attack, can be steadily exploited and enlarged, with the chance of damaging wood (Harris, 1971; Postle & Abbott, 1991), leading to a significant loss.

In managed eastern Amazonian tropical rain forests, 43% of heartwoods of trees are damaged by termites, with *Coptotermes testaceus* (Linnaeus) the most abundant species (76%) (Eleuterio et al., 2020). From an economic standpoint, forests in which trees with unsound trunks are common, are less valued for their timber and are neglected in the forest or on log decks regularly accounts for a sizable proportion of the carbon emissions from logging (Ellis et al., 2019).

Deterioration of trees in the urban areas is a common issue all over the world. Improper selection of tree species and poor management may lead to attack of macro- and microorganisms, like pests and diseases (Zorzenon & Campos, 2014). The infestation of up to 27% of the trees in the city of São Paulo, Brazil, was found to be contributed by four subterranean species of termites, but *C. gestroi* (Wasmann) being the dominant species. In many countries, the termite damage in urban forestry is not quantified and needs assessment.

5.3 Wood Degradation in Structures and Buildings

Wood is a traditional-natural-organic material and is being used for generations for varieties of soft and hardwoods, for the production of working, playing or fighting tools, furniture, and for various timber structures such as doors, windows, ceilings, wooden trusses, furniture and wooden log-cabin. In tropical and subtropical regions, termites cause significant structural and building damages (Pearce, 1987). Each year, hundreds of thousands of structures, including homes, dams, bridges, decks, roads, retaining walls, pipes and utility poles, require treatment to avoid termite damage. The timber damage in buildings has been reported in most part of world being sever in tropical and subtropical countries. Once trees felled, it remains susceptible to attack by termite, and indeed many tree species which were comparatively resistant while in stand become susceptible, particularly logs. Nearly 5% of termite species are known as serious pests to wooden structures and timber-in-service globally (Ahmed et al., 2000). Observations in the teak depots showed that an average 12% of logs were injured in varying levels by the termites, microbes and heartwood borer attacks. In India, the economically important species of termites, *Coptotermes* spp. and *Heterotermes* spp., caused significant damage to timber - in storage and in service (Edwards & Mill, 1986; Pearce, 1987; Ahmed et al., 2000; Su & Scheffrahn, 2000; Ngee et al., 2004). Less than 35 to 40 species have been reported to damage crops and timber in buildings in India where more than 300 species have been reported.

In a study conducted at Oyo state of Nigeria, 140 buildings built of various materials were surveyed for damage by termites. About 60% houses made of damp-proof course with either block or brick were significantly attacked, and buildings built of block and brick walls without damp-proof course were 80% and 90% damaged, respectively (Olaniyan et al., 2015). *Coptotermes gestroi* is the predominant termite species attacking buildings in urban area of Taiwan. However, *C. gestroi* was still an active attacker to buildings in rural areas, but some mound building species such as *Microcerotermes* spp., *Odontotermes* spp., and *Macrotermes* spp., were reported as pests of structural and buildings. The major reasons for infestation by termites in buildings include improper construction of foundation, woodworks in direct contact to ground, high humidity and improper drainage, insufficient clearance of termite food source in and around buildings, inadequate ventilation in crawl space and termite nest and infested timbers around the building (Sornnuwat, 1996).

Infestation of buildings is generally beginning from a subterranean nest in the ground from which the termites make galleries over walls or piers (Fig. 5.9) to infest the structure from underneath. Mostly, the nest is exterior to the building boundary, but rarely may it be buried beneath the structure in soil or fill. Termites living inside the structure generally retain connection with the soil for moisture and the main nest for communications. The chemicals released by the queen from the central nest are circulated throughout the colony and regulate its behaviour and structure. In occasional cases, a nest may be built inside the structure as an offshoot from an existing colony, or by mated pairs after a swarming flight. Such nest formation can happen where a source of stable moisture and food is accessible to the termites inside the structure and in this condition and there may be no direct contact between soil and nest. It is reported that previously forested land or plantation with subterranean termites damage contribute to severe damage in buildings (Mo et al., 2006). This is due to presence of left over stump and piles in the human settlements after clearing lands of plantation or forest.

Fig. 5.9 Galleries produced by termites in building to have entry point

5.4 Ecology and Physiology of Wood Degradation by Termites

Wood is the most widely used building material. Due to ease of its use in construction, appealing aesthetic properties, the ability to be repaired, a high strength-to-weight ratio and less cost, it is one of the sought after material in construction industry. It is a renewable resource, cultivation and production is less energy-intensive than other building materials, such as steel, concrete or aluminium. On molecular basis, wood mainly consists of cellulose, hemicellulose, lignin and extractives (chemicals responsible for colour, taste, odour, flammability, resistance to decay and hygroscopicity properties) and inorganic minerals in very minor quantities. The elemental composition of dry wood is approximately carbon (50%), oxygen (44%), hydrogen (6%) and nitrogen (0.1%). The general chemical configuration is nearly as $C_6H_9O_4$. However, different wood species have varying degrees of resistance to biotic stress like insect damage. The sufficient oxygen present in wood makes it susceptible to wood feeding organisms. When the wood is dry, it is comparatively resistant to fungi but few insect species do attack dry woods. Hence, avoiding wood deterioration is usually not an easy task, and different types of protection measures are needed which are exposed to various environmental conditions. In general, the longevity of the wood can be extended if it is kept dry and infestataion of wood eating insects is avoided (Mindess, 2007).

There is an excellent symbiotic association that persists between the microorganisms and termites. There is a long-standing symbiosis between termite and protists, which helps in lignocellulose digestion and is emerged in the late

Jurassic and thus has ecological importance (Brune, 2014). Wood digestion supported by mutualistic bacteria was a characteristic of the common ancestor of the bivalve families Teredinidae and Xylophagainae (Distel et al., 2011). Deconstruction is attained in wide ranges of environmental situations, such as pH, pressure, temperature and redox potential. There are some preliminary indications that termites wish to consume comparably soft decaying wood with lower density (Arango et al., 2006).

Endogenous cellulases secreted in the salivary glands and midgut in termites are supplemented by enzymes secreted by bacteria and flagellates in the hindgut (König et al., 2013). In termites, hemicellulases such as galactanase and xylanase are majorly of bacterial origin (König et al., 2013), but the activity of mannanase has been attributed to a protist (Tsukagoshi et al., 2014). Whilst the majority of the termites depend on gut-inhabited microbiota (Zheng et al., 2015), species belonging to Macrotermitinae cultivate the Termitomyces, a basidiomycete fungus on faecal pellets within the mounds which are moulded into comb-like structures. This fungus can produce glycoside hydrolases which is capable of hydrolysing complex polysaccharides. Similarly, symbiotic bacteria present in the worker termites are capable of digesting the oligosaccharides produced by the fungus, Termitomyces (Poulsen et al., 2014). Yoshimura et al. (1996) developed a summary of cellulose degradation process in *C. formosanus.* It starts with initial chewing of wood into smaller pieces by mouthparts and the midgut enzymes such as endo-*β*- 1-4-glucanases and *β*-D-glucanases break the cellulose matrix into smaller but still indigestible fragments. The food material then moves to hindgut and is encountered first by *Pseudotrichonympha grassii*, which releases cellulase that breaks down the polymerised cellulose. In hindgut, less polymerised pieces are further fragmented down by *H. hartmannii*, thus finishing the breakdown of cellulose into acetate.

5.5 Economics of Wood Degradation by Termites

In recent past, factors like building costs and growing urbanization have contributed to the considerable upsurge in monetary expenditure due to termite damage and management (Su & Scheffrahn, 2000). Harris (1971) reported that the annual cost of repairing termite damaged buildings in West Africa was 10% of their total capital cost. Edwards and Mill (1986) concluded the data of Pinto (1981) and estimated a $1.02 billion economic impact by termite damage in the USA. It estimated that the management cost alone might have exceeded 1.5 billion US dollars as based on sales of termiticides, in which 80% or $1.2 billion share accounts for subterranean termite management. In the United States, the annual management cost for termite problems in structures and buildings is more than $1 billion; however, the latest report on the global damage was estimated at US $22 billion to US $40 billion (Su, 2002; Rust & Su, 2012). Out of which in 2010 alone, $32 billion economic losses are accounted only by subterranean termites worldwide. Among the termite species, subterranean termites alone contributed 90% total economic loss and about 70% of the damage of construction (Rust & Su, 2012).

In China and Australia, termite infestations are extensive. It is assessed that 20% of homes of Australia and up to 90% of homes of Chinese south of the Yangtze River are damaged by termite infestation (Ghaly & Edwards, 2011). Economic losses due to termite attack in China exceed $ 1 billion (US) annually. In southern China, tens of thousands of tons of pesticides have been applied. Infestation rates of buildings in Hainan and Guangdong provinces may be as extreme as 80%. In Australia, the annual cost for management and damage repairs by termite infestation is estimated as more than 100 million dollars.

Termites can be observed everywhere in Japan excluding the northern half of Hokkaido Island. It is estimated that at least 800 million (US$) is being invested annually for preventing and managing termite infestations. Japan is the third leading user of pesticides for structural pest management in the world, as more than 50% of the homes are generally constructed out of wood (Tsunoda, 2005).

In Southeast Asia alone, approximately US $ 400 million is estimated for managing termite infestation annually (Lee, 2007).USD 8–10 million in 2000 and 2003 were estimated towards subterranean termite management in Malaysia, which recently exceeded up to USD 10–12 million (Lee, 2007; Yeoh & Lee, 2007; Verma et al., 2009). *Coptotermes gestroi* (Wasmann) is the major and serious pest of buildings in Southeast Asian countries (Kirton & Brown, 2003; Lee, 2007). In Peninsular Malaysia, 85% of buildings are infested by this species, whereas in Thailand, 90% of termite infestations in urban area were also caused by *C. gestroi* (Kirton & Azmi, 2005; Sornnuwat, 1996). Another subterranean termite, *C. formosanus* (Shiraki), is the most important pestiferous species in Japan, Taiwan (Su & Hsu, 2003) and China (Zhong & Liu, 2002) where as it is *C. curvignathus* (Holmgren) in Indonesia.

In India, the exact figure of monetory loss due to termite attack is not clear but thier ability to destroy household was well documented by Roonwal (1955). He cited that an entire township of Shri Hargovindapur in Gurdaspur, a place in the Punjab state of India, was gradually ruined by the termite, *Heterotermes indicola*, and that led to resemblance of bombed-out ghost town. Intensity of the damage was so high that the entire township of 1900 houses were infested and nearly 400 buildings collapsed. In Guwahati, the 170-year-old Christ Church is slowly dying as termites are feasting on the precious teakwood pillars that hold the structure (Times of India, 2011). But the funniest example of termite damage in India is probably where instead of attacking wood and causing monetary damages termite preferred to feed on money itself worth of which is $220,000 (Anonymous, 2011). Verma et al. (2009) reported that India annually spends 35.12 million dollars for termite control where as Australia spends 100 million dollars (Scholz et al., 2010); China, 300–375 million dollars (GEI 2005); Japan 800 million dollars and in the United States 1000 million dollars (Verma et al., 2009). Although, the total annual economic loss due to termite damage and their prevention is estimated in the billions globally, in under-developed countries data on damage is unavailable and it is difficult to estimate the cost of repair as funds are also not available (Ghaly & Edwards, 2011). To avoid these damages it is often recommended to use naturally durable termite-resistant timbers for major constructions.

5.6 Invasive Termites of the World

Around 28 species of termite are considered invasive throughout the world and have spread outside their native ranges, often with considerable economic implications (Evans et al., 2013; Buczkowski & Bertelsmeier, 2017). *Coptotermes* is one of the widespread subterranean termite genera of economic significance and some species of the genus are effective intruders. Invasive termites species have some characteristics like, they all eat wood, capable of nesting within wood, and they can easily produce secondary reproductives. These characters are common in two families, the Rhinotermitidae and Kalotermitidae, which contribute to 21 species on the invasive termite list, mostly belonging to three genera *Cryptotermes*, *Coptotermes* and *Heterotermes* (which together constitute 16 species). The Termitidae (comprise 70% of all termite species), which is the largest termite family, has only two invasive species, because relatively few species have these characteristics. Islands outnumber the invasive species than continents; with South Pacific islands being the most invaded region. The perusal of termite invasion indicates that a majority of the invasive species are native to Southeast Asia. Among the efforts to eradicate the termites in the place of invasion, only two eradication efforts, one in South Africa and another in New Zealand, seem to have been successful against *Coptotermes* species. The ecological and economic damage caused by invasive termites is likely to increase substantially in response to climate change (Buczkowski & Bertelsmeier, 2017). They continue to expand their presence and cause significant ecological and economic damage. There is a need for strong quarantine measures to restrict their entry. Recently, successful intervention of two *Coptotermes* species have been reported from India (Nagaraju et al., 2020).

5.7 Management of Termites in Natural Forestry

Some species of termites which affect forest production have the ability to build mounds, which include *Macrotermes* spp. and *Odontotermes* spp. (India), *Macrotermes* spp. (Africa), and *Coptotermes* (Australia). Termites present in the mound can be killed by poisoning the mound with any insecticide toxic to termites, hence killing the queen, or mechanically removing the queen from the nest (Brown, 1965; Rajagopal, 1982; Thakur & Sen-Sarma, 1980). The mound-building species are targeted by these methods. Chances of young colonies missing from toxic chemical may again gain access to trees. In the case of *Macrotermes* and *Odontotermes* attacking young Eucalyptus trees, control operations should continue till the trees establish back (Thakur & Sen-Sarma, 1980). In the case of *Coptotermes* where mature trees are attacked, continuous destruction is the necessity as mounds appear.

5.8 Management of Termites in Urban Forestry

Urban termite studies highlighting the significance of pest species control began in 1983. Most of the termites were tested with chemical products. The most tested chemical is hexaflumuron on termite species such as *Coptotermes formosanus* and followed by *Reticulitermes flavipes*. The studies also compared the diversity of termites in different locations within urban areas, thus indicating *C. formosanus* as the most tested and problematic invasive species, which is followed by *R. flavipes* in urban areas (Santos, 2020).

In urban forestry, termite control can be achieved with the injection of imidacloprid (0.25 mL/L) or thiamethoxam (2 g/L) into the tree trunk (Zorzenon & Campos, 2014). Insecticides can be injected by a pressurized spray or by plastic funnels and watering cans. Injection of imidacloprid resulted in 100% mortality of *C. gestroi* and other three tree infesting species. The occurrence of new infestation of termites was only 2.5% on trees which were initially identified as non-infested by termites. Treatment on these new infestations with thiamethoxam also showed 100% efficacy. These two neonecotinoids are major termiticides used around the world in urban ecosystems.

5.9 Management of Termites in Buildings

There is increasing interest among scientists and engineers to develop preventive measures against termite attack. Chemical treatments are the only solution if termites have already gained access to wood/timber structures in houses. The best protection against termites is to prevent them accessing the wooden structures by ensuring the timber parts are not in contact with soil. Providing proper ventilation and preventing cracks in concrete slabs is the necessary procedure to avoid termite infestation in buildings. Painting of timbers before installation will usually prevent the entry of drywood termites. Effective controls probably depend on a combination of various strategies, and it may also vary from region to region depending on local situations and availability of materials.

5.9.1 Termite-Resistant Tree Timbers for Construction Works and Furniture

The naturally durable and resistant wood provides a front line of defense against attack of termites. However, from the study it is important to note that only heartwood contains secondary metabolites which impart resistance against insects but not sapwood. Some of the tree species mentioned here provide varied degree of resistance against subterranean termites. *Chamaecyparis nootkatensis* (Yellow Cypress or Alaska cedar), *C. obtusa* (Grace & Yamamoto, 1994) and bark of neem deter the termites (Delate & Grace, 1995).

Bultman and Southwell (1976) evaluated the heartwood of 112 tropical woods in the Panamanian forest for natural resistance to subterranean termites and fungi. Thirty-nine of the 112 woods survived the 158 months of exposure; of these only six were considered to be highly resistant to all wood-destroying organisms present. These include *Dalbergia retusa*, *Tabebuia guayacan*, *Tectona grandis*, *Ocotea rodiei* and *Vouacapoua americana*. Similarly, Arango et al. (2006) reported Alaska Yellow-Cedar (*Chamaecyparis nootkatensis*), Juniper (*Juniperus* sp.), Erisma (*Erisma* sp.), Atlantic White-Cedar heartwood (*Chamaecyparis thyoides*), Ipe (*Tabebuia* sp.) and Qualea (*Qualea* sp.) as resistant to *Reticulitermes flavipes*. In India, outer heartwoods of sal and toon proved to be resistant, but the inner heartwood of sal was only moderately resistant (Sen-Sarma & Gupta, 1978). A review by Sundararaj et al. (2015) on the natural durability of 351 timbers which were tested under Indian environmental conditions indicated that 53% belonged to durability class III (ex. *Butea monosperma*, *Ficus benghalensis*, *Grevillea robusta*, *Hevea brasiliensis*, *Samanea saman* etc.), 21% to durability class II (*Acacia auriculiformis*, *Dalbergia sissoo*, *Dysoxylum* sp. *Eucalyptus* sp. etc), and 26% to durability class I (*Tectona grandis*, *Shorea robusta*, *Terminalia alata*, *Pterocarpus marsupium*, *Madhuca latifolia*, *Artocarpus* sp. *e*tc).

5.9.2 Use of Wood Preservatives

The use of creosote in wood preservation was researched and implemented in the last century. During those days, Wolman salts, water-soluble preservatives that constitute dinitrophenol, chromates, fluorides, and arsenic, developed by Wolman and Malenkovic, were widely used. However, potential leaching of water-based preservatives was understood and copper chromate arsenate (CCA), which can be impregnated into wood, was developed in 1933. As a result, CCA has become the preservative for wood protection (Webb, 1999).

Over the years, wood preservatives are increasingly used by pressure techniques or non- pressure technique. Generally water-borne or oil-borne preservatives are used in many countries. Non-pressure methods of application, such as brushing, spraying or dipping, are used so that preservatives will not be observed or penetrated into the wood. The effective application can be achieved by high pressure to force preservative to move deeper into the wood. The chemical preservatives may be dissolved either in oil or water. Water-borne preservatives are generally used for timber and plywood in residential and commercial structures. They are odourless and leave a clean wood surface hence can be painted (Fig. 5.10) which lead to their popularity (Mindess, 2007). In many countries, water-borne preservatives such as chromated copper arsenate (CCA), Ammonical copper arsenite (ACA), Acid copper chromate (ACC), Fluor chrome arsenate phenol (FCAP) and Chromated zinc chloride (CZC) are used in many countries. Water-borne preservatives consist of salts which are dissolved in water.

By far the most widely and commonly used oil-borne preservative is creosote, a by-product coal tar distillation. It is insoluble in water, highly toxic to the fungi and

Fig. 5.10 Worker painting the wood preservative on the wooden door before installation

wood eating insects. It is relatively inexpensive and can easily be applied due to its low volatility. It is particularly effective on large timbers, such as sleepers and bridge timbers. It becomes oily on applied surface and releases unpleasant odour, hence not suitable for residential use. Creosotes can also be obtained from organic materials, but tend to be less effective when compared to coal tar.

Another wood preservative, Borate, provides excellent protection against all forms of wood-destroying organisms, fungi and termites (both dry wood and subterranean termites). Borax powder is used in termite control, but has limitation as only the directly consumed individuals will be killed. Bioassay studies showed that the treated soil mixed with borates is toxic to termites (Kard, 2001). Studies have demonstrated that 3% borax and Zinc borates efficiently protected wood-plastic composites (WPCs) containing 40 wt% of pine wood residues, 60% recycled HDPE (Lopez-Naranjo et al., 2014). The insecticidal activity and low water solubility borates indicate its potential to be used as treatment to high pressure laminates and wood composites and also for soil application to create barriers against subterranean termites. Liquid borate solution such as sodium borate is used in pressure-treated wood. The borate solutions applied to existing construction are not much effective as the compounds do not seep into the wood uniformly. Therefore, the inner layers may not be protected from termites. The subterranean termites are controlled by low solubility borates. These borate compounds vary with respect to their water solubility depending on chemical structure. However the process of application of the wood preservatives to timber is tedious, and hence the use of liquid termiticides in the protection of homes and buildings from termite attack is still popular (Potter, 2004).

5.9.3 Insecticidal Management of Termites in Buildings

The soil which has immediate contact with the floor of a building is treated with an insecticide forming a toxic barrier to termite entry. Direct liquid treatments of insecticides are done outside, inside and also in the foundation to eliminate the termites completely. The organochlorine cyclodienes (chlordane and heptachlor) are the first class of insecticides registered for termite control in 1952 and remained dominant in the market until 1987. Their use was banned because of their negative effects on human health and environment (Ahmed & Frech, 2008). Followed by these, the pyrethroids and organophosphates are the next two groups of chemicals used in termite control (Mix, 1988). Chlorpyriphos was the widely used chemical till recent days.

In 2000, organophosphorous insecticides against wood feeding insects were phased out for use in termite control by the EPA because of the side effects on public health and wildlife. Due to this, pest control professionals shifted to use of synthetic pyrethroids but were reported to give unsatisfactory control. Followed by this, many new generation insecticides were registered against termites during the 1990s, which are less toxic to the environment and more effective (Hu, 2005). These insecticides can be used for soil application which included imidacloprid, chlorfenapyr, indoxacarb, chlorantraniliprole and fipronyl. The toxic effects of these insecticides are transmissible from wood ingested individuals to other colony members which are not directly exposed to treated soil; hence decline in the population was high (Hu, 2011).

5.9.4 Baiting- Insecticides System

As termites are attracted to cellulose rich materials, feeding habit can be best exploited by developing attract and kill strategy. Hexaflumeron was the active ingredient registered as first termite bait formulation in United States and currently several other chemicals are in use, and all of which fall into two classes: insect growth regulators (IGR) and energy production inhibitors.

Both classes are considered as slow-acting and rely on foraging termites to transfer the small amounts of consumed bait material to the colony though contact, grooming, trophallaxis, fecal consumption and cannibalism. Baiting systems using IGRs are tend to be used as standalone treatments. The energy production in termite is affected when AI is used as a bait formulation for soil treatment. There baits are designed to use both underground to prevent structural infestation and above-ground in areas with known termite activity. Compounds that have been marketed include noviflumuron (Sentricon® Recruit III and Recruit IV), hexaflumuron (Sentricon® Recruit II, Hex-Pro™), and chlorfluazuron (Exterra™, Requiem™).

In recent studies Chitin synthesis inhibitors (CSI) baits play important role in eliminating colonies of termites. Due to availability of durable baits which requires less-frequent inspection, many termite control professionals prefer the baiting systems in recent years (Su, 2019). Bait method is usually based on less toxic AIS

(32-fold) in lesser quantities (600-fold). Baits eliminate colonies of termites and reduce their population (Su, 2011). They have the ability to reduce the damage potential instead of excluding them from a house. The advantages of baits in IPM are reduced risk for non-target organisms, less active ingredient required and long lasting. The active ingredient used is odorless, no mixing is needed and hence lesser risk to humans. Baiting has attracting and phagostimulant nature which enhance consumption resulting in faster spread through trophallaxis.

5.9.5 Biological Control of Termites

There is a little confidence about biological control of termites for specifically using in forestry. The augmentation and encouragement of predatory ants to reduce termite activity is suggested (Beeson, 1941). Fungal and bacterial pathogens, including some strains of *Bacillus thuringiensis*, are known to be effective against various termite species in the laboratory but have not been successful in the field, even when applied directly to the mound (Hänel & Watson, 1983: Khan et al., 1985). In tea plantation, dry wood termites were controlled successfully by nematodes but are unlikely to be successful in control of subterranean termites (Mix, 1985). The reduced effectiveness of pathogens may be due to the reason that many termite species have the ability to remove the isolate dead or infected individuals from the nest (Pearce, 1987), thus avoiding further spread of the pathogen. Chouvenc and Grace (2011) pointed out that failure of biological control in management is due to poor understanding of termite biology.

5.10 Conclusion

As a part of cellulose feeding habit, termite damages the wood and becomes detrimental to natural and urban forestry as well as structures. One of the impediments in successful management of termites is lack of understanding of their biology. Both preventive and curative measures are available against termite attack in structures but are not long-lasting. There is an increased number of termiticides registered over the years and evaluated for their efficacy in both in natural environment and in structures. The application methods of these termiticides are continuously evolving to fit into IPM programmes.

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Wood Borers of Important Fruit Trees with Special Reference to Cerambycids

6

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https://doi.org/10.1007/978-981-16-8797-6_6

Abstract

In an agricultural economy like India, fruit farming proves to be a profitable business in many ways. The cultivation of fruit crops plays an important role in overall status of the mankind and the nation. The standard of living of the people of a country is depending upon the production and per capita consumption of fruits. Fruit growing has more economic advantages. The importance of fruits in human diet is well-recognized. India is the largest producer of fruits in the world and is known as fruit basket of world. The major fruits grown in India are mango, grapes, apple, apricot, orange, banana fresh, avocados, guava, lichi, papaya, sapota, and watermelons. Insect pests are one of the important production constraints of fruits. The wood and borers of the family Cerambycidae consist of many economically important pests among the recorded insects on fruit crops in the world. In this chapter, the wood borers of family Cerambycidae on important fruit crops like grapes, apple, mango citrus, cashew, litchi and pomegranate are discussed and summarized. The new wood borer of grape *Dervishiya cadambae* (Cossidae: Lepidoptera) is discussed looking into its potential of becoming one of the major pests in grape ecosystem.

Keywords

Fruits · Cerambycid wood borers · India

6.1 Introduction

Fruit growing is one of the important and age-old practices, practiced in India since ancient times. Cultivation of fruit crops plays an important role in overall status of the mankind and the nation. The standard of living of the people of a country is depending upon the production and per capita consumption of fruits. Fruit growing has more economic advantages. Importance of fruits in human diet is well-recognized. Man cannot live on cereals alone. Fruits and vegetables are essential for balanced diet and good health. Nutritionist advocates 60–85 g of fruits and 360 gm vegetables per capita per day in addition to cereals, pulses, egg, etc. Fruits and vegetables are good sources of vitamins and minerals without which human body cannot maintain proper health and develop resistance to disease. They also contain pectin, cellulose, fats, proteins, etc. Fruits have high productivity, i.e., high yield per unit area, and give high net profit. Through the initial cost of establishment of an orchard is high, it is compensated by higher net profit due to higher productivity or high value of produce. Fruit farming provides raw materials for various agro-based industries-canning and preservation (fresh fruits), coir industries (coconut husk), pharmaceutical industry, transporting and packaging industries, etc. Growing fruits being perennial in nature enables grower to remain engaged throughout the year in farm operations and to utilize fully the resources & assets like machinery, labor, land, and water for production purpose throughout the year compared to agronomic crops. Although most of the fruit crops require perennial irrigation and good soil for production, there are many fruit crops of hardy in nature like mango, ber, cashew, custard apple, aonla, phalsa, and jamun etc., which are grown on poor shallow, undulated soils considered unsuitable for growing grain/agronomical crops. Many fresh fruits, processed products, and spices are exported to several countries earning good amount of foreign exchange.

Good number of fruits is grown in India under varied climatic conditions. They include almond, anola, apple, ber banana, citrus fruits, custard apple, grapes, guava, jackfruit, kiwi, litchi, mango, muskmelon, papaya, passion fruit, peach, pear, pineapple, plum, pomegranate, sapota, strawberry, walnut, watermelon etc. During 2017–2018, the total area under fruits cultivation was 6506 thousand ha with a productivity of 97358000MT (Table 6.1).

A large number of insect species are recorded as pests of tropical and subtropical fruit trees, but relatively few cerambycid species are of economic importance to these crops (Hill, 2008). The grubs of most species develop for about 1 year or more in the tree trunk either as sapwood or as heartwood feeders. Larvae of some species develop in highly decomposed wood, while others develop in herbaceous plants or roots. Larvae have strongly sclerotized mandibles capable of tunneling the heartwood timber. The microclimate of tree trunks, canopy, and branches is a very important factor for their normal growth and development. Intensive agriculture and severe deforestation coupled with global warming have resulted in many longhorn beetle species becoming serious pests of agriculture, plantations, and forest plant species causing unavoidable economic losses. Some longhorn species have been permanently established outside their natural distribution range due to the significant increase in international marketing and exchanging materials, which have resulted in the severe setback on trade (Kariyanna et al., 2017a, b).

Worldwide, more than 100 cerambycid species have been or currently are economic pests of crops. However, the pest status or identity of several species has not been confirmed, and several others are no longer considered economically important. The estimated loss due the borers in major fruit crops is shown in Table 6.2. Consequently, only cerambycid species of important fruit crops of India are discussed in this chapter.

Table 6.1 Fruit cultivation in India

Crops	2017–2018 (Final)		2018–2019 (First advance estimate)	
Fruits	Area	Production	Area	Production
Almond	11	14	10	11
Aonla/Gooseberry	93	1075	94	1098
Apple	301	2327	307	2371
Banana	884	30,808	874	30,006
Ber	50	513	50	633
Citrus		0		
(i) Lime/Lemon	286	3148	283	3221
(ii) Mandarin	428	5101	404	4964
(iii) Sweet orange (Mosambi)	185	3266	179	2876
(iv) Others	103	1030	107	1192
Citrus total (i to iv)	1003	12,546	973	12,253
Custard apple	46	401	38	320
Grapes	139	2920	137	2951
Guava	265	4054	270	4107
Jackfruit	185	1830	187	1857
Kiwi	4	12	4	12
Litchi	92	686	93	711
Mango	2258	21,822	2313	22,353
Muskmelon	54	1231	54	1145
Papaya	138	5989	139	5831
Passion fruit	14	82	14	85
Peach	19	114	18	123
Pear	44	318	42	304
Picanut	1	0	1	0
Pineapple	103	1706	106	1810
Plum	23	89	23	89
Pomegranate	234	2845	246	2865
Sapota	97	1176	101	1200
Strawberry	1	5	1	5
Walnut	109	300	108	301
Watermelon	101	2520	89	2299
Others	238	1977	237	2015
Total fruits	6506	97,358	6530	96,754

Source: http://agricoop.nic.in/sites/default/files/2018-19%20%281st%20Adv.Est_.%29_updt.pdf

Table 6.2 Estimated monitory loss due to borers in major fruit crops (Krishnamoorthy et al., 2014)

Sl. No.	Crop	Annual production ('000 ton)	Average yield loss due to borers (%)	Monitory loss (Rs. cores)
1.	Apple	2891	15	255
2.	Banana	29,780	30	893
3.	Citrus group	14,143	10	1414
4.	Grapes	1234.5	10	370
5.	Litchi	497	30	596
6.	Mango	15,188	30	6834
7.	Pomegranate	743	30	668

6.2 Grapes

6.2.1 Grape Stem Borer *Celosterna scabrator* Fab.

Stem borers pose serious problems to grapevine cultivation in many countries. In India, grapevine stem borer, *C. scabrator,* was observed for the first time at Pune by Upasani and Phadnis (1968) and subsequently in other parts of Maharashtra (Gandhale et al., 1983; Mani et al., 2008, 2014), Andhra Pradesh (Azam, 1979; Rao et al., 1985), Karnataka (Balikai & Kotikal, 2003; Jagginavar et al., 2006), and Tamil Nadu (Chandrasekaran et al., 1990), causing damage to grape in the field. Though earlier reported as moderate pest (Balikai & Kotikal, 2003), Jagginavar et al. (2006) reported that stemborer *C. scabrator* is a serious pest, which is becoming one of the limiting factors in grape cultivation and attaining a major pest status in the recent past in grape-growing areas of Northern Karnataka causing up to 30% vine damage. *C. scabrator* is a serious pest on grape and caused 18.00–46.50% vine damage in Vijayapura District (Jagginavar et al., 2006). Stem borers pose serious problems to grapevine cultivation in many countries (Mani et al., 2014). Stemborer of grape *C. scabrator* is a serious pest and becoming one of the limiting factors in grape cultivation in the recent past in grape-growing areas of Rangareddy, Nalgonda, and Medak districts (Anitha & Vijaya, 2015). Sunitha (2018) studied in detail on population dynamics, nature, and symptoms of damage and management of *C. scabrator*.

According to Mani et al. (2008), *C. scabrator* beetles start emerging from last week of June with the onset of monsoon rains till September. Females make conspicuous slit on the bark of the trunk and branches and deposit 12–15 eggs in the slits singly covered with gummy substances. Eggs are white in color and similar to rice grain in shape and hatch about in 10 days. Newly hatched grubs are flat-headed, cream-colored, apodous with powerful mandibles, enter directly into the trunk and branches to start feeding, and grub period lasts for 6–8 months. The full-grown grub measured 7.5 cm and pupates in tunnel itself within a calcareous cocoon. Pupal period lasts for 25–35 days. Adult beetles measuring 40 mm are stout and dull

Fig. 6.1 Female and male beetles of *Celosterna scabrator*

yellowish in color with minute light orange-colored spots and live for 20–25 days. Whole life cycle occupies 10 months. Sunitha (2018) found sexual dimorphism with males having longer antenna compared to females (Fig. 6.1).

Beetles are generally black or dark brown; body is clothed with pubescence of reddish-brown, which alternate with grayish white; head vertical with tawny pubescence; eyes brown to black with ocular lobes connected to each other by six to seven rows of facets at posteriorly; clypeus very short, glossy, and translucent, labrum comparatively large, protruding, and densely clothed with golden-yellow pubescence; elytral disc clothed with grayish pubescence with scattered reddish-brown pubescence, which appears like alternative brown and gray spots; and ventral portion of the abdomen covered with medially grayish pubescence and either sides with yellow pubescence (Kariyanna, 2016).

The investigations on population dynamics of *C. scabrator* between 2015 and 2017 indicated that the timing of the appearance of the adults of this pest in the vineyards varies greatly between years and locations and they showed a staggered and/or prolonged emergence period over time and their first emergence starts from 26th SMW to 32nd SMW (Standard meteorological week) and they continue to emerge up to 52nd SMW (between June to December). Grubs were active in vine orchards for a period of 6–8 months (Sunitha, 2018).

The adults after emergence alight on various parts of grapevines. 98% of beetles observed were found on branches rather than on main trunk (Fig. 6.2). Females make ovipositional injury by making a conspicuous slit on the bark on trunk and arms, and both females and males were found to scrape the green matter from tender twigs and shoots and gnaw the shoots resulting in wilting beyond that point (Fig. 6.3). While emerging out, they cut circular holes from inside tree on trunks and branches of tree (Fig. 6.4). The grubs immediately after hatching make their way into the tree by drilling a small entry hole.

Fig. 6.2 *Celosterna scabrator* beetles on grapevine.

Fig. 6.3 Symptoms of damage by *Celosterna scabrator*

Extrusion of frass, i.e., excretory pellets and fine wood powder from the entry holes on trunk and branches (Fig. 6.5), is the typical symptom of damage like many of the cerambycid wood borers. Oozing of gummy substances from the entry holes can also be seen (Fig. 6.6). Grubs feeding on their way make extensive tunneling in both the directions from the entry holes affecting the translocation of the nutrients

Fig. 6.4 Exit hole of *Celosterna scabrator*

Fig. 6.5 Frass ejected from vine

(Fig. 6.7). Leaves turn yellow, develop symptoms like nutrient deficiency (Fig. 6.8), and later turn brown and wither. The borer-affected vines become weak with reduced growth and very low berry yield (Fig. 6.9).

Fig. 6.6 Exudation of gum

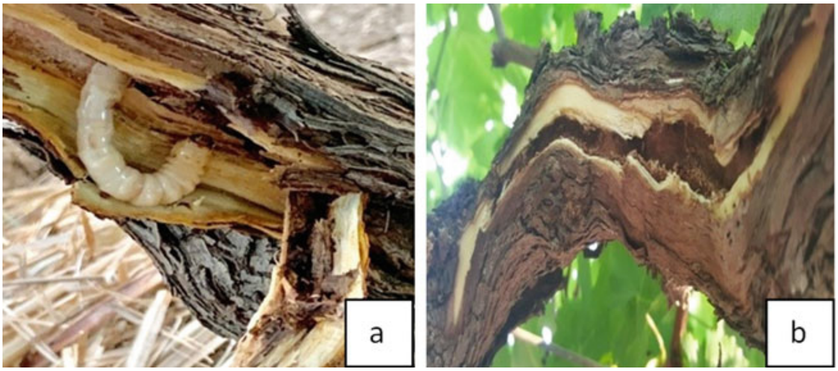

Fig. 6.7 (**a**, **b**) Tunnels created by grubs of *Celosterna scabrator*

6.2.1.1 Management

Insertion of one tablet or 1 g powder of aluminum phosphide in each live hole made by the stemborer helps to kill the larva inside the stem (84% control) (Gandhale et al., 1983). Mani et al. (2008) reported that collection and destruction of affected branches in April–May with full-grown larvae and pupae, collection and destruction of adult beetles and installation of light traps @ 2–3/ha in July and August, monitoring and destruction of pests on alternate hosts, spraying with chlorpyrifos 25EC @ 2.5 ml/l to manage adults, mechanical removal of eggs and young larvae from the slits on branches, application of IIHR mixture, and injecting with fumigants

Fig. 6.8 Symptoms on foliage by *Celosterna scabrator*

Fig. 6.9 Grapevines affected by *Celosterna scabrator* (Source: Sunitha, 2018)

like dichlorvos, chloroform, methyl bromide, and carbon disulfide @ 5.0 ml/hole are effective in managing stem borer *C. scabrator*.

Anitha and Vijaya (2015) found dichlorvos injection 76% EC @ 80 ml per vine very effective followed by aluminum phosphide tablet @ 1 g/vine, chloroform injection @ 2 ml/ vine, carbon disulfide @ 2 ml methyl bromide @ 2 ml, and petrol injection @ 5 ml per grapevine effectively. Chlorantraniliprole 0.4G @ 15 g/vine can be effective means in managing the stemborer, which reduces the cost on plant protection and increases the returns (Kambrekar et al., 2017). Similarly, Sunitha (2018) reported that the application of chlorantraniliprole @ 20.00 g/vine can be effective means in managing the stemborer and highest cost–benefit ratio (1:2.83) was obtained in soil application of chlorantraniliprole @ 0.4%G at 20.00gm/vine.

6.2.2 Dry Wood Stem Borer *Stromatium barbatum* Fab.

Adults appear dark brown or black to reddish-brown; head coarsely punctured; clypeus, labrum reddish-brown; remaining whole part of body brownish-black; antennae around one-third longer than body in make, occasionally longer in female; scape dorsally with shallow pit at its base; antennomeres from second onwards reddish-brown; pronotum generally reddish-brown with 5 raised tubercles on disk, placed first two coarsely punctured tubercles present before middle, next two tubercles present near to base and last tubercle of sparse punctures with shiny area present behind the middle; sides placed four protuberance of coarse punctuation present. Elytra coarsely with punctured compactly, each with two prominent longitudinal costae on dorsal and one or two short costae on lateral side, apex elytra with short sutural spine or tooth (Kariyanna, 2016).

As a pest on grape, in Maharashtra, it is reported by Salini and Yadav (2011). Subsequently, Jadhav et al. (2017) conducted studies on morphometric parameters of *S. barbatum* and DNA barcoding for correct identification of the pest cytochrome c oxidase-1 regions were sequenced for morphologically identified *S. barbatum* large male (2.6 cm), large female (2.9 cm), small male (1.6 cm), and small female (1.8 cm). These sequences showed $\leq$2.5% divergence among each other and $\leq$ 2.5 divergence with the DNA barcode confirming that the four specimens of different sizes belonged to the same species, and variation was due to size polymorphism. Later, Sunitha and Chavan (2020) conducted DNA barcoding of *S. barbatum* collected from the grape orchards of Vijayapura District of Karnataka State (13° 17' N and 77° 48′ E), India. The sequences of *S. barbatum* have been deposited to the NCBI with accession numbers MT280795 and MT280796, and voucher specimens were deposited at Department of Agricultural Entomology, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India. The nature and symptoms of damage are extracted from Sunitha and Chavan (2020).

Eggs of the pest were observed below the bark, in cracks and crevices of wood either singly or in groups. They are white, oval resemble rice grains (Fig. 6.10a). Grubs are elongated, cylindrical, creamy white in color with brown head and reduced legs (Fig. 6.10b). Pupae are also creamy white in color and execrate type (Fig. 6.10c). Beetles immediately after emergence are yellowish-brown in color (Fig. 6.10d). Later, they turn into black color after 3–4 days of emergence due to sclerotization of cuticle. Further males are smaller than females. Antennae in case of females equal to the body length, whereas in case of males it is about 1.5 times the body length (Fig. 6.10e). Size polymorphism is observed in both pupae and adults.

The grubs immediately after hatching bore into the wood. No external signs of pest infestation were seen immediately after attack by the pest except the gnawing or Kit kat sound, which could be heard on careful observation near the infested vines, which is made by feeding grub on wood. In majority of cases, its damage was manifested after a long-time infestation due to long larval life, which can be seen during fruit-bearing period. Grubs form irregular tunnels and galleries and tunnels were found clear with grubs and minute granules of excretory pellets, at the beginning of the infestation. As the infestation continued, galleries and tunnels are

Fig. 6.10 *Stromatium barbatum* (**a**) eggs; (**b**) grubs; (**c**) pupae; (**d**) adult immediately after emergence; (**e**) female and male of *S. barbatum;* (**f**) grub seen in gallery on grapevine; (**g**) exit hole cut by adult (Source: Sunitha & Chavan, 2020)

found tightly packed with very fine powdery frass (sawdust-like substance). Under heavy infestations, tunnels and galleries get interlaced so the interior of the wood is reduced to powder, but exterior surfaces are left intact (Fig. 6.10f). Powdery frass created by grub is packed tightly in their galleries and can be seen in both sapwood and heartwood. Excretory pellets in the form of minute granules can be seen only during the early periods of infestation, which were later covered by powdery frass. Grubs pupate at the end of their galleries, and no discrete pupal cells are observed. The adults immediately after emergence are found within the tunnels or galleries before they come out by cutting near circular exit holes (Fig. 6.10g). All the three stages viz. grubs, pupae, and adults were seen covered with or dusted with fine wood flour under severe infestation conditions. The leaves did not show any symptoms of chlorosis and wilting and remain intact, and the vine orchards look fully green though they are fully loaded with grubs. But the vines attacked by the pest, particularly the cordons with feeding grubs, did not bear any fruit bunches, which are also a typical symptoms of damage by *S. barbatum.* The cordons harboring grubs were very weak and could be easily broken into pieces with little force. *S. barbatum* caused up to 90% yield loss. The dry conditions of the vines favored the heavy incidence of this pest. Vines attacked by *S. barbatum* were also found to harbor termites.

Management: Studies on bioecology and management strategies are in progress (Sunitha & Chavan, 2020).

6.2.3 Wood Borer *Dervishiya cadambae* (Cossidae: Lepidoptera)

Morphology, biology, nature, and symptoms of damage and management strategies of this new wood borer of grapevines are extracted from Yadav et al. (2020) who reported *D. cadambae* for the first time from the vine orchards of Maharashtra. In 20 infested vineyards located in Sangli and Nashik districts of Maharashtra, 12–72% of grapevines were found to have active infestations between the years 2016 and 2018.

Moth is medium-sized and dark-colored. Male antennae are bipectinate with long comb processes, while the female antenna is of filiform type, fore wing with rounded apex, thin undulated pattern of fine transverse lines, more developed in proximal half of wing, and hind wing with poorly developed reticulated pattern. Eggs of *D. cadambae* are yellowish-white and round in shape. All the life stages are shown in Fig. 6.11a-d, and symptoms of damage in each stage are given in Fig. 6.12a-h.

The eggs are mainly laid in groups in cracks and crevices or under the loose bark of the main trunk and cordons of grapevines. The young larvae remain under the bark and feed on sapwood in grapevines. As larvae feed under the bark, their presence goes undetected. Careful observation allows to detect excreta entangled with webbings protruding outside bark. After the removal of loose bark, the larva becomes visible feeding on softwood. The later instar larva bore inside and makes galleries in the direction along the length of the main trunk and cordons. The average length of the gallery is 71.94 cm (range 8.4–184 cm), and the average diameter is 3.43 cm (range 1.56–4.7 cm). The galleries are mostly irregular, elongated round or oval-shaped; however, few galleries are also round and dumbbell-shaped. The entry hole made by later instar larva is closed with excreta and webbings. 60% of the infested grapevines also had infestations in the roots as well. The galleries are filled with mud; however, no larva or pupa was observed in any of the uprooted vines indicating the old infestation in the roots. The pupa is brownish in color and had rows of spine-like processes on the dorsum of abdominal segments. *D. cadambae*-infested vines had lower number of bunches per vine, which ranged from 5.14 to 9.76 as compared to 20.46 to 34.16 in healthy vines. The average yield per vine ranged from 2.39 to 4.12 and 7.01 to 12.87 kg in *D. cadambae*-infested and healthy vines, respectively.

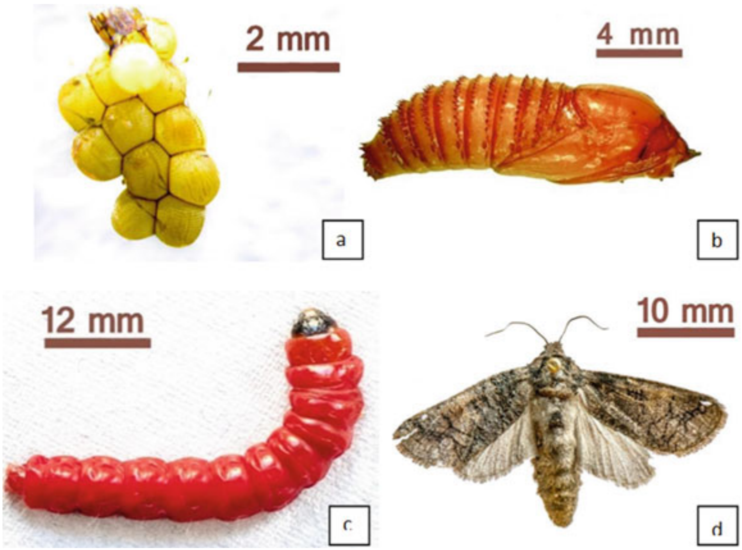

Fig. 6.11 Life stages of *Dervishiya cadambae*. (**a**) Eggs; (**b**) larva; (**c**) pupa; (**d**) adult

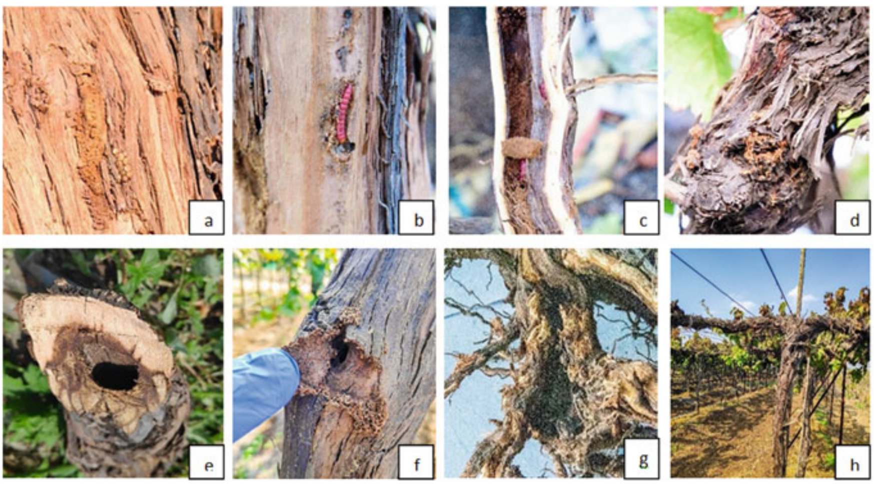

Fig. 6.12 Symptoms of infestation of *D. cadambae* in grapevine. (**a**) Eggs; (**b**) larva feeding on sapwood; (**c**) excreta mixed with webbings protruding over loose bark; (**d**) larval gallery; (**e**) larval gallery shape; (**f**) entry hole covered with excreta and webbings; (**g**) root infestation; (**h**) dead vine due to infestation (Source: Yadav et al., 2020)

Management: A green muscardine fungus was isolated from the field infected larvae of *D. cadambae*. The pathogenicity test confirmed Koch's postulates. The fungus was identified as *Metarhizium brunneum* (Petch), which proved to be an efficient antagonist of this pest in laboratory bioassays.

6.2.4 Grapevine Stem Girdler *Sthenias grisator* (Fab.)

Synonym: *Lamia grisator* Fabricius.

Body brown to black; densely covered with grayish pubescence and velvet black bands; on head, front coarsely punctuate (Fig. 6.13a, b); vertex with two short longitudinal median bands of dark brown pubescence between them distinct median lines run from apex to clypeus; pronotal central disk with reddish-brown pubescence, and two median longitudinal short lines of velvety black pubescence, neither reaching anterior nor basal margins, but bridged to both ends by short wavy grayish pubescent; elytra base of with strongly raised tubercles, and few faintly elevated tubercles present between humeral prominence and scutellum of each side; on elytral distance of one third from base, near sutural line, a distinct eye spot bordered on each side by whitish pubescence in few and filled with similar color pubescence in other individual; elytral disk, next to sutural eye spot, provided with oblique band of grayish white pubescence reached to edge, near the elytral slope; slope of elytral disk decorated with broad irregular reddish-brown band, above which big velvety black spot partly occupies front and stretched forward with brownish banding on both side; sutural line prominently spotted black; elytra with two raised costae arranged one below the other; small raised crest present on lateral axis of disc; near elytral apex distinctly punctured (Kariyanna, 2016).

The pest was reported to be found in India and Sri Lanka (Duffy, 1968; Sengupta & Sengupta, 1981; Bhaskar & Thomas, 2010). The hosts for this girdler pest represent more than 30 tree species from the plant families Apocynaceae, Casuarinaceae, Euphorbiaceae, Anacardiaceae, Fabaceae, Moraceae, Moringaceae,

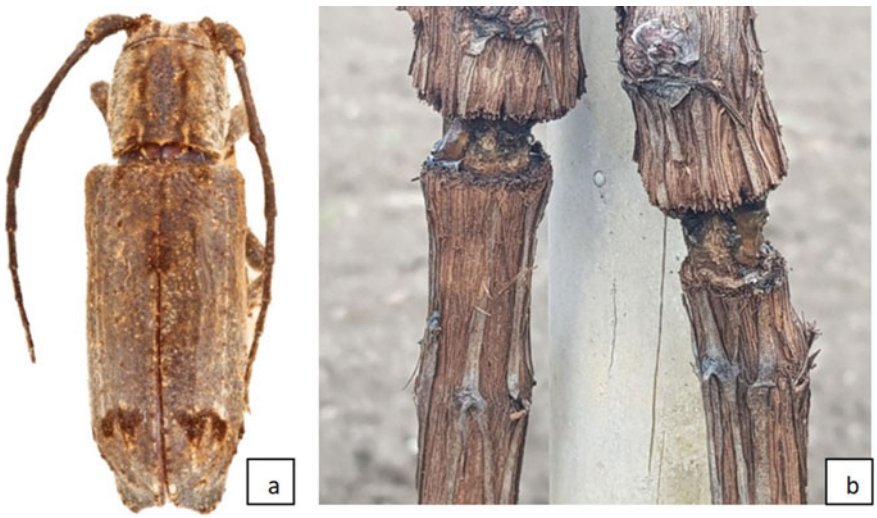

Fig. 6.13 (**a**) *Sthenias grisator*; (**b**) grapevine damaged by *S. grisator* (Source: (**b**) Sunitha et al., 2020; (**a**) https://www.nbair.res.in/Databases/insectpests/Sthenias-grisator.php)

Nyctaginaceae, Rosaceae, Rutaceae, Menispermaceae, and Vitaceae (Duffy, 1968; Satyanarayana et al., 2013).

The grapevine stem girdler is considered as a minor to moderate pest of mulberry, grapevine, jatropha, mango, almond, jackfruit, and several ornamental plant species such as roses (Singh & Singh, 1966; Duffy, 1968; Butani, 1978; Sengupta & Sengupta, 1981; Rahmathulla & Kumar, 2011; Satyanarayana et al., 2013; Mani et al., 2014). The major damage is done by the adult girdling for egg laying (Sanjeeva Raj, 1959; Duffy, 1968). Portions above the girdle wilt and die. The adults emerge almost all year round but mainly in July and August (Beeson & Bhatia, 1939). The females completely girdle the shoots, tree branches up to 2 cm in diameter, vines, or bushes and then lay eggs singly in the wound (Sanjeeva Raj, 1959; Duffy, 1968). The larvae bore in the portions above the girdle to avoid contact with ascending flow of sap. The life cycle may be completed within 5 months, but under dry conditions, a generation may take a year.

The most commonly used practice for the control of this pest is pruning and destruction of girdled apical portions from the point just below the girdle as soon as girdles are found or shoot withering is noticed (Duffy, 1968; Bhaskar & Thomas, 2010). Swabbing the base of the trunks or branches with insecticides may also be effective (Butani, 1978).

6.3 Apple

6.3.1 Apple Stem Borer *Aeolesthes sarta* Solsky

It is also called as city longhorn beetle because the pest causes significant damage to trees of urban areas and also sarta longhorn beetle. Adults of the city longhorn beetle are 2.8–4.7 cm in length. They are dark reddish-brown with their elytra covered in fine, shining white pubescence. They are characterized by their large kidney-shaped eyes, thick and wrinkled antennal scape, and pronotum that narrows apically and is transversely wrinkled. Males are generally smaller than females and have antennae twice as long as their body, while female antennae do not extend past apices of elytra (Royals & Gilligan, 2019) (Fig. 6.14a, b).

A. sarta also known as Quetta borer is polyphagous in nature. It is generally believed that it originated from Pakistan and western part of India with wide distribution in Afghanistan, Iran, and up to Central Asian countries (Orlinski, 2006; Farashiani et al., 2001). Apple orchards and shelterbelts were observed as highly infested areas, and oviposition preference was seen on apple orchards, which are the prime host for this pest. The extreme infestation results in destruction of the canopy of the tree and the infested tees completely dry out within 2–3 years (Krivosheina & Tokgaev, 1985). It is a serious pest of apple and walnut trees in Asia and also impacts cherry, apricot, peach, and plum trees (Duffy, 1968; Sengupta & Sengupta, 1981; Shiekh, 1985; Farashiani et al., 2001; Mir & Wani, 2005; Bhat et al., 2010; Khan et al., 2013). For example, *A. sarta* was first reported as a serious pest of apple and other temperate fruit trees in Jammu and Kashmir (Northern India)

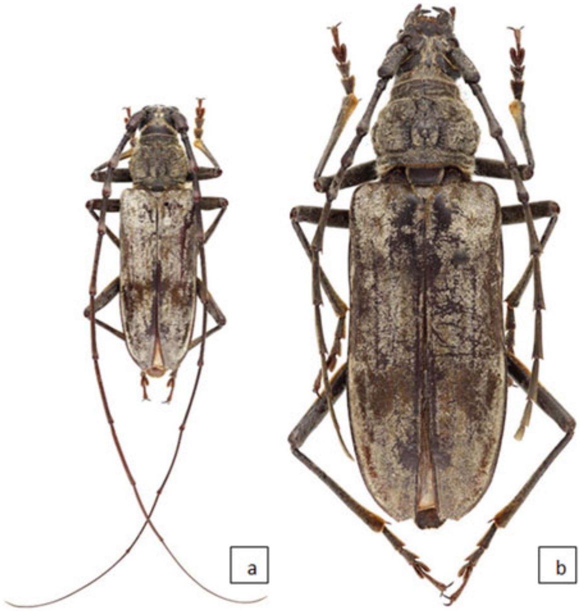

Fig. 6.14 (**a**) Dorsal view of an adult male of *A. sarta;* (**b**) dorsal view of an adult female of *Aeolesthes sarta* (Source: Kadyrov et al. 2016)

in 1980s (Shiekh, 1985). According to Bhat et al., (2010), depending on apple cultivars and tree age, infestation rate ranges from 6.5% in American Apirogue to 23.2% in Red Delicious and from 5.5% in 10- to 15-year-old trees to 27% in those more than 30 years old in northern India. Khan and Qadri (2006) reported a 50% infestation rate in Indian apple and apricot orchards. The pest causes enormous damage to walnut trees, with a 30–40% infestation rate in northern India (Khan et al., 2013). In Iran, 40–100% of apple and walnut trees can be infested (Farashiani et al., 2001).

Larvae bore into the large branches and trunks where sizable emergence holes and borings at the base of infested trees are indications of this pest's presence (Fig. 6.15). The infested trees may not die, but the vitality and productivity are impaired and leaves become wilted and dry. Usually, several generations develop on the same tree until it is eventually killed. So far, the distribution of this species still appears to be limited to Asia. However, if introduced, they can potentially become established in other parts of the world such as Europe where pome and stone fruit trees are widely grown (Vanhanen et al., 2008). Mazaheri et al., (2007) studied the biology of the pest. Pupation usually occurs in October and November, and the adults emerge from March to June. The eggs are usually laid in small batches of 5–10 on living trees, particularly in wounds in the bark, on broken ends of branches, and in pits gnawed down to the living bark. A female can lay about 50.00 (Duffy, 1968), 123.00 (Mazaheri et al., 2007), or 240–270 eggs (EPPO, 2005) in her lifetime. The eggs hatch in 10–14 days, and neonate larvae bore into the bark and sapwood. Frass is ejected through the entry hole. The grown larvae (Fig. 6.16) enter the wood and, at the end of the first season of development, make a long (about 25 cm) tunnel that first

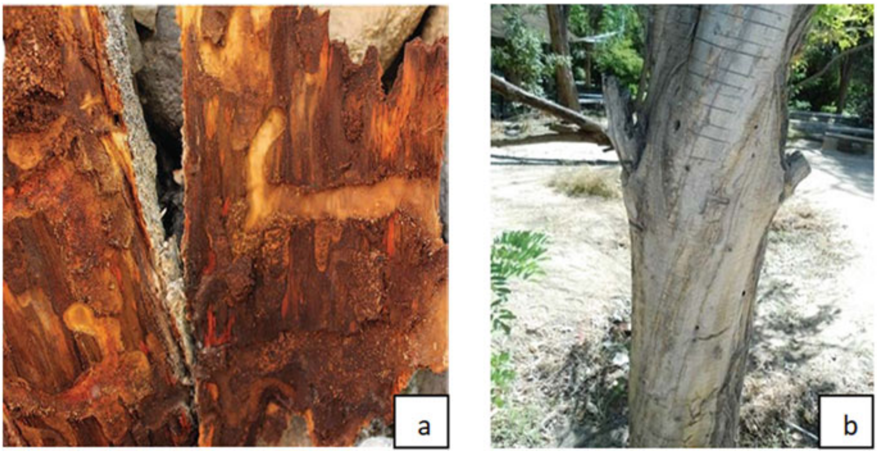

Fig. 6.15 (**a**, **b**) Larval damage and emergence holes of *Aeolesthes sarta* on the trunk (Source: Kadyrov et al., 2016)

runs parallel to the axis of the trunk or branch and then turns to form a downward gallery about 15 cm long. At the bottom of this gallery, the larva overwinters, protected by a double plug made from frass. Next in the spring, the larvae continue to feed, making tunnels deep into the wood. At the end of July, they prepare pupation cells protected by double plugs made from borings. Pupation occurs in these cells, and the pupal stage lasts about 2 weeks. After eclosion, the adult remains in the pupation cells over the winter and then emerges in the spring. The life cycle lasts 2 years.

Cultural measures have been used to control the pest in orchards and gardens (Duffy, 1968). For example, during outbreaks, adults can be trapped and killed using freshly cut logs of hosts. Heavily infested trees should be felled and removed before November. In a field trial, two entomopathogenic fungal isolates *Beauveria bassiana* and *Metarhizium anisopliae* gave some control (Mohi-Uddin et al., 2009). Bhat et al., (2010) have tested the pathogenicity of three fungal isolates *B. bassiana, B. brongniartii,* and *M. anisopliae*, in the laboratory, and indicated that *B. bassiana* is most virulent against *A. sarta* larvae. Insertion of organophosphate insecticide-soaked small pieces of sponge into borer holes in the trunk achieved >60% larval mortality in the field (Khan & Qadri, 2006). The similar application of organophosphate or aluminum phosphide can kill 70% of larvae within 3 weeks of application (Mohi-Uddin et al., 2009; Bhat et al., 2010).

Fig. 6.16 *Aeolesthes sarta* grubs along with frass (Source: Kamran et al., 2017)

6.3.2 Apple Stem Borer, Cherry Stem Borer *Aeolesthes holosericea* (Fab.)

Synonyms: *Pachydiscus similis* Gahan, *P. velutinus* Thomson, *Cerambyx holosericeus* Fabricius.

The scientific name *Trirachys holosericeus* was established by Vitali et al., (2017) when transferred from the binomial *Aeolesthes holosericea*, which was in general usage for over a century since it was proposed by Gahan (1906a, b). Therefore, most scientific papers dealing with this insect refer to *Aeolesthes holosericea*, as well as most Internet resources at the time of writing in 2019. The genus Trirachys was originally described by Hope (1843) and the genus Aeolesthes by Gahan (1890). The type species selected for Trirachys had an armed prothorax, whereas the prothorax was unarmed in the type species selected for Aeolesthes. In addition, there were differences in the location of spines along the antennal segments between the two types of species. Vitali et al. (2017), however, noted wide variation among the species of Trirachys and Aeolesthes in occurrence and placement of spines on the prothorax and antennae and therefore conducted a major revision that resulted in transferring A. holosericea to Trirachys along with using the original species epithet used when this species was first described by Fabricius as *Cerambyx holosericeus*. It is important to note that Gahan (1891) synonymized *Cerambyx holosericeus* and three other binomials under the name *Aeolesthes holosericeus* in

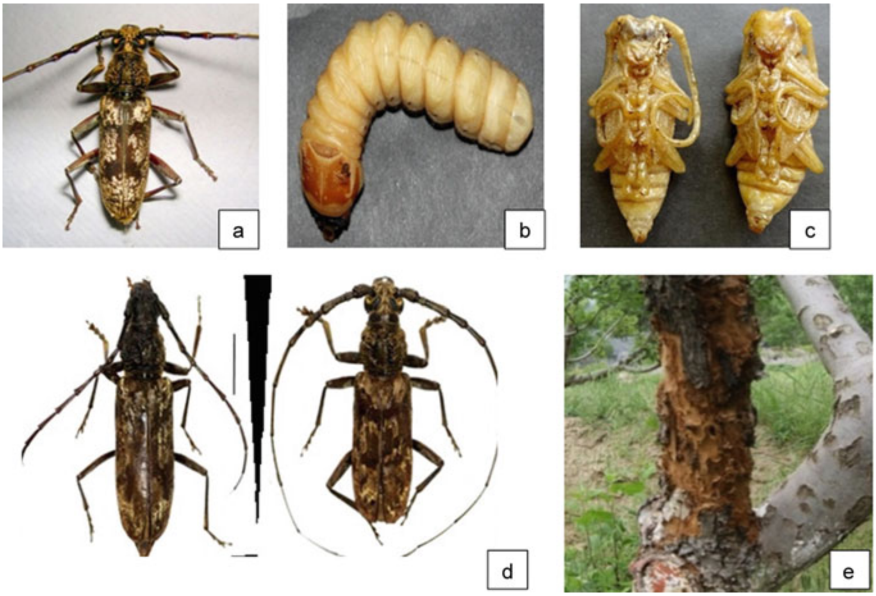

Fig. 6.17 (**a**) *Trirachys holosericeus* (Source: https://www.cabi.org/isc/datasheet/3428); (**b**) grub (Source: https://www.cabi.org/isc/datasheet/3428); (**c**) pupae (Source: https://www.cabi.org/isc/datasheet/3428); (**d**) adults (female and male) (Source: Kariyanna, 2016); (**e**) apple tree infested with *A. holosericea*

1891, but later apparently misspelled the species epithet as holosericea in his later publication (Gahan, 1906a, b), which then continued in common usage until the recent revision by Vitali et al. (2017).

Trirachys holosericeus is a typical longhorned beetle (Fig. 6.17a) in which the body is elongated and the antennae are as long as or longer than the beetle's body length, depending on the sex. Detailed descriptions of the adults and other life stages can be found in Stebbing (1914), Beeson (1941), and Duffy (1968). Vitali et al. (2017) provided a key for several genera of Oriental Cerambycini, including Aeolesthes and Trirachys, along with several characters that are possessed by *T. holosericeus*.

6.3.2.1 Eggs

Eggs are white, shiny, and oval and have a short stalk-like process at one end (Gardner, 1925). Typical egg length and width were reported, respectively, as 2.5 mm and 1.4 mm by Gardner (1925) and 2.2 mm and 0.8–1.2 mm by Gupta and Tara (2013). Drawings and photographs of *T. holosericeus* eggs appear in Gardner (1925), Rahman and Abdul (1942), Mamlayya (2011), and Gupta and Tara (2013).

6.3.2.2 Larva

Detailed descriptions of *T. holosericeus* larvae are given in Gardner (1925) and Duffy (1968). Larvae are yellowish-white in body color, cylindrical, with a brown head, black mandibles, and a hard dorsal brown thoracic plate (Stebbing, 1914; Gardner, 1925). Reports on typical length of mature larvae vary from 45 mm (Gardner, 1925) to 75 mm by (Rahman & Abdul, 1942). Gupta and Tara (2013) stated that *T. holosericeus* has seven larval instars, with final instars averaging 60 mm long. (Fig. 6.17b) Therefore, it is likely that the larvae examined by Gardner (1925) were not final instars. The regions between abdominal segments of larvae are highly constricted, giving the abdomen a corrugated appearance (Stebbing, 1914). Larvae have very short, distinct 4-segmented legs (Gardner, 1925; Rahman & Abdul, 1942). Drawings and photographs of *T. holosericeus* larvae appear in Gardner (1925), Rahman and Abdul (1942), Mamlayya (2011), Salve (2014), and Gupta and Tara (2013).

6.3.2.3 Pupa

Pupae are yellowish-white in color and 30–42 mm in length (Stebbing, 1914; Beeson, 1941; Gardner, 1925; Rahman & Abdul, 1942; Gupta & Tara, 2013). The pupae are of the typical exarate type in which appendages are free from the body (Fig. 6.17c) Images of *T. holosericeus* pupae appear in Rahman and Abdul (1942) and Gupta and Tara (2013).

6.3.2.4 Adult

Adults are elongate, parallel-sided, dark brown to reddish-brown in color, with patches of grayish to light-brown pubescence on the elytra that give the beetle a silky appearance (Stebbing, 1914; Beeson, 1941; Duffy, 1968). Most authors reported that adults are 20–36 mm long (Gahan, 1906a; Stebbing, 1914; Duffy, 1968; Wang, 2017); however, a range of 38–45 mm was given by Gupta and Tara (2013). Females tend to be larger than males (Tara et al., 2009; Gupta & Tara, 2013). The sides of the prothorax are rounded, not armed, and the pronotum is highly wrinkled (rugose) (Stebbing, 1914; Beeson, 1941). Antennae tend to be about 1.5 times the length of the body in males, whereas in females the antennae are about the same length as the body (Beeson, 1941). Drawings and images of T. holosericeus adults appear in several publications, including Stebbing (1914), Rahman and Abdul (1942), Duffy (1968), Sengupta and Sengupta (1981), Mamlayya (2011), and Gupta and Tara (2013), Salve (2014), Bhawane et al., (2015), Jiji et al., (2016), Kariyanna (2016) (Fig. 6.17d), and Kariyanna et al., (2018).

The detailed biology and morphometry for the pest are extracted from Gupta and Tara (2014) (Tables 6.3 and 6.4).

It is widely distributed in India (particularly northern India), Pakistan, Sri Lanka, southern China, Myanmar, Vietnam, Thailand, Malaysia, and Laos. So far, this species still appears to be limited to Asia. Being highly polyphagous, attacks many tree species from Meliaceae, Fabaceae, Rutaceae, Betulaceae, Myristicaceae, Combretaceae, Malvaceae, Phyllanthaceae, Myrtaceae, Sonneratiaceae, Lythraceae,

Table 6.3 Duration of different stages of the life cycle of *Aeolesthes holosericea* (Fab.)

Stage	Duration	
	Months	Days
Incubation period		10.55 ± 0.44
Larval period	17.33 ± 0.21	13.66 ± 3.31
Pupal period	1.50 ± 0.22	11.16 ± 3.36
Winter rest	4.45 ± 0.16	5.56 ± 0.29
Total life cycle	25.16 ± 1.83	
Adult longevity (male)		32.8 ± 2.65
Adult longevity (female)		15.8 ± 1.60

Source: Gupta and Tara (2014)

Table 6.4 Morphometric measurements of different stages of in the life cycle of *Aeolesthes holosericea* (Fab.)

Stage	Duration		
		Body width (mean ± SE)	
	Body length (mean ± SE)	Anterior	Middle
Egg	2.21 ± 0.12	0.95 ± 0.05	0.58 ± 0.08
First instar	4.70 ± 0.47	1.10 ± 0.06	3.85 ± 0.34
Second instar	13.42 ± 0.52	5.42 ± 0.61	6.00 ± 0.36
Third instar	22.33 ± 0.76	8.00 ± 0.36	7.00 ± 0.48
Fourth instar	28.28 ± 0.28	9 ± 0.57	8.37 ± 0.46
Fifth instar	34.25 ± 0.81	11.87 ± 0.95	9.10 ± 0.96
Sixth instar	43.50 ± 2.67	12.5 ± 1.43	9.50 ± 0.56
Final instar	59.73±	13.12 ± 0.44	
Pupa	40.81±	14.75 ± 0.95	
Adult male	33.00±	9.20 ± 0.40	
Adult female	39.20±	10.25 ± 0.33	

Source: Gupta and Tara (2014)

Euphorbiaceae, Anacardiaceae, Annonaceae, Moraceae, Dipterocarpaceae, Pinaceae, Rosaceae, Fagaceae, and Tamiaceae (Salve, 2014).

The insect is cosmopolitan in distribution and is found in different parts of the country viz. Andaman and Nicobar Islands, Arunachal Pradesh, Assam, Bengal, Uttarakhand, Himachal Pradesh, Andhra Pradesh, Madhya Pradesh, Punjab, Tamil Nadu, Rajasthan, and Jammu and Kashmir. It is reported as a polyphagous pest infesting wide variety of forest trees, and fruit plants include apple, apricot, cherry, crabapple, guava, mango, mulberry, peach, pear, plum, and walnut. (Ahmed et al., 2004).

This stem borer has become an increasingly important pest of apple trees in northern India (Tara et al., 2009; Gupta & Tara, 2013, 2014). It also attacks cherry, apricot, guava, mango, mulberry, peach, pear, plum, and walnut trees in India (Tara et al., 2009). Similar to *A. sarta*, the larvae cause the damage, making horizontal zigzag tunnels into the trunk and main branches (Fig. 6.17e) and thereby reducing the longevity and fruit yield of trees (Gupta & Tara, 2014). Trees can be killed in successive years of damage. The biology of this pest is similar to that of *A. sarta* (Duffy, 1968; Tara et al., 2009; Gupta & Tara, 2013). Pupation occurs in October in northern India, and adults emerge in the following March–May with a peak in April. The females lay eggs in batches of four to six in the cracks or crevices under the bark during May–October. A female can lay about 200 eggs in her lifetime but, in confinement, can lay up to 92 eggs. The larvae bore into the bark, sapwood, and finally into heartwood. Their life cycle lasts about 2 years; the first winter is spent in the larval stage, and these condition the larval or pupal stage in galleries. So far, only chemical control appears to be effective for this pest.

The management of Apple longicorn borer, *Aeolesthes holosericea* Fabricius, was attempted using different treatments, viz. check untreated, mud plugging, petrol plugging, Odonil plugging, paradichlorobenzene, carbaryl, dichlorvos, and aluminium phosphide. In all the treatments, the borer holes were plugged with mud after treatment, while plain mud plastering was done in control. All the treatments were significantly effective against the pest compared to check, but dichlorvos gave best results (100%) in reducing the pest population after 30 days up to 60 days after treatment. The order of efficacy of different treatments was dichlorvos followed by carbaryl > Odonil plugging > aluminium phosphide > paradichlorobenzene > petrol plugging > mud plugging (Gupta & Tara, 2014).

6.3.3 Apple Root Borer *Dorysthenes huegelii* (Redtenbacher)

Synonyms: *Lophosternus falco* Gahan, *L. hugelii* Gahan, *L. palpalis* Gahan, *Cyrthognathus falco* Thomson, *C. hugelii* Redtenbacher.

The beetles are very large, about 29–53 mm long; the body generally is castaneous in color, with the head and prothorax slightly darker than the elytra. The species is recorded in India, Pakistan, and Nepal. There is no report on expansion of this species outside its native region. The larvae feed on roots of apple, pear, peach, cherry, and plum trees—with apple being the preferred host; adults do not feed (Duffy, 1968).

The apple root borer is a serious pest of apple trees in India (Singh, 1941; Verma & Singh, 1986) with an infestation level ranging from 2 to 16 larvae per tree. The pest infests all commercial cultivars and groups of apple plants (Sharma & Khajuria, 2005; Singh et al., 2010a, b). According to Singh (1941), the larvae bore into or girdle the roots and occasionally the stem below the surface of the ground. The infested trees generally are weakened and yield reduced. Heavily infested trees can die in a few years.

Biology of this pest has been studied by various authors (Sharma & Khajuria, 2005; Singh et al., 2010a, b). The adult emergence peaks with the onset of monsoons in late June and early July. They live for a few days to about 3 months and are attracted to light. The female prefers sandy and sandy/loam soils for oviposition and, in her lifetime, lays 300–600 eggs, usually singly, at a depth of about 8 mm in the soil. The egg, larval, prepupal, and pupal stages occupy about 1, 42, 3, and 2–3 months, respectively. The neonate larvae move down and start feeding upon reaching the roots. The life cycle lasts 3–4 years, and overwintering occurs at the larval and pupal stages.

Control measures for killing adults using light trapping (Sharma & Khajuria, 2005) or insecticides (Rana et al., 2004) should be directed during late June to mid-July (Singh et al., 2010a, b). According to Sharma and Khajuria (2005), most larvae are present within a 90 cm radius and 30 cm depth of apple tree basins, where control measures should be directed.

Singh and Sreedevi (2018) observed *Dorysthenes* (*Lophosternus*) *huegelii* (Redtenbacher, 1848) as a new insect pest infesting roots of 35-year-old Kinnow mandarin in trees in District Hoshiarpur of the Punjab State. The borer was active from June to October. Grubs were observed in the soil up to 10–25 cm deep below the infested trees. The number of grubs from a single tree ranged from 10.5 to 23.5, while the number of beetles per tree ranged from 20.3 to 28.3. About 39% of trees in the orchard were found to be infested by the borer. The main symptoms of damage of the grubs observed on the affected trees included drying of trees, and leaf size becomes small, cracking on trunks. Affected trees have drooping leaves. Leaves on top of the affected trees were small in size, and branches were withered. New growth was not observed on severely infested trees. About 150 trees of Kinnow mandarin were uprooted by the grower during 2013–2014 due to this borer infestation. Discussion with the orchard manager revealed that dogs, crows, and cranes predate upon the beetles as soon as they emerge from the soil. The first author observed that the adult beetles were attracted towards bulb light in large number and event toward light of vehicles on the main road outside the orchard during night. It is a serious pest of apple trees in Chamba (Verma & Thapa, 2005), Shimla (Rana et al., 2004), and Kullu (Singh et al., 2010a, b) districts of Himachal Pradesh. Sherwani et al., (2016) reported that *D. huegelii* is confined to foothills of Himalayan range and is a serious pest of apple in Kumaon hills. The main host of this borer is roots of apple trees including other hosts like apricot, cherry, peach, pear, and walnut and a few forest trees. David and Ramamurthy (2012) reported that the grubs also bore into the roots of oak trees, Quercus sp., and Kumawat et al., (2015) reported this borer from forest ground in Pasighat, Arunachal Pradesh (India). In Himachal Pradesh, the adults appear in June–July and lay about 300 eggs singly or in small clusters of 2–4 up to 1 cm depth in the tree basin. The eggs hatch in 3–7 weeks. Young larvae feed on organic matter and bore into the roots when coming in contact with them. Grubs become full-fed (7–10 cm) in 3.5 years. Thus, their life cycle is completed in about 4 years in apple tree. Adults start emerging with the onset of pre-monsoon rains during the second fortnight of June and the majority of the beetles (75–80%) emerge by the first week of July (Sharma & Khajuria, 2005). The data on the larval distribution indicated that 98.56 and 71.26% grubs were present within 90 cm radius and 30 cm depth, respectively, of apple tree basins. Singh et al. (2010a, b) reported that well-distributed, light rainfall was conducive for adult emergence, egg laying, and population build-up. Pre-monsoon showers resulted in maximum (40%) emergence of total adult population. Adult, grub, and damaged trees are shown in Fig. 6.18a–f.

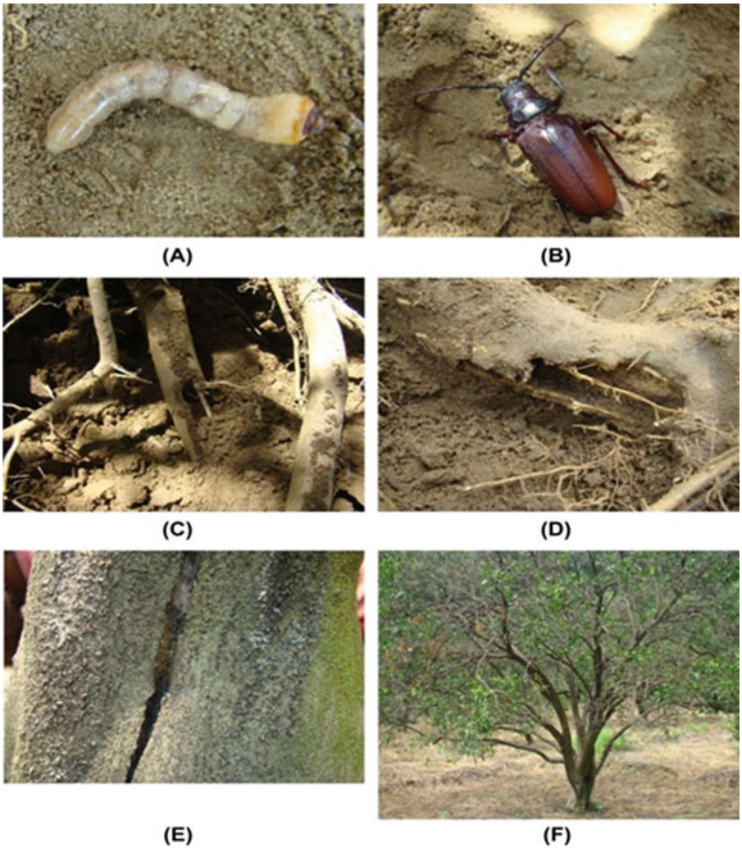

Fig. 6.18 Different stages and damage of *Dorysthenes huegelii* on Kinnow mandarin (**a**) grub; (**b**) adult; (**c**–**d**) holes in root; (**e**) cracking on trunk; (**f**) dried symptoms of whole tree (Source: Singh & Sreedevi, 2018)

They concluded that *D. huegelii* might be a new emerging insect pest of Kinnow mandarin trees in the Punjab state of India. It is expected that this beetle might have migrated from Himachal Pradesh to Punjab as this orchard is near to border of Himachal Pradesh. Integrated management of this beetle needs serious attention for timely control so that the borer may not spread to other areas.

6.3.4 Apple Borer *Linda nigroscutata* (Fairmaire)

Synonym: *Miocris nigroscutatus* (Fairmaire).

The adults of the longicorn are 15–20 mm long and bright orange-red; the pronotum has four small, round, black spots in the form of a trapeze on the disk; the elytra have an elongate scutum-shaped black mark behind the scutellum, reaching to the end of the basal quarter or basal third of suture, and the humeral is generally an area also marked with a black spot (Fig. 6.19).

This species occurs in southwest China and northeast India (Gressitt, 1947; Duffy, 1968; Sachan & Gangwar, 1980; Cao, 1981). So far, there is no report on occurrence of this lamiine outside Asia. The apple twig borer is an apple tree pest of some economic importance in southwest China and northeast India (Fletcher, 1919; Gressitt, 1947; Duffy, 1968; Sachan & Gangwar, 1980; Cao, 1981). The adult females girdle twigs and tender shoots and lay eggs in the wound subcortically, and the larvae bore in the twigs and shoots and eventually hollow them, reducing growth and yield (Beeson & Bhatia, 1939; Duffy, 1968; Sachan & Gangwar, 1980; Cao, 1981). Frass is ejected from holes made by larvae in twigs. According to Cao (1981), the adults emerge from May to July, peaking during May. The eggs are laid singly in the girdled wounds of the current year's shoots. The larvae bore into the shoots and then continue to bore into 1- and 2-year-old twigs. This pest has one generation a year and overwinters as mature larvae that pupate in infested twigs. According to Cao (1981), pruning and burning of infested twigs are probably the only effective measures for the control of this pest. These practices should be carried out during June–August. If the larger twigs are infested, a pesticide solution may be injected into larval tunnels.

Fig. 6.19 *Linda nigroscutata* (Source: museum.ioz.ac.cn)

6.4 Mango

6.4.1 Mango Longhorn, Lateral Banded Mango Longhorn, Rubber Root Borer, Mango Longhorn Borer *Batocera rubus* (L.)

Synonyms: *B. sarawakensis* Thomson, *B. Sabina* Thomson, *B. mniszechii* Thomson, *B. formosana* Kriesche, *B. bipunctata* Kriesche, *B. albofasciatus* Stebbing (necDeGeer), *Lamia downesii* Hope, *L. maculate* Fabricius, *Cerambyx albofasciatus* DeGeer, *C. albomaculatus* Retzius, *C. rubus* Linnaeus.

The beetle measures 30–60 mm long; the body is grayish-brown with two orange or red marks on the pronotum ranging longitudinally; each elytron has about four whitish or yellowish spots with them median third spot being the largest; sometimes, an additional one or two much smaller spots may be present on the elytron (Fig. 6.20). This species is widely distributed in southern and southeastern Asia (Duffy, 1968) and has recently been intercepted in France and Italy (EPPO, 2011, 2012). The borer is polyphagous, attacking many tree species from Anacardiaceae, Apocynaceae, Burseraceae, Fabaceae, Malvaceae, Moraceae, and Phyllanthaceae (Duffy, 1968) in tropical and subtropical regions, but its main hosts relevant to the scope of this chapter are mango, fig, jackfruit (EPPO, 2011), and mulberry (Butani, 1978). This beetle is considered a minor to moderate pest of mango and fig, particularly mango, in India (Atwal, 1963; Hill, 1975, 2008). The larvae bore into the trunk and main branches and mainly pupate in the branches. On the damaged branches, the foliage may die and fruit set may be impaired (EPPO, 2011); severely infested trees may die. In India, the adults emerge in May–June and lay eggs singly in the crevices or under the loose bark of the trunk and branches. The fecundity is

Fig. 6.20 *Batocera rubus* (Source: https://www.thailandnatureproject.com/batocera-rubus.html)

unknown. This beetle has one to three (EPPO, 2011) generations a year depending on climate. Overwintering occurs at the larval or pupal stage. Pruning and burning all infested branches appear to be the most effective control measures for this pest (Butani, 1978).

Injection of insecticides or petroleum products into tunnel openings and sealing them also may be effective.

6.4.2 Mango Tree Stem Borer *Batocera rufomaculata* (DeGeer)

Synonyms: *B. Diana* Nonfried, *B. polli* Gahan, B. *thysbe* Thomson, *B. chlorinda* Thomson, *Cerambyx cruentatus* Gmelin, *C. rufomaculata* DeGeer.

Body reddish-brown to dark brown color; head dark brown, corrugate on front and vertex and band on lower lateral sides appears white; eyes and mandibles look black; antennal tubercles, with short groove on their inner side; antennomeres appear reddish-brown; in males eighth and ninth antennal segments provided with prominently recurved lateroventral spine near to apex; pronotum dark brown with two reddish-orange bean- to kidney-shaped spots and between them blunt eruption distinct; scutellum tongue-like, which is clothed with white pubescence; elytra reddish-brown, tuberculations towards base and produced sharply pointed spine on shoulder; sub-parallel elytra with wavy lateral margin and adorned with countable spots of orange color, which occasionally unite in few places of disc; apex of elytra truncated with spine on sutural angle; sternum generally dark brown-colored, and pubescence on lateral sides makes white; legs reddish-brown (Kariyanna, 2016) (Fig. 6.21 a).

This beetle is distributed throughout its primary regions, including India, Bangladesh, Nepal, Pakistan, Myanmar, Thailand, Laos, Vietnam, Malaysia, Indonesia, Sri Lanka, Andaman, and southern China, and has been introduced into Lebanon, Israel, Iran, Iraq, Turkey, Egypt, Madagascar, Comoros, Mauritius, the Virgin Islands, and Puerto (Rico (Duffy, 1968; CABI, 1994; Ben-Yehuda et al.,

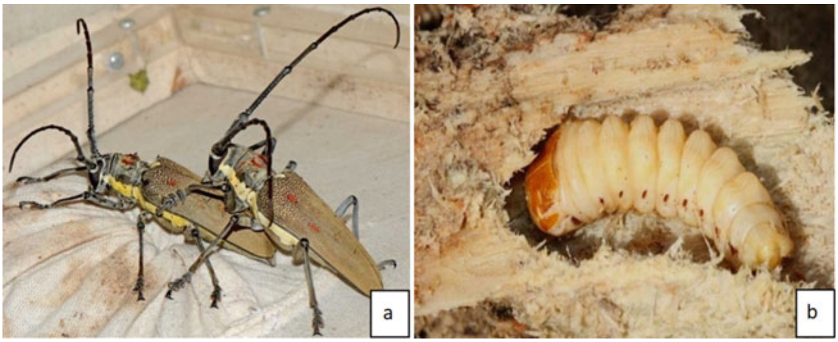

Fig. 6.21 *Batocera rufomaculata* (**a**) adult; (**b**) grub (Source: https://www.nbair.res.in/Databases/insectpests/images/Batocera-rufomaculata7.jpg)

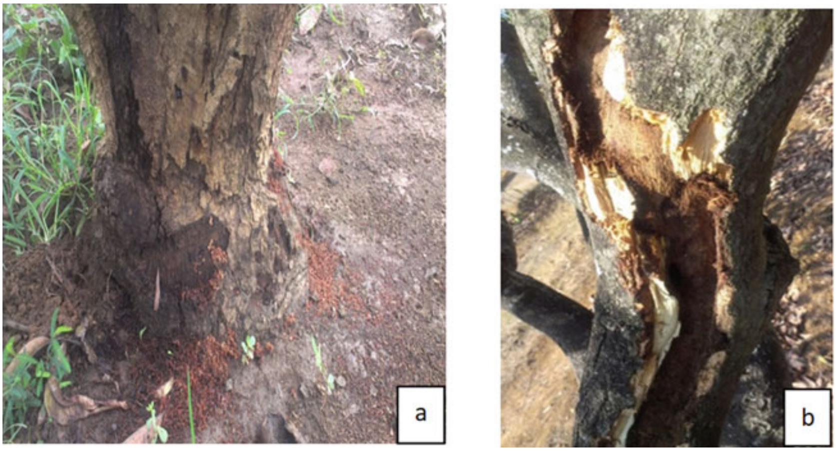

Fig. 6.22 Damage to mango trunk by stem borer *Batocera rufomaculata* (**Source:** https://www.nbair.res.in/Databases/insectpests/images/Batocerarufomaculata12.jpg)

2000; Tozlu, 2000; Batt, 2004; Potting et al., 2008). It is highly polyphagous, attacking at least 50 plant species from Anacardiaceae, Annonaceae, Apocynaceae, Arecaceae, Burseraceae, Caricaceae, Dipterocarpaceae, Euphorbiaceae, Fabaceae, Lauraceae, Lecythidaceae, Malvaceae, Moraceae, Moringaceae, Musaceae, Myrtaceae, Platanaceae, Rosaceae, and Rubiaceae, but its main hosts relevant to the scope of this book are mango, fig, durian, guava, jackfruit, pomegranate, cashew, apple, walnut, and mulberry (Haq & Akhtar, 1960; Atwal, 1963; Duffy, 1968; Palaniswami et al., 1977; Butani, 1978; Sharma & Tara, 1984, 1986, 1995; CABI, 1994; Ben-Yehuda et al., 2000; Godse, 2002; Sundaraju, 2002; Batt, 2004; Sudhi-Aromna et al., 2008; Swapna & Divya, 2010; Maruthadurai et al., 2012; Zeta Boards, 2021; Ahmed et al., 2014). Over the past five decades, this species has become a serious pest of tropical and subtropical fruit tree crops particularly mango, fig, durian, and jack fruit causing significant production loss in India, Bangladesh, Thailand, Nepal, Egypt, and Israel (Palaniswami et al., 1977; Ben-Yehuda et al., 2000; Batt, 2004; Sudhi-Aromna et al., 2008; Upadhyay et al., 2013; Ahmed et al., 2014). Considering its invasive ability, this species should be listed as an important quarantine pest in all subtropical and tropical regions where it has not become established. Attack by *B. rufomaculata* often leads to the death of trees (Fig. 6.22).

The life cycle is summarized from Browne and Foenander (1937), Beeson (1941), Duffy (1968), Sudhi-Aromna et al. (2008), and Maruthadurai et al. (2012). The adults can be found throughout the summer when they chew small oviposition slits in the bark of branches and trunk and lay eggs singly in the slits. Most oviposition occurs during July–August. The lifetime fecundity is up to 200 eggs. The larvae (Fig. 6.21b) initially feed under the bark, then bore into the phloem tissue, and finally bore into the heartwood to pupate. In the tropical regions, the larval feeding occurs throughout the year; in subtropical regions, the larvae overwinter. The life cycle lasts from 6 months to 1 year depending on climate.

Various mechanical and chemical measures are recommended for the control of this pest. Pruning infested branches, and covering the cuts with pruning paste may be highly effective before the larvae enter the trunk (Ben-Yehuda et al., 2000). However, heavily infested trees should be felled and burned (Haq & Akhtar, 1960; Duffy, 1968). Spraying insecticides on the main branches and trunk (Haq & Akhtar, 1960), or even entire trees (Upadhyay et al., 2013), during the oviposition period, can also be effective. The injection or insertion of insecticides into the tunnels made by the larvae can lead to satisfactory control by contact or fumigant or by both modes of action (Haq & Akhtar, 1960; Palaniswami et al., 1977; Butani, 1978; Sharma & Tara, 1986; Ben-Yehuda et al., 2000).

Orchard sanitation and destruction of dry shoots from the tree followed the application of imidacloprid 17.8% SL @ 1.0 ml/L of water or thiomethoxam 25% WG @ 1.0 g/L of water for 5 times starting from second week of Ashadh (July) at 15 days of interval (Upadhyay et al., 2013).

6.4.3 Yellow-Spotted Ridge-Necked Longicorn *Rhytidodera bowringii* White

The information on this pest is extracted from Qiao Wang (2017). This cerambycine beetle is 25–40 mm long and generally dark brown in color; the antennae are slender and slightly shorter than the body; the pronotum has regular, longitudinal ridges; the elytra are covered with gray pubescence and a number of yellow pubescent markings arranged longitudinally; the elytral apex is truncated obliquely (Fig. 6.23). The species is distributed in southern China, northern India, Nepal, and Myanmar (Duffy, 1968; Hua, 2002). It was intercepted in Florida in 2006 (NAPPO, 2006). However, there is no evidence of its establishment outside its primary distribution region. The host range of this longicorn appears to be narrow, with only several species recorded as its hosts—including mango and cashew (Fletcher, 1930; Gressitt, 1947; Duffy, 1968; Hua, 2002; NAPPO, 2006). The yellow-spotted ridge-necked longicorn is a moderate to serious pest of mango in northern India and southern China (Fletcher, 1930; Gressitt, 1947; Duffy, 1968; Luo et al., 1990; Ding et al., 2014). The larvae bore into the center of shoots, branches, and trunks (Duffy, 1968; Luo et al., 1990), causing death of the infested parts (Gressitt, 1947; Luo et al., 1990). They keep their tunnels clear by means of frass-ejection holes. However, early infestation is difficult to detect because the bored branches continue to look healthy, bear green leaves, and develop side shoots until they die back and drop off the tree. The adults emerge during May–June. The females lay their eggs on the living shoots and branches of 8- to 10-year-old trees, and the larvae bore right down their center, making clear circular tunnels (Beeson & Bhatia, 1939; Duffy, 1968). Pupation occurs in the tunnel. The life cycle lasts 1 year in India (Beeson & Bhatia, 1939). Overwintering occurs at the larval or pupal stage. Because the adults are nocturnal and attracted to light, Gressitt (1947) suggested that the most effective measure for the control of this pest probably is the application of light traps in the orchards. The pruning and destruction of infested branches and shoots can be highly

Fig. 6.23 *Rhytidodera bowringii* White (Source: Natasha Wright, Cook's Pest Control, Bugwood.org)

effective in preventing further damage by this pest (Luo et al., 1990). Insertion of cotton wool saturated with insecticides into frass-ejection holes and then sealing them results in effective control (Luo et al., 1990; Ding et al., 2014). Ding et al. (2014) indicated that two applications of this method during the season achieve 100% control, but injection of insecticides into the holes is less effective. Pan et al., (1997) described an integrated approach to the management of this pest including cultural measures to increase the vigor of trees, pruning infested parts to remove the larvae, and application of insecticides to kill the larvae. Shen and Han tested the effectiveness of a nematode, *Steinernema carpocapsae* (Weiser), for the control of the larvae in the laboratory, achieving 80–100% larval mortality. However, these authors suggested that the method may not be practical for large-scale control in the field. In addition, Zhang (2002) has evaluated the resistance of various mango varieties in China and suggested growing potentially resistant varieties in regions where *R. bowringii* is abundant.

6.5 Citrus

6.5.1 Greenish Lemon Longicorn *Chelidonium argentatum* (Dalman)

Synonym: *Cerambyx argentatus* Dalman.

The adults of this cerambycine species are 24–27 mm long; the body is dark green and shining; the ventral side is green and covered with silvery-gray pubescence, and the antennae and legs are dark blue to blackish purple (Fig. 6.24). It is distributed in China, India, Myanmar, and Vietnam, and its host range appears narrow, feeding on plants from Rutaceae, particularly citrus species (Duffy, 1968) and Sri Lanka (New record), India, Myanmar, Vietnam, Laos, Hainan Is, and S. China (Makihara et al., 2008). The greenish lemon longicorn is an important pest of citrus trees in southern China (Gressitt, 1947; Chang, 1958; Chen et al., 1959; Chien, 1981; Li et al., 1997) and southern India (Beeson & Bhatia, 1939; Ramachandran, 1953; Singh et al., 1983). The larvae bore into the branches, which wither and become vulnerable to wind breakage, and continue to tunnel down to the trunks. Fine, dry, and yellowish-white frass is obvious on infested branches and trunks as well as on the ground. Young trees can be hollowed to the root and killed. The biology of this pest is summarized from Gressitt (1947), Chang (1958), and Chen et al. (1959). The adults are diurnal and present between May and August, with an emergence peak during May–June. The females lay eggs on slender branches. The lifetime fecundity is about 22 eggs. The larvae bore into the tender bark and then the wood of main

Fig. 6.24 *Chelidonium argentatum* (Dalman) (Source: https://www.nbair.res.in/Databases/insectpests/Chelidonium-argentatum.php)

branches and the trunk. They become mature in 6 months, overwinter in the tunnels, and pupate in April. The life cycle lasts 1 year. Several methods are recommended for the control of this borer. For example, the pruning and burning of all the branches containing larvae in August (before they enter the main trunk) can significantly reduce the damage caused by *C. argentatum* (Gressitt, 1947; Singh et al., 1983). In addition, Singh et al. (1983) injected 15 ml of gasoline or insecticide solutions in larval tunnels to kill those *C. argentatum* larvae that have entered the trunk. Wang et al., (1999) tested the effectiveness of an entomopathogenic nematode, *Steinernema glaseri* (Steiner), for the control of *C. argentatum* larvae in the field and achieved 70% larval mortality. The whole of the information furnished on this pest is taken from Wang (2017).

6.5.2 Lime Tree Borer *Chelidonium cinctum* (Guerin-Meneville)

Synonym: *Callichroma cincta* (Guerin-Meneville).

Appearance dark metallic green; basal three fourth area of head and mandibles green; tip of mandibles and eyes black; silvery-gray pubescence on underside of body; shiny head impressed with transverse line between front and clypeus, impunctate area lies above; on vertex similar shiny areas present between upper lobes of eyes; antennal segments blue with short gray pubescence on third and succeeding segments antennomeres; pronotum, scutellum, elytra green; underside of body light green; pronotum rugulose and striate on each side of disk with median sub-nitid band and scattered punctures toward distal end; rugulose dark area lies on each side of this band; scutellum nitid, with lateral edges slightly raised posteriorly. Elytra proximally rugulose near suture and other part very densely punctate; elytral disk marked each, between base and middle with yellow band which is irregular and transverse on inner half and prolonged little posteriorly near its outer sides; yellowish band clothed with yellow pubescence and bordering tinted with black or dark brown color. Femora, tibiae blue or occasionally metallic green; band on elytra yellow; tarsomeres black; first tarsomere of hind legs longer than combined length of succeeding two (Kariyanna, 2016) (Fig. 6.25).

Wang (2017) detailed on this pest. The species occurs in southern China, India, Laos, Myanmar, and Cambodia, and so far, only citrus species are recorded as hosts of this borer (Duffy, 1968; Chiang et al., 1985).

The lime tree borer is a minor to moderate pest of orange and lime trees in southern India (Kunhi Kannan, 1928; Beeson & Bhatia, 1939; Ramachandran, 1953; Singh et al., 1983). Younger branches suffer the most damage, wilting, and dying. When trees are 3–4 years old, a single larva can kill a tree. In older trees, the borers can significantly reduce the yield and may eventually kill the trees in several successive years of infestation. Frass from frass-ejection holes is also obvious.

C. cinctum adults emerge in April–June (Beeson & Bhatia, 1939) and lay eggs in the axils of young living twigs; larvae bore into the twigs, causing death, and eventually bore into the main branches (Fletcher, 1919). Lifetime fecundity is unknown. Young larvae bore into the center of the twigs, turn upward for about

Fig. 6.25 *Chelidonium cinctum* (Guerin–Meneville) (Source: https://www.nbair.res.in/Databases/insectpests/Chelidonium-cinctum.php)

3 cm, and cut a complete spiral around the twigs. The lifecycle lasts 1 year and overwintering occurs at the larval stage.

Pruning and burning of all the branches containing larvae in November and January can be effective for the control of *C. cinctum* (Fletcher, 1919; Kunhi Kannan, 1928; Beeson, 1941). The girdled twigs turn black and are easily recognizable (Beeson, 1941). Other control measures used for *C. argentatum* may also are effective for this species.

6.5.3 Citrus Trunk Borer *Pseudonemorphus versteegi* (Ritsema)

Synonyms: *Anoplophora versteegi siamensis* Breuning, *Monochamus glabronotatus* Pic, *M. albescens* v. *Subuniformis* Pic, *M. albescens* Pic, *M. versteegii* Ritsema.

P. versteegi has been placed in the genera *Monochamus* and *Anoplophora* but transferred to the genus *Pseudonemorphus* by Lingafelter and Hoebeke (2000) in their major revision of *Anoplophora*.

General coloration black; body covered with a very dense bluish-white pubescence and rounded black spot in between, which covers the sculpture, but leaves smooth dots on the prothorax, elytra, and metasternum; head with transverse face; lower lobes of the eyes are longer than broad; front triangularly emarginated between the antennary tubercles; antennae ciliated on the undersurface with black pubescence

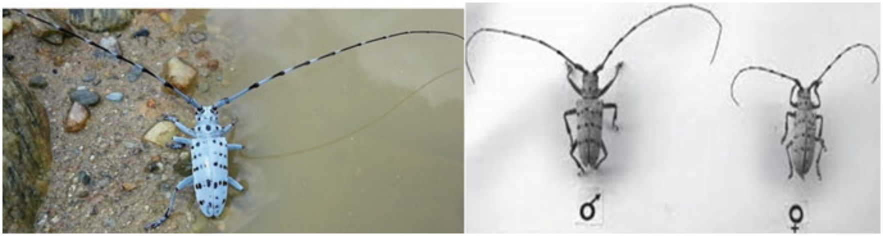

Fig. 6.26 *Pseudonemorphus versteegi* (Ritsema). (**a**) Adult (Source: www.projectnaoh.org); (**b**) male and female (Source: www.projectnaoh.org; Bioone.org)

and further white is gradually replaced by black pubescence, from beginning to apical third of the third joint; antennal scape of the sub-cylindrical and as long as two thirds of the length of the third joint; the cicatrix sharply defined and closed; the fourth joint a little shorter than the 3rd; the 5th–tenth almost inconspicuously increasing in length. Prothorax broader than long, little behind the front margin with a widely interrupted transverse linear groove, lateral spines are strong and acute and obliquely directed upwards; pronotum possesses ovate small spot on the middle of the disk and two round dots at little inside from the base of the spines; scutellum triangular, rounded at tip; elytra with few dots along the suture and lateral margins; sutural margin with single longitudinal row and the lateral margin possess two alternatively longitudinal rows; the elytral shoulders and apices rounded. The pro- and mesosternum rounded, neither produced nor tuberculated. Legs ventrally clothed with black pubescence on tarsi and anterior tibiae, and apical third of the mid- and hind tibiae (Kariyanna, 2016) (Fig. 6.26a, b).

The longicorn is distributed in India, Myanmar, China, Laos, Vietnam, and Indonesia, and its host range appears to be narrow (Duffy, 1968). So far, the species has not been reported to have expanded outside its primary distribution range (Qiao Wang, 2017).

This species is a serious pest of citrus trees in northern India particularly the northeastern Himalayan region of India (Saikia et al., 2012). For example, about 68% of citrus trees were infested during 1992–1995 in Meghalaya, India (Shylesha et al., 1996).

P. versteegi is only considered a minor pest of citrus trees in southern and southwestern China (Li et al., 1997). In several other southeastern Asian countries, it is not reported as a pest. The longicorn attacks almost all commercially grown citrus species but prefers mandarin and orange (Shukla & Gangwar, 1989; Singh & Singh, 2012). Although several tree species other than citrus have been recorded as hosts, such as *Aglaia spectabilis* (Miguel) (Beeson & Bhatia, 1939), *P. versteegi* is recognized as a pest of citrus trees only (Phukam et al., 1993).

Most adults emerge in May with some variations in different reports: April and May (Beeson & Bhatia, 1939), April to June (Banerjee & Nath, 1971), and March to September with a peak in May (Shylesha et al., 1996). The adults feed on citrus leaves and young bark. Oviposition occurs on the main trunks (Beeson & Bhatia, 1939). Females make oviposition slits in the living bark with their mandibles and then lay eggs singly in the slits. The lifetime fecundity ranges from 35 to 85 eggs (Banerjee & Nath, 1971) and 40 to 50 eggs (Shylesha et al., 1996) to an average of 69 eggs (Chatterjee & Ghosh, 2001). Young larvae feed on the outer sapwood, forming a horizontal gallery before tunneling toward the center of the trunk (Banerjee & Nath, 1971). This cerambycid has one generation a year and overwinters at the larval stage (Beeson & Bhatia, 1939; Banerjee & Nath, 1971; Shylesha et al., 1996).

The larvae can be killed in their tunnels by the introduction of a flexible wire (Duffy, 1968). Banerjee and Nath (1971) and Shylesha et al. (1996) recommended the destruction of eggs and young larvae before penetration into wood using mechanical methods such as pressing oviposition slits to crush the eggs and neonate larvae. Injection of gasoline into larval holes (5–10 mL per hole), followed by the sealing of the hole with mud or cotton plugging twice at 15-day intervals, proves to be highly effective in killing the larvae, achieving up to 82% success (Shukla & Gangwar, 1989; Chatterjee & Ghosh, 2001; Kalita et al., 2003).

6.5.4 Citrus Shoot Borer *Oberea posticata* Gahan

The adults of this borer are 15–21 mm long and slender; the antennae are shorter or slightly longer than the body, and the body is dull brown (Fig. 6.27). This species is found in India, Myanmar, Nepal, and Taiwan. The larvae feed on tree species from Rutaceae and Moringaceae (Duffy, 1968; Sasanka Goswami & Isahaque, 2001b).

Fig. 6.27 *Oberea posticata* Gahan (Source: Wang, 2017)

The biology of citrus shoot borer, O. *posticata*, was studied under laboratory conditions during 1999 at Jorhat, Assam, India. Copulation took place 2–3 days after adult emergence. Pre-oviposition period and oviposition period varied from 6 to 7 and 7 to 10 days, respectively. Fecundity was found to vary from 14 to 23 eggs. Eggs were laid singly. The grubs passed through six instars. Total grub period, prepupal period, and pupal period ranged from 50 to 65, 13 to 16, and 14 to 18 days, respectively. The duration of developmental period (egg to adult emergence) varied from 87 to 105 days. Under laboratory conditions, only one generation in a year could be observed. *Moringa oleifera* Lam was recorded as a new alternate host plant of the borer (Goswami & Isahaque, 2001a).

The citrus shoot borer is considered a moderate pest of citrus, particularly mandarin and orange, in India; its larvae bore into the twigs and growing shoots, causing death and substantially reducing yield (Isahaque, 1978; Ghosh et al., 1998; Goswami & Isahaque, 2001a, b). Fresh frass ejected from the twigs is evidence of infestation. Infested seedlings can be killed.

Spraying insecticides such as pyrethroid on the shoots and twigs during the oviposition period may be effective for adult control. Pruning and burning the infested twigs and shoots before the spring may also be effective.

6.5.5 Orange Shoot Borer *Oberea lateapicalis* Pic.

Synonym: *O. mangalorensis* Gardner.

It is recorded only in India and feeds on plants from Rutaceae (Duffy, 1968; Bhumannavar & Singh, 1983). Adults are 12–20 mm long and slender; the body is yellow with the antennae, eyes, and apical half of the elytra being blackish-brown to black; the antennae are shorter than the body (Fig. 6.28).

The orange shoot borer is a minor pest of citrus, particularly mandarin and orange, but in neglected orchards it can be a serious pest (Bhumannavar & Singh, 1983; Singh et al., 1983). The larvae bore into shoots and twigs, weakening and

Fig. 6.28 *Oberea lateapicalis Pic*. (Source: https://www.nbair.res.in/Databases/insectpests/Oberea-lateapicalis.php)

killing them. Fresh frass ejected from shoots and twigs is obvious. The life cycle is summarized from Bhumannavar and Singh (1983). Emergence occurs in April and May, and the females girdle the tender shoots before laying eggs in the bark of the girdled shoots. The larval stage lasts 304–385 days including 120–135 days in diapause, and pupation occurs at the onset of pre-monsoon rains in March. *O. lateapicalis* overwinters at the larval stage in diapause. The life cycle lasts 1–2 years.

Spraying insecticides on the shoots and twigs during the oviposition period may effectively kill the adults (Singh et al., 1983). Pruning and burning the infested twigs and shoots before the spring may also be effective (Wang, 2017).

6.6 Cashew

6.6.1 Cashew Stem and Root Borer *Neoplocaederus ferrugineus* (Linnaeus)

Synonyms: *Plocaederus ferrugineus* (Linnaeus) and *Cerambyx ferrugineus* Linnaeus.

Reddish-brown or ferrous red; head, eyes, and lateral sides of sternum black; body covered with yellowish-gray pubescence which somewhat dense ventrally. Antennae longer than body in males and in females shorter; antennomeres reddish-brown; first segment rugose dorsally and ventral side concave in both sexes; antennomeres strongly asperate in males and in females smooth; pronotum black, transverse, unevenly corrugated above with large, sharply pointed, bent spine at middle on lateral side. Elytra closely punctuate and sparsely covered with short gray pubescence on lateral sides and without pubescence on base, truncate apex, dentate at sutural angle, and more or less acute at outer angle; abdominal ventrites ferrous red, thickly covered with long grayish pubescence; middle and hind femora with prominent carinae toward inner edge dorsally (Kariyanna, 2016) (Fig. 6.29).

It is widely distributed in southern and southeastern Asia, particularly in India, Sri Lanka, Myanmar, Thailand, Vietnam, and Cambodia (Duffy, 1968; Devi & Murthy, 1983; Punnaiah & Devaprasad, 1995; Senguttuvan & Mahadevan, 1997a, b; Chaikiattiyos, 1998; ChauIn, 1998; Lay, 1998).

The cashew stem and root borer (CSRB), *P. ferrugineus,* is one of the serious pests of cashew. The extent of attack is assessed in different cashew plantations of forest (David & Ananthakrishnan, 2004). Reports reveal that departments of Kerala and Tamil Nadu were found to be 7–20% and 30–35% loss, respectively (Misra & Basu Choudhary, 1985). In Guntur and Prakasam districts of Andhra Pradesh, the infestation was recorded up to 40% (Arjuna, 1978; Ayyanna & Devi, 1986). Haldankar et al., (2004) highlighted the strategies and constraints for cashew production in Maharashtra.

Cashew trees were first recorded as hosts of this longhorn by Bhasin and Roonwal (1954). So far, about nine plant species are recorded as its hosts, of which four

Fig. 6.29 Male and female of *Neoplocaederus ferrugineus* (Source: Kariyanna, 2016)

(including cashews) belong to Anacardiaceae (Duffy, 1968; Mohapatra & Jena, 2007; Asogwa et al., 2009).

The tiny grub of CSRB bores into the fresh tissue and feeds on the phloem and xylem tissues of the trunk and root with making irregular tunnels, resulting in exudation of gum (gummosis) and extrusion of fibrous frass from damaged portion (Sathiamma, 1977). Due to extensive feeding damage caused by the grubs, the flow of sap is arrested and the leaves become yellow and are shed prematurely. The cash tress succumbs to attack within a period of 1–3 years depending on pest load, bark circumferences damaged, and age of the trees (Misra & Basu Choudhary, 1985).

In the past few decades, this species has become a serious pest of cashew trees in India and in several southeastern Asian countries, evoking massive studies on its biology and control. In India, this pest is particularly damaging on the east and west coast, with the infestation rate being up to 40%, and severely infested trees die within 2 years, causing substantial losses (Bhaskara, 1998; Sahu & Sharma, 2008; Maruthadurai et al., 2012; Naik et al., 2012; Sahu et al., 2012; Vasanthi & Raviprasad, 2013a, b). The major damage symptoms include extrusion of frass through the holes at the root collar region, oozing of gum at the base of the tree trunk, leaves turning yellow and falling off, and death of the tree. Affected trees may also tilt on one side due to loss of anchorage if the injury to anchoring roots is severe (Maruthadurai et al., 2012).

Emergence and oviposition occur almost all year round in the field (Mohapatra & Mohapatra, 2004); there are two peaks, one in March–May and another in December–February (Senguttuvan & Mahadevan, 1997a, b; Mohapatra & Jena, 2009). However, Raviprasad and Bhat (2010) reported that most eggs are laid during December–June. The life cycle lasts 6 months to 1 year, depending on climate. For example, this longhorn has two generations a year with some overlaps in southeastern India (Senguttuvan & Mahadevan, 1997b; Mohapatra & Mohapatra, 2004), while it has only one generation a year in southwestern India (Maruthadurai et al., 2012). In the laboratory, this beetle can complete one generation a year on a natural or semisynthetic diet (Rai, 1983; Senguttuvan & Mahadevan, 1998; Vasanthi & Raviprasad, 2013b). The larvae continue to feed and develop throughout the year.

According to Maruthadurai et al. (2012), the females prefer to lay their eggs in the bark crevices or physical wounds caused by previous borer damage or heavy pruning on the trunk and roots exposed above the soil; the larvae bore into the fresh tissue of the bark, feeding on the subepidermal tissues, and then into phloem and xylem. Each female lays 60–90 eggs in her lifetime. Portions of the trunk below 50 cm are most frequently attacked (Mohapatra & Mohapatra, 2004). Furthermore, the females prefer trees older than 4–5 years (Maruthadurai et al., 2012) or more than 10 years old (Kumar et al., 1996; Senguttuvan & Mahadevan, 1999a) for oviposition. Pupation occurs in the heartwood (Beeson & Bhatia, 1939).

The biology of cashew stem and root borers *P. ferrugineus* was studied on cashew bark under laboratory conditions. The mean grub period was recorded 163.10 ± 20.55 and 168.37 ± 30.32 days, and mean pupal period was 144.33 ± 29.57 and 145.16 ± 29.10 days for males and females, respectively. The total development period ranged between 261 and 363 days (male) and between 242 and 356 days (female). The duration of grub stage was more than 40% of the total life duration of *Plocaederus* spp. The details of adult morphometrics of *P. ferrugineus* L. indicated that in case of males, the mean body length was 38.8 mm; mean body width was 8.76 mm; and mean body weight was 0.89 g; the females had mean body length of 33.5 mm; mean body width of 10.29; mm and mean body weight of 1.39 g (Vasanthi & Raviprasad, 2013b).

Many studies have been carried out for the development of control measures for this pest including chemical, cultural, and biological control. Control actions taken at the early stage of infestation are essential if they are to work at all and trees with moderate and severe infestation cannot be saved (Devi & Murthy, 1983; Sundararaju, 1985; Senguttuvan & Mahadevan, 1997a, b; Mohapatra & Jena, 2008; Asogwa et al., 2009). Cultural measures recommended include (1) removing eggs during oviposition peaks and also subsequent early instar larvae (Rao et al., 1985; Bhaskara, 1998; Chaikiattiyos, 1998); (2) removing heavily infested and dead trees (Chaikiattiyos, 1998; Lay, 1998; Anikwe et al., 2007; Mohapatra & Jena, 2008); and (3) cleaning the bases of infested trees (Mohapatra & Jena, 2008). Among these cultural practices, destruction of eggs and early instar larvae appears to be the most effective. In addition, evidence shows that the level of resistance and tolerance against the pest differs substantially among cashew cultivars (Kumar et al., 1996; Sahu et al., 2012), providing opportunities for further investigation into plant breeding programs for the control of *N. ferrugineus.* Chemical methods consist of (1) swabbing, painting, or spraying the exposed roots and trunk up to a height of 1–2 m (depending on trunk length) with synthetic (such as chlorpyrifos), botanical (such as neem oil), or fossil-fuel (such as kerosene) insecticides and repellents two to four times a year (Rao et al., 1985; Senguttuvan & Mahadevan, 1997a, b; Bhaskara, 1998; Lay, 1998; Mohapatra & Satapathy, 1998; Mohapatra et al., 2000, 2007; Chakraborti, 2011; Anikwe et al., 2007; Mohapatra & Jena, 2008; Raviprasad et al., 2009); (2) application of chemical dust or granules around the tree base and incorporation into the soil (Devi & Murthy, 1983; Rao et al., 1985); and (3) insertion of chemicals in cotton wool under the bark (Sundararaju, 1985) or injection of chemicals into the larval tunnels (Chaikiattiyos, 1998). The first method is the most effective, and the synthetic insecticides are superior to others. So far, no effective predators or parasitoids have been found for *N. ferrugineus*. Biological control only involves painting the trunk with saturated conidial-mud slurry of two fungus species, *Beauveria bassiana* (Bals.-Criv.) Vuill. and *Metarhizium anisopliae* (Metchnikoff) Sorokin (Mohapatra et al., 2007; Sahu & Sharma, 2008; Mohapatra & Jena, 2008; Raviprasad et al., 2009; Ambethgar, 2010), or pouring a saturated aqueous suspension of conidia through larval entry holes and soil incorporation of fungal spawn (Ambethgar, 2010). However, biological control using these fungi is not very effective for the control of this pest (Mohapatra & Jena, 2008; Raviprasad et al., 2009). The relative susceptibility of different life stages viz. egg, larvae, and pupae to three entomopathogenic fungi (*Beauveria bassiana* (Balsamo) Vuillemin, *Beauveria brongniartii* (Sacc.) Patch (Hyphomycetes: Moniliales), and *Metarhizium anisopliae* (Metsch.) Sorokin 1 (Deuteromycotina: Moniliales) was evaluated in laboratory by topical application of conidial suspension of 107 conidia/ ml. Of them, *M. anisopliae* was found to be more effective with 36.0 and 33.3% egg and larval mortality followed by *B. bassiana* with 30.0 and 30.9% egg and larval mortality, respectively. Pupal mortality was 10.00 and 8.00% with *B. bassiana* and *M. anisopliae*. There was moderate increase in terms of larval mortality due to fungal pathogens with a decrease in larval age (Saminathan et al., 2004).

6.6.2 Cashew Stem Borer *Neoplocaederus obesus* (Gahan)

Synonyms: *Plocaederus pedestris* Cotes, *P. obesus.*

This cerambycine species is similar to *N. ferrugineus* in appearance. The adults are 27–45 mm long; the body is pale brown to light reddish-chestnut or testaceous, clothed with short pubescence (Fig. 6.30a). The borer is also widely distributed in southern and southeastern Asia, including India, the Andaman Islands, southern China, Thailand, Myanmar, Vietnam, Sri Lanka, and Bangladesh (Duffy, 1968; ChauIn, 1998; Liu et al., 1998b; Hua, 2002). So far, it has not been recorded outside its primary distribution region. *N. obesus* is more polyphagous than *N. ferrugineus.* At least 28 plant species from 12 families are recorded as its hosts, of which 7 species, including cashew, mango, and chironji, belong to Anacardiaceae (Duffy, 1968; Hua, 1982; Meshram, 2009; Maruthadurai et al., 2012; Vasanthi & Raviprasad, 2013a, b).

The cashew stem borer is considered an important pest of cashew trees in India (Khan, 1993; Maruthadurai et al., 2012; Vasanthi & Raviprasad, 2012, 2013a, b), Vietnam (ChauIn, 1998), and southern China (Pan & van der Geest, 1990; Li et al., 1997; Liu et al., 1998b). Infestation eventually kills the trees if no action is taken.

The biology of this species is very similar to that of *N. ferrugineus*, with damage caused to trunks and roots. It has only one generation a year in the field (Meshram, 2009; Maruthadurai et al., 2012) and the laboratory (Vasanthi & Raviprasad, 2013b). Each female lays 40–50 eggs in her lifetime. Mean grub period was 152.75 ± 31.35 and 158.49 ± 33.26 days, and mean pupal period was 142.90 ± 22.57 and 152.34 ± 38.46 days for males and females, respectively (Fig. 6.30b, c). The

Fig. 6.30 *Neoplocaederus obesus* (a) adult female; (b) grub; (c) pupa (Source: Kariyanna, 2016)

morphometric details of adults of *P. obesus* males indicated a mean body length of 38.6 mm; mean body width of 8.63 mm; and mean body weight of 1.4 g, while females had mean body length of 36.6 mm; mean body width of 9.31 mm; and mean body weight of 1.76 g (Vasanthi & Raviprasad, 2013b).

Several studies have evaluated the effectiveness of cultural, biological, and chemical control methods for this pest. Gressitt (1947) recommended trimming and destroying infested branches as well as the removal of bark, frass, and larvae from attacked trunks followed by an application of tar. Pan and van der Geest (1990) suggested that manual removal of the beetle larvae from the infestation sites is probably the most effective control measure. Vasanthi and Raviprasad (2012) evaluated the effectiveness of three entomopathogenic nematodes, *Heterorhabditis indica* Poinar, *Steinernema abbasi* Elawad, and *S. bicornutum* Tallosi, against the borer and concluded that all these tested nematodes can kill the larvae about 2 weeks after exposure. However, it is not known whether these nematodes can successfully control the pest in the field. Meshram and Soni (2011a, 2011b) tested the effectiveness of softwood fungus species, *Metarhizium anisopliae* (Metsch.) Sorok and *Beauveria bassiana* (Bals) Vuill., and insecticides for the recovery of trees infested by the borer in the field. After removing the larvae and cleaning the frass materials, they evaluated three application methods: swabbing saturated conidial mud slurry over the tree trunk, pouring a saturated aqueous suspension of conidia through borer entry holes, and soil incorporation of fungal spawn. Results show that pouring the conidial suspension has achieved a recovery rate of 16.0–25.0%, followed by swabbing with a conidial slurry (17.0–20.0%) and soil application (13.0–14.0%). Using the same delivery methods, conventional insecticides achieve the highest recovery rate (38.0–43.0%). However, implementation of fungal application in the integrated control of *N. obesus* should be considered because the fungi would not only be safer to non-target organisms but also more effective in a long-term pest control program. Finally, Liu et al., (1998a) suggested that cut-end coating, trunk whitewashing with a lime solution, and injection of insecticides into borer tunnels also can give effective control.

6.7 Litchi

6.7.1 Litchi Trunk Borer *Aristobia testudo* (Voet)

Synonyms: *Aristobia clathrator* (Thomson), *Celosterna clathrator* Thomson, *Lamia reticulator* Fabricius, *Cerambyx testudo* Voet.

The adults are 20–35 mm long and black in color; the vertex and pronotal disk are covered with yellow pubescence and two longitudinal black pubescent stripes; the elytra are covered with black pubescence and a number of yellow pubescent spots; the antennal segments 1–2 are black and segments 3–11 yellow, with segments 3–4 or 3–5 bearing black tuft hairs at the apex (Fig. 6.31). The beetle is distributed in northern India, Myanmar, Thailand, Laos, Vietnam, and Southern China and its larvae feed on tree species from Annonaceae, Lythraceae, Myrtaceae, and Sapindaceae (Chen et al., 1959; Duffy, 1968; Hua, 2002; Shylesha et al., 2000). The species has not been recorded outside its primary distribution area. The litchi longicorn is a moderate to serious pest to litchi, cocoa, and jack fruit (Li et al., 1997). The damage is caused by the adult ring barking and larval boring. The infested twigs and branches wilt and die. In severe infestation, the tree can be killed. The twig ring barking by ovipositioning adults causes the extremities to die and snap off. In addition, this pest can cause minor to serious damage to guava in India. For example, in northeastern India, the infestation rate ranges from 8% to 76% in different guava orchards; although the pest prefers older trees (10 years old), young trees may be killed within 1 year of infestation (Shylesha et al., 2000). According to Ho et al. (1990) and Waite and Hwang (2002), the adults emerge during June–August. They

Fig. 6.31 *Aristobia testudo* (Voet) (Source: https://www.nbair.res.in/Databases/insectpests/images/Aristobia-testudo1.jpg)

girdle the branches and twigs by chewing off strips of bark and then lay eggs singly in the wound, covering the wound and eggs with exudate. The lifetime fecundity in the field is unknown. The eggs hatch in August and September. The larvae initially bore under the bark and then into the xylem in January, making tunnels in the wood up to 60 cm long. These tunnels have openings packed with frass at regular intervals for aeration. The tunnels are blocked with wood fiber and frass just before pupation in June. This pest has one generation a year and overwinters at the larval stage.

Shylesha et al. (2000) recorded the pest on Guava. It was found in and around Shillong, Meghalaya, India, in guava orchards. Damage by *A. testudo* ranged from 8.1 to 76% in different orchards. Among the 1068 plants surveyed, 431 were killed due to *A. testudo* incidence. Among the cultivars, Lucknow-49 recorded a mean infestation of 76% in 10-year-old plants and 22.72% in 8-year-old plants. Young plants were killed within 1 year of infestation, and trees less than 10 years old were severely damaged. This is claimed to be the first record of *A. testudo* on guava.

Xu et al., (1995) trialed the injection of the nematode *Steinernema carpocapsae* (Weiser) (Agriotes strain) into larval tunnels and achieved 73–100% larval mortality under experimental conditions. Shapiro-Ilan et al., (2005) discussed the possible application of entomophagous nematodes to control cerambycid larvae, including *A. testudo*. The most effective control measures for this pest (Waite & Hwang, 2002) include (1) regular in section of orchards during the adult activity period and removal of the beetles manually, (2) removal of eggs and young larvae from branches and twigs during July–September, and (3) identification of larval location based on the presence of tunnel openings packed with frass and removal of larvae with wire hooks or a knife. A skilled worker can kill larvae in 2 h (Wang, 2017).

6.8 Pomegranate

6.8.1 Pomegranate Stem Borer *Coelosterna spinator* (Fab.)

It is a polyphagous pest. Though considered to be a minor pest of pomegranate, in the recent past the stem borer incidence has been on the rise in major pomegranate growing areas of Karnataka and Maharashtra.

Adult beetles are pale yellow in color with light gray elytra and measure about 30–35 mm long (www.agropedia.iitk.ac.in). Female beetle lays 20–40 eggs under the bark, which hatch in 12–15 days. The grubs initially feed on the soft tissues around the oviposition cavity and then bore into the stem and roots. The feeding by grubs inside stem and branches results in yellowing and subsequent death of plant. Larval period lasts for 240–300 days. They pupate inside the tunnels and adults emerge after 16–18 days by cutting a hole on the bark. Adults live for 45–60 days, and there is only one generation per year. The borer infestation can be identified by the presence of holes on bark of main stem and the excreta and powdery material on the ground around the base of the plant (Krishnamoorthy et al., 2014; Ahuja & Chattopadhyay, 2015) (Fig. 6.32a, b).

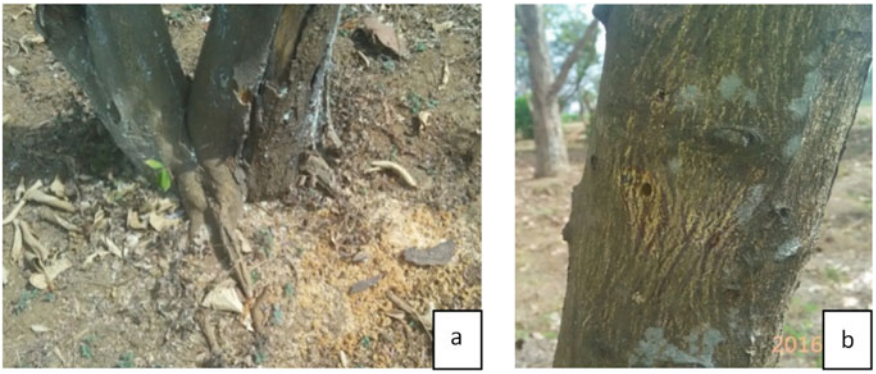

Fig. 6.32 (**a**) Pomegranate affected by borer; (**b**) pomegranate stem with borer adult emergence hole

Management of stem borer includes (i) **e**xtraction of larvae by a metal hook and killing them; (ii) stem injection into holes with solutions of chlorpyrifos or fenvalerate @ 5 ml/L and sealing them; and (iii) pasting on stem with red soil mixed with neem oil and copper up to a height of about 60 cm (Ahuja & Chattopadhyay, 2015).

6.9 Conclusion

This chapter covered the most important cerambycid pests of grapes, apple, mango, citrus, cashew, litchi and pomegranate fruit crops and their status in India. Many of the pests covered are polyphagous, and some important fruit crops are not the hosts for cerambycid wood borers. Long life cycle, concealed habitat of damaging stages, and their polyphagous nature poses a challenge for their management. As fruit farming proves to be a profitable business in many ways in India, future work should focus on understanding their bioecology and formulating suitable eco-friendly management strategies.

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Prospects and Advances in the Management of Coconut Wood Borers

7

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Contents

Abstract

Coconut is considered as the "Tree of Life" and is one of the most important crops for the Asia and Pacific region providing food, nutrition, and livelihood to millions of coconut farmers in the region. In the major coconut-producing countries, bulk of their coconut products are exported, and hence, coconut cultivation and industry play a pivotal role for the growth of their economies. Flooring items are in high demand in Asia, America, and Europe. The senile or overgrown coconut trees provide a good raw material basis for the manufacture of lumber and other products used for construction and furniture. With a vast

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_7

demand for wood and a depleting forest resource, India relies heavily on imported wood to meet its different wood product needs. However, the development of viable coconut wood-based industries is mostly determined by the structure and composition of the raw material, processing technique, and the location and availability of over mature, diseased, and dead stems. Being evergreen with a unique morphology, the coconut palm provides shelter and food for a wide array of arthropod borer pests and their natural enemies. Insect pests like rhinoceros beetle, *Oryctes rhinoceros* Linn. and red palm weevil (*Rhynchophorus ferrugineus* Olivier) are the main biotic constraints hampering coconut production by causing 30% yield loss. The borer pests are reported to cause irreversible damage to frond, trunk, and stem in the coconut palm, while some species are associated with nuts and emerging inflorescence. Their nature and severity of the problems, however, vary with the height of the cultivars, location, weather, and cultural practices. The palm wood should be free of pest damage and suitable for building applications when it gets senile if integrated pest management measures against main pests in the standing crop are implemented in a timely manner. This chapter summarizes the current updates on pest dynamics and management tactics including monitoring, agrotechnical measures, biological control, semiochemical-based control, and chemical control. The implementation of integrated pest management strategies against major pests, based on the abovementioned tactics, is discussed in detail. In addition, training and educating the farmers are expected to play a central role in area-wide IPM of major coconut pests.

Keywords

Borers · Coconut · Management · Pheromones · Strategies

7.1 Introduction

Cocos nucifera L. is one of the most versatile and economically important palms, and it is cultivated in all the tropical and subtropical regions of the world (Moore, 1948; Subramanian, 2003). India, Indonesia, and Philippines are the major coconut-growing countries in the world and account for about three-fourth of the global production. The share of India in global coconut production has increased from 22.9% in 2008 to 34.2% in 2018. Coconut is a major plantation crop of coastal regions of Kerala, Tamil Nadu, Karnataka, and Andhra Pradesh accounting 92.3% of total production and about 89.5% of acreage in the country during 2019–2020 (CACP, 2021). Coconut industry directly or indirectly employs about 12 million people in India. Coconut palms have a wide spectrum of uses since it supplies food, drink, shelter, and raw materials for a number of industries, and millions of people rely on the coconut plantation and its products for their livelihood across the world (Djokoto, 2013; Menon & Pandalai, 1958; Oduor & Githiomi, 2006). Because of its distribution, cultivation, and management, the crop is susceptible to biotic and

Fig. 7.1 House constructed with coco wood

abiotic stress, such as drought, cyclones, and epidemic and endemic pests, which frequently create chaos and losses. Many biotic and abiotic factors limit the palm plantation productivity worldwide, causing loss to the tune of 30% (Gitau et al., 2009). There are at least 850 insects and mite species reported to limit the coconut productivity all over the world (CPCRI, 1979; Joseph Rajkumar et al., 2018). Generally, a coconut palm begins producing nuts at the age of 5 or 6, and reaches its peak production capacity between the ages of 15 and 50. When the palm becomes senile and ceases its production due to age factor (60–70 years), disease, or storm damage, the trees become accessible for conversion to various economic products (FAO, 1985). Palms that have been felled must be removed as soon as possible from a plantation; otherwise, they will serve as a breeding ground for the coconut rhinoceros beetle *Oryctes rhinoceros* (L.), which can harm growing palms (Peek, 1994). In order to minimize infestation by the rhinoceros beetle and red palm weevil in the standing crop, it is of great importance to dispose the dead and damaged palm by converting them into viable products (Fig. 7.1).

And also replanting is economically sustainable and viable when the coconut stems are sold for coco wood processing. In 2004, the global market for flooring items was estimated to be worth $5.4 billion, with significant growth forecasts (Arancon Jr., 2010). Smallholders and rural communities may benefit from the growing coco wood harvesting and processing industry. The higher density stem fibers of coco lumber or coco woods have properties similar to many hardwood timbers and may have a high-value flooring product (DEEDI, 2010). Coco wood is an attractive material, highly suitable for esthetic applications (Hopewell et al., 2012). The dermal zone, subdermal zone, and core region of the coconut stem are the three distinct zones based on its density, and the density of wood decreases from the outside to the interior, as well as from the base to the top regions of the coconut stem (Fathi, 2014; Killmann & Fink, 1996). Coco wood is graded as hard, intermediate, or soft, corresponding to high density (> 600 kg/m^3), medium density (between 400 and 600 kg/m^3), and low density (< 400 kg/m^3), respectively (Peters et al., 2014). The variability in density can have a dramatic impact on processes such as machining and drying of coco wood and on its resistance to biological degradation, e.g., by termites and fungi (Jourez et al., 2012). The density of coco wood can have a significant impact on operations such as machining and drying, as well as its resistance to biological degradation, such as by termites and fungus. However, in tropical climates with high relative humidity, the service life of coco wood is shortened due to a variety of environmental factors such as precipitation and increasing ambient temperature, both of which promote biological decay. When exposed to certain environmental variables, coco wood and other forms of wood become sensitive to biodegradation (Ney et al., 2019). Wood with a high moisture content is susceptible to microbiological (particularly fungi) and insect attack, resulting in dimensional instability, particularly under varying moisture conditions (Mohan et al., 2008; Temiz et al., 2010). Unlike most forest trees, the coconut palm does not produce heartwood. It has a substantial impact for its use. The lack of heartwood has the primary effect of making the wood of the coconut stem vulnerable to wood-boring insects and decay fungi. Because it contains high levels of sugar, starch, and moisture throughout the trunk, freshly felled coconut wood is highly sensitive to wood-boring insects, molds, and stain fungus. Beetles are members of the insect order Coleoptera, which contains almost a quarter of a million known species, or almost 40% of the world's insect population, and is the largest group in the animal kingdom. The habits of the many distinct types of beetles are so diverse that they can be found in almost every type of environment that is suitable for their existence. Borers like *Oryctes rhinoceros* (Scarabaeoidea) and *Rhynchophorus ferrugineus* (Curculionoidea) cause palm mortality. Timber-inhabiting beetles are yet another important group of this order. Certain wood-inhabiting beetles, like *Anobium punctatum* (Anobiidae), *Lyctus africanus* (Lyctidae), and *Sinoxylon anale (Bostrichidae)*, are economically important (Mathew, 2004). Timber beetles have a wide range of habits, and they can be divided into four major functional groups based on the nature of their attacks: primary borers, secondary borers, scavengers, and predators. Standing trees that are weak or mechanically injured, freshly cut timber with intact bark, debarked timber, sawn logs, converted timber, or other finished products are all targets for the primary borers. During 1914, Stebbing initiated research work on the Indian subcontinent's timber beetles. He studied morphology, taxonomy, biology, and bionomics of many species that attack valuable timbers. Beeson (1941) later compiled subsequent research on timber beetles. The CAB Identification Guide on Coleoptera (Booth et al., 1990) contains a full description of beetles and their categorization. Subsequently, Gnanaharan et al. (1985) and Mathew (1982) investigated the control of timber insects connected with commercially important stored wood in Kerala.

7.2 Coconut Wood Borers

7.2.1 Termites: *Odontotermes* spp.

Order: Isoptera.

7.2.1.1 Nature of Damage and Symptoms

Termites are present in all coconut-growing areas of our country as described by Menon and Pandalai (1958) in their monograph. In India, coconut trees are attacked by many species of termites (Table 7.1), majorly by *Odontotermes* spp., in both cultivated and uncultivated (wild/semi-wild) conditions. The attack occurs both in the plantation and in nursery seedlings. Areas with laterite soils are more prone to the attack by termites. The infestation occurs at the collar region and at the basal part of the seed nut. The characteristic symptoms of termite attack in the nursery are wilting of the leaf bud, and also, the bud gets easily detached on slight pulling. These seedlings show damaged husk of the seed nut and also soil incrustations in the nut when examined. In plantations, the attack confines to the roots and also up to 15 cm of the trunk of palms (Figs. 7.2, 7.3, and 7.4) (Anonymous, 2006).

Roonwal (1979) reported that the extent of damage caused by termites can range up to 30–40%. Another extensively spread termites is *Coptotermes formosanus*—

Table 7.1 Termite species reported to cause damage to standing coconut palms

Termites associated with coconut in India	Coconut-growing tracts	Features	References
Odontotermes obesus (Rambur)	Andhra Pradesh	Severe infestation during dry season, Damages up to 40% of the sown seedlings. Present in both nursery and plantation. Present in root zone and up to 6 ft above ground level	Krishnamoorthy and Ramasubbiah (1962)
O. obesus (Rambur)	Kerala	Pest of nursery seedlings, prefer husk of seed nuts.	www.agritech.tnau.ac.in; Nair (1986, 1999), Panwar (1995)
O. redemanni (Wasmann) and *O. obscuripes* Wasmann	–	Attack the young coconut seedlings and cause damage to the husk of the seedlings resulting in plant death.	Fernando (1962), Sankaran (1962)
O. malabaricus Holmgren and Holmgren	Tamil Nadu	–	Beeson (1940)
O. obesus (Rambur) *O. redemanni* (Wasmann)	–	Attacks at the basal collar region and the central shoot wilts	Roonwal (1979)

Source: Mahapatro and Kumar (2015)

Fig. 7.2 Termite attack on coconut

Fig. 7.3 Termite runways on coconut tree

the formosan subterranean termite. However, it is said to have originated in China, but has since spread to Hawaii, Japan, South Africa, Sri Lanka, and the southeastern USA. It is the most commercially significant insect pest in Hawaii, affecting structures and a variety of plants, including palms. Other termite species such as *Microtermes, Microcerotermes, Coptotermes,* and *Nasutitermes* are abundant in Sri Lanka (Mahapatro & Kumar, 2015). Termites pose a serious hazard to woods because they can cause harm to exposed buildings and their timber components. They can attack wood in a structure from the ground level to the roof's highest point. The high moisture content of the woods, along with extensive termite infestation, develops into a problem that requires prompt attention and resolution. The species of Kalotermitidae known as dry wood termites are mainly pests of seasoned timbers and woodwork rather than living coconut trees (Lever, 1969a, b). Several studies have shown that on average the higher the density of the wood the lower the degradation by termites (Owoyemi et al., 2013; Shanbhag & Sundararaj, 2013). Termites are known to damage senile coconut palms, but only the less dense portion is generally damaged (Subramanian, 2003). It appears that coco wood possesses the

Fig. 7.4 Termite damage as secondary infestation on damaged palm

same characteristic with respect to density and the propensity for damage by termites. As such, the less dense coco wood flooring product may be prone to termite damage, but the more dense wood may be less prone or even resistant.

7.2.1.2 Management

Cultural Control

Orchard sanitation is an important criterion to be followed to get rid of the termite infestation. The fallen fronds, spathes, dried unmarketable nuts, and dead palms should be collected from the field and burnt. The termite mounds appearing in the plantation should be destroyed along with extracting and killing the queen. The mulching applied to the palms must be observed for infestation and if present should be destroyed. The practice of covering the germinating nuts with a layer of river sand is recommended for managing the infestation in the nursery (Roonwal, 1979). Husain and Sundaramari (2011) recommended the practice of incorporating sand in the nursery beds of the coconut. The sand increases the aeration and drainage of the bed and promotes the better germination and root growth and reduces the infestation (cuticular aberration by the sand on the termite body).

Chemical Methods

To prevent the attack by termite's application of fish oil resin soap along with irrigation water was recommended. Swabbing the basal trunk with neem oil 5% once up to 2 m height and spraying copper sulfate 1%/cashew nutshell oil 80%/ chlorphyriphos at 3 ml/l of water, and neem oil at 5% or NSKE at 20% to preserve plaited coconut leaves is also recommended (http://agritech.tnau.ac.in). Coconut Board recommends the adoption of field sanitation by proper disposal of organic debris in nursery and covering germinating nuts with a layer of river sand, drenching nursery with chlorpyrifos (0.05%) twice at 20- to 25-day interval, along with swabbing termite affected trunk with the same pesticide (http://coconutboard.nic.in).

Seed Nut Treatments.

The application of chlorpyrifos at 3.8 g per nursery bed (7.5 m^2) or application of Fipronil granules at 2.3 g/nursery bed before sowing the seed nuts is recommended (Josephrajkumar et al., 2012). The practice followed in Kerala is to remove the soil in the infested area up to 15 cm depth and then dusting the soil and seed nut with chlorpyrifos (Kerala Agricultural University [KAU], 2002).

Indigenous Traditional Knowledge (ITK)

The traditional practices followed by the farmers of Kerala include the planting turmeric, arrowroot, and aloe vera in nursery. Termite attacks are controlled by applying crushed fenugreek, salt, and ash to the coconut basin. Another practice of application of neem cake and salt in equal proportion has been followed (Swapna, 2003).

Husain and Sundaramari (2011) documented the various traditional practices taken up in coconut cultivation. The report suggests the procedure of nursery planting with 50% of the nut size above the nursery bed for better rooting and reducing termite attack. The lower planting depth improves the rooting and germination of the nut and position of the stalk above the soil reduces attack, and it was also recorded pre-transplanting application of a mixture of sand, salt, and ash in the pits for better drainage and improvement in soil condition and also protection from termites.

Protecting Coco Wood Against Termites

Many techniques including chemical control have been developed to extend the shelf life of wood and building materials against termites. Pesticides such as chlordane and heptachlor are effective tool against termites. Wood preservatives containing active ingredients like permethrin, propiconazole, and tebuconazole are now available in the market.

Other borer pests affecting the standing coconut palms reported so far are listed in Table 7.2.

7.3 Coconut Stem Borers

7.3.1 Asiatic Rhinoceros Beetle, *Oryctes rhinoceros* Linn. (Coleoptera: Scarabaeidae)

7.3.1.1 Taxonomy

Scientific name: *Oryctes rhinoceros* Linn.

Order: Coleoptera.

Table 7.2 Some of the borer pests that attack coconut palm across the world

S. No	Insect	Order	Countries reported	Status
A	Stem borers			
1	*Oryctes rhinoceros L.* (Scarabaeidae)	Coleoptera	Widespread	Major
2	*Rhynchophorus ferrugineus* Olivier (Curculionidae)	Coleoptera	India, Sri Lanka, Philippines, Myanmar, Indonesia, Thailand, Vietnam	Major
3	*Diocalandra taitensis* Guerin (Curculionidae)	Coleoptera	Pacific Is.	Minor
4	*Xyleborus perforans* (Wollaston) (Scolytidae)	Coleoptera	Sri Lanka	Minor

Family: Scarabaeidae.

Subfamily: Dynastinae.

The genus *Oryctes* has about 42 species, out of which 15 species are pests of coconut palm (Gressitt, 1953). Other predominant species are *Oryctes monoceros* Oliv., *Oryctes gigas* Cast., *Oryctes boas*, Fa. and *Oryctes owariensis* P.de B. (East Africa); *Oryctes chevrolati* Geu. and *Oryctes tarandus* Ol. (In Mauritius and Reunion). *Oryctes latecavatus* Fair., *Oryctes pyrrhus* Burm., *Oryctes ranavalo* Coq., and *Oryctes similar* (Madagascar), and *Oryctes trituberculatus* Lamb. (Malaya).; *Oryctes australia* from Papua New Guinea (Lever, 1969a, b; Menon & Pandalai, 1960).

7.3.1.2 Distribution

Widespread; *O. rhinoceros* is an endemic pest to all the coconut-growing countries.

7.3.1.3 Host Plants

Coconut (*C. nucifera*) and African oil palm (*Elaeis guineensis* Jacq.) are known to be the primary host plants (Giblin-Davis, 2001). Minor host plants include date palm (*Phoenix dactylifera* L.), areca palm (*Areca catechu* L.), palmyrah palm (*Borassus flabellifer* L.), toddy palm (*Phoenix sylvestris* (L.) Roxb.), and various ornamental palm species. Other occasional hosts reported are agave, sugarcane, pineapple, tree fern, banana, and taro (Menon & Pandalai, 1960).

7.3.1.4 Economic Importance

In India, O. *rhinoceros* damage to the spathe was estimated to cause yield loss up to 10% (Nair, 1986; Nair et al., 1997; Ramachandran et al., 1963). An infestation to the tune of 39–75% was incurred on juvenile palms in Kerala (Sathiamma et al., 2001). Zelazny (1979) reported 5–10% damage resulting in 4–9% yield reduction; similarly, 30% damage resulted in 13% yield reduction.

7.3.1.5 Damage Symptoms

The robust adult black beetles cause damage to the palm by boring into unopened spear leaves, spathes, and inflorescences in contrast to the grubs, which feed only on

Fig. 7.5 Damage due to *O. rhinoceros*

decaying organic matter. As the beetles bore deeper into the palm, the chewed fibers are seen extruding from the entry holes. The damaged fronds show characteristic "V" or wedge-shaped cuts as they unfold, reducing the photosynthetic area (Sadakathulla & Ramachandran, 1990) (Fig. 7.5).

In most of the cases, repeated attack results in stunted growth (Giblin-Davis, 2001) and occasionally leads to palm death (Bedford, 2013). Seedlings and juveniles are highly susceptible to beetle attack than the grown-up palms (Figs. 7.6 and 7.7). Stunted growth and delayed flowering were more evident on juvenile palms because of beetle attack (Bedford, 1980; Ghosh, 1911; Howard et al., 2001; Nirula, 1955; Pillai, 1919; Rajan et al., 2009). Twisting of the spear leaves (Fig. 7.8), stunted growth, and improper establishment of seedlings were observed when the seedlings got attacked repeatedly at the growing portion, and such seedlings tend to get disposed by farmers in high numbers (Sujithra et al., 2021). Recurrent attack on the same seedling is often noticed due to the emanation of odor in the healing process of the injured portions (Josephrajkumar et al., 2015). Besides the direct injury, the boreholes made by this beetle serve as entry points for lethal pests and pathogens like red palm weevil and bud rot fungi viz. *Phytophthora* sp. (Bedford, 1980; Menon & Pandalai, 1960; Nirula, 1955; Rajan et al., 2009).

7.3.1.6 Bio-ecology

Adult of *O. rhinoceros* is a large stout black beetle, 35–50 mm long, and 14–21 mm breadth and possess a characteristic cephalic horn, which is longer in males (Fig. 7.9). The pygedium is densely clothed with reddish-brown hairs on the ventral

Fig. 7.6 Severity of beetle attack in seedlings and juvenile palms

Fig. 7.7 Affected juvenile palm

Fig. 7.8 Improper growth and spear leaf twisting

Fig. 7.9 Adults of rhinoceros beetle

surface in females (Nirula et al., 1952), whereas males are devoid of pygidial hairs. Antennae are lamellate with short and strongly toothed mandible. Adults are nocturnal active fliers and remain hidden during daytime either in the feeding sites or in the breeding sites where mating occurs. In India, adult longevity is about 3–6 months and average fecundity per female is 108 eggs (Nirula, 1955).

Eggs are white and globular in shape with incubation period of 8–12 days. Larvae are creamy white in color, "C"-shaped with well-developed brown head capsule, mandibles, and thoracic legs. Larval period ranges from 82 to 207 days with three developmental instars (Kurian & Pillai, 1964; Nirula, 1955). Pupal period is about 20 to 29 days (Menon & Pandalai, 1960). Conditions suitable for larval development are at the temperature 27–29 °C and RH 85–95% (Bedford, 1980). Larva feeds on the deadwood, dead palm logs, and dead standing coconut palms killed by pest/disease/lightning, and decaying organic materials like compost and sawdust heaps are the major breeding sites (Bedford, 1980). Besides, more beetle breeding activity was found in cattle-dung heaps in India (Kurian & Pillai, 1964; Nirula et al., 1952). The pest might have spread to newer areas through floating logs containing larvae in tunnels (Bedford, 1980). Nirula (1955) estimated that a single pair of beetle under optimum condition can reproduce 15 million beetles in a span of 3 years. Although pest occurs throughout the year, peak adult emergence is noticed during June to September. Beetle population was comparatively high in younger plantations with multiple breeding sites coinciding with high rainfall and humidity (Joseph Rajkumar et al., 2018).

7.3.1.7 Integrated Pest Management

Oryctes rhinoceros is persistently active and reproductive throughout the year, and its detection is often difficult due to its nocturnal activity and cryptic nature of residence within the palms (Manjeri et al., 2013). Damage monitoring is possible largely by visual inspection of damage symptoms developed in the host palms. Integrated pest management (IPM) strategies for rhinoceros beetle comprehend a series of phytosanitary, preventive, and curative methods and should be deployed on a community basis to bring effective results.

7.3.1.8 Phytosanitary Method

Farm hygiene and sanitation within and surrounding coconut plantations form the first line of pest defense. Since *O. rhinoceros* profusely breed on the organic matter, potential breeding sites like dead palms and decaying coconut logs from the coconut gardens must be cleared off. Compost heaps, cow dung pits, and vermicomposting tanks have to be covered with nylon net (Gopal et al., 2009) and turned out frequently for collection of grubs. Proper planting at recommended spacing (tall and hybrids at 7.5 m × 7.5 m; Dwarfs 7 m × 7 m) with adequate light is also important to reduce pest attack (Josephrajkumar et al., 2015; Rajan et al., 2009).

7.3.1.9 Mechanical Method

This method is the most commonly followed control measure against *O. rhinoceros* wherein the adult beetles are extracted from the boreholes/entry holes using hooks during peak periods of pest activity, i.e., June–September (Joseph Rajkumar et al., 2018). However, this technique is labor- and time-intensive and needs to be conducted regularly. Studies conducted at ICAR–CPCRI, Kasaragod, Kerala, during 2017–2018 indicated that loosely wrapping the unopened spear leaf including the adjacent leaf bases with locally available fishnet/nylon nets was found to be effective in reducing leaf damage by 60–70%. These nets were also found effective in trapping adult beetles by entangling them in the nylon net mesh (Sujithra et al., 2019, 2021) (Figs. 7.10 and 7.11).

Fig. 7.10 Loosely wrapping spear leaf with adjacent leaf base

Fig. 7.11 Beetles entrapped in the nylon net mesh

7.3.1.10 Prophylactic Method

- Application of oil cakes of neem (*Azadirachta indica* A. Juss.), or marotti (*Hydnocarpus wightiana* Bl.) or pongamia cake (*Pongamia pinnata* Linn.) in powder form at 250 g mixed with equal volume of sand, into the topmost three leaf axils around the spindle leaf thrice a year during May, September, and December, is recommended as a prophylactic measure against rhinoceros beetle and red palm weevil (Chandrika & Nair, 2000; Josephrajkumar et al., 2014a).
- Placing three or four naphthalene balls (12 gm per palm) in the leaf axil at the base of spindle leaf and covering them with sand to prevent quick evaporation provide

good protection against the pest for 45–60 days (Gurmit, 1987; Sadakathulla & Ramachandran, 1990).

- Placement of two perforated sachets containing chlorantraniliprole (3 g) or Fipronil (3 g) was found effective in monsoon phase for successful seedling establishment and warding off rhinoceros beetle attack. During dry period, 100 ml of water may be poured over the sachet after placement to release the molecule.
- Placement of two botanical cakes made out of extracts from *Clerodendrum infortunatum* Linn. and *Chromolaena odorata* Linn. (each tablet weighing 1.9 g, 2.5 cm diameter, and 4.0 mm thickness) on the topmost leaf axils reduced 54% leaf damage and was found superior to chlorantraniliprole sachets (34%). A paste based on botanical extracts/oil was developed, and 10 g of the formulation was swiped over the spindle and adjoining petioles to safeguard juvenile palms for about 3 months from rhinoceros beetle attack (CPCRI, 2016; Joseph Rajkumar et al., 2018).

7.3.1.11 Attractants and Pheromones

Placing rotten castor cake slurry 1 kg in 5 l of water in wide-mouthed mud pots in the coconut gardens to attract and kill beetles was found effective. Subsequently, Hallett et al. (1995) exploited the potential of using ethyl 4-methyl octanoate (E4MO), a male-produced aggregation pheromone, in monitoring and mass trapping of rhinoceros beetle. Installing specially designed PVC trap employing rhino lure or Oryctalure at 1 trap per hectare was found effective in trapping beetles in high numbers. The trapped adult beetles should be periodically collected and killed or used for field release by inoculating them with *Or*NV (Rajan et al., 2009). However, the traps are to be placed away from the seedlings and young palms (Subaharan et al., 2019) (Fig. 7.12).

7.3.1.12 Biological Control

Although various predators are reported against this pest (Nirula, 1955), but none of them provide adequate results. Some of the important predators are *Santalus parallelus* Payk., *Pheropsophus occipitalis* Macleay, *Pheropsophus lissoderus*, *Chelisoches morio* (Fab.), and species of *Scarites*, *Harpalus,* and *Agrypnus* (Kurian et al., 1983). Two microbial pathogens are highly employed in the IPM of *O. rhinoceros,* i.e., using *Oryctes rhinoceros nudivirus* (*Or*NV) and *Metarhizium anisopliae* (Metchnikoff) Sorokin.

(a) ***Green Muscardine Fungus:*** *M. anisopliae* (Metchnikoff) Sorokin is an entomopathogenic fungus, and the fungus is very active when the relative humidity is high (90%) and the temperature at 26–28 °C (Antony & Kurian, 1975). This fungus gains entry into the body of host through the cuticle region. This fungus is highly pathogenic to all life stages of the *O. rhinoceros*. The fungus can be easily mass multiplied on the cheaper substrates in both solid and liquid media like par-boiled rice, cassava chips, and rice bran mixture enriched with nitrogen source, or by sterilizing coconut water and coconut jaggery broth

Fig. 7.12 PVC trap for rhinoceros beetle

and the multiplied spores could be harvested and used for treating the breeding sites at 5×10^{11} spores/m^3 (100 gm per liter of water) (Danger et al., 1991; Mohan & Pillai, 1982). Gopal et al. (2006) observed that the application of *M. anisopliae* spores at the highest dose killed and mummified all third-instar larvae in vermicomposting units taking only 8 days.

(b) ***Oryctes rhinoceros*** **Nudivirus (*Or*NV):** The entomopathogenic *Oryctes rhinoceros* virus was first discovered in Malaysia by Huger (1966). Previously known as baculovirus, *Or*NV is presently grouped under nudivirus category with a rod-shaped virion as infective agent (Burand, 1998). By oral ingestion, the viral particles enter into the host body and get multiplied in the midgut and fat bodies of grubs and adults. Due to viral infection, shortened adult life span and ceased oviposition were noticed in females (Bedford, 2013). *Or*NV is very effective in killing the grubs within 15–20 days' time after infection, thereby significantly reducing the longevity and fecundity of adult beetles. Grubs die from the infection, and their cadavers release emerging virus into the breeding sites, where adults are infected by ingesting it there or during mating. During 1967, the Malaysian isolate of *Or*NV was successfully introduced into many South Pacific countries to control *O. rhinoceros* on coconut. In the last decade, a highly damaging *O. rhinoceros* outbreak was reported from Guam (Marshall et al., 2017), which could not be controlled by *Or*NV. Subsequently, such new invasions have been reported from Port Moresby, Papua New Guinea (2009); O'ahu, Hawai'i (2013); and Honiara, Solomon Islands (2015). All the new outbreaks are found to be caused by a previously unrecognized haplotype, CRB–G (Guam strain), which appears to be tolerant to *Or*NV. The best practical method of dissemination of this virus is by releasing the infected adults in the field and 10–15 number/hectare. Healthy adult beetles are allowed to crawl on the viral inoculums at 1 g infected midgut 100 ml^{-1} of buffer, for half an hour. The beetles are then kept under starvation for 12–24 h. The beetles are released preferably at dusk in the infested coconut gardens at 12–15 beetles ha^{-1} (Joseph Rajkumar et al., 2018; Mohan et al., 1983; Rajan et al., 2009).

7.3.1.13 Botanicals

The incorporation of small cut pieces of stems of weed plant, *Clerodendrum infortunatum* Linn. (Verbenaceae), is very effective in controlling the pest build-up in the breeding sites. Alkaloids of *C. infortunatum* are known to have juvenile hormone analogous activity on *O. rhinoceros*. The formation of larval–pupal intermediates, pupal–adult intermediates, or adults with malformed wings was noticed after incorporation of the weed plant into the breeding sites. The emerged adults were found abnormal, unable to fly, and had shortened life span of 6–8 days than normal and healthy adults (Chandrika & Nair, 2000).

7.3.2 Red Palm Weevil: *Rhynchophorus ferrugineus* Olivier

Order: Coleoptera.

Family: Curculionidae.

Subfamily: Rhynchophorinae.

Red palm weevil is a key lethal pest and concealed borer pest of coconut (Figs. 7.13 and 7.14). This pest is now continuously spreading in all the areas of palm cultivation throughout the world. It was first reported as a sporadic pest on palms in India by Lefroy (1906). The damage caused by these weevils is widespread and causes complete destruction of the palm gardens leading to total crop loss. The

Fig. 7.13 Red palm weevil infestation in dwarf palm

Fig. 7.14 Red palm weevil

Fig. 7.15 Crown damage by RPW

characteristic symptoms of this pest attack include yellowing and wilting of inner and outer whorls of leaves, presence of circular holes and tunnels on the palm, fermented odouration, gnawing sound of grubs while feeding, oozing out of a brownish viscous fluid from the holes/tunnels, and presence of fibrous cocoon and/or chewed-up fibers at the leaf axil or palm base (Fig. 7.15).

7.3.2.1 Taxonomy

Red palm weevil is among the most destructive pests of palms throughout the worlds, and this invasive genus of *Rhynchophorus* consists of more than 10 species, which include *Rhynchophorus ferrugineus* Oliver, *Rhynchophorus vulneratus* (Panzer), *Rhynchophorus distinctus* (Wattanapongsiri), *Rhynchophorus lobatus* (Ritsema), and *Rhynchophorus bilineatus* (Montrouzier) (Murphy & Briscoe, 1999; Wattanapongsiri, 1966).

7.3.2.2 Nature of Damage

All stages of red palm weevil survive inside the palm trunk, and it cannot survive without the concealed condition of palm trunk. The fecundity of females is about 300 eggs, which they deposit on the injured points on the palm. Apodous grubs hatch from the eggs and bore into succulent and soft tissues of the palms, and the chewed frass can be seen expelled from the point of infestation. The larval period ranges between a period of 1 to 3 months, and the pupation occurs in elongated and oval cocoons built by using the fibers. The pupation lasts for about 14 to 21 days, and the adults emerge out from the cocoons (Murphy & Briscoe, 1999). The grub bored internally and feeds on the palm, without exhibiting any external symptoms until the damage has become severe. The voracious feeding causes the development of hollow cavities on the palm trunk making the palm susceptible to collapse due to mechanical resistance (Howard et al., 2001) (Fig. 7.16).

Fig. 7.16 Red palm weevil infestation causing hallow cavities in the coconut wood

7.3.2.3 Damage Symptoms

RPW is most likely to attack young palms aged below 20 years (Abraham et al., 1998). The mechanical injuries caused during intercultural operations, attack by rhinoceros beetle, and bud rot are among the factors that predispose the palm to RPW attack (Josephrajkumar et al., 2014b). The main symptom exhibited by the palms infested with red palm weevil occurs at the later stage of infestations (Menon & Pandalai, 1960). The peculiar symptoms include the oozing of brown viscous liquid along with the frass-emitting fermented odor, drying of the outer fronds and nuts. In case of extremely severe damage, the breaking or toppling of trunks also takes place (Howard et al., 2001).

7.3.2.4 Integrated Pest Management

The most important step in the management of the RPW is the prevention of entry and spread into newer areas and implementing domestic and international quarantine to prevent the movement of infested materials. Maintenance of proper field sanitation, reducing injuries to the palms, and destruction of the existing population in field can be helpful in the management of the pest.

7.3.2.5 Early Detection--Bioacoustics

The life cycle of the weevil is such that the larvae and the adults feed internally causing damage to the trunk of the palm without exhibiting any external damage symptoms initially (Mohammed et al., 2020). The most challenging aspect of the management of RPW is early detection due to its cryptic habitat. So far, the detection of this pest is merely based on visual symptoms, which are shown when the damage has advanced and management is nearly impossible (Blumberg et al., 2001). The management technologies revolve around the most damaging stage of pest, which is larvae. The major prevailing method of control is the use of aggregation pheromone trap in the field, which acts as management, and in pest surveillance. A reliable and quick method of detection and management is extremely important since the crop is perennial and losses can be high. Recent development in electronic technologies, artificial intelligence, and computer software packages has opened a new dimension of remote sensing systems, bioacoustics, irradiations, and radio telemetry. The modern-day detection systems are based on acoustic sensors, which recognize sound and the waves having longitudinal and transverse wave pattern in solid. These wave frequencies range from 20 Hz to 20 kHz and can be heard by humans. The sound produced by insect inside the tree during its movement and feeding can be used as signals for detection. The prevailing RPW detection system utilizes acoustic sensors by inserting them into the palm trunk to detect the sounds produced by the attack of these insects. Arshy et al. (2020) used an optical fiber-distributed acoustic sensor (DAS) technology for early detection of infestation. This technology could detect the larval infestation at the early stage of even 12-day-old larvae. This efficient technology could be used in real time as it is cost-effective and also noninvasive.

Radio telemetry: Ansi et al. (2020) utilized radio telemetry for tracking the movement, habitat preference, and flight distance of RPW for the first time. Wild-caught red palm weevils were attached with the radio transmitters and were monitored for its movement in the orchards with and without pheromone traps, and the results of the study indicated that the flight distance is more in the presence of pheromone traps and the RPW were more attracted toward the previously infested palms, surface water bodies, and pheromone traps. So, this appears to be effective and suitable technique method for tracking the weevil infestation.

7.3.2.6 Cultural Control

The maintenance of proper spacing and population of the palms is necessary to prevent the overcrowding and development of microclimate, which can lead to increased pest incidence. Close monitoring of individual palms for the damage symptoms, prevention of mechanical injury to the palms, and prevention of disease like bud rot can be taken up to reduce pest incidence. Cutting off fronds at a distance of 120 cm from the trunk can also prevent the attack to the crown region (Josephrajkumar et al., 2014a).

7.3.2.7 Biological Control

RPW serves as host for more than 50 natural enemies (Mazza et al., 2014), and these natural enemies can be deliberately used in biological suppression of the pest. In India, Gopinadhan et al. (1990) reported the presence of cytoplasmic polyhedrosis virus (CPV) for the first time having high virulence and capacity to infect all stages of the host. Entomopathogenic bacteria *Bacillus thuringiensis* subspecies *kurstaki* isolated from larvae in Egypt showed promising control in vitro (Alfazariy, 2004). Several insect natural enemies belong to different orders viz. Dermaptera, Heteroptera, Coleoptera, Diptera, and Hymenoptera (Murphy & Briscoe, 1999). Abraham and Kurian (1975) reported dermapteran species *Chelisoches morio* (Fabricius) as a common predator of RPW eggs and larvae in coconut plantations in India. Burkill (1917) reported *Scolia erratica* Smith as parasitoid of RPW from Malaysia. Indian tree pie bird, *Dendrocitta vagabunda parvula,* was reported to be effective predator of RPW adults by Krishnakumar and Sudha (2002). Entomopathogenic nematodes viz. *Heterorhabditis indica*, *Steinernema glaseri,* and a local isolate *Steinernema* sp. were reported to infect both the grubs and adult stages (Banu et al., 2003). Henry (1917) evaluated different attractants for trapping RPW adults and reported that fermented kithul palm wood could be used effectively utilized for trapping. In India, fresh toddy smeared on coconut logs was more effective in trapping the adults (Abraham & Kurian, 1975).

7.3.2.8 Botanicals

Hussain et al. (2019) suggested the use of sesquiterpene (Picrotoxin) as a novel biopesticide for the management of RPW. Ali et al. (2019) reported that essential oils extracted from orange and lemon had highest efficacy on the eggs and larva of RPW followed by eucalyptus, basil, and castor. Ahmed et al. (2015) evaluated the efficacy of four botanical oils viz. *Melissa officinalis, Borago officinalis, Laurus nobilis,* and *Carapichea ipecacuanha* on RPW, and the results of the study indicated that males are more susceptible than females. The highest mortality was induced by *C. ipecacuanha* oil, whereas least mortality was observed to *L. nobilis* oil at LC50 level. Dehvari et al. (2019) studied the anti-ovipositional effect of botanicals and concluded that thymol can be effectively used as an oviposition deterrent on open wounds present on palms. Mona (2020) demonstrated that ether petroleum or chloroform extracts of cardamom and clove seed oils exhibited 100% mortality of RPW after 3 days of treatment. The GC-MS analysis of oils indicated the presence of large number of terpene compounds majorly eugenol and also two novel compounds viz. hydroxy-alpha-terpenyl acetate and lambda-8(17),13(E)-diene-15.

7.3.2.9 Pheromone

Pheromone traps are one of the most important components of integrated pest system which is useful in pest monitoring and trapping of the adult weevils. Hallett et al. (1993) identified and synthesized "ferrugineol" (4-methyl−5-nonanol) by male-produced aggregation pheromone. Bucket traps were used in India and Sri Lanka, whereas upright bucket traps were commonly used in Saudi Arabia and fabricated plastic traps were used in UAE (Faleiro, 2006; Faleiro et al. 1998). The trap consists of several windows, and the RPW will get attracted by the pheromone and pineapple or insecticide solutions are kept as bait in traps. Subaharan et al. (2019) suggested that food bait along with improved delivery matrix for pheromones can increase the efficiency of trapping (Fig. 7.17).

Fig. 7.17 Bucket trap for RPW

7.3.2.10 Chemical Control

The recommended chemical control strategies utilized chemicals, which have been phased out. Meridja-Chihaoui et al. (2020) suggested that use of stem injection or endotherapy using systemic and persistent insecticides viz. emamectin benzoate, imidacloprid, and thiamethoxam. The results of field assay suggest that emamectin benzoate was able to protect the palm from RPW infestation up to a period of 9 months. Abd El-Fattah et al. (2021) tested the efficacy of chlorpyrifos, imidacloprid, and nanoderivatives of the same insecticides and came to the conclusion that nano-chlorpyrifos was most effective in both laboratory and field conditions.

7.3.3 Shot Hole Borer or Bark Borer

7.3.3.1 Taxonomy

Scientific name: *Xyleborus Perforans* Wollaston.
Family: Scolytidae.
Order: Coleoptera.

7.3.3.2 Distribution

This insect is sub-cosmopolitan in distribution, being recorded in the tropics from Australia, Barbados, Ceylon, Fiji, Ghana, Grenada, Guyana, Jamaica, Kenya, India, Fiji, Malaysia, Mauritius, New Britain, Nigeria, Pakistan, Papua, St. Vincent, Samoa, Sarawak, Seychelles, the Solomon Islands, and Trinidad. It is unselective in its choice of host, being recorded as breeding in the wood of more than 100 tree species. Usually, it breeds in newly cut logs, felling slash, dead trees, and temporarily unhealthy or injured trees.

7.3.3.3 Host Plants

It has a wide range of host plants, including coconut, *Elaeis, Eodoicea*, sugarcane, rubber, teak, avocado, cocoa, nutmeg, guava, *Terminalia,* loquat, and areca nut.

7.3.3.4 Damage Symptoms

The presence of this pest is indicated by numerous small circular holes in the palm trunk interconnected by fibrous galleries. Other visible symptoms of attack are the presence of white powdery deposits at the base of the palm and extrusion of frass material from the holes. Large numbers of larvae, pupae, and adults could be seen in the galleries of the affected palm. Damaged palms lose their vigor, and they are easily prone to secondary infestation. The infested palms die in 6 months (Lever, 1969a, b). The life cycle of this pest is usually 2–3 weeks.

7.3.3.5 Identification of the Pest

Adult: Beetles were breeding profusely in the bark and outer sapwood. Beetles measure 2 mm in length. Pronotum is cylindrical with a conical prominence at about 2/3 distance from the apex. Rows of tiny warts are present in the anterior

Fig. 7.18 Shot hole borer, *Xyleborus perforans* (courtesy: www. Invasive.org)

half. Elytra with parallel dark brown streaks slightly pitted (Fig. 7.18). The gallery consists of irregularly branched tunnels, without communal chambers, lying in the transverse plane of the wood, or sometimes there may be two or more such systems connected by longitudinal shafts. The beetles are polygamous and the males, which are few, short-lived, and incapable of flight, normally do not leave the parent nest, in which they fertilize members of the same brood. Females are darker and larger (1.5–1.8 mm), and males are dull and small (0.8–1.0 mm).

7.3.3.6 Management

- Cleaning the frass and other materials on the base of the trunk and then swabbing the bark with 2% chlorpyrifos can effectively manage the pest.

7.4 Conclusion

Plantation crops are one of the complex ecosystems in agriculture owing to their perennial nature. Surveillance and sustained monitoring form the basis of integrated pest management (IPM) strategy for the early detection of pests and diseases in plantations. In the agricultural context, the Food and Agricultural Organization (FAO) defines integrated pest management (IPM) as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment." IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms. Judiciously integrating various IPM strategies with components of crop management practices on need-based manner are very much needed to make farmer competitive enough to face challenges arising in the changing agrarian scenario.

Besides, the use of coconut wood offers an attractive economic prospect for industry development in those countries where there is a scope of timber used in the internal market trade. Most of the coconut products are exported in the major coconut-producing countries, coconut farming, and industry play a critical part in their economies' growth. The coconut palm stem has several characteristics that distinguish it as a wood source material. There is almost no doubt that in the future, the coconut stem will be used as a traditional wood substitute in a variety of applications, and in many cases, it will perform and or better than traditional wood.

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8 Teak Heartwood Borer *Alcterogystia cadambae* (Cossidae: Lepidoptera): A Potential Wood Pest of Teak and Its Management

R. Veeranna and O. K. Remadevi

Contents

Abstract

The wood borer of teak *Alcterogystia cadambae* Moore is economically important as it causes severe damage to the heartwood of teak. As any one method is not sufficient for the management of this tree boring pest, cultural methods along with mechanical, light traps and biological methods including nematode application, and use of microbial pesticides were recommend as a package of practices for the management of this pest.

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_8

Keywords

Teak heartwood borer · *Alcterogystia cadambae* · Karnataka · Management · Biocontrol · Biopesticide · Nematodes · Fumigation

8.1 Importance of Teak as a Timber Species

Forests in India occupy 21.67% of the total geographical area (FSI, 2019) with diverse type of forests, scrub to evergreen, inhabiting a large number of naturally growing trees, of which only few are valuable as timber species. The most important timber species in terms of value and abundance are teak, sal, larua, gurjan, haldu, etc. Teak (*Tectona grandis* Linn. f.) is one of the most favored timbers all over the world, since it has been used for many centuries for a wide range of products and services. It is a celebrated timber that has significant ecological and sociological importance throughout the tropics. India is one of the major teak growing and utilizing countries. Domestication through plantation of teak for more than one and half centuries has made it as the most widely planted and researched tropical hardwood. It is known for its strength, durability, and maintaining attractive appearance. The ever-increasing need for teak timber resulted in taking up of large-scale plantations throughout the world. The worldwide demand for teak is much greater than the resource availability (Dupay, 1990). Myanmar and Ivory Coast dominate the export trade in teak logs, while China and Thailand are the largest importers. The largest manufacturers of teak products are Indonesia, Thailand, and India.

Nearly 280 insects have been found to be associated with teak all over the country. All the stages in the growth of teak from seed to mature trees are attacked by insects. They include flower and seed feeders, defoliators, sapsuckers, gall formers and leaf miners, root and bark feeders, borers of living and dry wood, but only few species cause serious damage (Mathur & Singh, 1961; Tewari, 1992). Many of these insects are minor or occasional pests, and very few are recognized as major pests. Teak defoliator, viz. *Hyblaea puera* (Cramer), and *Paliga machaeralis* (Walker) commonly known as teak skeletonizer are the major defoliating pests of teak in India. *H. puera* feeds on tender foliage in the early part of the growth season, and *P. machoeralis* feeds on older foliage toward the end of the season. Defoliation by these pests in younger plantations can cause 44% of loss of potential volume increment (Nair et al., 1985). The stem/wood borers deteriorate the quantity and quality of timber produced by teak. Deformity in the bole of the plant is reported to be caused by Lepidopteran trunk borer, *Alcterogystia cadambae* Moore, and sapling borer *Sahyadrassus malabaricus* in which the damage by *A. cadambae* is very serious because the whole worth of teak is spoiled by this pest.

A. cadambae Moore (=*Cossus cadambae* Moore) is a relatively new insect pest of teak in India, which has achieved major pest status reaching several plantations in Kerala, Karnataka, and Tamil Nadu. It belongs to the lepidopteran family, Cossidae, and cossids are popularly known as “goat moths” because of the production of characteristic odour and “carpenter worms” due to the larval habit of boring into the wood. All the members of this family without exception are internal feeders inside the woody tissue of plants. Although the number of recorded species is rather few, species belong to many genera and are widely distributed.

Beeson (1941) reported it as a minor pest of teak in southern India where it affected unhealthy or mechanically damaged trees. Bhandari and Upadhyay (1986) reported it as a pest of tendu (*Diospyros melanoxylon*) in Madhya Pradesh. Some of the bio-ecological aspects of the pest occurring in Kerala were studied by Mathew (1990). Lingappa et al. (1991) reported the distribution and damage potential of the pest in North Canara District of Karnataka State. Recently, *A. cadambae* has assumed a major pest status in certain plantations of North Canara in Karnataka and is causing extensive damage to the timber. Based on the surveys made on teak plantations in Karnataka, the findings on distribution, bio-ecology and nature of damage, seasonal incidence, economic importance, and management of *A. cadambae* are elaborated.

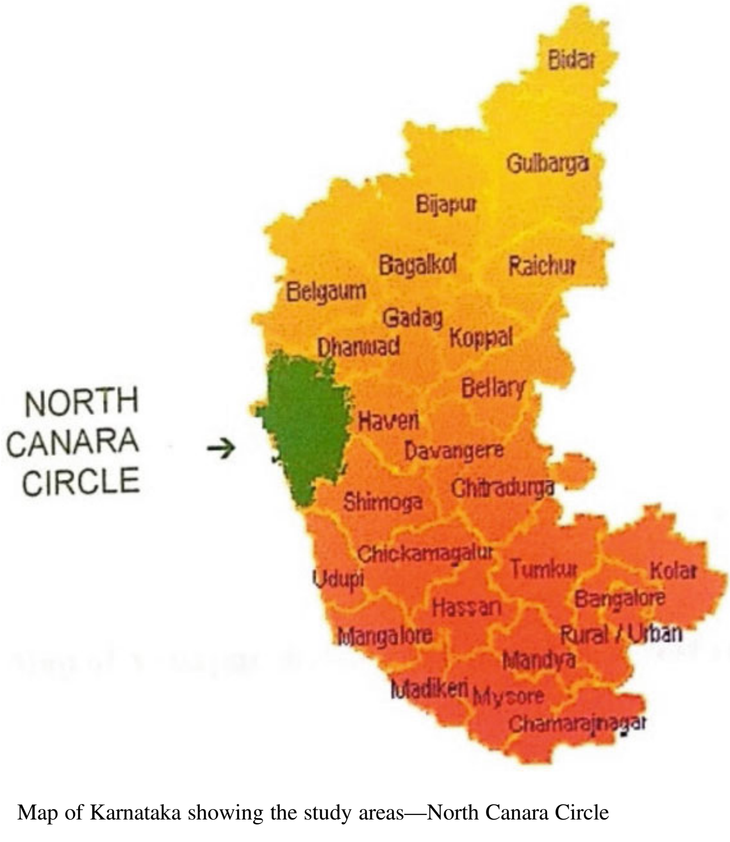


Fig. 8.1 Map of Karnataka showing the study areas—North Canara Circle

Fig. 8.2 Map of Yellapur division showing the forest ranges selected for survey

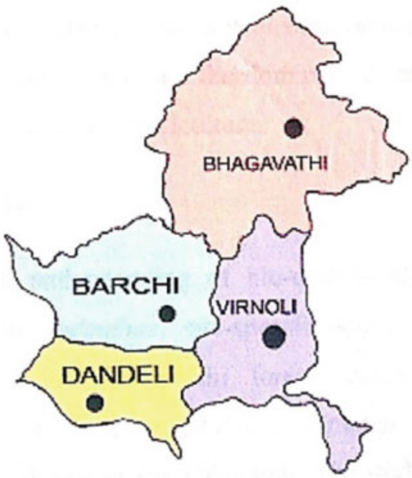


Fig. 8.3 Map of Haliyal division selected for survey showing the forest ranges selected for survey

8.2 Ecology

8.2.1 Study Area

The Karnataka State in south India has nine forest circles in which North Canara Circle (Fig. 8.1) is one of the important circles with large areas of teak plantations where the field studies were conducted. This forest circle is located in Karwar District of Karnataka, and it consists of five divisions, viz. Yellapur, Haliyal, Sirsi, Honnavar, and Karwar. Among them, due to good growth of teak plantations, Yellapur (Fig. 8.2) and Haliyal (Fig. 8.3) divisions are considered as major teak areas. The climate of the North Canara Circle ranges from subtemperate to tropical. Majority of teak plantations are moist deciduous forests shedding of leaves takes place from the month of November. March and April are the hottest months, and December and January are the coolest months. The rainfall is highest during the months, June–September.

For detailed understanding of bio-ecological aspects of the teak borer, *A. cadambae*, site-specific studies were conducted in Gunjavathi forest area. Gunjavathi forest section is located in the Mundgod range of Yellapur division, situated 15 km from Mundgod and 25 km from Yellapur. The study site is a rain-fed teak plantation established in 1941 with an area of 2 ha. The trees are heavily infested with *A. cadambae*; the soil is of red and light black type. The planting spacing is 2.5 × 2.5 m and is a pure plantation. Studies on light traps, nature of damage, pupation behavior, moth emergence pattern, and management aspects were carried out in this plantation.

8.2.2 Survey the Teak Plantations of North Canara Circle of Karnataka

A. cadambae is the most important pest of teak in the plantations of North Canara Circle of Karnataka. The incidence, distribution, nature of damage, predisposing factors, seasonal occurrence, and alternate hosts of this pest have been studied in detail by survey in this circle. The survey was carried out in the teak plantations of North Canara Circle for 3 years from 2001 to 2003. Since the symptoms of pest attack remain in the tree throughout its life and it is no way connected to the seasons, survey was conducted in the different plantations of the different divisions at any one time as per the convenience.

Details of the teak plantation in the five divisions of North Canara Circle under the control of Karnataka Forest Department were collected from the respective Deputy Conservator of Forest. To study the distribution and incidence of the pest, survey was conducted under a stratified multistage sampling scheme. The ranges formed the strata and plantations of the first-stage units. Plantations were selected on the basis of probability proportional to size (PPS); 5% of the total area was covered. 101 plantations were selected from a total of 2043 plantations in North Canara Circle.

Table 8.1 Division-wise distribution of plantations selected for survey

Sl. no	Name of the division	Total no of plantations in the division	Total no of plantations selected for survey
1	Yellapur	212	12
2	Haliyal	571	29
3	Sirsi	182	7
4	Honnavar	803	42
5	Karwar	275	11
Total		**2043**	**101**

Table 8.2 Percentage of infestation in the forest divisions of North Canara Circle

		Estimated mean infestation			Estimated variances of infestation		
Name of division	Name range	Range	Division	Circle	Range	Division	Circle
Yellapur	Idagundi	17.39%	13.01%	4.72%	0.1459848	0.3072161	0.0709898
	Kirwatti	6.72%			0.2990492		
	Manchikere	9.46%			0.2302710		
	Mundgod	13.66%			0.1685392		
	Yellapur	22.50%			0.6922367		
Haliyal	Bhagavathi	6.74%	10.59%		0.0351199	0.0477331	
	Barchi	10.61%			0.0488597		
	Dandeli	11.36%			0.0718881		
	Virnoli	12.60%			0.0349646		
Sirsi	Janamane	0					
	Banavasi	0					
	Siddapur	0					
	Sirsi	0					
Honnavar	Bhatkal	0					
	Gersoppa	0					
	Honnavar	0					
	Katagal	0					
	Manki	0					
	Kumata	0					
Karwar	Kadra	0					
	Karwar	0					
	Ramanguli	0					

The number of plantations selected in a particular division (Table 8.1) was based on the proportion of teak area, subject to a bare minimum of one plantation per range. Survey was conducted with the help of Karnataka forest officials in the different ranges of each division. Information on division, range, locality, block/ compartment number, area, year of plantation, irrigation facilities, soil type, inhabitation, approach to road, any other plants, etc., was recorded beforehand. This also helped to assess the predisposing factors for infestation of the borer. The division-wise plantation survey results are summarized below (Table 8.2).

The trees were classified under six age groups, i.e., 1–15 years, 16–30 years, 31–45 years, 46–60 years, 61–75 years, and 76–90 years. In each age group, the percentage of woodborer infestation was calculated and computed. Correlation between the different age groups and infestation rate was estimated to find out the susceptible age groups for infestation.

From the estimated mean and variance of different divisions of the circle, the mean and variance of the entire circle were estimated. The estimated mean for the entire circle was found to be 4.72%. The estimated variance in the infestation rate for the entire North Canara Circle was 0.0709898 (Table 8.2). The present study indicated that only two forest divisions (Yellapur and Haliyal) are affected by *A. cadambae* and other three divisions are free from the borer attack; it may be due to the limited dispersal ability of moths from these two divisions to other areas and also due to the high prevalence of predisposing factors in these divisions. The tribal communities (Siddi and Gouli) are settled in the forest plantations of these divisions, their main occupation being cattle and sheep keeping and trench cutting, timber cutting, etc.; as the activities of the tribals wound on the trees, the moths are getting attracted to these trees, and thus, wherever human settlement is there, infestation was found to be more. Monoculture of teak also appears to favor the spread of the pest. Islam et al. (1989) and Wazihulla et al. (1996) also observed that monoculture inhabits more infestation of *Zeuzera conferta* in *Sonneratia apetala* than the mixed plantations. Similarly, *Z. multistrigat*a, a primary pest of *Casuarina equisetifolia,* is found to be low in mixed stands in Fuji (Haung, 1989). Honnavar, Karwar, and Sirsi forest divisions are free from the borer attack. In these three divisions, the communities are Marathas, Bhats, and Gowdas whose main occupation is agriculture and allied activities; also, unlike Yellapur and Haliyal, these divisions have many tree species in the plantations. These findings are similar to those by Mathew (1990) who reported 3 to 58% incidence in different teak plantations of Kerala. Lingappa et al. (1991) reported the occurrence of the pest in heavy rainfall tracts of Yellapur, Dandeli, and Haliyal causing damage up to 5–10%, while Veeranna and Remadevi (2007a, b) reported damage up to 4.72% by this pest in these areas.

8.2.2.1 Relation between Age of Trees and Infestation

Relationship between the age of trees and pest infestation was estimated based on the observations from 101 plantations of North Canara Circle. Of the 101 plantations covered, 41 plantations belonging to two forest divisions were affected by *A. cadambae*. The maximum level of infestation was in the age group of 76 to

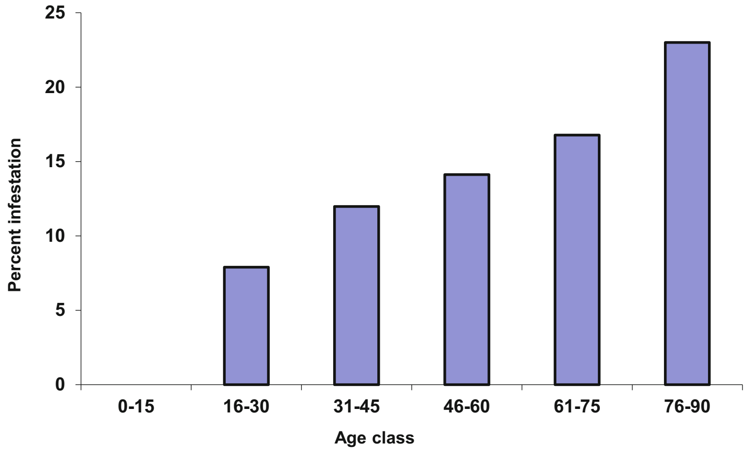


Fig. 8.4 Percent infestation of *A. cadambae* in different age classes of teak plantations

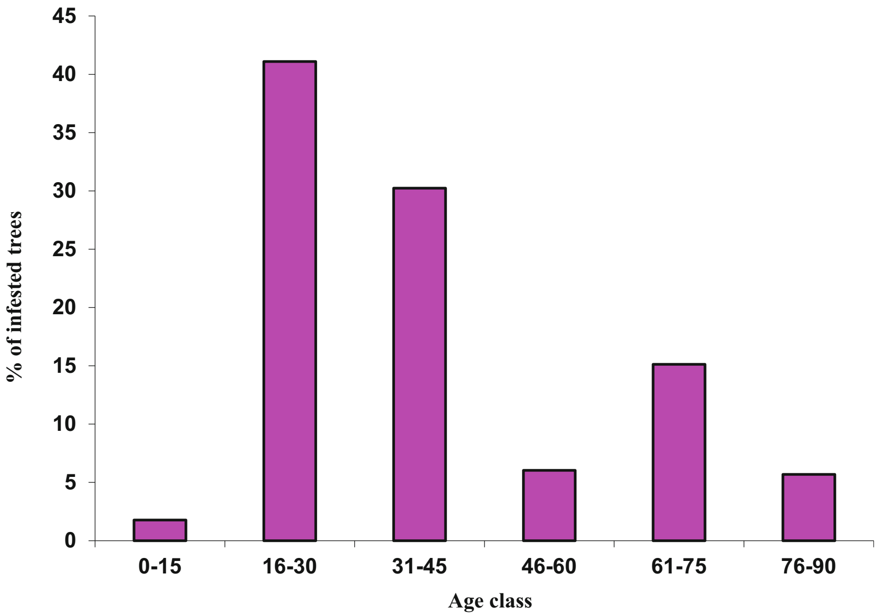


Fig. 8.5 Percentage of infested trees of *A. cadambae* in different age classes of teak plantations

90 (23.88%), while the minimum level of infestation was in age group 16 to 30 (7.9%) (Fig. 8.4). The youngest affected plantation was 15 years old, and the number of affected trees in this plantation was low (6.25%). The oldest affected plantation was 84 years old with a large number of trees in the plantation being infested by the borer. As the older plantations were very less in number, the

Table 8.3 Correlation between age of the teak plantation and infestation

1	Yellapur division ($n = 12$)	0.53309903[a]
2	Haliyal division ($n = 29$)	0.56043335[a]

[a]significant at p = 0.05%

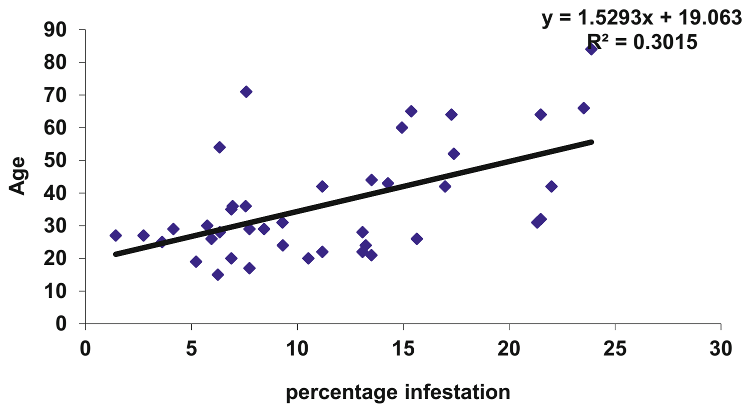


Fig. 8.6 Correlation between age of the teak plantation and infestation

proportion of older infested trees out of the total infested trees was less. The percentage of infested trees was more in the age group, 16–30 followed by 31–45 years (Fig. 8.5). In Kerala, Mathew (1990) reported that the youngest affected plantation was of 22 years with 3.4% of affected trees and oldest plantation was of 56 years with 38% of affected trees. Thangavelu and Isa (1992) found *Z. multistrigata* prefers trees of 3–10 years old though seedlings and older trees (20 years) were also attacked. But *A. cadambae* prefers to attack trees older than 15 years.

The correlation coefficient between age and proportion of infestation was calculated for 2 divisions, Yellapur and Haliyal (Table 8.3). The infestation level was positively correlated with the age of plantation (Fig. 8.6).

8.2.2.2 Alternate Hosts

The borer larvae collected and reared to confirm the identity revealed that *Terminalia bellirica,* (Haliyal division), *Butea monosperma,* and *Terminalia tomentosa* (Yellapur division) were serving as alternate hosts to the borer.

8.2.2.3 Spatial Distribution Pattern

Spatial distribution of the pest was studied in heavily infested teak plantations for which survey was conducted both in smaller plots (1 ha) and in bigger plots (<5 ha). In smaller plantation, all the trees were scanned and observed, while in bigger plantations, 5 sample plots were taken, 4 in corners and 1 in the center of the plantations. Distribution pattern of woodborer in heavily infested roadside teak plantations was also studied. Plantations were selected at Doginal area (25 plots along the roadside) in Yellapur division and Bhagavathi area (25 plots along the

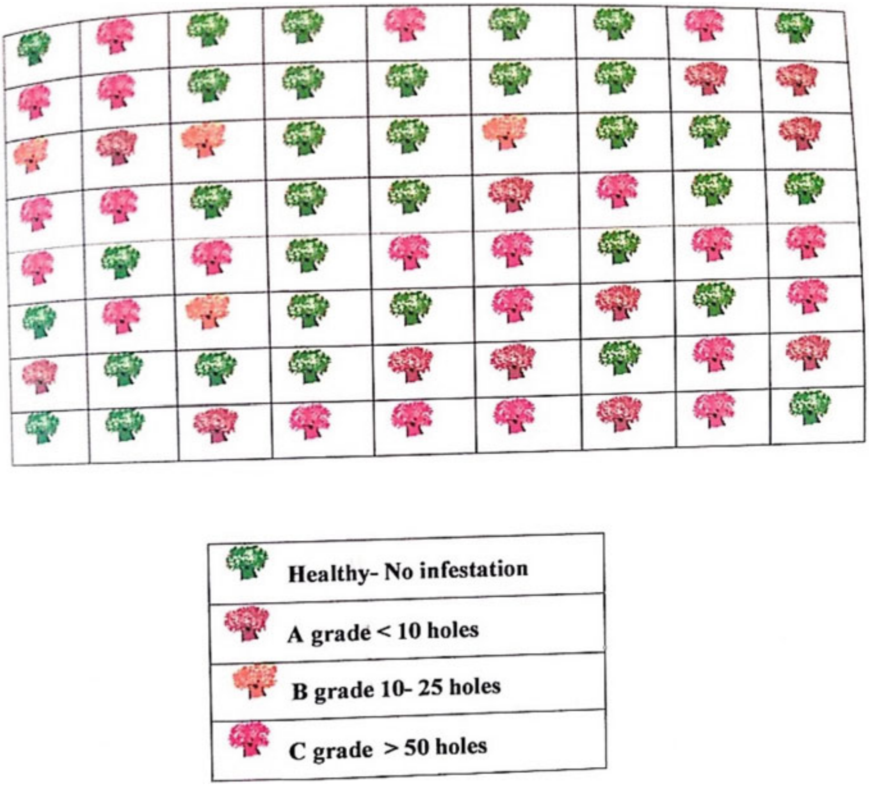


Fig. 8.7 Pictogram of Gunjavathi plantation (Yellapur division) infested by *A. cadambae*

roadside) in Haliyal division.of North Canara Circle. In each area selected, a series of rectangular plots of size 10 × 15 m were taken parallel to the road. Each plot contained 10–12 trees depending on the terrain and the extent of distribution due to various factors like illicit felling, windfall, girdling, mechanical thinning, silvicultural system. The number of healthy and affected trees and the intensity of attack on each of the affected tree were recorded.

The following visual scoring system was followed to assess the borer damage.

H—healthy trees, no infestation. (Fig. 8.8a).

A—low level of infestation, with up to 10 borer holes on the stem (Fig. 8.8b).

B—medium level of attack with 10–50 holes distributed on the stem.

C—heavy infestation characterized by the occurrence of exit hole complexes with scars and holes (>50), trees more or less dead, debarked.

The spatial distribution of different grades of trees (H, A, B, and C) in a small plot of 1 ha located at Gunjavathi area is represented in the pictogram (Fig. 8.7). The healthy trees are represented by green color, A grade by brown, B by yellow, and C by red color. The total number of A grade trees is 12, B grade 4, C grade 22, and

Fig. 8.8 Grading of trees in infested plantations. (**a**) H grade. (**b**) A grade

healthy trees 34. This indicates that in small patches, the distribution of different grades of trees was in a random fashion.

In bigger plots (<5 ha), the sample plots were scanned for the distribution of healthy and infested plants, and the distribution based on mean values of 5 plots is represented (Fig. 8.10). In the corner plots, 1 to 4, the distribution is H—36.36%, A—36.36%, and C—27.27% in plot 1; H—55.55% A—22.22%, B—11.11%, and C—11.11% in plot 2; H—41.66%, A—33.33%, and C—25.00% in plot 3; and H—50.00%, A—25.00%, B—8.33, and C—16.66% in plot 4. In the center plot, the infestation was H—87.5% and A—12.5%. The result shows that the center plots are comparatively less infested with 87.5% of healthy trees and 12.5% of A grade trees.

Studies at Doginal (Yellapur division) and Bhagavathi (Haliyal division) revealed that trees were affected by the pest in different degrees. In Doginal, the distribution of different grades of trees was 15.74% (A), 6.18% (B), 15.21% (C), and 63.33% (H) (Fig. 8.9). In Bhagavathi, A grades trees were 14.19%, B were 4.93%, C were 17.66%, and healthy trees were 64.19% (Fig. 8.11). Results show that distribution of infestation is similar in both the divisions. The study indicates that in the heavily affected plantations, the number of C grade trees was more than B grade trees. The higher infestation (average 36%) in roadside plantations revealed that the distribution of pest was more near the human inhabitations and where human activities were concentrated (Veeranna & Remadevi, 2007a, b).

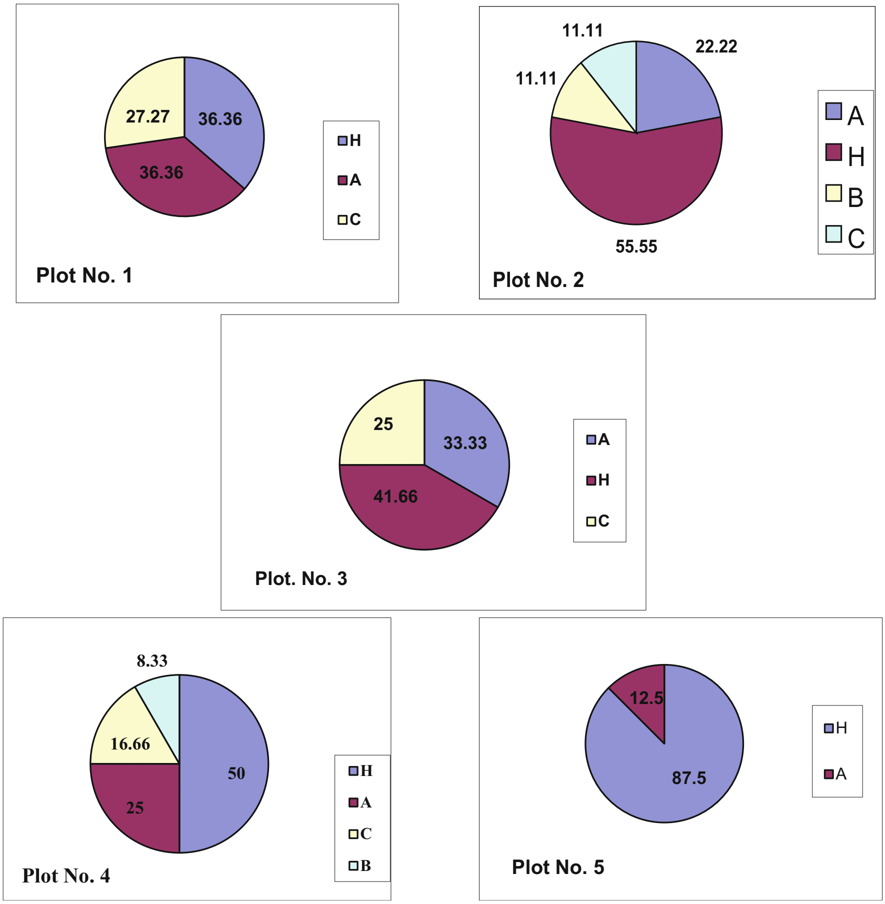
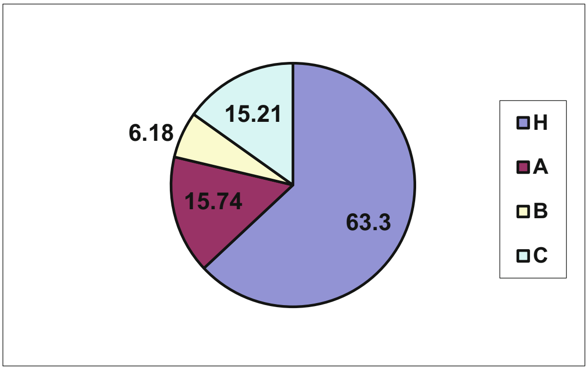


Fig. 8.9 Spatial distribution of healthy and infested trees in bigger plots

Fig. 8.10 Distribution pattern of different grades of infested trees in Yellapur division



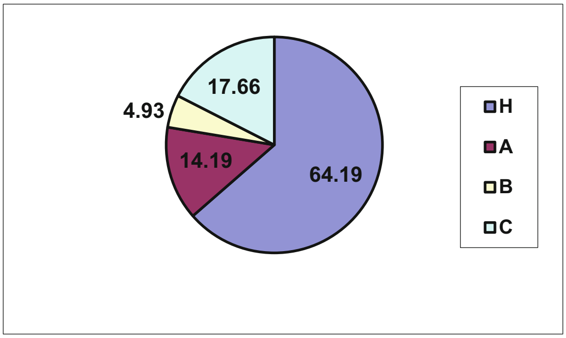


Fig. 8.11 Distribution pattern of different grades of infested trees in Haliyal

Fig. 8.12 Severely affected teak tree near tribal inhabitation

8.2.2.4 Predisposing Factors

The predisposing factors leading to the borer infestation in plantations have been studied in Gunjavathi and Tataval (Yellapur division). The damage due to nearness of human settlement and presence of road has also been estimated. The forest plantations of teak selected for the study were those, which did not have any houses inside the interior areas of the forest. The observations were taken in 8 m × 10 m plots starting from near the human settlement area and progressing toward the interior forests (Fig. 8.12). A total of 25 plots were taken leaving a gap of 25 m between the plots. The total number of infested trees and healthy trees in each plot was recorded (Fig. 8.13). Observations were taken for 10 trees in each row up to the fifth row starting from the roadside and proceeding toward forests. The procedure

Fig. 8.13 Tribal man lopping the branches of teak tree

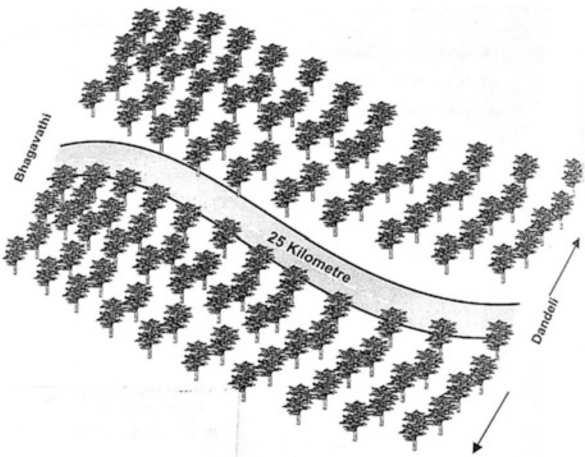


Fig. 8.14 Pictorial representation of trees chosen for surveying the roadside plantations

was repeated for 25 km stretch of road from Bhagavathi to Dandeli, leaving a gap of 100 m between each set of trees. The pictorial representation of trees chosen for survey is given in Fig. 8.14. The number of healthy and infested trees in each row was recorded.

The infestation rates of the borer in different plots located at different distances from the settlement area are given in (Table 8.5). The rate of infestation in the trees adjacent to the residential area was found to be as high as 66%. The infestation decreased toward interior, and it was almost nil 210 m from the human inhabitation.

Table 8.4 Developmental periods and life stages of *A. cadambae* in field condition

Stage of insect	Duration in days Range	Mean ± SD
Egg	14–19	17 ± 2
Total larval period	192–234	218 ± 15.8
Total pupal period		
Male	14–18	16 ± 1.5
Female	18–20	19 ± 1.0
Adult longevity		
Male		5.16 ± 0.40
Female		6.0 ± 0.40
Total period	250–275	260 ± 13.5
Sex ratio	4:1	

Table 8.5 Borer infestation in the plantation near the human settlement area

Locality	Location of the plot						
Mundgod (Gunjavathi)	Ist plot 10 m	2nd plot 35 m	3rd plot 60 m	4th plot 85 m	5th plot 110 m	6th plot 135 m	7th to 25th plot 160–210 m
	66%	50%	40%	16.68%	14.2%	12.5%	0
Yellapur (Tataval)	56%	45%	35%	12.5%	9.2%	7.5%	0

Table 8.6 Infestation in the trees in different rows near the roadside

Rows of trees in the plantations	Percentage of infestation
1st row	89
2nd row	70
3rd row	49
4th row	33
5th row	9

Human activities like lopping of branches for feeding cattle, cutting of branches/ stem for making hutments, and for fuel purposes increase the chances for egg laying by the adult moth. Thus, the plantation near the settlement area was found to be prone to the infestation by the pest.

As in the case of the human settlement area, the rate of infestation in the roadside plantations also showed that infestation decreases as one moves from the roadside plantations toward the interior. The first row of plantation was severely affected with 89% of the trees infested with the borer, while the fifth row showed 9% infestation (Table 8.6). The infestation decreased from outer to inner rows.

In the well-drained areas, infestation is more than in waterlogged areas. Since the pupation is in the soil, the water logging affects their survival and helps in the reduction in emergence of moths. Higher age of trees is a predisposing factor for the pest attack. As seen from the plantation survey, the incidence is found to increase with age (Tables 8.5 and 8.6; Fig. 8.14) (Veeranna & Remadevi, 2007a).

Fig. 8.15 Extraction of larvae from infested tree

Fig. 8.16 Collection of larvae from the live the infested trees

8.2.2.5 Nature of Damage

Observations were taken on the number of holes present on the surface of tree, within first 1 m height and second 1 m height of stem. The trees were cut longitudinally and also sawn at different points of radius to study the intensity and nature of damage (Fig. 8.15).

Study was conducted at 2 heavily infested areas (Tatvala and Gunjavathi) to observe the occurrence pattern of emergence holes on the trunk of borer-infested trees (Fig. 8.16).

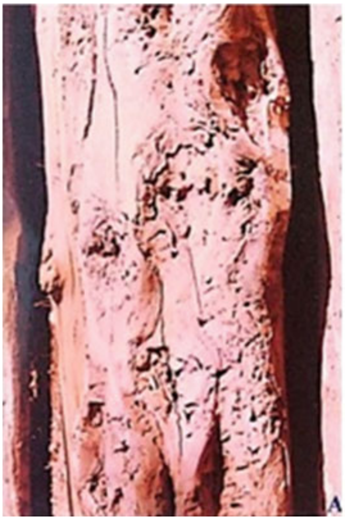


Fig. 8.17 Teak tree affected by “Gandu Maale Roga”

Fig. 8.18 Surface of the tree showing damage done by cadambae (**a**) and close up of the borer holes on the teak tree (**b**)

Since the eggs are laid on the bark of the main stem and branches, the larvae were visible beneath the bark (Fig. 8.17) but without any symptoms of attack. As the larval feeding progresses, symptoms get more pronounced. Larval feeding results in the girdling of the side shoots, leading to die back which is one of the early symptoms of borer attack. The second instar larva scrapes the sapwood for its initial settlement, starts feeding, and gradually moves toward the heartwood (Fig. 8.18a,b). During this period, the larva completes its third and fourth instars, which was confirmed by the presence of head capsules in the tunnel. The larval tunnel measures 7–8 cm in length and 1.0–1.2 cm in width. The inner surface of the tunnel gets a charred look. In general, 6–8 larvae could be seen in 1 m length of log.

Wood particles could be seen accumulated around the tunnel entrance at this stage. Sometimes, these wood particles get lodged in the spider webs present on the bark and also fall down below the tree. In rainy season, the larval tunnel points can be seen as dark, moist patches covered with frass on the surface. The inner tunnels

Fig. 8.19 Teak logs in depots showing complexes of borer holes

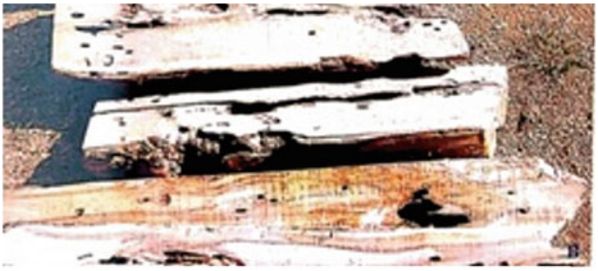


Fig. 8.20 Teak plants showing the borer holes and tunnels

are "C"-shaped, and the larva rests inside. When disturbed, the larva moves briskly within the tunnel and ejects a pink fluid with a pleasant odor. The feeding of larvae leads to the formation of many tunnels within the heartwood.

Extensive larval feeding leads to callus growth and often distorted bark formation. After many years of persistent infestation, entire bark gets removed, with many holes distributed in groups (hole complex). Since the larval feeding aggregation is localized, the emergence holes congregate in localized areas forming a complex of holes. Because of the special look of the holes, local tribal have named this condition as "Gandu male roga" (Fig. 8.19). As the infestation progresses, the number of small complexes increases, reaching a maximum of up to 30. Holes being 20–30, the total number of holes in a tree may be up to 1000. The bark that is lost due to larval feeding never recovers, and as a result, the wood is exposed, which may subsequently get infected by pathogenic/saprophytic fungi leading to decay of wood. The occurrence of borer holes in timber is a serious defect, which adversely affects its commercial value. The larval tunnels are extended radially, reaching as far as the innermost heartwood. Planks sawn from such billets will have numerous tunnels and holes and not cherished for use in building construction, furniture making, etc. (Fig. 8.20).

The observations taken from infested trees showed that the maximum number of holes occurred above 1 m height from ground level. The average number of holes seen within 1 m from the ground level was 19.92, while an average of 33.32 holes could be seen in the next 1 m area in Gunjavathi. In Tatvala, the average number of holes within the 1 m was 17.42 and the next 1 m area was 31.32. Holes seen above 2 m could not be estimated properly.

In the areas where culling operations were going on, observations were taken on trees of different diameter for recording the presence of borer holes at different points across the diameter of the cut tree. The larval tunnels were found distributed up to the center of the heartwood which shows the feeding habit and nature of damage they cause. Similar observations were made by Mathew (1990) in Kerala condition.

8.2.2.6 Seasonal Incidence

The emergence pattern of the moths was studied by trapping the adults in Robinson light trap (Fig. 8.21) in which 200 W bulb was used for illumination. Cotton soaked in benzene kept in the collection chamber served as fumigant for immobilizing the insects trapped. The trap was installed 1 ft above the ground level within a teak plantation at Gunjavathi in the Mundgod range (Yellapur forest division), which was heavily affected by A. *cadambae*. The trap was operated throughout night on alternate days from 7p.m to 6a.m for a period of 3 years (2001 to 2003). The emergence pattern of the moths in the field condition was also studied using the emerged pupal cases as indicators of moth emergence. For this, the pupal cases seen within 1.5 m around the base of the tree were observed.

The seasonal occurrence of the life cycle stages of the borer in the field was studied for 3 years from 2001 to 2003. The moth population was very low in January and February, after which a slight increase could be noted in March and remained more or less steady until April. The population suddenly increased by the end of April following pre-monsoon showers, reaching a peak in May. The population builds up declined after June; from August onward, the population is very less. The moths were not found in the field from November to February. In all the years, the

Fig. 8.21 Robinson light trap setup in a heavily infested teak plantation at Gunjavathi

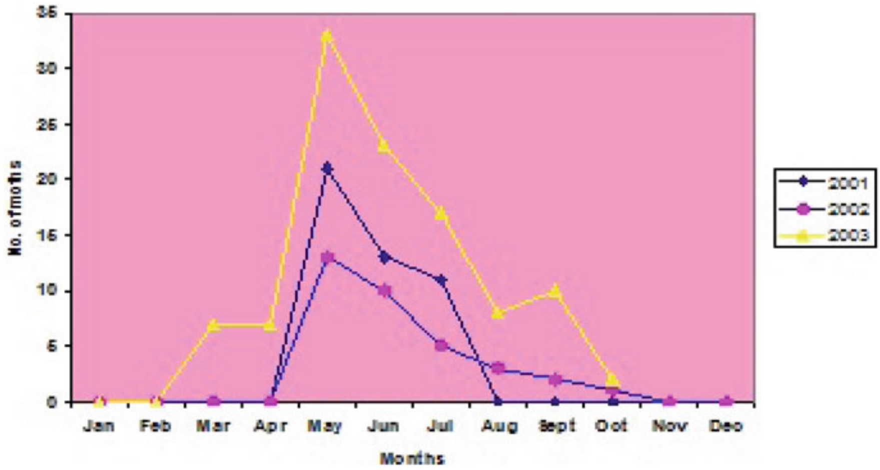


Fig. 8.22 Light trap collection of moths during different months

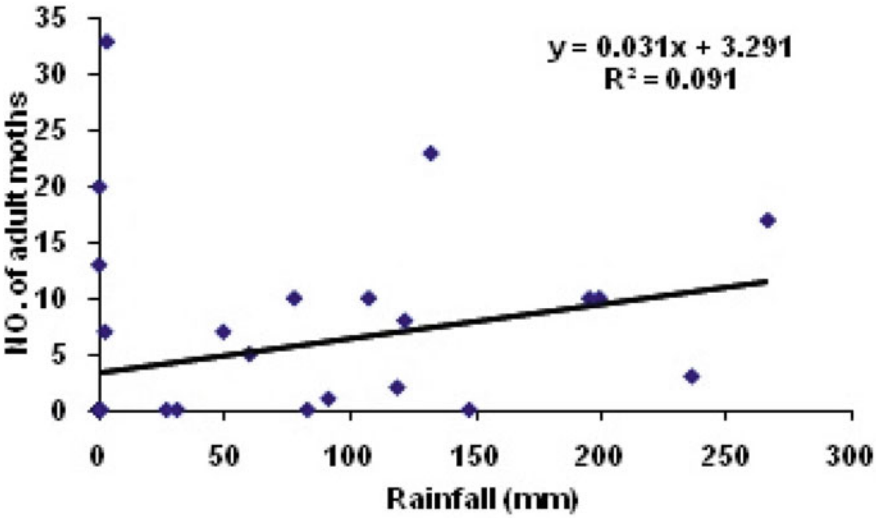


Fig. 8.23 Correlation between moth emergence and rainfall

maximum number of moths was in the month of May (Fig. 8.22). Moths could not be trapped during the months of November, December, and January of all the years.

A positive correlation existed between moth emergence and rainfall intensity (Fig. 8.23). Moth emergence always coincided with rainfall in all the 3 years during the study. During the years 2001 and 2003, there was a severe drought and less rainfall and hence the adult catches were lesser. Though the incidences of different

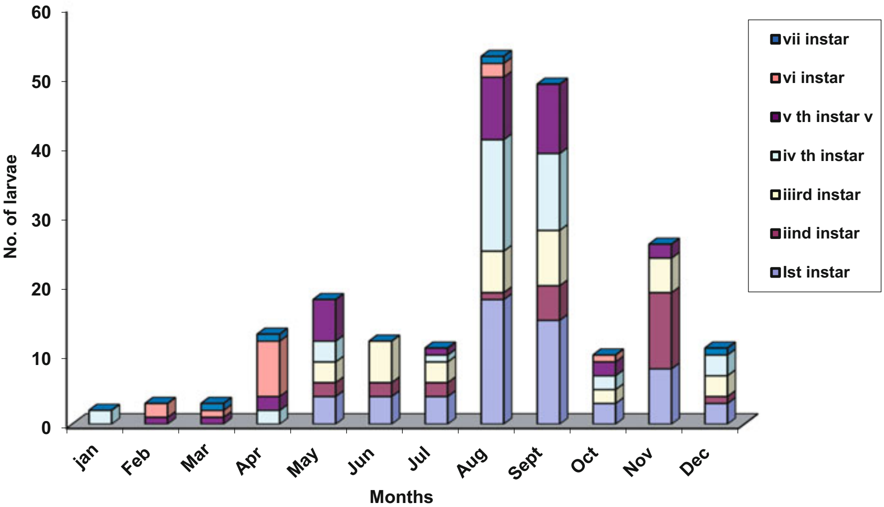


Fig. 8.24 Distribution of larvae of different instars in different months of year

larval stages were observed throughout the year, the pupation and emergence of the moths coincided with the rain.

In heavily infested plantations, due to overlapping generations, various stages of this insect were present throughout the year. Larval activity by the early instars was found to be more during the months of June and July. Larvae collected during the months of January to December for 3 years (2001, 2002, and 2003) were classified into different instars based on the length and width of larva and also width of head capsule. The distribution of larvae of different instars in different months of year is represented in Fig. 8.24. The study indicates that larvae are available throughout the year, and all stages of larvae could be collected in all the months. The total larval period is very long, and also, there is overlapping of generations. Though the incidence of different larval stages was observed throughout the year, the pupation and emergence of the moths coincided with the rains. In Kerala conditions, there are two peaks of adult once in April–May and other peak in September–November (Mathew, 1990).

8.3 Biology

8.3.1 Collections of Insect Stages

8.3.1.1 Egg

Eggs were found in cracks, crevices, debarked areas, lopped branches and girdles on trees. Eggs were also laid in light traps set up in plantations.

8.3.1.2 Larval Stages

The bark of infested trees were peeled and chopped to observe the earlier instars of larvae. Infested teak trees in the plantations were cut horizontally at different planes to collect the different larval instars (Fig. 8.17). To study the seasonal occurrence of larvae, 5 dead poles each were cut every month, for 3 years from 2001 to 2003, in Gunjavathi (Yellapur Division). Larvae were also collected from live trees by chipping out the wood at places where symptoms of infestation were visible (Fig. 8.16).

8.3.1.3 Pupae

To know the pupa population, pupation habit, and pattern of emergence, soil was dug out randomly in and around tree up to one and half meter distance from the tree base. The live pupae and pupa cases were collected and studied. Arrangements were also made to trap the fresh pupae from tree base. After trenching the soil up to 1 ft deep, plastic sheets were spread around the trees; soil was replaced on the sheets. The larval pupation takes place in the soil during rainy season to know the site of pupation and the number of pupae found surrounding the tree.

8.3.1.4 Adult Moths

Adults were collected using Robinson light trap installed in infested area. Moths sitting on the bark of the tree and illuminated walls of the houses were also collected during night time studies of the field biology. The incubation period ranged from 14 to 19 days, and the larva period ranged from 192 to 234 days. In case of male, the pupal period ranged from 1 to 18 days, while in case of females, it ranged from 18 to 20 days. The males have the mean longevity of 5.16 days, while females have the longevity of 6.0 days. The field population has the male–female sex ratio of 4:1 (Table 8.4). It indicates that life cycle of *A. cadambae* is annual (Veeranna & Remadevi, 2011) (Fig. 8.25).

8.4 Management

Management of the teak borer has ever remained an elusive aspect because studies were made to manage the borer damage to teak plantations by applying the integrated management strategies including mechanical, cultural, physical, and biological control in both in laboratory and in field condition. A package of practices including mechanical, chemical, and biological methods was developed and recommended for tackling the borer pest in the field conditions.

8.4.1 Mechanical: Larval, Pupa, and Adult Traps

Mass trapping of the larvae, pupae, and adult of the borer was attempted using mechanical devices. Taking advantage of the fact that larvae come out of the stem and fall to the ground for pupation during the rainy season, larval traps were

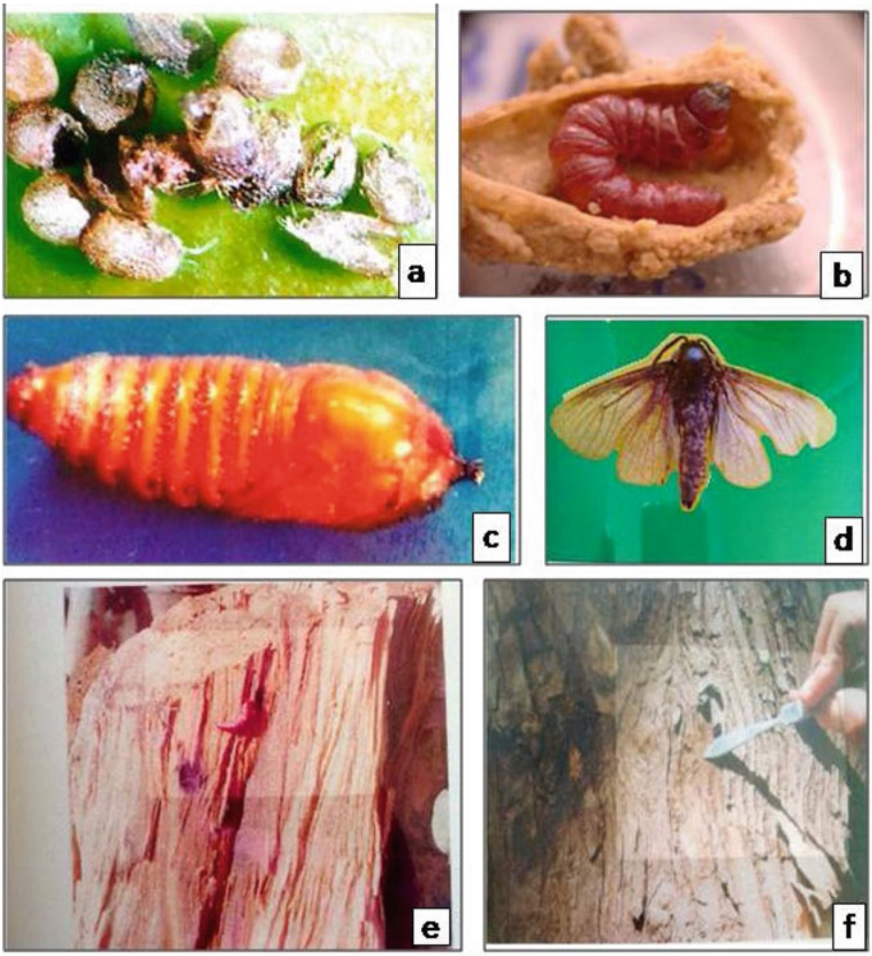


Fig. 8.25 Life cycle of teak heartwood borer *Alcterogystia cadambae* (Moore): (**a**) egg; (**b**) larva; (**c**) pupae; (**d**) adult; (**e**) and (**f**) larva feeding on heartwood of teak

fabricated to collect the falling larva; the traps used were made up of plastic polyethylene sheets and metallic sheets. The larval traps were employed in heavily infested teak trees. Plastic sheets were used to make protected area at the base of the tree where litter was spread to trap (Fig. 8.26a) the larvae falling down for pupation. Tray trap (metallic) made of semicircular sliding trays with rim (15 cm) and adjustable arms were fabricated using galvanized iron or aluminum or tin. They were fastened to the stems of trees of different girths using screws (Fig. 8.26b). Such traps were fitted in trees, which showed the symptoms of live attack. Sheets of sticky traps (marketed by PCI, India) were glued on the traps.

The larval stages were collected from larval traps set up during rainy season. Once the larvae fall on the traps, they got caught in the adhesive and were trapped.

Fig. 8.26 Larval traps: (**a**) plastic and (**b**) metallic

These larvae could be handpicked and killed by putting in hot water, kerosene, or any low-cost insecticide. It was observed that 3 to 5 larvae fell in the traps depending on the intensity of larvae in the tree. The larvae falling on soil were also trapped in plastic sheets spread around the base of the tree; 7 to 8 pupae per tree could be collected during June to September. This shows that periodical raking of soil near the root zone will enable the pupae getting exposed to sun and getting eaten by predators. Similar methods are being followed for most of the agricultural pests like paddy stem borer, white grub, and red hairy caterpillar where summer ploughing is practiced.

8.5 Biological Control

Attempts were made to trap the parasitic insects by setting up sticky traps near the boreholes or by pasting the eggs on the bark and also by periodical larval sampling. Sticky traps were randomly tied near to boreholes in the infested trunk (Fig. 8.27), and the insects trapped on them were collected and identified. Observations were made for other predatory birds in the field (Fig. 8.28). Biocontrol agents like nematodes and *Bacillus thuringiensis* and botanical products were tested against the pest.

During the study period, cocoons of *Apanteles sp.* (Braconidae) could be collected from near the larval feeding areas in the bark, but it is not sure whether they are from *A. cadambae.* No parasite could be collected from the field and in the laboratory rearing. In the field, woodpecker (*Dinopium bengalensis*) was found to peck out larvae by making holes in the infested trees both in Yellapur division and in Haliyal division. The holes can be distinguished from the borer emergence holes. The holes made by woodpecker are rectangular 4×3 cm (L $\times$ B) and seen in a linear fashion on the stem; 8–10 such holes could be located in some of the trees. Natural enemies usually play an important role in regularizing the population of cossids in the field. Attempts were made using sticky traps for collecting the parasites of *A. cadambae,* if any, existing in nature. No parasite could be got in the present

Fig. 8.27 Sticky trap setup for parasites

Fig. 8.28 Series of holes made by wood collecting the pecker for predating larva

study. Similar observation was made by Mathew (1990) from Kerala. Predatory insects including ants are reported from the galleries of cossid borers. Wiwatwitaya and Wiwatwitaya (1996) observed that ant species *Crematogaster spp.* and *Anoplolepis longipes* were predatory on teak bee hole borer, *Xyleutes ceramicus.* Two species of bird predators, golden woodpecker, *Dinopium bengalensis,* and Indian barbet are known to feed on the caterpillars of *A. cadambae* after extracting them from the larval tunnels (Sudheendra Kumar, 1994). Baksha and Islam (1999) observed the woodpeckers (*Dinopium bengalensis and Picoodes canicapilles*) and small black ants feeding on the larvae and pupae of the Z. *conferta.*

8.5.1 Nematodes

Bioassay studies were conducted with the nematode, *Heterorhabditis indica,* to fix the dosage levels and to estimate the time taken for causing mortality to the larval stage of *A. cadambae.* The nematode formulation (as a powder) was supplied by the Project Directorate of Biological Control (PDBC, the presently NBAIR), Bangalore, and also was produced from market. Two concentrations, 600 and 800 ijs/ml (infective juveniles), were tested on the larvae placed on filter papers taken after 48 h and 72 h for recording the mortality of larvae. The success of nematode infection was verified under microscope (Fig. 8.29). The dosage of 800 ijs/ml of the nematode preparation was tested in field in infested teak plantations at Doginal. The nematode suspension was applied by either injection with a disposable syringe or using a rectangular sponge of 10 × 7.5 × 2 cm (L × W × H) (Fig. 8.30a). The sponge was pressed on the trunk portion with live borehole and fixed with cello tape, and the solution was poured onto this and covered with polyethylene sheet to avoid the entry of rainwater (Fig. 8.30b). The Infected larvae were taken treatment after 48 h and 72 h and observed under the microscope in the laboratory to confirm the presence of infective juveniles.

The investigations revealed that lower dosages are good enough to kill the early instars, whereas higher dosages (600–800 ijs) are required for the mortality of later

Fig. 8.29 Larvae killed by infective juveniles of the nematode *H. indica* coming out of dead larva

Fig. 8.30 (**a**) Sponge method of application of nematodes on borer-infested areas; (**b**) Tree injection method for the application of biopesticides

instars. Field studies using stem application technique in Yellapur division have given positive results. The entomopathogenic nematode, *Heterorhabditis indica,* when applied at a dose of 800 ijs caused 100% larval mortality of various larval stages of *A. cadambae* in 72 h. Using injection method or sponge method, the nematode solution could reach the borer affected area in the infested teak tree, resulting in larval mortality. This method appears useful for the biocontrol of the pest in field conditions, and the nematodes were able to locate and invade the larvae inside the wood, and it indicated the feasibility of application of nematodes for teak borer control in the field conditions. It would be useful to also verify whether the larvae of *A. cadambae,* which tend to drop to the soil for pupation, can be killed by the nematodes applied to soil, so to offer a supplementary option for biocontrol of the pest. Many workers have established use of nematodes for cossid control. Entomophilic nematodes, *Steinernema feltiae* and *S. bibionis,* were tested for controlling *Prinoxystus robiniae* by gallery injection and surface treatment (Forschler & Nordin, 1988). Qin et al. (1988) recommended the use of entomopathogenic nematode, *S. feltiae,* for the control of the cossid, *H. insularis,* and mortality of the worm was 99.84%. The efficacy of the entomophilic nematodes, *S. carpocapsae, H. heliothis,* and *H. bacteriophora* against the cossid, *Zeuzera pyrina,*

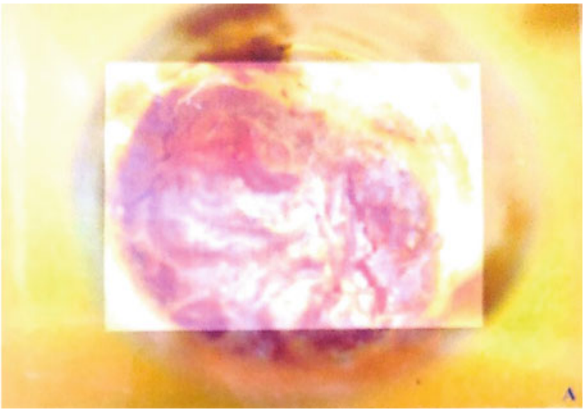


Fig. 8.31 Larva dead in the in vitro testing for the pesticidal efficacy of *Bacillus thuringiensis*

was tested and the rates of mortality were positively correlated with the concentration of the nematode suspension (Abdel-Kawy et al., 1992).

8.5.2 Bacillus Thuringiensis

Biopesticide containing *B. thuringiensis* (var. k*urstaki*) was mixed to the diet of the larvae to test the pesticidal effect. Required quantity of the different concentrations (0.5 g, 1 g, 2 g 250 ml diet) of the biopesticide was mixed in the diet. This mixture was left undisturbed for 1 day to allow the settlement of the biopesticide. The diet was then placed in petri dishes, and larvae were released. Observations were taken at 24, 48, and 72 h after application. *B. thuringiensis* was tested in the field at Doginal of Yellapur divisions. Two concentrations of the biopesticide (2 g/l and 3 g/l) and water as control were used for the study. Selections of trees were similar to those used for nematode applications. Solutions were injected into larval galleries using syringe or portable sprayer. Observations on the mortality of the larvae were taken after 48 h and 72 h (Fig. 8.31).

The effectiveness of *B. thuringiensis* (var. *kurstaki*) as a pathogen was tested in the laboratory. In treatments, at the concentration 0.5 g/250 ml diet, there was no mortality of larvae. In case of treatment at concentration of 2 g/250 ml diet, the larval mortality was 50% at 24 hrs and 100% at 48 hrs. In case of treatment at concentration of 3 g/250 ml liter diet, the mortality of larvae was 100%. The color of larvae turned brick red initially and turns dark. In case of field application of *B. thuringiensis,* two concentrations, 2 g/l and 3 g/l of water, were applied on larval galleries by either injection or spraying. Among two concentrations, 3 g/l gave 100% mortality at 24 h and 2 g/l treatment gave 50% mortality at 24 h and 100% mortality at 48 h.

B. thuringiensis is one of the available broad spectrum yet selective and safe bacteria being harmless to plants and vertebrates. Its preparations are available as wettable powders, dusts, and water-dispersible emulsions. *B.t* is being used for control of important insect pests of agriculture and forestry in many countries.

Several commercial preparations of *B.t.* have been tested against agricultural and forest insect pests like various species of genus *Helicoverpa, Spodoptera, Plutella, Earias, Diacrisia, Agrotis,* and *Amsacta* (Joshi et al., 2000). The endotoxins or protoxins are activated by midgut proteases and the activated toxins interact with larval midgut epithelium causing a disruption in membrane and ultimately leading to insect death. Among the varietal toxins, *var dendrobiums* endotoxins and *var. thuringiensis* and its exotoxins proved to be highly effective and appeared to be the best in killing larvae of *Atteva fabriciella* (Joshi et al., 1996) and *Eutectona machaeralis,* respectively (Roychoudhury et al., 1994).

8.5.3 Botanical Pesticide

Water-soluble neem-based pesticide SoluNeem (6% azadirachtin) was tested as a systemic insecticide in the laboratory at 6 concentrations (0.0125 g/250 ml, 0.05 g/ 250 ml, 0.10 g 0.15, 0.20, 0.5 g/250 ml diet). Five replications of the above concentrations were prepared. Two concentrations of the biopesticide (1 g/land 2 g/l) and water as control were used for the field study at Doginal, Yellapur. Solutions were injected into larval galleries using syringe or portable sprayer. Observation on mortality of the larvae was taken after 48 h and 72 h (Fig. 8.32).

Observations were taken at 24 and 48 h of interval for the effect of treatments. In all the treatments except 0.5gm/250 ml, there was no mortality of larvae. The larvae fed on diet treated with 0.5 g/250 ml were dead (100%) after 48 h. The concentrations, 1 g/l and 2 g/l of water, were applied by injection/spray method on larvae in bore by tunnels in tree. Water application on larval galleries served as controls. Both the concentrations gave 100% mortality after 24 h of application.

Botanical insecticides could be of great use along with other options in future to minimize the use of chemicals. Integrated pest management system (IPM) advocates that every available option is to be involved in a planned manner to minimize the use of chemicals. Neem products containing azadirachtin act as antifeedant, growth

Fig. 8.32 Larva dead in the inviter testing for the pesticidal efficacy of SoluNeem

inhibitor, sterility agent, etc. In the present study, neem product 0.5 g/250 ml diet in laboratory and 1 g/l water solution in field condition gave 100% mortality within 48 h. The effect of neem extracts has been tested on some of the forest pests like teak skeletonizer, *Paliga machoeralis* (Meshram et al., 1994). Neem products have not been tested against any tree borers.

8.5.4 Fumigation of Infested Tunnels by Phosphine

Aluminum phosphide tablets were crushed to make small pieces and inserted through the holes of the infested trees. The holes were mud-plastered so that the phosphine gas does not escape out. To ascertain the effect on larvae, live larvae extracted from infested trees were introduced into the holes of trees before inserting the tablets and plastered with mud or clay. The mud casts were removed after 3 days to locate the larvae. It was observed that the aluminum phosphide tablets were found to have liberated the gas and became ash-type powder and the larval galleries of fresh infestation were not fully visible outside; even if frass was removed, inserting tablets was difficult. But the already open holes were wider and usable for this treatment. The closing of holes and moisture in the holes are the requirements for effective killing of larvae. The effect of phosphine on tree is also to be investigated, though it appeared to have no effect. Gallery injections of carbon disulfide, Serafume (mixture of carbon tetrachloride, carbon disulfide, ethylene dichlorobenzene), were found to provide control of the cossid, *P. robiniae* (Solomon, 1985).

Recommended Package of Practices for the Management of Teak Heartwood Borer

- Any mechanical damage to the trees by way of lopping of branches, wounding the trees, etc., should be avoided.
- Severely infected trees may be uprooted and removed to avoid the spread of the pest to healthy trees.
- The boreholes in trees should be plugged with sterilized mud/lime paste/wax so that the microbial invasion into the wood is prevented. The decay fungi and termite attack lead to hollowing of the inner wood of the infested tree.
- Mixed plantations shall be helpful to restrict the spread of pest from tree to tree/the trees known as alternate hosts of the mixed plantations of teak.
- Alternate host trees may also be checked for the presence of borer infestation.
- Making bunds around the individual trees to retain rainwater shall help in killing the larvae falling of soil around the base of the trees during summer months shall expose and kill the pupae.
- Conservation of predacious birds shall help in reduction in larval population.
- Setting of light traps throughout the year shall help in monitoring the adult population and also catching and killing the adults.
- Mechanical traps can be used in severely infested plantations to catch the larvae falling out of trees.

- Biopesticide (*Bacillus thuringiensis* and neem products) application can be practiced in intensely managed plantations for spot killing of larvae.
- Nematodes can be used by gallery injection, by sponge method, or by introducing nematode-infested insect larvae into the trunk holes.
- Aluminum phosphide tablets can be introduced into the holes and holes can be plugged for percolation of phosphine gas inside the holes.
- Routine inspection and detecting the infestation on trees are very important to decide on the treatment and also follow practices to check the build-up of pests in the field.
- Field staff should be imported the knowledge on the pest, its habits, and symptoms of infestation.

Acknowledgements The authors would like to acknowledge the encouragement and support extended by the Director General (ICFRE) and the authorities of Karnataka Forest Department in carrying out this investigation. Thanks are also due to the staff of wood biodegradation division and field staff of Karnataka Forest Department for assistance in fieldworks. Dr. Javare Gowda is also thankful to the authorities of Forestry College, Sirsi, in supporting the collaborative study.

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Hoplocerambyx spinicornis Newman: Major Heartwood Borer of *Sal*, *Shorea robusta* and Its Management in India

9

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_9

Abstract

Sal (*Shorea robusta*), the most important semi-evergreen natural forest timber tree species having dominant distribution in India, harbors almost around 350 insect pests, infesting at various stages of the tree growth. However, the *sal* heartwood borer, *Hoplocerambyx spinicornis,* is the most devastating insect pest and has been the primary cause of large-scale mortality. Interestingly, this tree trunk borer species has reoccurring history almost periodically. The enormity of the devastation caused in every outbreaks and epidemics has brought this insect pest into the forefront of the attraction as far as forest insect pests are concerned. This is more as a challenge to find out the suitable management alternatives, mainly due to the complex life cycle of this cerambycidae longhorn beetle. It is only because of the above that the species has been reviewed comprehensively. The present review discusses our current status of information on various aspects like biology, nature of damage, host selection, symptom-based categorization and tree mortality, history of population outbreaks, possible factors affecting the outbreaks, economic losses, and the most important one, i.e., available management options. While the available information from various outbreak areas has been discussed, it also includes information and relevant data related to the recent outbreaks in the central India.

Keywords

Alaus sordidus · biology · Cerambycidae · coleopteran · epidemics · forest insect pests · heartwood borer · insect outbreaks · integrated pest management · plant kairomone · *Sal* borer

9.1 Introduction

9.1.1 *Sal* (*Shorea robusta*)

Sal (*Shorea robusta*) (family Dipterocarpaceae) is a gregarious tree. It is native to Indian subcontinent and attains height of about 30 m, at altitudes from 10 m to over 1500 m and rainfall from 1000 to 3000 mm. The species is capable of tolerating temperatures as high as 45^0 C and as low as 0 °C. In its naturalized areas, it is an economically and ecologically important tree species (Tewari, 1995). While it is a source of valuable timber, seeds are used industrially in soap industries (Anon, 1972;

Gautam et al., 1975; Sharma & Jain, 1981a, b; Swalesh et al., 1975). The semi-evergreen natural forest cover of the species across ten million hectares with the individual volume of 476.94 m cum and 10.87% of the total growing forest stock in the country makes it a species of ecological significance (ISFR, 2021). The distribution is primarily controlled by climatic and edaphic factors with the natural range lying between 20° and 32° N latitude and 75° and 90° E longitude, extending into the subtropical zone. There are three other species of the genus *Shorea*; *S. assamica, S. talura,* and *S. tumbuggaia* (Anon, 1972; Troup, 1921) known in India. However, *S. robusta* is the only species having dominant distribution on the plain and lower foothill of the Himalayas and also along the valleys.

Sal forests have a very wide distribution in the country from Uttarakhand in the north up to Andhra Pradesh in the south and Tripura in the east (Champion & Seth, 1968). It covers Himachal Pradesh, Haryana, Uttar Pradesh, Bihar, West Bengal, Odisha, Madhya Pradesh, Chhattisgarh, Maharashtra, Jharkhand, Sikkim, Assam, and Meghalaya. In the central Indian belt, *sal* tract begins on the Ganges near Rajmahal and passes through the Santhal, Parganas, Chhota Nagpur in Jharkhand, Rewa in Madhya Pradesh, and most part of Chhattisgarh, Orissa (Fig. 9.1a, b, c).

9.1.2 Insect Pests of *Sal*

Sal hosts nearly 346 insect pest species, which is the highest number of insect pests reported on any other tree species (Thakur, 2000). These insect pests cause damage at various stages of tree growth, like 155 are reported to attack standing trees (114 defoliators, 19 seed feeders, 18 borers, and 4 sapsuckers) and rest are miscellaneous species on felled, dry, or rotten wood (Choubey et al., 2004, 2008; Kulkarni et al., 2018; Sambaraju et al., 2016). The recent report includes incidence of *sal* defoliator *Paectes subapicalis* in central India (Roychoudhury et al., 2007). While most are occasional insect pests and never lead to tree mortality, *Hoplocerambyx spinicornis* Newman, among them is the most devastating pest and has been the primary cause of large-scale mortality. This tree trunk borer insect causes multiple tunnels in standing tree trunks, disrupting the nutritional channels bringing about the mortality (Fig. 9.2 a, b, c, d). Proceeding sections are devoted to detailed discussion on available information and current status of research on *H. spinicornis*. The insect species will be referred to as *sal* heartwood borer or *sal* borer in the proceeding sections for discussion.

9.2 *Sal* Borer: Taxonomic Details, Distribution, and Geographical Variation

The full-grown *sal* borer grubs and their tunnels were seen in railway sleepers made out of *sal* trees from Singhbhum District in erstwhile Bihar State in 1897 (Stebbing, 1899). However, the identification as *Hoplocerambyx spinicornis* from the British Museum was completed in 1906 by Stebbing (1906, 1907). Later, recurring

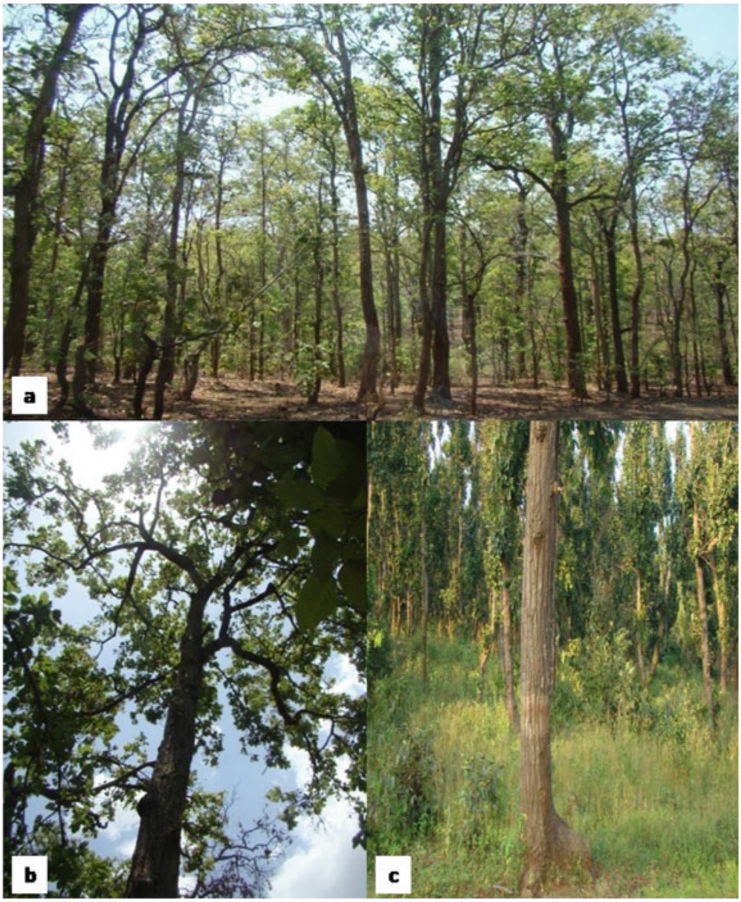

Fig. 9.1 (**a**) View of *sal* forests; (**b**) a single *sal* tree; (**c**) healthy tree trunk

periodical epidemics and incurring huge economic losses due to the devastation caused by this pest in *sal* forests in many parts of the country attracted many workers like Beeson (1919, 1921, 1924, 1927, 1928, 1934, 1941), Atkinson (1927), Benskin (1927), and Sabharwal and Garland (1938). These countable numbers of rarely available reports include important field tour notes of pre-independence period, published by Government of India as Indian Forest Records and Forest Bulletins, and thus, they are being discussed here along with recent observations as bibliographic records for readers of the future generations.

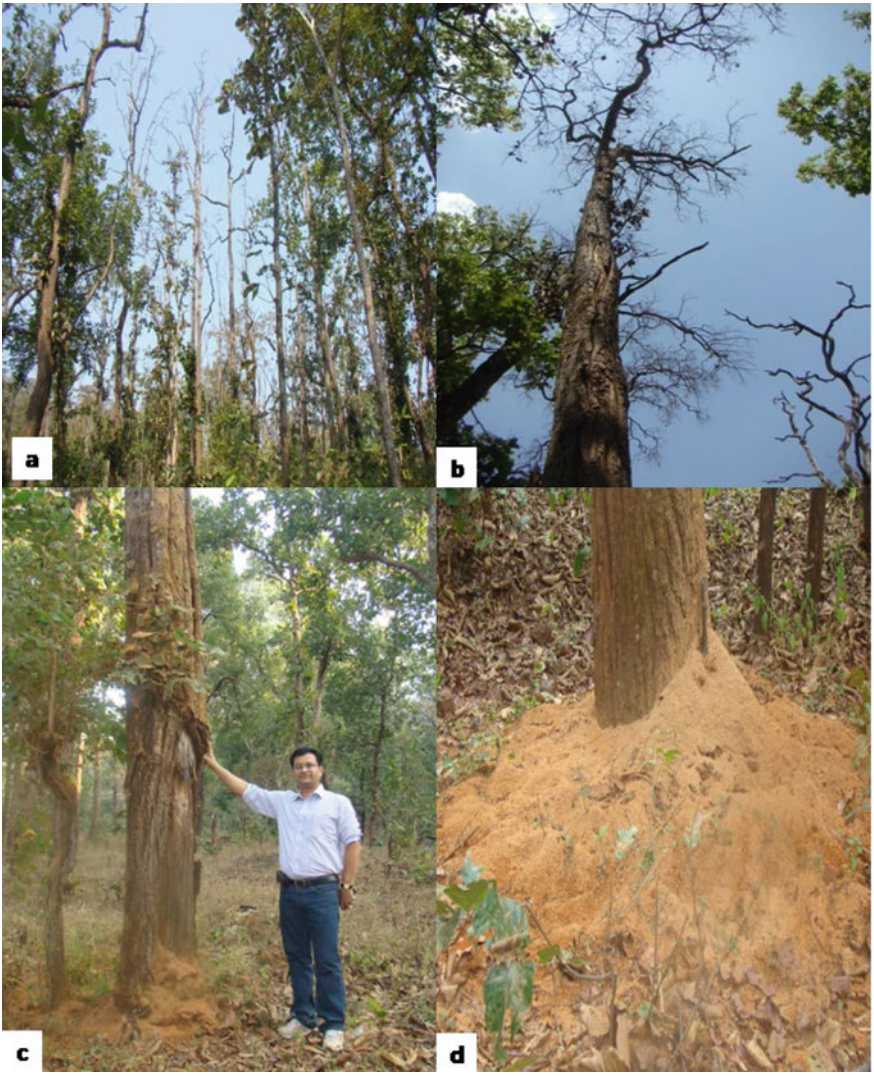

Fig. 9.2 (**a**) View of *sal* borer-affected forest; (**b**) affected *sal* tree; (**c**) tree with some wood dust at root zone; (**d**) close-up of the large amount of wood dust

9.2.1 Taxonomic Details

The taxonomy and distribution of *sal* borer have been studied by Gahan (1906), Aurivillius (1912), and Schwarzer (1930), and taxonomic position is summarized below (Roonwal, 1978):

1842. *Hoplocerambyx spinicornis* Newmen, Entomologist, London No. 15245 pp.

1857. Cerambyx morosus Pascoe, Trans. Ent. Soc. Land., 2 (4) 92 pp.

1866. *Hoplocerambyx relictus* Pascoe, Proc. Zool. Sac Land., 1866 528 pp.

1869. *Hoplocerambyx morosus* (Pas.) Pascoe, Trans, ent. Soc Land., 3(3) 515 pp.

1906. *Hoplocerambyx spinicornis* (Newm.) Gahan, Fauna Brit. India, Coleopt. I. Cerambycidae. London, 131–132 pp.

9.2.2 Distribution and Geographical Variation

The insect species is widely distributed in Asia—Burma, Bhutan, India, Indo-China, Indonesia, Malaysia, Nepal, Papua New Guinea, Pakistan, Philippines, Singapore, and Thailand (Appanah & Turnbull, 1998). It has been reported as pest on *Parashorea robusta, P. malaanonan, P. stellata, Shorea siamensis, S. assamica, S. obtusa, S. robusta, Anisoptera glabra,* and *Hopea odorata* (Appanah & Turnbull, 1998).

The morphological details, such as the size of body parts, length and width of head and elytra, and their ratios, were studied by Kumar et al. (1975). For this, examples from several regions in India were studied to investigate the existence of any geographical variation. While the insect does not show any marked geographical variation to justify separation into subspecies, however, Madhya Pradesh examples are generally larger than those from other regions (Roonwal, 1978).

9.3 Biology of *Sal* Borer

9.3.1 Life Stages

Stebbing (1906) was the first to study ecological field observations on oviposition, followed further by Atkinson (1927) and Beeson (1941). The morphological description of the immature stages of *sal* borer was described and discussed by Gardner (1925) Muir (1929) and Roonwal (1978).

9.3.2 Eggs

The egg is whitish or cream-colored to pale red, opaque, elongate, and subcylindrical in shape (length 3.2 mm, width 1.2 mm) with the two ends rounded: One end is slightly larger than the other end has a slight protuberance. The egg shell is white and of papery-like consistency, and the surface is shiny and is covered with a fine hexagonal reticulation, and minute spines as in some cerambycids are absent (Stebbing, 1907). Female lays eggs singly, placing it by means of the ovipositor as deeply as possible in cracks, holes, and preferably on shady (underside of fallen tree or shady side of standing tree), moist, and sappy areas of bark. However, females are capable of correcting errors by moving the eggs to a suitable place, by using palpi (Atkinson, 1927). Stebbing (1907) observed 150 eggs on a 15 ft strip of bark of a

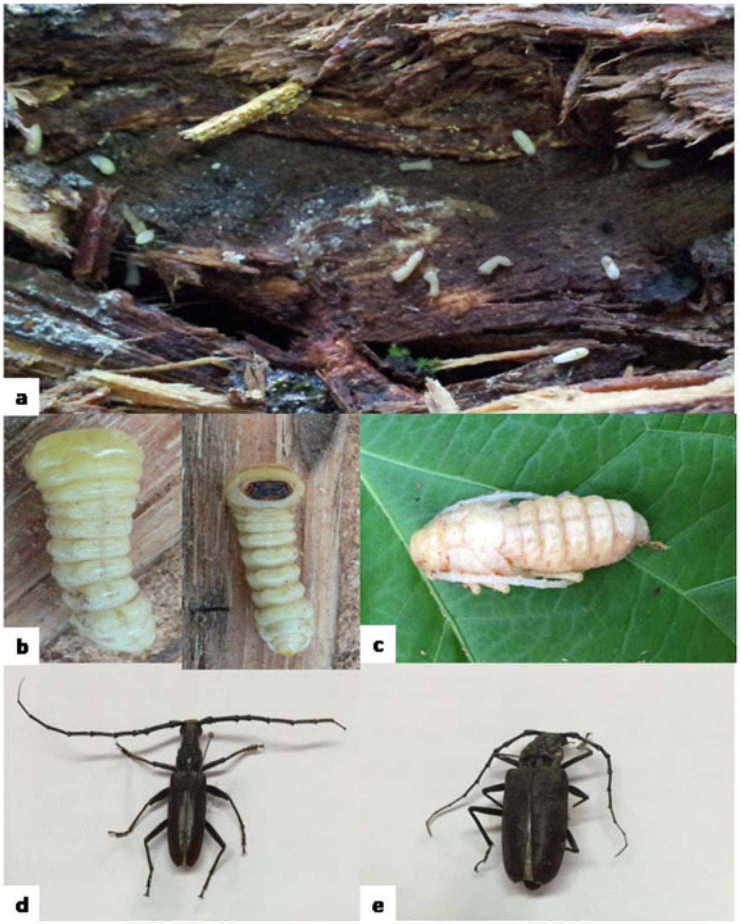

Fig. 9.3 (**a**) Eggs laid on undersurface of the bark and the young larvae; (**b**) larva (dorsal and ventral view); (**c**) pupa; (**d**) male adult; (**e**) female adult

fallen tree during three nights and around 6000 eggs on a 55 ft bole. Beeson (1941) had reported a maximum record of 468 eggs by a single female during a 30-day period. Eggs are laid underlying surfaces of bark. The number of eggs laid in 1 day varies widely, and maximum recorded is 183 (Beeson, 1941) (Fig. 9.3a, b, c, d, e).

9.3.3 Larvae

A 2-day-old first-stage larva is fleshy white; it is about 4 mm long and 1.2 mm wide at the prothorax. The mature larva is long, stout, fleshy, and white. Like the beetles, it varies greatly in size, depending probably upon the varying amounts of woody nutrition available. The length is generally about 33–61 mm, but a well-fed larva may reach a length of about 90 mm and a width of 18 mm at the prothorax (Roonwal, 1978). In heavy epidemic year in Madhya Pradesh, Muir (1929) recorded exceptionally large larvae of about 127 mm in length. Just before pupation, the larval body becomes shorter and stouter.

A mature larva is elongate, tubercular, with a squarish section, consisting of head and body segments. Head is black, transverse, with powerful mandibles. The segment following the head (the prothorax) is greatly enlarged and dark yellow in color with a dorsal shining plate of thicker consistency than the rest of the body; the following two prothoracic segments are narrow and yellow in color along with the next nine segments of the body. There are two prominent elevations or tubercles placed transversely on the dorsal surface of segments 4 to 10 inclusive. The 12th segment tapers to a blunt point behind. There are a pair of minute legs on each of the thoracic (first to 3rd) segments and a pair of short sucker feet on each of the segments 4–10 (more prominent on seventh to tenth segments). Length of full-grown larva is 8.89 cm, but may vary (Stebbing, 1906) (Fig. 9.3a, b).

9.3.4 Pupae

The pupa is yellowish-white, about 30–60 mm long, and of the E*xarate adecticous* (with immovable mandibles) type. Head is pressed down upon the upper part of the chest upon which, below it, are folded legs and the rudimentary wings, the latter being curved round so as to lie in this position. Seven abdominal segments are visible on the dorsal surface. The antennae are curved backward and lie pressed against the sides of the insect. Length is variable and may be 5 cm. It shows sexual dimorphism (Gardner, 1925) as antennae are longer than the body in males and shorter in females; posterior to abdominal sternite 8, there is a transverse rectangular lobe in males and 8 pairs of contiguous rounded lobes in females (Roonwal, 1977, 1978; Stebbing, 1906) (Fig. 9.3c).

9.3.5 Prepupal and Pupal Chambers, Fibrous Plug, and Operculum

Larva, immediately after emergence, tries to enter the tree trunk. All the larvae are unable to enter because of the defensive secretion in the form of resin from the trunk. After successfully entering the tree trunk, it bores tissues and moves toward heartwood by constantly feeding on them, during which it also grows. The mature larva excavates a roomy, vertical prepupal chamber in the heartwood. It also bores a horizontal exatunnel opening to the outside by means of an exit hole leading from the prepupal chamber. After excavating the exatunnel and hole, the larva retires to the prepupal chamber. Before retiring in the prepupal chamber, it throws out all the frass and wood dust from the exit tunnel and blocks the tunnel with a plug of long wood fibers. The refuse matter ejected by the larva from the exit hole accumulates at the base of trees. This refuse material is composed of irregularly shaped wood particles, mostly 1–2 mm long, or shorter and about as long; they are mixed with a few larger fibers 6–12 mm × 1–1.5 mm. In addition, there is frass, which is composed of small, subcylindrical particles, 1 × 2 mm, of dark red pellets of larval excreta.

The larva regurgitates a calcareous substance from the mouth, which is said to be produced by two or six malpighian tubules, one on either side (Beeson, 1919). This substance is molded by the larva into a helmet-shaped cap or operculum, which blocks the mouth of the prepupal chamber. The larva then becomes quiescent and is called a prepupa, and its chamber is called prepupal chamber, which on pupation becomes the "pupal chamber." The fibrous plug fills the entire exit tunnel and consists of a large number of long, loosely packed, reddish-brown wood fibers, which are excavated from the heartwood. A plug from a single tunnel may generally contain about 115–357 fibers, with a total dry weight of 0.25–1.0 gm; an exceptionally large plug may contain as many as 1352 fibers and weight 2.8 gm. The calcareous operculum is a whitish structure-shaped like a Roman helmet and consists of two parts—a hollow cap or body and a solid rest or ridge (Beeson, 1919, 1941; Roonwal, 1978). The base, which fits the pupal chamber, is oval in outline and has a slightly thickened rim. The crest varies in size, attaining a height of about 3 mm and a thickness of 0.8 mm. The operculum is largely pure white, but the upper edge of the crest and the lower one-third of the inside of the cap are dirty brown. The outer surface is rugose, with fine transverse ridges or fine granulations; the inner one is more or less smooth. The operculum varies considerably in size (basal length 12.5–22.0 mm; total height 6.0–14.5 mm), so also in dry weight (0.086–0.501 gm mean 0.293 gm). It is composed of calcium carbonate 91.0 parts, alkali salts 4.3 and organic matter, etc.

9.3.6 Adults (Beetles)

Sal borer on an average is 3–9 cm long (size greatly varies), black, dark brown, blackish to reddish-brown or chestnut-maroon in color, and scarcely shining, with long antennae; mandibles are stout, black; antennae are black, shining, except the last 4 joints, which are dull and yellowish-brown; and eyes are kidney-shaped, placed behind and around the antennae. Thorax is rather longer than broad constricted in front, where there is a collar consisting of two transverse ridges with a channel between them. This collar is repeated on the basal margin, but is not so well defined and lines are wavy. The thorax is covered with a series of wavy, transverse, prominent ridges, which are interrupted in the center by a small longitudinal shining black area with two smaller ones placed on either side and below it. Elytra are elongated, broader at base than thorax, with well-marked shoulders with a depression just behind them. Surface is smooth with slight scattered depressions and faint longitudinal costa. Apex terminates in two spines, a sutural and median one. Elytra are slightly paler in color toward extremity, under surface and legs shining black. There is enormous size variation in adults, larvae, and pupae. Longevity of beetles is 3 or 4 weeks from emergence. The longest life span of the male beetle lasts for 38 days and that of the female about 49 days. Almost similar observations were recorded during the epidemics of 1997–1997 to 2000–2001 and 2012–2013 to 2015–2016 in Madhya Pradesh and Chhattisgarh (Fig. 9.3d, e).

9.3.7 Sexual Dimorphism

The overall body size of the insect varies a lot (Sen-Sarma et al., 1974; Stebbing, 1914), and exhibits weak sexual dimorphism in body size, in the populations of the same region, and the length in proportion of the body length is the identification character for sexes. Males have antennae longer than the body by one fifth to one third of their length according to the size of the beetle (relative to body length, the male antennae is shorter in small specimens and longer in the larger and more fully developed example) (Gahan, 1906); faintly pubescent; first segment sparsely and strongly punctured; and third to sixth or seventh segments more or less roughened at the edges, and flattened or slightly canaliculated above. The females have antennae shorter than the body, more pubescent than in males; first segment sparsely punctured; and third and succeeding segments somewhat flattened above, but not roughened at the edge. Thus, *sal* borers exhibit weak sexual dimorphism in body size (Sen-Sarma et al., 1974; Stebbing, 1914). According to the report by Gardner (1925), measurements of males from the base of the labrum to the most posterior tip of elytra were 33.20 mm, whereas females measured 33.59 mm. Male antennae are longer (mean length, males 43.67 mm; females 32.37 mm). Pupae also displays sexual dimorphism, where antennae are longer than the body in males and shorter in females, and posterior to abdominal sternite is a transverse rectangular lobe in males and a pair of contiguous rounded lobes in females (Fig. 9.3d, e).

9.3.7.1 Sex Ratio

Earlier studies in the south Mandla Division, Madhya Pradesh, had recorded nearly equal ratios in July, but in August males greatly preponderated (1F: 5 M) (Muir, 1929). Sex ratios studied on 232,000 freshly emerged beetles trapped during a 3-year epidemic period exhibited a ratio of 35 M: 65F with almost similar trend in case of the monthly male: female ratio (June ratios, 32:68; July, 35–65; August, 40:60) (Sarma, 1952). Female preponderance was also reported by Roonwal (1952, 1977) during an epidemic in the Nahan Forest in Himachal Pradesh, observed in the case of 289 beetles with the ratio as 38M: 62F (Joshi et al., 2002). However, as against the above, the field data recorded during the epidemics during the years 1998–2001 in Karanjia forest range in Madhya Pradesh and 2012–2016 in Chilphi forest range in Chhattisgarh revealed that male: female ratios of emerged beetles were on an average 70:30 in the month of June after the emergence begins, but with the time it is almost 50:50 in July and onward. A detailed research observation is already being brought out separately (Kulkarni: personal observation). This is pertinent to note that these sex ratio data are based on trap tree records, as there is no other standard method available.

9.3.8 Seasonal Life Cycle

Complete life cycle of *sal* borer as discussed by Beeson (1941), and later re-investigated (Joshi et al., 2006), can be summarized point-wise as below:

1. The life cycle has four stages: egg (3–7 days in June–July), larva (July to April), pupa (April to May), and adult (June–July), which is completed in a complete year.
2. The first heavy shower of the monsoon triggers the beetle emergence and continues further for a few weeks.
3. Beetles begin laying eggs in cracks as deep as possible on the trunk and branches of standing trees on *sal* trees each year, soon after the emergence within 7–9 days after mating and successful fertilization. During this life period, a single female may lay 100–400 eggs.
4. Around 80–90% of the eggs hatch within 3–7 days of the laying, and 80 to 90% of eggs hatch into larvae. The young larvae immediately start boring and entering into the wood and slowly move inward and upward through the bast and sapwood to the heartwood, which is their final destination.
5. They feed, molt, and gradually increase in size, maturing by midwinter. At this stage, they return to the periphery where they excavate a tunnel and prepupal chamber horizontally to the sapwood and an exit hole; the letter is blocked by wood fibers and an operculum. The larva rests here for several months as a "prepupa." The heaps of wood dust, which accumulates at the base of trees, indicate the progress of boring by the larvae. Before pupation, the larva bores a running tunnel and makes a pupal chamber where it pupates.
6. After almost a month of pupal period starting from Summer (April), they convert to immature beetles (pharate adults), which are ready to emerge a few weeks later in the early monsoon. Some grubs may pupate in February, March, or even in the month of April. Depending upon the onset of monsoon, life history is advanced by about a month in the eastern region. Due to early monsoon, emergence of Sal borer in eastern region from May to July and June to September for western region was recorded (Roonwal, 1982).

9.3.9 Reproductive Behavior

Beetles prefer the warmest part of the day and daylight time, around 1–5 or 6 pm for the maximum activity. However, they avoid direct sunshine by sheltering in shady places, but readily take longer flights when the sky is overcast and if a drizzle or moderately heavy rain is falling. Normally, in the jungle the flight is low and slow and frequently interrupted by halts on trees or bushes accidentally encountered. For matting, hind legs of the female are grasped by the middle pair of legs of the male. The male, with exerted aedeagus, is carried about by the female until she halts and voluntarily accepts coitus. The actual pairing lasts only a few seconds and both organs are then retracted, but the male remains mounted. Sexes of very unequal size may pair successfully. Pairing is frequently repeated and during the period a female lays eggs, usually alternating with the deposition of a few eggs (Beeson, 1941; Kulkarni: unpublished observations).

9.4 Nature of Damage, Host Selection, Symptom-Based Categorization, and Tree Mortality

9.4.1 Nature of Damage and Symptoms

As discussed in the preceding sections, young grubs, in the course of boring and moving toward heartwood, tunnel the trunk almost perpendicular to the trunk up to heartwood and then horizontal for pupal chamber. At this stage, an affected tree can be identified from the outside by the presence of wood dust around the tree. The amount of wood dust, less or more, together with the extent of drying of tree crown, indicates intensity and stage of *sal* borer attack. It is at this stage an infested tree is identified and marked. It is through the above external symptoms, three are categorized for the convenience of silvicultural management and maintenance of forest hygiene. This has been discussed in proceeding sections in detail.

9.4.2 Host Selection and Related Factors

The visual selection of new oviposition hosts has already been denied due to inability of the insect eye to focus and register definite shape except for light intensity and movements (Atkinson, 1927). Instinctively, a female searches for another *sal* tree suitable for her egg laying through chemotropic attraction (kairomonal response) (Kulkarni et al., 2004) of invariably newly felled, fallen, or green sickly standing trees in the forest with least resistance (Stebbing, 1907) even from 2 km distance against the wind direction (Singh & Misra, 1981). This is followed by search for other sex for mating (Atkinson, 1927; Joshi et al., 2006), after the female settles on the newly selected host as oviposition site. The laboratory observations carried out in the Forest Entomology Division, Tropical Forest Research Institute, Jabalpur (India), also confirmed the sequence of events from settling to mating, for which no data to substantiate the assumption were available earlier (Kulkarni: unpublished).

The exact behavioral mechanism involved in the above, known as kairomonal property of host plants, was talked about and could also be experimentally confirmed later (Kulkarni, 2014; Kulkarni et al., 2004, 2018; Sambaraju et al., 2016). Kulkarni et al. (2004) experimentally ascertained kairomonal activity with extracted *sal* sap fractions and bioassays with beetles. The number of chemicals and their combination responsible for the activity has now been identified during the recent epidemic in Chhattisgarh and their individual activity being confirmed at Tropical Forest Research Institute, Jabalpur (Kulkarni: Unpublished data). However, the practical application of this kairomonal property may not be directly feasible immediately, due to a very short window available for the related bioassay experiments, when live beetles (adults) are available for bioassays and that during endemic period population is not easily available for continuation of the experiments.

The preference of host girth by the Sal borer while selecting a healthy host with good girth for augmenting the next generation has earlier been discussed by a few workers. History of attacks since 1916 indicated that during the population build-up, preference to larger (apparently healthy) trees in the beginning (Beeson & Chatterjee, 1925) disappeared during the epidemic and became random (Beeson, 1941). Nevertheless, for the Nahan epidemic discussed below, the narrow initial range of maximum attack is only slightly widened on either side (not the lower side alone). Mathur (1962) in his observations on epidemic in Timli Range, Dehra Dun Forest, found attacks to be more evenly distributed over all age classes, but prefer 24 to 72 in. girths and further more heavier in 36 to 60 in. girth classes. Chatterjee and Thapa (1970) in a young forest in the same region (Thano Range, Dehra Dun Forest) found the attacked trees ranging between 8 and 20 in. girths. From these contradictory statements, it is not clear as to which girth class is really preferred.

It has been very interesting to review the preference of a particular girth class by borer during epidemics. It varied from maximum (50%) in girth class 60–105 cm to minimum in 30 and above 165 cm (Sarma, 1952), in 1963 epidemic in South Mandla Forest maximum in girth class 60–117.5 cm (Chatterjee & Thapa, 1964), in May 1949 through attack concentrated to girth class 60–117.5 cm (74%), was highest in class 90–102.5 cm (25%) with no attack below 30 cm girths and almost none above 210 cm, in January 1950 (150 trees), attack concentrated to girth class 75–132.5 cm (74%); and highest in class 90–102.5 cm (25%). No attack below 45 cm or above 210 cm girth, in 1949–50 (2365 trees), attack mainly in girth class 62.75–149.25 cm (84%); highest in class 86.75–117.75 cm (36%), in 1950–51 (2225 trees); concentrated in girth class 62.75–117.75 cm (66%); and less in class 118–149.25 cm (19%).

In the early period of the epidemic the attack is apparently heavier on relatively smaller girth 60–117.5 cm (74%); later, it spreads out a little more evenly to higher girth up to 150 cm. The same general trend applies to girth with highest attack 90–102 cm in the early days and 87.5–117.5 cm later on. There is very little attack below 45 cm girths, none below 30 cm, and almost none above 210 cm.

The study of a 2-acre area in the Gorakhpur Compartment of Nahan Forest, with 401 trees shows that the total stock is concentrated mostly in the girth class 45–117.5 cm (77.7%) where it is more or less evenly distributed. The attack trees, on the other hand, are largely grouped in the region 75–132.5 cm (70%) even though this range forms only about 55% of the entire stock, thus indicating preference. The healthy trees follow the pattern of the "total stock" with concentration in the 45–117.5 cm region (76%). It can be concluded that a wide girth range of 30–270 cm is attacked. However, it has been only 12.7% below the preferred range of 75 cm against the growing stock of 30.7%.

During last epidemic in Madhya Pradesh from 1997 to 2001, incidence of borer attacked trees during 1997–98 at Motinala Range, Mandla Forest Division, varied from 3.7% in compartment with mixed tree species to 22.98% in pure compartments, which further enhanced to 24.23% in the subsequent years. Roychoudhury et al. (2019a, b) have compiled the data recorded during the recent epidemic from 2012–2013 to 2015–2016 and come to the conclusion that the girth class of 90–150 cm is the most preferred by the borer. However, in our opinion, while the highest girth classes are preferred by the beetles in endemic stage and at the initiation of the epidemic, but gradually the borer starts laying eggs on the trees of girth classes even below and above the preferred class, due to many factors including competition and nonavailability of suitable hosts probably (Kulkarni: Unpublished Observation). This conforms to what was discussed by Beeson (1941) and the data are being published separately by the authors.

9.5 History of Population Outbreaks and Epidemics

While the *sal* heartwood borer is available endemically, it periodically flares up more due to environmental, anthropological biotic factors and physiological status of trees (Kulkarni et al., 2007) than population of natural enemies (predators and parasites) (Roonwal, 1978). In a given area, the infestation status of trees below 1.0% of the total growing stock of the trees (Beeson, 1941) or less than 2.5 trees per hectare (Roonwal, 1978) is considered endemic.

After its first report (Stebbing, 1899, 1906), there have been 87 large and small epidemics recorded only up to 1977 in Assam, West Bengal, Bihar, Madhya Pradesh, Uttar Pradesh, and Himachal Pradesh (Roonwal, 1977). However, it appears that population build-up of the pest in a limited area should have been called population outbreaks rather than epidemics. Several epidemics of this pest have been reported from different *sal* growing areas of India existing from Himachal Pradesh to Assam and Orissa to Madhya Pradesh. The available records show that the infestation of this borer was reported in Apalchand Range of Jalpaiguri Forest Division of West Bengal, Banjar Valley Reserve, Motinala, Dindori, Karanchira, and Khannat ranges of South Mandla Forest Division of Madhya Pradesh, etc., in 1905–06. Later, population again broke out gradually leading to an epidemic in Timli Range of Dehradun Forest Division in 1958 and continued till 1960.

In Madhya Pradesh, the first report of borer infesting standing trees was recorded in 1905 from Balaghat, followed by Khannat forests of Mandla Forest Division in 1912. The borer was endemic to this area and ultimately increased to a considerable number in Banjar and Motinala ranges of Madhya Pradesh where 423 and 63 trees, respectively, were found to be attacked by the *sal* borer. It was brought under control by felling the attacked trees. This infestation, which was endemic between 1915 and 1922 in Karanjia and Dindori suddenly reached epidemic levels in 1923–24, ultimately spreading in 27 acres in Banjar Range. The infestation in this range was severe in nearly half of the standing stock of *sal* trees that were attacked by this borer. During the same year, the infestation was noticed in Motinala, Dindori, and Karanjia ranges of South Mandla Forest Division. Felling of heavily attacked *sal* trees was carried out from 1924 onwards. Nearly 2960 attacked trees were felled in 1924 from the above ranges, whose number rose to 28,521 trees in 1925 and nearly

150,000 trees in 1926–27. Of these, a few thousands were sold, nearly 40,000 were debarked and stoved, and between 50,000 and 60,000 were burned to check its further spread. The number of attacked trees also increased in other neighboring forest divisions. Baihar and Raigarh ranges of Balaghat and Lamni range of Bilaspur, Rewa State, Pendra, etc., were also affected (Roonwal, 1977). The total number of trees attacked over the whole infested *sal* area before epidemic was checked and was estimated to be about 70 lakh (seven million–10 lakh being one million).

Some important reports on epidemic and the control operation include Beeson and Chatterjee (1925) in Thano *Sal* forests of Dehra Dun Forest Division (Uttar Pradesh), Muir (1929) in Mandla Forest Division (Madhya Pradesh), Roonwal (1952) in Nahan Forest Division (Himachal Pradesh), Mathur (1962) in Timli Forest Range, Dehradun Forest Division (U.P.), Chatterjee and Thapa (1964) in Karanjia and Dindori Range of South Mandla Division (M.P.), and Thano range in Uttar Pradesh and south Mandla Division (M.P.). As soon as the population of the borer was observed to increase in the year 1944–45 in Banjar range, it was immediately brought under control. The population of borer was again noticed to increase in a few compartments of Dindori forest range in 1961–62 (now a forest division) that reached epidemic levels not only in Dindori but also in Bajag and Karanjia forest ranges in 1962–63. Trap tree operations were carried out from June 1963 to the first week of September 1963 by using about 54,208 trap trees to combat the epidemic, which kept the problem under control for a few years. The epidemic of *sal* borer was again reported from Pachmarhi Hills in Hoshangabad Forest Division in 1976. This epidemic considerably increased in 1978–79. Control remedies were initiated with the help of scientists of the then Regional "Forest Research Centre of Forest Research Institute, Dehradun" (now Tropical Forest Research Institute, Jabalpur), from 1979 and were carried out continuously for 4 years. It was found that the population reached endemic by the year 1982 (Table 9.1).

In Chhattisgarh, the first report of green *sal* trees apparently dying under the attacks of an insect borer was recorded from 1997 to 2000 from the Rajnandgaon, Bilaspur, and Sarguja forests where 204,692, 153,856, and 13,163 trees, respectively, were found to be attacked by the *sal* borer. It was brought under control by felling the attacked trees. The infestation was noticed in Koleng Range and Kanker Forest Division at Bastar District (Kulkarni, 2009; Roychoudhury & Soni, 2007). Trap tree operations were started in Mundagarh, Chandameta, and Chindagur 33 sites in the Koleng Range in 2007. There have been some reports on *sal* borer infestations from the Sargipal forest depot, Jagdalpur Forest Division with the affected area being 118 ha (Table 9.1).

9.6 Recent Insect Outbreak in Central India

Recently, the states of Madhya Pradesh and Chhattisgarh experienced *sal* borer outbreaks in 22 forest ranges in 5 forest divisions in Madhya Pradesh and 7 forest ranges under 3 forest divisions in Chhattisgarh. The recent outbreak, particularly in

Table 9.1 History of *sal* borer outbreaks in India till the year 2000

State	Forest Division/ Range	Infested Area (km^2)	Year	Number of Affected Trees
Assam	Goalpara	–	1906, 1961	–
	Amosi, Nowgong	–	1961	–
Himachal Pradesh	Nahan	85	1948, 1954	6955
Jharkhand	Palamu	491	1961	2,946,000
	Singhbhum	–	1899, 1906	–
Madhya Pradesh and Chhattisgarh (undivided)	Balaghat	–	1905	–
	Balaghat	–	1997–2000	68,641
	Supkhar and Baihar	122	1927–1928	4500
	Supkhar and Mukki	–	1948–1952	2963
	Mandla	–	1923–1928	7,000,000
	Mandla	–	1950–1955	56,500
	Mandla	324	1959–1962	350,000
	Mandla	–	1997–2000	2,620,157*
	Chada	–	1997–2000	823,997
	Sarguja	–	1997–2000	13,163
	Shahdol	–	1997–1998	97,824
	Bilaspur	–	1997–1998	153,856
	Rajnandgaon	52	1997–1998	205,692
	Pachmarhi	–	1979–1982	8085
Uttarakhand	Dehradun	18	1916–1924	80,000
	Timli	–	1958–1960	1760
	Lachhiwala	–	1961	–
	Thano	–	1964	8475
	Thano	5	1965	2379
	Kalagarh	–	1924–1925	–
	Kalagarh	–	1934–1937, 1994	–
	Phandowala	30	1994	–
West Bengal	Sevoke, Kurseong	7	1931–34	3177
	Rajabhatkhawa	14	1974	23,120

Source: Anonymous (2017), Kulkarni et al. (2018), and Roychoudhury et al. (2019a)
"–" denotes data not available, *Including Kanha National Park

Chhattisgarh, was closely monitored by the Tropical Forest Research Institute, Jabalpur (India), under a Memorandum of Understanding (MoU) with the Chhattisgarh State Forest Department. Under the program, the institute surveyed and monitored the *sal* borer incidence through periodical surveys, reported field status periodically, and imparted training to the frontline staff of the State Forest

Department. A final report was submitted at the end of the program (Anon, 2017). Tables 9.2 and 9.3 present data related to the recent outbreak, based on field surveys, data received from the concerned State Forest Department, and available published literature (Tables 9.2 and 9.3).

9.7 Causes of Population Outbreaks/Epidemics

9.7.1 Biotic Factors

The population outbreak of *sal* heartwood borer is assumed to be a result of complex combination of multiple factors, viz. biological factors, anthropological factors, effect of other pests, and disturbed natural enemy complex of the borer and physiological condition of *sal* trees (Kulkarni et al., 2007). It has been invariably observed that forests in vicinity of human inhabitation and roadsides (Fig. 9.4a, b, c) are invariably severely attacked, as compared to remote areas with less biotic pressure. Major kinds of interference include manual destruction of trees and collection of *ral* (resin from tree), thereby making it more prone to insect attack, and grazing by cattle and wrong methods of Non-Timber Forest Products (NTFP) collections using fire for cleaning litter. Some affect the insect population directly, while others exert a negative impact on local conditions, thereby reducing soil fertility and resulting in the tree's own resistance in the long term.

Kulkarni and Soni (2006) observed that several compartments of Sarona Range, Kanker Forest Division, Chhattisgarh Forest Department, were severely affected by recurrent fire in patches induced time and again by residents for collection of Mahua (*Madhuca longifolia*) flowers as their traditional NTFP and debarking activities. Such areas had no natural leaf litter left for developing natural mulching during the next rainy season, affecting deleterious effects on soil nutrient status. Similarly, other pests and pathogens and imbalance in the natural enemy complex of the border and physiological condition of trees like weakness and senescence also affect population in a given *sal* forest area (Kulkarni et al., 2007). The mechanical damage to the trees by the human population due to their vested interests also attracts insects to lay more eggs on such damaged trees and ultimately become breeding places.

9.7.2 Abiotic Factors: Environmental Factors

There are climatic and edaphic factors affecting the outbreak of sal borer. However, despite the repeated outbreaks over the years and observations recorded over the time, we only can conclude that the resultant of the factors cumulatively affecting negatively on the forest and tree health and positively on the insect reproduction play a major role at a given time and region. Soil nutrient status (Devlin, 1975), porosity or compactness (Beeson, 1921; Hole, 1919), and effect of frost are some of the important factors affecting the health of the *sal* forests along with the actual age of the trees, i.e., coppicing generation of the area (Prasad & Jamaluddin, 1985).

Table 9.2 Recent *sal* borer incidences in Madhya Pradesh

Forest Division/ Reserve Forests	Forest Range	Sal Forest Area (ha)	Year/s of Infestation	Incidence of Affected Trees in Numbers	
				Total	Trees per ha
East Mandla	Mawai	23,910	2014	22,583	0.94
		23,999	2015	5932	0.25
Dindori	Bajag	12,247.42	2012	167	0.01
		16,267.01	2013	1664	0.10
		20,574.37	2014	6435	0.31
	East Karanjia	6265.13	2012	345	0.06
		13,844.59	2013	2039	0.15
		14,476.11	2014	5291	0.37
	West Karanjia	–	2012		
		15,104.25	2013	1365	0.09
		14,810.48	2014	3991	0.27
	South Samnapur	10,041.77	2012	187	0.02
		11,900.46	2013	1071	0.09
		14,715.67	2014	13,571	0.92
	North Samnapur	–	2012	–	–
		–	2013	–	–
		327.02	2014	94	0.29
Satpura Tiger Reserve	West Pachmarhi	5715.69	2013–14	3922	0.69
	East Pachmarhi	8521.20	2013–14	4091	0.49
	Denwa buffer	3835.99	2013–14	1931	0.50
Kanha Tiger Reserve Core zone	Kisli	4022.16	2012	278	0.07
			2013	809	0.20
			2014	1441	0.36
			2015	1503	0.37
	Kanha	4495.65	2012	139	0.03
			2013	2900	0.65
			2014	4902	1.09
			2015	5453	1.21
	Sarhi	1952.55	2012	65	0.03
			2013	931	0.48
			2014	2061	1.06
			2015	2619	1.34
	Bhesanghat	3228.21	2012	411	0.13
			2013	5828	1.81
			2014	8227	2.55
			2015	5342	1.66
	Supkhar	11,866.7	2012	440	0.04

(continued)

Table 9.2 (continued)

Forest Division/ Reserve Forests	Forest Range	Sal Forest Area (ha)	Year/s of Infestation	Incidence of Affected Trees in Numbers	
				Total	Trees per ha
			2013	3104	0.26
			2014	5801	0.49
			2015	2160	0.18
	Mukki	7304.16	2012	810	0.11
			2013	6957	0.95
			2014	8721	1.19
			2015	5758	0.79
	Fen sanctuary	6306.72	2012	411	0.07
			2013	1081	0.17
			2014	1165	0.19
			2015	813	0.13
Kanha Tiger Reserve buffer zone	Khapa	2888	2012	29	0.01
			2013	211	0.07
			2014	443	0.15
			2015	15	0.03
	Motinala	6525.43	2012	0.00	0.00
			2013	576	0.09
			2014	816	0.13
			2015	62	0.84
	Gadi	4065.87	2012	175	0.04
			2013	197	0.05
			2014	558	0.14
			2015	348	0.05
	Sijhora	73.67	2012	0.00	0.00
			2013	0.00	0.00
			2014	56	0.76
			2015	197	0.05
	Khatiya	571.95	2012	0.00	0.00
			2013	7	0.01
			2014	4	0.01
			2015	1420	0.80
	Samnapur	1771.87	2012	307	0.17
			2013	396	0.22
			2014	1267	0.72
			2015	577	0.20

Source: Roychoudhury et al. (2019a, b)
"–" denotes data not available, *—including Kanha National Park

Table 9.3 Extent of sal borer infestation recorded in Chhattisgarh during 2012–2015

Forest Division	Sal Forest Cover (ha)	Forest Range	Year of Infestation	Affected area (ha)	Number of Affected Trees
Bhanupratappur	24,163.370	Amabeda	2012–2015	493.925	565
Kabirdham	25,584.175	Chilpi (Bhoramdev sanctuary)	2013–2014	7452.00	9925
			2014–2015		22,874
		Kabirdham	2013–2015	2069.74	2692
		Taregaon	2013–2015	–	2284
			2014–2015		5047
Korba	109,765.280	Korakchar	2015	39.636	2757
		Basin	2015	639.061	1314
		Pasarkhet	2015	40.00	1268

Source: Kulkarni et al. (2015) and Anonymous (2017)
"–" denotes data not available, *—including Kanha National Park

However, factors governing corresponding build-up of the *sal* borer population are the major factors promoting the insect outbreaks (Kulkarni et al., 2007).

According to Beeson (1941), the initial date of emergence of beetles and the rate of emergence of the first 60 to 70% of the total annual population are apparently influenced by the initial date of the preliminary monsoon shower and by the quantity of the monsoon rainfall in the first 2 months (June and July in the western breeding zone), and these effects are believed to be mediated through the pupal chamber and acting on the immature beetles. Theoretically, 100% emergence may be affected with a minimum of 89 cm of rainfall or a maximum of 165 cm. These figures apply to the western breeding zone, especially to the Dehra Dun area and Madhya Pradesh.

The pupal and the late larval stages can withstand considerable degree of desiccation in the dry season, as well as considerable exposure to a saturated atmosphere with free moisture. Larvae, were subjected to temperature lower than normal pupate late by some 3 weeks. Lower temperature may also prolong the pupal stage by 1 or 2 days (Beeson, 1941). More detailed work on these aspects is called for, especially in regard to the beetle's physiological adaptation under situations of stress.

Biology of *sal* borer, like all other living organisms, depends largely on the suitability of environmental conditions. Suitable rainfall with that of conducive temperature and relative humidity is required for population build-up of the pest (Beeson, 1941; Kulkarni et al., 2007). First direct impact of the environmental factors is on the biology of immature stage (grubs) inside the standing tree trunk and the flying adults (beetles) of *sal* heartwood borer. In situations of favorable climate, their population increases due to increased oviposition and increased survival of the life stages. Beetle's life is considerably shortened or ceases under dry atmosphere conditions and in the presence of temperature above the threshold limits. It is due to desiccation, observed first in maxillary and labial palpi, which lose flexibility and power of movement. The apical segment of the antennae and the tarsal segments of the hind legs are next affected, becoming rigid. The antennae stiffen and

Fig. 9.4 Roadside trees showing more damage due to biotic pressure

cannot vibrate. Mortality of *H. spinicornis* exposed to saturated air is preceded by a swelling of the abdomen and a rapid decay of the tissues. A dying beetle is recognizable by the production of a foul smell and the dead beetle rapidly putrefies (Beeson, 1941). Sal borer has a maximum life of about 50 days and is reached at about 93% relative humidity and 27 °C, when the individual is exposed to these conditions throughout life. Under natural conditions, the beetle encounters a wide range of diurnal and nocturnal variations, but it does not expose itself voluntarily to temperature higher than normal shade temperature or to saturated highly heated air. Survival is reduced to only a day or two at humidity as low as 55% and temperature 37.7 °C, during which reproductive behavior is also adversely affected. Mean relative atmospheric humidity plays a major role, which can be accessed directly by the presence of beetles in the forests. Kulkarni et al. (2007) have discussed the results of experiments carried out during the last epidemic on tree trapping from June 16 to July 15, 1998, at Jagatpur, Karanjia Forest Range, Dindori Forest Division, Madhya Pradesh. Results revealed that mean maximum temperature had negative correlation and relative atmospheric humidity and rainfall in the local environment had the positive correlation and affected the beetle emergence. Kulkarni et al. (2007) has discussed only 1 month's observation on the number of beetles emerged based on tree trap data and correlated it with the environmental factors, substantiating the presumptions of Beeson (1941) that higher the relative atmospheric humidity higher and more successful the emergence, survival, and population build-up of the beetles; i.e., the relative humidity becomes positively correlated with the population build-up of the pest, unlike the negative correlation wrongly interpreted by the Prakasham et al. (2017) and Roychoudhury et al. (2019a), which was based on overall year-wise incidence vs the year-wise environmental factors from 2012 to 15 and wrongly correlated incidence of attack (number of trees damaged per ha) with the year-wise RH and temperature data, reporting overall incidence to be negatively correlated with relative humidity and positively correlated with temperature, which seems scientifically illogical and misleading. Thus, workers need to be very careful while correlating the two factors, which should consider environmental factors corresponding to phases of the insect's own life cycle, so as not to reach wrong conclusions.

Similarly, low status of nutrients badly affects the tree vigor and resistance against pests (Kulkarni et al., 2007). Kulkarni and Soni (2006) observed that pathogen, *Phellinus (Polyporus) gilvus,* was prevalent in *sal* trees of all seven compartments of Sarona Range, Kanker Forest Division (C.G.), which were deficient in nitrogen content, besides other biotic pressure in the area. The observations were important and in conformity with Bakshi (1976), who had earlier reported a similar case where this pathogen appeared as a pest of *sal* trees. What is noteworthy is this fungus emerges as a pathogen pest only under stress conditions and not a primary pathogen of *sal*. Such trees are further more prone to attack by *sal* heartwood borer in the subsequent years (Kulkarni et al., 2007).

Soil porosity as an environmental factor has also been dealt by Prasad and Jamaluddin (1985). Observations noted by Totey et al. (1998) on extent of cases of mortality or weakening of trees and profuse epicormic branching due to excessive and repeated cases of frost in *sal* forests of Baihar Range, Balaghat Forest Division, during 1998, are in conformity with similar observations by Benskin (1927) in Kalagarh, Dehradun Forest Division. In such areas, borer was the secondary causative agent; however, requirement of necessary precautionary and remedial measures in such areas, as in case of any other borer-affected *sal* forest area, has been recommended (Anonymous, 1998a, b).

9.8 Economic Losses by *Sal* Borer

The *sal* heartwood borer is considered as "the potentially most injurious forest insect in India" (Beeson, 1941). In nonepidemic years, the normal loss caused by it to *sal*, *Shorea robusta,* in Uttar Pradesh alone was estimated at Rs. 250,000 (or about one eighth of a rupee per *sal*-acre); in epidemic years, this loss jumps up nearly 144 times (Rs.18/− par *sal*-acre). In the worst known epidemic, that of the years 1923–28 in five forest divisions in Madhya Pradesh, some seven million trees were killed, resulting in a loss of forest capital worth Rs.13,750,000 and, in addition, control operation cost Rs.125,800/−. The logs from the affected *sal* trees lose their industrial value and can only be of fuelwood value (Fig. 9.5a, b). However, there is no recent

Fig. 9.5 (**a**) Team including author, inspecting the borer-affected logs ready to transported away for maintaining forest hygiene; (**b**) close-up of an affected with multiple tunnels

assessment of economic losses, but from the above the current value may be extrapolated using various standard methods.

9.9 Management Options

The management of *sal* borer has been a major problem not only for the forest managers but also for the forest entomologists of the country. It is due to the complex life cycle of the species in which only the life stage of the species is adults, i.e., beetles, which are on wings only for a limited time from June/July till August/September. Rest all stages are inside the tree bole, as has already been discussed in length under preceding paragraph on life cycle of the pest. This makes the management at an immature stage become more difficult, as is the case with most of the longhorn beetles in the world (Joshi et al., 2006). The management options in practice or being investigated are being discussed as hereunder.

9.9.1 Silvicultural Management Option: Removal of Affected Trees

9.9.1.1 Categorization

Based on the stages of progression of borer infestation in a tree and symptoms visible externally as discussed in the preceding paragraphs, the trees are classified into various categories for convenience of silvicultural forest management (Beeson, 1941; Kulkarni et al., 2018). The earliest categorization was given by Beeson in 1941 (Beeson, 1941) taking amount of wood dust around the tree trunk as the main criterion (Fig. 9.6) and then further improvement in it (Roonwal, 1978) (Fig. 9.7).

Following are the characteristics of categorization by Beeson (1941).

1. Crown dead, leafless, epicormics leafless, wood dust in a large heap.
2. Crown dead, brown, epicormics dead, brown, wood dust in a large heap.
3. Crown dead, brown, epicormics or bark dead in upper part, alive in lower part of trunk, wood dust in heap more than 3 in. deep, or less abundant.
4. Crown entirely alive and green, epicormics green, wood dust in a large heap.
5. Crown partially alive, green and partly dead, brown, epicormics green, wood dust scattered, less than 3 in. deep.
6. Stumps with bark intact and a large heap of wood dust.
7. Crown entirely alive, green epicormics, resin abundant or absent, wood dust scattered or scanty.

Roonwal (1978) brought out more practical categorization based on visible state of health of the crown and interchanged types IV and V, which appear to be a more practical categorization (Fig. 9.6). Roonwal (1978) included category VIII, for the completely healthy tree. This classification was more practical, than simply based on availability of wood dust as in the case of Beeson (1941). This is because the wood dust is sometimes misleading under field conditions, as either the wood dust is

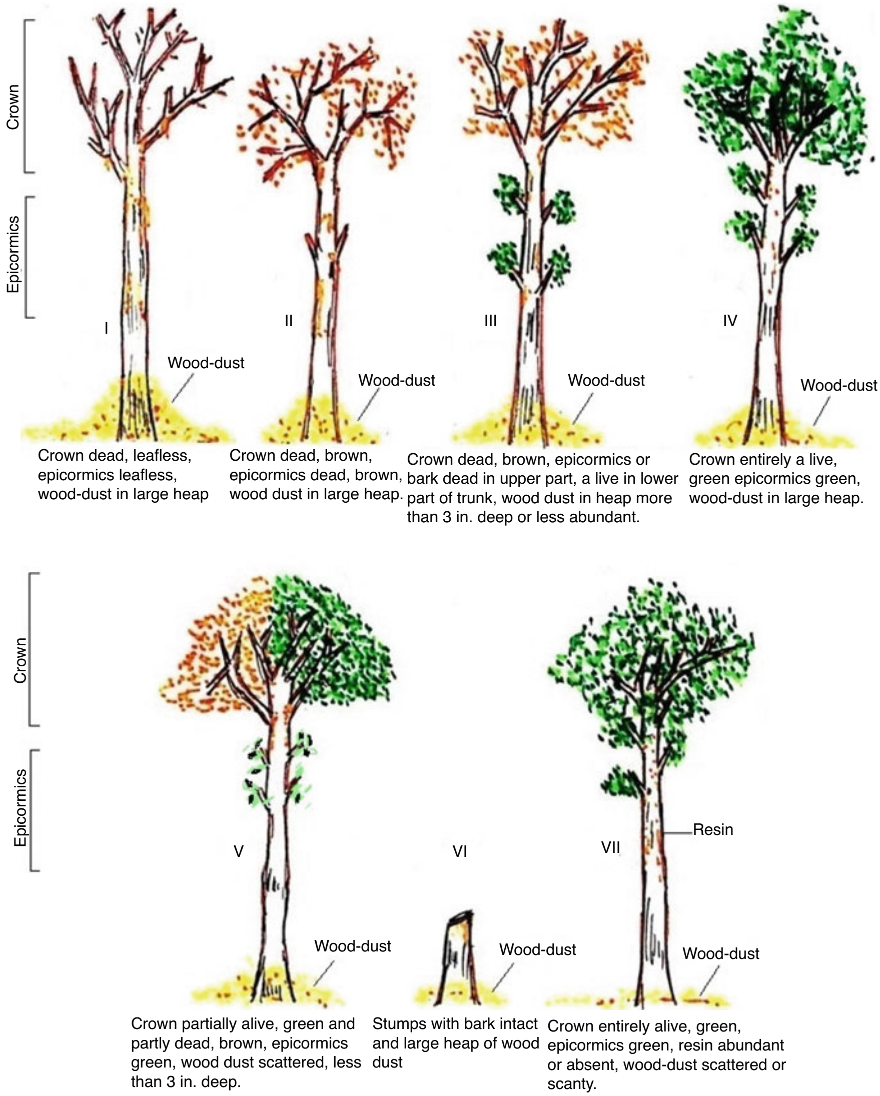

Fig. 9.6 Categorization of *sal* borer-affected tree (after Beeson, 1941)

swayed away by winds or drowned by occasional rains (Fig. 9.7). There are further modifications in the above classification being published separately, based on field observations, which will help field foresters to classify the trees more easily (Kulkarni: unpublished). The characteristics as per Roonwal (1978) are as given below:

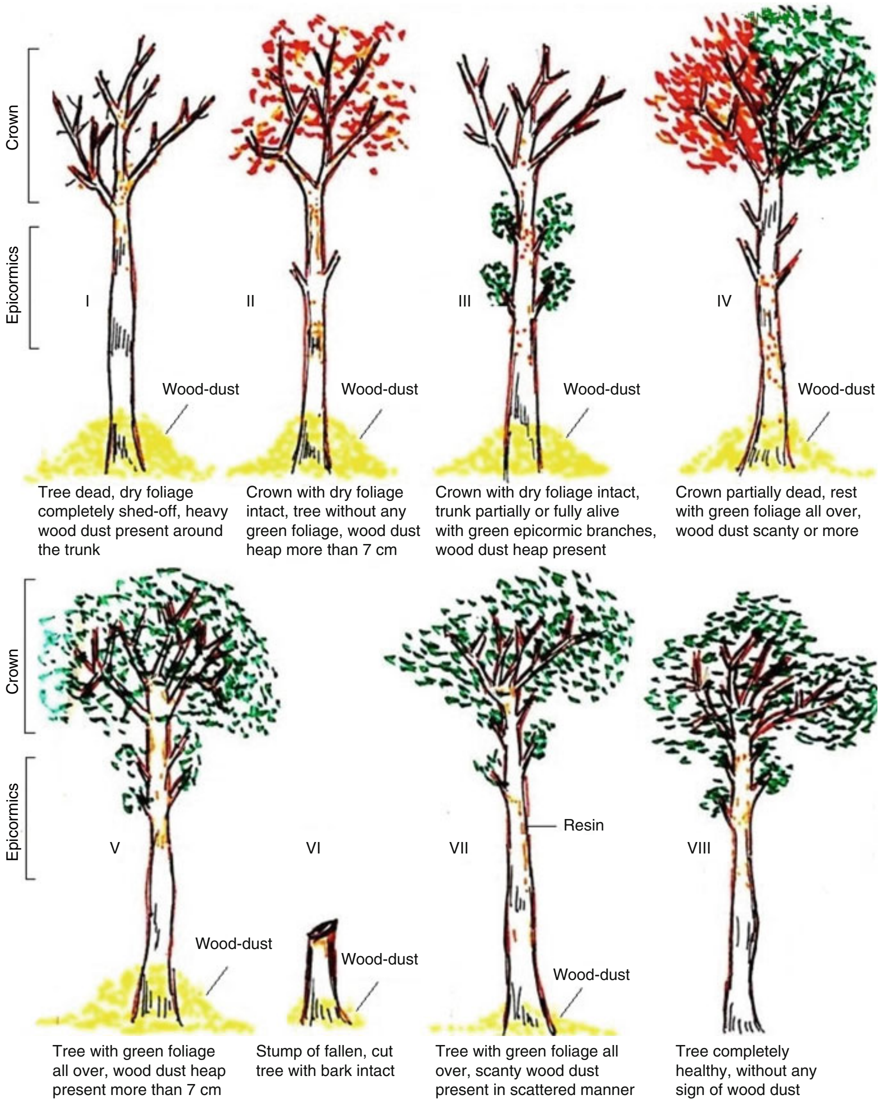

Fig. 9.7 Categorization of *sal* borer-affected tree (after Roonwal, 1978)

1. Tree completely dead, dry foliage completely shed-off, heavy wood dust present around the trunk.
2. Crown with dry foliage intact, tree without any green foliage, wood dust heap more than 7 cm depth.
3. Crown with dry foliage intact, trunk partially or fully alive with green epicormic branches, wood dust heap present.
4. Crown partially dead, rest with green foliage all over, wood dust scanty or more.

5. Tree with green foliage all over, wood dust heap present more than 7 cm.
6. Stump of fallen, cut tree with bark intact.
7. Tree with green foliage all over, scanty wood dust present in scattered manner.
8. Tree completely healthy without any signs of wood dust.

9.9.1.2 Forest Hygiene

One of the available, extensively promoted and commonly practiced preventive measures to manage *sal* borer outbreak is to maintain forest hygiene based on the above categorization of the symptomatically affected *sal* trees. To achieve that, complete enumeration of the affected trees in a given compartment, based on the categorization discussed above, is performed by the forest managers. The technical assistance and advisory services in confirmation of the *sal* borer attack, categorization of trees based on entomological symptoms, and enumeration of trees in affected areas were always provided by the institutes under the Indian Council of Forestry Research and Education, Dehradun, to the State Forest Departments. For insect outbreaks in central India like Madhya Pradesh and Chhattisgarh Forest Entomology Division of the Tropical Forest Research Institute, Jabalpur has played a major advisory role. Similarly, Forest Research Institute, Dehradun, has been providing a similar kind of advisory services to the northern part of the country.

In Madhya Pradesh, the *sal* borer outbreak from 1996 with peak during 1998–2001 was one of the worst in the series of outbreaks, as listed in Table 9.1, and was in epidemic form (Kulkarni et al., 2018; Prakasam et al., 2000). This is because, as against the limit of endemic presence of the insect (1% of the trees counted as per Beeson, 1941 or 2.5 trees per ha as per Roonwal, 1977), the affected trees ha^{-1} in Dindori Forest Divisions were as high as 50 with the larvae in some severely damaged trees reaching up to 1500/tree (Dwivedi, 1998).

According to Prakasam et al. (2000), during 1996–1998, large scale removal of all affected trees of categories I to VI attracted public interest litigations. Consequently, a committee in December 1997 consisting of senior Forest Officers and Forest Entomologists from Central and State Governments and research organizations under the leadership of the Director General, Indian Council of Forestry Research and Education, Dehra Dun the Ministry of Environment and Forests (MoEF), and Government of India was set up to find the causes of epidemic and extent of damage and to suggest remedial measures. The committee, having inspected the affected area, submitted its report to MoEF suggesting the removal of category I to V trees and approving the measures taken by the State Forest Department. However, this suggestion was again questioned by certain quarters, culminating in the constitution of a Task Force and a Steering Committee. One of the important terms of reference was to examine the impact and the necessity or otherwise of felling of borer-affected *sal* trees with respect to management plan prescriptions. The steering committee was to suggest appropriate guidelines on ecological and management aspects to prevent and control such epidemics. The MoEF after considering the recommendations of the Task Force permitted felling of trees of categories I, II, III, and VI. On February 23, 1998, the hon. Supreme Court of India stayed all felling operations. After hearing, the hon. Supreme Court of India

Table 9.4 Infested trees felled in Mandla and Dindori Forest Divisions, Madhya Pradesh during 1996–2001 insect outbreak

Year	Name of Division	No. of Trees Felled
1996–97	Dindori	13,728
	Mandla	–
1997–98	Dindori	560,718
	Mandla	146,640
1998–99	Dindori	368,272
	Mandla	60,690
1999–2000	Dindori	19,230
	Mandla	9335
2000–01	Dindori	109,004
	Mandla	19,013
2001–02	Dindori	219,776
	Mandla	63,659
Total		1,590,065

Source: Prakasam et al. (2000)

ordered category-wise marking of affected trees and constituted a committee under the leadership of the Director, Tropical Forests Research Institute, Jabalpur. Then, the hon. Supreme Court permitted felling of affected trees of categories I, II, and VI only. Table 9.4 taken from Prakasam et al. (2000) presents year-wise number of trees felled out of total of 2.56 million affected trees in Mandla and Dindori Forest Divisions in erstwhile Madhya Pradesh.

9.9.2 Mechanical Options

9.9.2.1 Light Trap Method

Beeson (1941) also reported that the sal borer beetles are, though attracted toward light, not sensitive to light sources. During the last two epidemics in the unified Madhya Pradesh and divided Madhya Pradesh and Chhattisgarh starting, respectively, from 1998 and 2012, there was a misconception among the field staff of the state forest departments that the beetle gets attracted to light sources. This was also a common feature, when the author and his team stayed in the forest rest houses that a few beetles used to get attracted to ordinary light sources during nights. To test this, if this attraction toward light can be implemented as one of the methods for its management through "trap-n-kill" strategy, the team experimented different types of light traps and light sources of varying intensities right in the *sal* forests using mobile battery systems for 6 h daily 7:00 pm in the evening till 01:00 am in sufficient replications (Kulkarni: Unpublished). We experimented with standard light trap and screen light trap with mercury bulb, CFL bulbs, and LED strips of different colors and intensities. While ordinary bulb and or CFL attracted negligible number of beetles, i.e., less than 6, the variations experimented did not attract even a single. Based on the experiments (detailed results are being published separately), it is substantiated that these beetles are not attracted to light, or at least not to the level to use this as a management option (Kulkarni: unpublished).

9.9.2.2 Trap Tree Method

Sal heartwood borer's immature stages are inside the tree trunk throughout the life cycle till they complete the cycle and emerge as adults. These adults, i.e., beetles, are attracted to a piece of 3-m-long log of broken, wind fallen branch, or weakened tree, beaten at two ends and bark separated to allow oozing out of fresh cell sap in the evening and covered with *sal* leaves. This is used as a trap, as beetles just after becoming active at dusk get attracted to the kairomonal compounds present in the cell sap and gather on the trap, mate rest. These are caught before dawn, collected, and killed. This beetle collection, along with maintenance of forest hygiene by removing type I, II, and VI category of trees from the compartment at least 3–4 km from the *sal* forest area, is a regular practice for the management of beetles during outbreaks (Fig. 9.8a, b, c, d) (Kulkarni, 2017).

In the worst affected Dindori and Mandla forests of Central Circle, Jabalpur, borer attack was first noticed in December 1995. Trap tree operation was carried out in 1996 rains in which 2.16 million beetles were killed and 14,478 trees were felled as traps. Besides this, 40,343 affected trees of all categories were also felled and removed from coupes due to working. In 1997 rains, trap tree operation was again carried out in which 15.17 million beetles were trapped, which indicates favorable climatic conditions for multiplication of insects beyond proportion Prakasam et al. (2000). To facilitate large-scale collection of beetles, before they multiply on healthy trees, local forest dwellers/tribes were promoted to collect beetles using trap tree method and paid for beetle collection at the rate of an amount decided by the respective states on each head of the beetles. For enumeration, record, and payment purpose, the collectors were promoted to collect, kill the insect, cut head, and bring them in strings of 100 heads per string (garlands), so that the strings can be counted easily multiplied with 100 for payments to be disbursed to individual, as an additional income (Fig. 9.8a, b, c, d). The details of infested trees felled, and the beetles killed in Mandla and Dindori forest divisions are shown in Table 9.5.

9.9.2.3 Improved Tree Trap

The authors have also experimented with an improved method of tree traps by designing and fabricating 4 new traps in collaboration with the State Forest Research Institute and experimented in the field during the *sal* borer beetle emergence period. The designed traps were advantageous over the conventional method by requiring less number of logs. Couple of designs was very successful and attracted the beetles. This was also demonstrated to the frontline forest staff of the Chhattisgarh State Forest Department at Chilphi Range under Kabirdham Forest Division. No details can be discussed here, as these are under the patenting process. However, these may further be modified and used in future for effectively trapping the beetles (Kulkarni: unpublished).

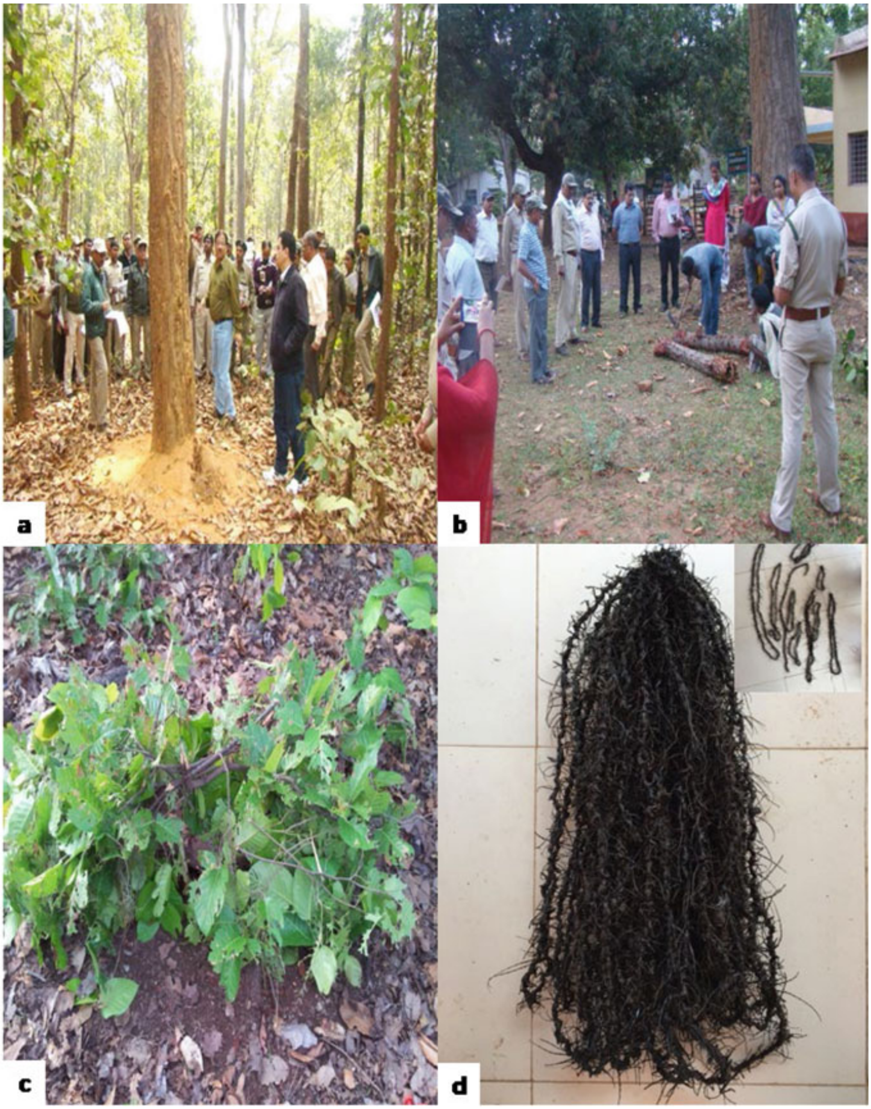

Fig. 9.8 (**a**–**c**) View of the field training to frontline forest staff on categorization and trap tree method; (**d**) single string of beetle heads (in inset) and bunch of strings

9.9.3 Chemical and Biopesticidal Treatments of Logs

The nature of damage, life cycle of the *sal* borer, and vast unapproachable area of working do not allow application of any treatment in natural forests, whether chemical or biological. However, with an aim to investigate and recommend possible treatment, (1) in forest depots, where the infested logs are transported and stored

Table 9.5 Infested trees felled and beetles killed in Mandla and Dindori divisions

Year	Name of Division	No. of beetles killed (Thousands)
1996–97	Dindori	2000
	Mandla	200
1997–98	Dindori	13,900
	Mandla	1100
1998–99	Dindori	31,000
	Mandla	1600
1999–2000	Dindori	12,100
	Mandla	1300
2000–01	Dindori	1700
	Mandla	100
2001–02	Dindori	–
	Mandla	–
Total		65,000

Source: Prakasam et al. (2000)

3–5 km away from the *sal* forest areas, so as to maintain the forest hygiene during the outbreak years, and (2) treatment of tree traps in fields (so that they are killed without requiring collection), a team from the Forest Entomology Division, Tropical Forest Research Institute, carried out a series of experiments on trap trees and stored logs in depots during the insect outbreak of 2012–2015. The treatments included a combination of biopesticide (spinosad 45% SL) and chemical (monocrotophos 36% SL, cartap hydrochloride 50% SL) insecticides in concentration ranges from 0.05 to 0.4%, while all the chemical insecticides caused mortality but comparatively higher doses were required for the mortality. Moreover, chemical insecticides cannot be recommended for widespread use in forests and thus are not recommended. However, these can be used as an emergency, but after considering the existing rules and restrictions in place for the specific chemical insecticides. The highest concentration of biopesticide tested caused 75% mortality in beetles after 72 h and can be used in case of requirements, if found economical for the treatment of Tree Traps.

For experiments in forest depots, a fumigant dichlorvos (83% EC) was also experimented along with others. All treated logs were covered so as to allow fumigation effect. Due to the fumigation property, logs treated with dichlorvos provided satisfactory levels of beetle mortality (Anon, 2017; Roychoudhury et al., 2014) (Fig. 9.9a, b).

9.9.4 Biological Control Options: Natural Enemies

9.9.4.1 Natural Enemies

While several biological control agents are known from history (Roychoudhury et al., 2013a, b), including the most promising elaterid species, *Alaus sordidus,* the immature stages of this predatory species have the potential to enter inside the larval galleries and feed on *H. spinicornis* grubs. While the population of this elaterid

Fig. 9.9 (**a, b**) View of the experiment being carried out by the team of entomologists from Tropical Forest Research Institute, Jabalpur (India)

species has been invariably recorded in proportions in light and tree traps with the increasing outbreaks of the *sal* heartwood borer, not much headway has been made on factors governing its population build-up beyond what was published by Beeson in 1941. In an effort to develop the rearing technique of this predatory elaterid beetle and mass produced for biological control of *sal* heartwood borer, the authors tried to multiply the predatory beetles in the laboratory and were successful in getting the oviposition in the laboratory. However, there was no survival, and thus, detailed protocol for mass multiplication is yet to be standardized (Fig. 9.10a, b, c, d) (Kulkarni: unpublished observations). Later, Roychoudhury et al. (2019a) reported an ichneumonid parasitoid, red ants among insects, and mole among rodents as predators of the *sal* heartwood borer. However, there are no data presented to substantiate these to be really parasitizing or predating on the *sal* borer, as merely

Fig. 9.10 View of laboratory rearing of *Alaus sordidus* carried out Tropical Forest Research Institute, Jabalpur (India), (**a**) close-up of the adult; (**b**) multiple adults on piece of log; (**c**) an adult on cotton swab; (**d**) grubs of *Alaus sordidus* developed in laboratory

presence of these agents near the dead insect does not prove that they are the primary agents for the death and not the scavengers after the death (natural or due to environmental factors). According to Beeson (1941), all of these agents do have not much role to play in population dynamics and population outbreaks of this pest (Beeson, 1941). However, woodpeckers can invariably be seen on the exit holes in the forests. Lot of work is required to be carried out to understand the relationship and their role in controlling population outbreak every 10–20 years. Table 9.6

Table 9.6 Reported natural enemies of *sal* heartwood borer feeding on grubs and pupae of *sal* borer

Natural enemy	Common name	Scientific name	Stages affected	References
Insect pathogens	Some unidentified molds	--	Eggs	Beeson (1941)
	--	*Beauveria bassiana*	Grubs	Subramanian (1971)
		Beauveria bassiana, Acremonium zeylanicum, aspergillus flavus, fusarium fusariosis, F. oxysporum, and *Metarhizium anisopliae*	Grubs	Joshi et al. (2002), Sharma and Joshi (2004)
Parasitoid	Larval parasitoid	*Disophrys dehraensis*, *Exobracon maculipennis,* and *Iphiaulax immsi* (hymenoptera: Braconidae)	Grub	Stebbing (1914), Beeson (1941)
	Larval–pupal parasitoid	*Ichneumon* sp.* (hymenoptera: Ichneumonidae)	Grubs and pupae	Stebbing (1914), Beeson (1941), Chatterjee and Misra (1974), Bhandari and Rawat (2001), Roychoudhury et al. (2013a, b)
Predators	Click beetle	*Alaus sordidus*	Grubs and pupae	Beeson (1941), Joshi et al. (2002)
	Red tree ant	*Oecophylla smaragdina* fab. (hymenoptera: Formicidae)	Grubs and pupae	Roychoudhury (2017)
	Large Indian black ant	*Camponotus compressus* fab. (hymenoptera: Formicidae)	Grubs and pupae	
	Small red ant	Unidentified* (hymenoptera: Formicidae)	Eggs	
	Woodpecker	*Brachypternus benghalensis* Linn. (Piciformes: Piddae)	Grubs	Joshi (2009)
	Woodpecker	13 species *Chrysocolaptes lucidus, Dendrocopos macei, Dinopium auriceps, D. Benghalense* [syn. *Brachypternus benghalensis*], *D. Canicapillus, D. mahrattensis, D. shorii, Micropternus brachyurus, Picumnus*	Grubs	Singh (2010)

(continued)

Table 9.6 (continued)

Natural enemy	Common name	Scientific name	Stages affected	References
		innominatus, Picus canus, P. Chlorolophus, Picus flavinucha, and P. xanthopygaeus		
	Jungle crow	Unidentified	Grubs	Joshi et al. (2002)
	Mole	Unidentified (Eulipotyphla: Talpidae)	Adults (beetles)	Roychoudhury (2017)
	Colydiid beetle	*Bothrideres* sp. (Coleoptera: Colydiidae)	Grubs	Stebbing (1914), Beeson (1941), Chatterjee and Misra (1974), Bhandari and Rawat (2001), Roychoudhury et al. (2013a, b)

presents some known records including the recent ones. However, it is again reiterated that except the *Alaus sordidus* and woodpeckers (which were though minor in status but found during surveys) (Kulkarni: unpublished observation), no other have been promisingly visible or recorded during the recent outbreaks in Madhya Pradesh, Chhattisgarh, and Uttarakhand and thus are in minor occurrence in status.

9.9.5 Behavioral Control Options: Plant Kairomones and Insect Pheromones

9.9.5.1 Plant Kairomone

While the isolation, identification, and synthesis and/or formulation is the most suitable management option (Roychoudhury, 1997) perhaps through a more effective trapping method without disturbing the forest ecosystem, however, their convenience and cost-effectiveness cannot be evaluated until such products are available and experimented in large tracts of *sal* forests in the country (Kulkarni, 2017; Kulkarni et al., 2004). Earlier, Kaur et al. (2001) have isolated and identified 9 essential oils and 17 resin compounds from *sal* heartwood by GC-MS and germacrene-D is found to be the chief constituent of both the oils. Kaur et al. (2003) reported 28 volatile compounds from the bast (cambium and secondary phloem) of *sal*, of which nine—T-cadinol, alpha-cadinol, globulol, alpha copaene, gamma-cadinene, viridiflorene, beta elemene, alpha-terpineol, and gamma muurolene—are made up nearly 49%. The essential oils from leaves, bast, heartwood, and ethereal extract of resin of *sal* and bioassays have been isolated with electroantennography and wild tunnel experiments to study the behavioral response of male-female borer beetles (Varshney et al., 2005). Essential oils from leaves, bast, heartwood, and ethereal extract of resin exhibited the electrophysiological activity in the female beetle, while essential oils of leaves and bast in the male beetle. In wind tunnel studies, only essential oils isolated from bast have elicited attractant activity to both the sexes of borer beetles. Negi and Joshi (2008) have evaluated the efficacy of extracts prepared from bast, heartwood, and leaf oil from *sal* tree under laboratory and field conditions using kairomone trap and olfactometer during the peak period of emergence.

The efforts have also been made to isolate kairomonal compounds from bark (Kulkarni et al., 2004), but field testing could not be possible due to sudden reduction in the beetle population during fag end of the epidemic (1998–2001) in Mandla Forest Division. However, with the population outbreak again going on in Chilphi and Kawardha forest ranges in Chhattisgarh during 2012–2015, further work on kairomonal compounds has been taken up by the authors and his laboratory, compounds isolated using the headspace arena collection, identified through GC-MS, and bio-assayed using the wind tunnel method against both the sexes of the borer (Kulkarni: unpublished observations).

9.9.5.2 Insect Pheromone

During the recent insect outbreak of 2012 to 2015, the authors have also experimented with isolation of different pheromonal compounds from both the sexes of the species. These were bio-assayed against the beetles in laboratory. The outcome is yet to be published, but the experiments indicated that the process of post-emergence aggregation in this insect pest involves a complex combination of behavioral chemicals, including the plant kairomones (Kulkarni: unpublished).

9.10 Conclusion

The *sal* heartwood borer, *H. spinicornis,* is a tough-to-manage insect pest with a history of recurring outbreaks every 10–20 years. The maximum life cycle of the insect pest is completed in tree trunks, and thus, many of the management options have not been very successful and economical. Moreover, the calcium carbonate operculum made by the larvae to protect the pupae from external environment and factors does not allow its natural parasitization and application of any biological or chemical control. While the biology and behavior of this pest are now extensively studied, more emphasis is required on the management options. During the outbreaks starting from 1998 and then 2012, recently, many of the possible management options were experimented by author and his teams from the Forest Entomology Division, Tropical Forest Research Institute, Jabalpur, under an Memorandum of Understanding (MoU) with the Chhattisgarh State Forest Department, as detailed above. However, the sudden outbreaks mainly depend upon the maintenance of forest hygiene as the first priority along with the trap tree operation on a large scale.

Further developments in using the plant attractant (Kairomones) and insect pheromones seem to be hampered for the want of synthesis of the identified chemicals in the country. However, if the task is achieved, the methods might prove a milestone in the management of *sal* borer in future insect outbreaks of *sal* heartwood borer, *Hoplocerambyx spinicornis,* in the country, saving industrially important timber tree species and the environment in general.

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10 Biodeterioration of Sandalwood (*Santalum album* L.): Agents and their Management

R. Sundararaj, S. Padma, N. Kavya, and K. N. Manjula

Contents

Abstract

Indian sandalwood is a highly priced tree, which grows naturally in different parts of India. Due to abiotic and biotic factors, particularly due to anthropological factors, the trees have become vulnerable in recent years, leading to widening the gap between demand and supply of sandalwood to the various industries. Biodeteriorating agents like fungi, insect borers, and termites play a crucial role in deterioration of sandalwood. The combined action of these agents on mechanically wounded or stressed trees increases the process of degradation. A detailed

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_10

understanding of these agents and their interactions with the sandalwood is essential for managing them in an ecologically and economically sound basis.

Keywords

Santalum album · Insect borers · Fungi · Termites

10.1 Introduction

Indian sandalwood (*Santalum album* L.) or white sandalwood, popularly known by its trade name East Indian Sandalwood tree, is an evergreen tree, indigenous to the Indian peninsula. It is an economically important tree species occupying a prominent position in Indian forestry known for its fragrance and heartwood. It is distributed naturally in India in an extent of around 9600 km^2 mainly in Tamil Nadu, Karnataka, Kerala, and Andhra Pradesh. Sandalwood is capable of growing in different kinds of soils like sand, clay, laterite, loam, and black cotton soil (Radomiljac et al., 1998). It is an integral part of Indian tradition, culture, pharmaceuticals, perfumery, cosmetics, artifacts, sculptures, etc.; hence, the tree is proudly regarded as "***Royal tree***" of India.

Indian sandalwood tree has become vulnerable in recent years, and the production of its wood in India had decreased annually at the rate of 20% since 1995 (Ananthapadmanabha, 2000). Natural and anthropogenic factors like illicit felling, disease, and smuggling are attributed to the depletion of sandalwood resources in the forest (Dhanya et al., 2010). In order to reduce the existing gap between the production of sandalwood and its demand in the market, Karnataka and Tamil Nadu state governments amended Forest (Amendment) Act in 2001 and 2002, respectively, stating that "every occupant or the holder of the land shall be legally entitled to the sandalwood tree in his land." The purpose of the amendment is to encourage farmers and corporate bodies to take sandalwood plantations to meet the growing demand (Gowda et al., 2008). Accordingly, many NGOs and farmers have volunteered into the growth of sandalwood in their private lands and farmlands. The sandalwood is habitually a hemiparasitic in nature, and it can parasitize over 300 species of plants (Sundararaj et al., 2018), which encourage the farmers to grow it in agroforestry, farm forestry, and varied agri–silvi–horticultural and also mixed plantation systems as per their choice for earning comfortable profit.

Biological agents like fungi and insects deteriorate the wood in living trees and also after harvesting in logs, thereby affecting the revenue of the wood and wooden products. The damage caused by the biodeteriorating agents often goes unnoticed. The wooden logs extracted from the forest (usually when the tree is dead), and also that confiscated from smugglers, were mostly with hollow when they were brought to the depots. Around 25% of logs reaching the depots was with hollow wood and 20% of the volume of heartwood was lost due to insect and fungal infection (Remadevi, 2012). The biological aspects of sandalwood deteriorating agents, their impact on the sandalwood, and control measures are discussed in this chapter.

10.2 Wood Borers on Sandalwood

Various groups of insects mainly belong to the order Lepidopteran larvae of the families Pyralidae, Oecophoridae, and Cossidae and order Coleopteran of the family Cerambycidae identified as active wood feeders of sandalwood. Stebbing (1903, 1905) recorded Cerambycid larvae attacking on sandalwood. Beeson and Bhatia (1939) observed that *Blepephaeus modicus* Gahan are bored on small branches and made tunnels running longitudinally into the heartwood filled with fine dust. Mathur and Singh (1960) reported two species of bostrychid beetles and a species of sapwood borers attacking on sandalwood under storage. *Indarbela quadrinotata*, *Aristobia octofasciculata,* and *Polyphagozeuzera coffeae* were reported as main woodborers of sandalwood in India (Remadevi & Muthukrishnan, 1998). Sundararaj et al. (2019a) observed maximum incidence of these borers in pruned plantations compared to unpruned plantations. Remadevi and Muthukrishnan (2006) studied the incidence and biology of *A. octofasciculata* on sandal and reported it as a serious borer. Muthukrishnan et al. (2008) recorded stem borer, *Purpuricenus sanguinolentus* Olivier, as a threat to sandalwood saplings. *Capnolymma macingalensis* incidence was reported by Ghate et al. (2011) for first time on sandalwood forest areas of Karnataka. Sundararaj (2012) listed six species of stem borers, five species of bark and deadwood feeders, and three dry wood feeders on sandalwood in India. All these borers infest and damage standing sandalwood trees and the affected trees show poor growth and produce poor-quality timber (Sundararaj et al., 2019b).

Wood/stem feeders include shoot borers, bark feeders, sapwood borers, and heartwood borers. These wood-feeding insects reduce the structural integrity of trees and often cause mortality of the trees. The deterioration of wood after harvesting in storage leads to reduction in quantity and quality of sandalwood. The known stem borers/wood borers are tabulated (Table 10.1), and their mode of damage and biology is discussed below.

10.2.1 On Standing Sandalwood Trees

1. ***Aeolesthes holosericea* Fabricius:** It is commonly known as round head stem borer and is a highly polyphagous, longhorned beetle, and cosmopolitan in distribution. It is a stem-boring pest in natural and planted forests and fruit trees. Frass coming out of the live holes on the trunk and branches is the main symptom of attack. Grubs tunnel the wood and lead the infested plants to die. Adult debarks the tender twigs of plant (Gupta & Tara, 2013). Females lay around 60 to 80 eggs under the cracks of bark. Eggs are oval, creamy yellow translucent and measure 2.21 to 2.25 mm in length and 0.75 to 1.15 mm in width. Incubation period lasted for 10 to 13 days. Newly emerged grubs are small, start feeding on phloem and cambium, and excavating a zigzag round feeding tunnel downward. Fully grown larva is yellow with dark brown head and measures 75 mm in length and 13.5 mm in breadth. The body is clothed in

Table 10.1 List of wood borers of sandalwood (*Santalum album*)

Species	Family	Order	Reference
Aeolesthes holosericea Fabricius	Cerambycidae	Coleoptera	Sundararaj et al. (2019b)
Aristobia octofasciculata Aurivillius	Cerambycidae	Coleoptera	Remadevi and Muthukrishnan (1998)
Blepephaeus modicus Gahan	Cerambycidae	Coleoptera	Beeson and Bhatia (1939), Sundararaj et al. (2019b)
Capnolymma macingalensis Gahan	Cerambycidae	Coleoptera	Ghate et al. (2011)
Ceresium gracile (Perroud)	Cerambycidae	Coleoptera	Sundararaj et al. (2019a)
Derolus volvulus Fab.	Cerambycidae	Coleoptera	Remadevi (2012)
Indarbela quadrinotata Walker	Metarbelidae	Lepidoptera	Remadevi and Muthukrishnan (1998)
Polyphagozeuzera coffeae Nietner	Cossidae	Lepidoptera	Remadevi and Muthukrishnan (1998), Sundararaj et al. (2019b)
Purpuricenus sanguinolentus Olivier	Cerambycidae	Coleoptera	Muthukrishnan et al. (2008)
Sahyadrassus malabaricus Moore	Hepialidae	Lepidoptera	Remadevi (2012)
Sinoxylon atratum atratum (Wasmann)	Bostrychidae	Coleoptera	Remadevi (2012)
Sinoxylon indicum Lesne	Bostrychidae	Coleoptera	Sundararaj et al. (2019b)
Stenodryas nigromaculatus (Gardner)	Cerambycidae	Coleoptera	Sundararaj et al. (2019b)
Xylopsocus capucinus Fab.	Bostrychidae	Coleoptera	Remadevi (2012)
Xylocopa latipes Drury	Bostrychidae	Coleoptera	Remadevi (2012)

fine bristles, which are abundant on the thorax and the last abdominal segment (Rahman & Khan, 1942a, b). The matured larva widened the central feeding tunnel and pupates by blocking the larval opening with fibrous frass. Beetle are large, stout, and elongate measuring 38 to 45 mm in length and 10 to 13 mm in width; mostly dark brown or reddish-brown densely covered with a golden-brown pubescence, when the elytra of the beetle are presented in different positions to the light, it gives them the appearance of being coated in the silk (Gupta & Tara, 2013).

2. ***Aristobia octofasciculata* Aurivillius:** It is also known as heartwood borer of sandalwood. Larvae live in the sap and heartwood of trees and their feeding activities lead to cavities and hollowness in the trunk of trees. The borehole is about 2 cm in diameter and has an average length of 2 m and can bring loss of about 0.5 kg (Srinivasan et al., 1992). Sandalwood trees in the girth classes of 11 to 15 cm and 16 to 20 cm were more prone for *A. octofasciculata* infestation (Remadevi & Muthukrishnan, 2006). Female bites crescent-shaped groove on the branch and lays up to 15 eggs. After an incubation period of 8 to 10 days, larva feeds into the branch or main stem through the bark and sapwood and

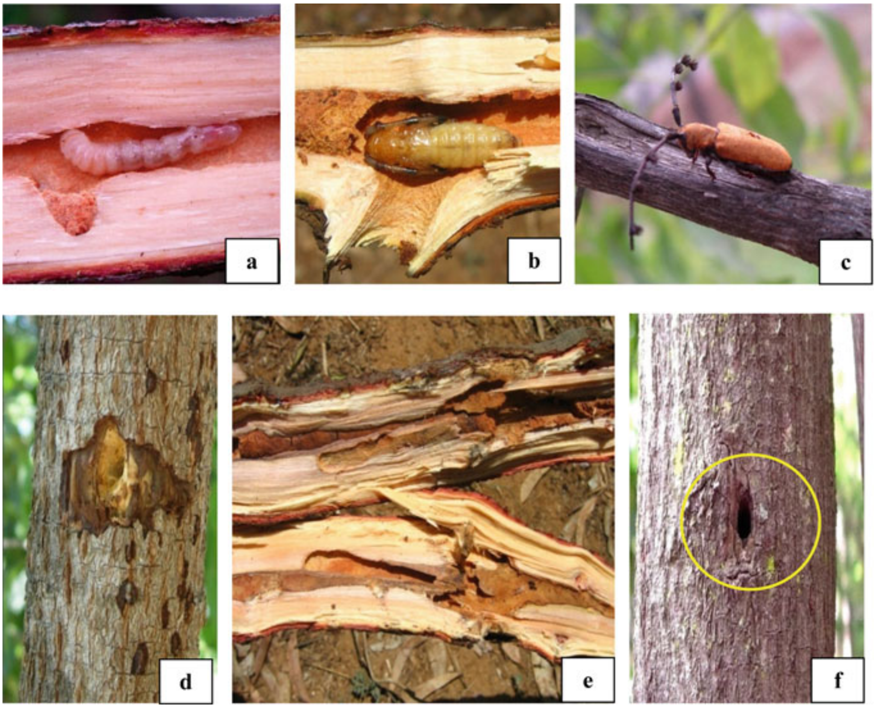

Fig. 10.1 *Aristobia octofasciculata* Aurivillius (**a**) young larva feeding on heartwood; (**b**) pupa; (**c**) adult; (**d**) feeding marks of adult; (**e**) severe tunneling in branches by larva; (**f**) emergence hole

excavates long tunnels downwards from 1 to 3 m. Fully grown larva measures 3 to 5 cm long with a yellowish thoracic dorsal shield (Fig. 10.1). In majority of cases, the larval gallery, which is packed with digested wood particles, is entirely confined to the main stem. Pupation occurs at the end of the tunnel, which goes up to root portion. The adult gnaws its way out through a circular hole. It measures about 1.7 cm to 2.95 cm; elytra and head brick red in color dorsally; abdomen, legs and ventral portion of head are black; antenna is 7 segmented; black, muffed at the joints of the segments; and longer in the male and brittle. The adult beetle lives up to 45 days in captivity (Sivaramakrishnan & Venkatesan, 1980; Srinivasan et al., 1992).

3. ***Capnolymma cingalensis* Gahan:** It was first report from India on sandalwood (Ghate et al., 2011). The body is brown (Fig. 10.2a) varying to reddish-brown on abdomen, legs, and disk of the elytra; covered with dark gray pubescence; prothorax brownish above, marked with some lines of ashy-white pubescence—one median, dividing just before the middle so as to enclose a lozenge-shaped area from the lateral angles of which two slightly curved lines run backward about halfway to the base of prothorax; antennae of male more than half as long as body; prothorax finely rugulose punctate; scutellum covered with dense white pubescence; elytra closely and rather strongly punctured; and

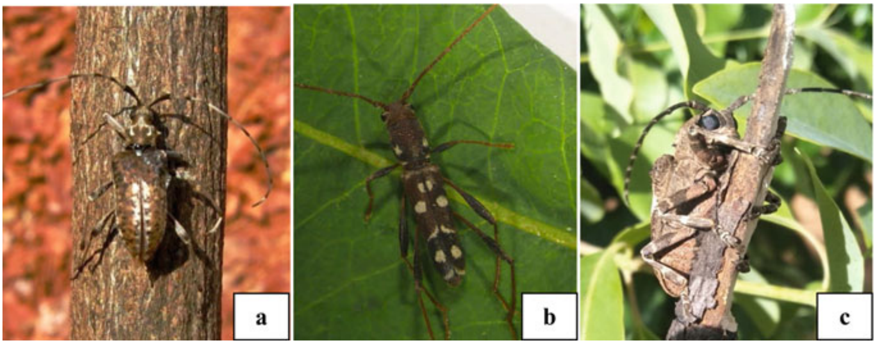

Fig. 10.2 Suspected borers—Adult (**a**) *Capnolymma cingalensis* Gahan; (**b**) *Clytocera chionospila* Gahan; (**c**) *Moechotypa asiatica* Pic.

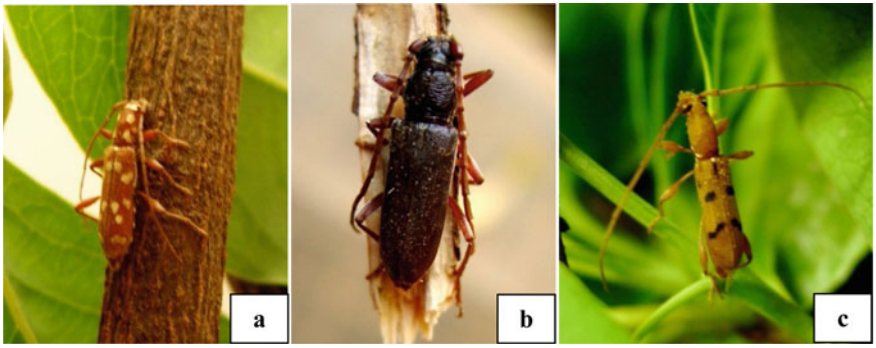

Fig. 10.3 Adult (**a**) *Ceresium gracile* (Perroud); (**b**) *Derolus volvulus* Fabricius; (**c**) *Stenodryas nigromaculatus* (Gardner)

its apices truncate and unarmed. Total length is around 14 mm, and 5 mm is breadth (Gahan, 1906).

4. ***Ceresium gracile* (Perroud):** This beetle is so far reported from Sri Lanka and India, and its host was unknown (Makihara et al., 2008). In India, it is first reported on sandalwood by Sundararaj et al. (2019b) with infestation ranging from 0.5 to 1.0%. Body of the beetle is narrow (Fig. 10.3a) and elongate, cinnamon-brown in color, sparsely pubescent, marked above and along the sides beneath with small spots of dense white pubescence; and head with two white spots on the vertex. Prothorax with four laterally placed white spots above two rounded spots anteriorly and two, more elongate, at the base; also, a smaller spot at the middle of each side; scutellum white. The antenna is longer than the body and prothorax is sub-cylindrical, about one-third longer than its width. Elytra parallel-sided, rounded at the apex, distinctly and rather closely punctured, the punctures feebler near the apex (Gahan, 1906).

5. ***Derolus volvulus*** **Fabricius:** It is a polyphagous pest on trees like *Acacia* spp., *Aegle marmelos, Albizia lebbeck, Bombax malabaricum, Shorea robusta, Pterocarpus marsupium*, and *Xylia dolabriformis* and distributed in many states of India. The beetle is very small in size about 12 to 17 mm and is dark brown in colour (Fig. 10.3b). The larval tunnels in bark are about 6 in. and groove the sapwood. The pupal chamber is short and is closed by a hemi-ellipsoidal calcareous plug. The life cycle is annual with emergence in the months of April–August (Remadevi, 2012).
6. ***Indarbela quadrinotata*** **Walker:** It is commonly known as bark-eating caterpillar, a polyphagous pest feeding on many important forest tree species. The larva feeds on the bark and leaves a long winding, thick and brownish ribbon-like masses composed of small chips of wood and excreta on the tree. The borehole was usually seen at the junction of the branches leading to the sapwood (CROPSAP, 2013). The larva bores into the bark making tunnel of nearly 20 cm depth, takes refuge during the day, and eats the bark of the tree during night. Bark damaged by the larva results in inhibiting translocation of cell sap and reduces growth of host species (Shasidharan et al., 2010). The infestation starts in the month of April with the emergence of moths (Mann & Bindra, 1977). Female lays egg below the bark or in between cracks and eggs in 15 to 25 days. Larvae initially feed on the bark and subsequently bore into the trunk. The larval period lasts for 9 to 10 months. The fully grown larva is smooth, with sparse hairs, and measures 3.5 to 4 cm in length. The thoracic legs are simple with the last segment ending in a curved claw. Abdominal legs are present on segments 6 to 9. Pupation occurs within the larval tunnel, with the cephalic end of the pupa slightly protruding outside. The pupal period lasts for about 15 to 25 days. The moth is light brown in colour and measures 15 to 18 mm across the wings (Fig. 10.4). Fore wing has a sub-apical brown spot and with several transverse rows of brown scales. Hind wing is light black in colour. Head is depressed and antennae strongly pectinate, with the pectination uniform throughout (Mathew, 1997; Sharma & Kumar, 1986).
7. ***Purpuricenus sanguinolentus*** **Olivier:** It is commonly known as sandalwood stem borer (Fig. 10.5) and reported gnawing living shoots of sandalwood (Muthukrishnan et al., 2012), Bamboo, Acacia, Arabica, *Dendrocalamus strictus* (Beeson, 1919), Acacia sp., Dendrocalamus and Bambusa (Duffy, 1995). It mostly affects the sandalwood sapling and is also found gnawing dead or dying shoots of sandalwood. The larva tunnel measures 50 to 60 cm or more as the larva progress in feeding and growth, causing accumulation of lot of frass in the feeding tunnel. It completely feeds on the sapwood causing disruption in the vascular supply resulting in death of main shoot (Muthukrishnan et al., 2012; Remadevi, 2012). Adult measures 12 to 21 mm in length and 3.5 to 7.5 mm in breadth. It is black in color, with two broad, bright red or sometimes pale yellow, bands across the elytra, one at the base, the other wholly or in its greater part behind the middle, which vary in width. Head very densely punctuate (Gahan, 1906).

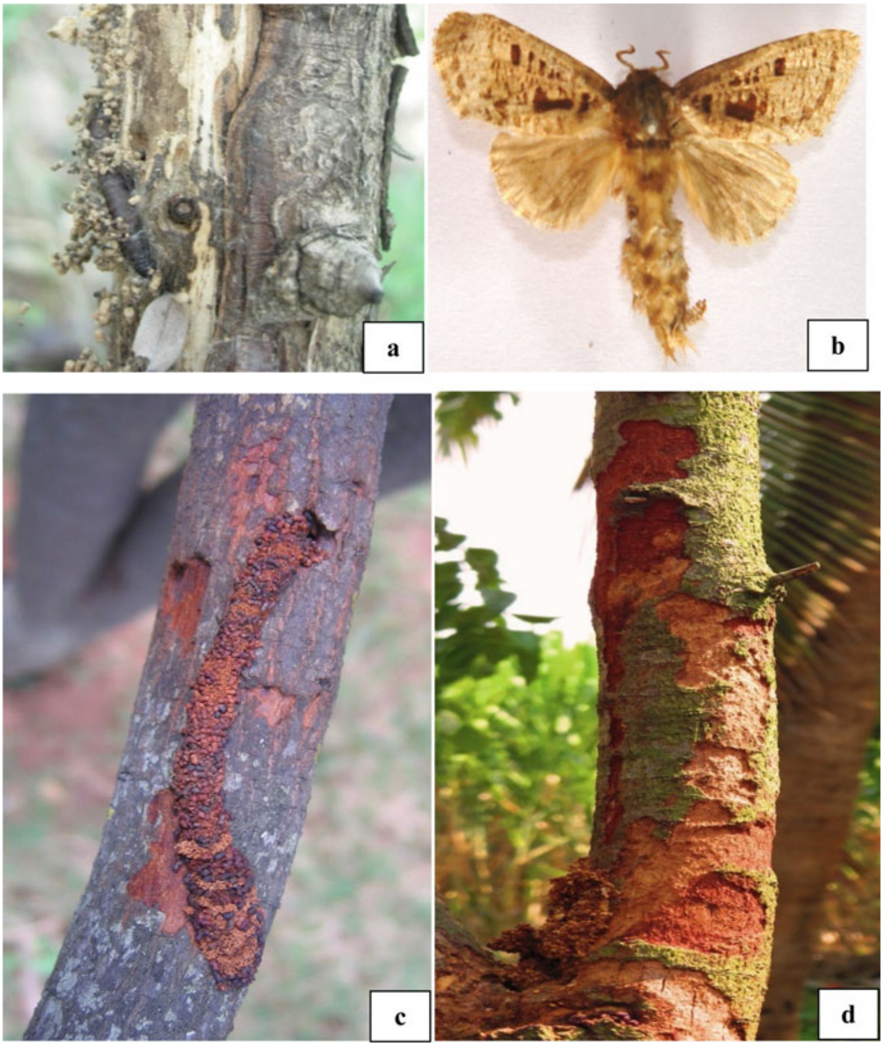

Fig. 10.4 *Indarbela quadrinotata* Walker (**a**) Larva feeding on Bark; (**b**) Adult; (**c**) Ribbon like larval fecal mass; (**d**) Sever bark damage

8. ***Sahyadrassus malabaricus* Moore:** It is a common sapling borer of many tree species. The larvae enter into the stem of young saplings by making boreholes and excavate a long cylindrical tunnel along the pith, sometimes extending to tap root resulting in the death of the saplings or breaking of the stem at the point of attack (Nair, 1987). The mouth of the tunnel is covered by a mat work consisting of coarse sawdust-like particles of wood and bark, spun together with silk secreted by the larva. Eggs are cream-colored when laid, turn into black

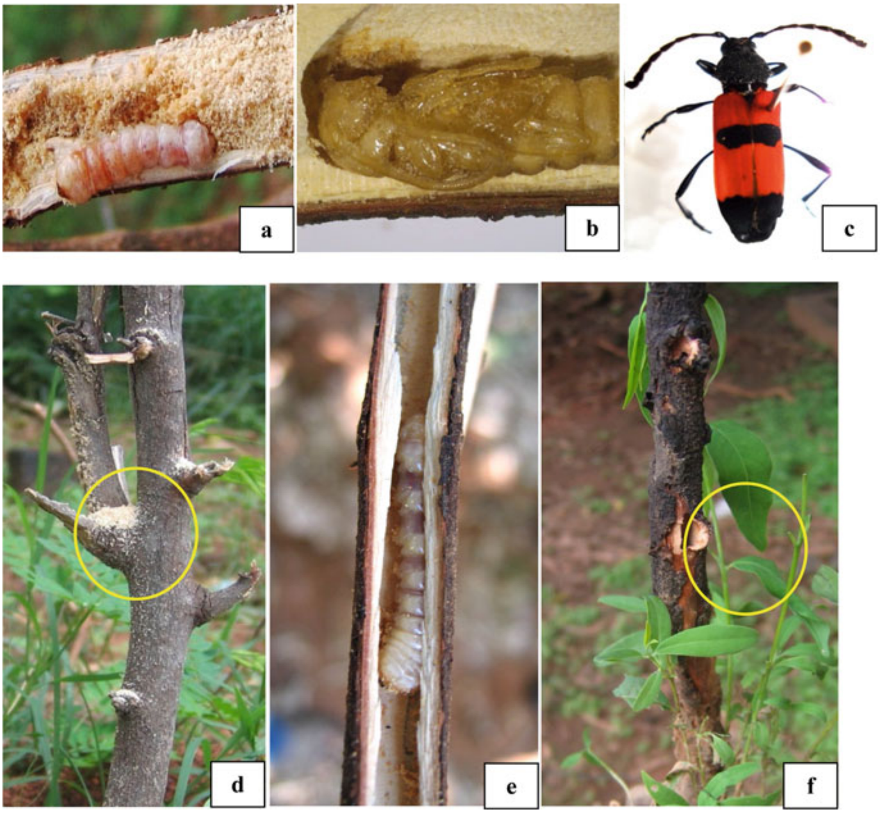

Fig. 10.5 *Purpuricenus sanguinolentus* Olivier (**a**) Larva; (**b**) Pupa; (**c**) Adult; (**d**) Fine fecal powder of larvae; (**e**) Severe tunneling by larva; (**f**) Emergence hole

gradually, and are believed to be broadcast by the female moth during flight. Full-grown larvae are large, conspicuous measuring 8 to 10 cm in length. They are yellowish-white in color with deep black head capsule. The larva retreats to the bottom of the tunnel for pupation. The moths are large and grayish brown with a wingspan of about 11 to 12 cm and body length of 5 to 6 cm (Rishi et al., 2018). Antennae are bare and pointed, with 22 visible segments. Legs are flattened and possess characteristically arranged tufts of hairs. Two black, well-developed claws are present in each leg. The third pair of legs is atrophied and is only about 1.5 cm long—about two third lengths of the first two pairs. In the male, the third pair of legs possesses scent-producing glands. They produce a sharp pungent smell, which apparently attracts the female for mating (Nair, 1987; Rishi et al., 2018).

9. ***Polyphagozeuzera coffeae* Nietner:** It is commonly known as red stem borer, a polyphagous pest, and commonly found on sandalwood. Larvae bore into the terminal part of the woody stems and branches, and make tunnels along the pith.

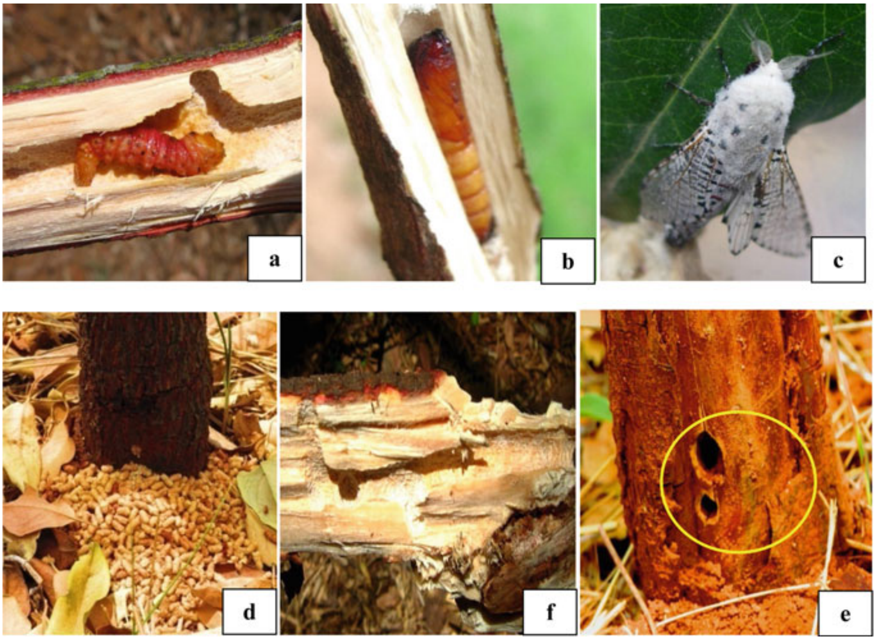

Fig. 10.6 *Polyphagozerra coffeae* Nietner (**a**) Larva feeding on heartwood; (**b**) Pupa; (**c**) Adult; (**d**) Fecal pellets of larvae; (**e**) Severe tunneling by larva; (**f**) Emergence hole

The presence of frass around the entrance hole and on the ground below due to larval feeding is a good indication of attack. Affected parts may be completely hollowed out, leaving a thin layer of wood and bark (Mannakkara, 2006). The eggs are laid in crevices in the bark of host plant and appear as ropy masses. It measures 1.2 ~ 1.4 mm long, 017 ~ 018 mm wide, oval in shape, and yellowish to ivory in color. Unfertilized egg is darker in colour. The eggs hatch in about 10 days (Feng et al., 2000; Kalshoven, 1940). Upon hatching, larvae move along the stem. Full-grown larvae are dark red in color and measure 35 to 50 mm long and 4 to 5 mm wide, with a brown shield on the thorax (Waller et al., 2007). The cuticle is tough, and the first thoracic segment and anal segment carry heavily sclerotized black shields. The mature larvae pupate inside larval gallery. Pupae are obtect type and brown in colour. The adult is a yellowish-white moth with black spots on the wings (Fig. 10.6). The moth is about 20 to 30 mm long with wingspan of 40 to 50 mm, and it is a strong flier. Life cycle may take 4 to 5 months depending on the climatic factors (Mannakkara, 2006).

10. ***Stenodryas nigromaculatus* (Gardner)**: It was reported infesting sandalwood (Fig. 10.3c) in south India which was earlier known to infest *Albizia procera* (Sundararaj et al., 2019b).

10.2.2 On Deadwood and Stored Logs of Sandalwood

1. ***Sinoxylon atratum atratum* (Wasmann):** It is commonly called as powder post beetle. It causes considerable damage in the stored wood. These bore very deep in the wood galleries reaching toward the center (Mathew, 1982). It has also been reported from dying saplings of *Artocarpus hirsutus* Lam. and sandalwood (Remadevi, 2012). The beetle is dark brown in color and measures 3 to 4 mm. Head is punctuate and finely rugose. Prothorax is transversely ridged, with the anterior part rugose bearing rasp-like structures. Laterally, 4 teeth-like structures are present, of which the innermost three are the longest (Mathew, 1982).
2. ***Xylopsocus capucinus* Fabricius:** It is commonly known as false powder post beetle. It damages already damaged wood due to lighting, cold, or another insect injury. The adults bore into the wood in order to lay eggs, leaving a hole larger than 1/8 in., usually in wood less than 10 years old. The larvae are curved and wrinkled. Their diet is dependent on the starch in the wood, more common in softwoods, but can attack hardwoods. The adult length ranges from 3 to 5.5 mm and width from 1.4 to 1.7 mm. The body color particularly the elytra, venter, antennae, and palpi is black or reddish. The apical elytral declivity (sloping) is abruptly, obliquely deflexed, flattened, without tubercles or callosities (swollen lumps). The lateral margins of the declivity are strongly elevated, crenulate (margin notched with small rounded teeth) toward top, and completely enclose the declivity (UF/IFAS).
3. ***Xylocopa latipes* Drury: As** commonly known as tropical carpenter bee, it is a serious pest, especially in the depots where sandal sapwood is stored. It reduces the quality of the wood and the wood is tunneled into fine powder (Remadevi, 2012).
4. **Other Suspected Wood Borers:** Recently, two cerambycids viz. *Clytocera chionospila* Gahan (Fig. 10.2b) and *Moechotypa asiatica* Pic. (Fig. 10.2c) were encountered in sandalwood and detailed studies may reveal their role of infesting and degrading sandalwood.

10.3 Termites Feeding on Sandalwood

Termites are one of the major biodeteriorating agencies, since wood cellulose is the major food source and attacks both dead and live woods. Arboreal termites namely *Odontotermes brunneus* (Hagen), *Coptotermes heimi* (Wasmann), and *Megachile fletcheri* Cockerell attack standing trees and dead logs of sandalwood (Fig. 10.7). In growing trees, mud plastering and feeding the dried bark by termites are an annual phenomenon without causing any damage to the trees, but in a wound/prune induced dried part of the tree, the termites feed the dried part, and such feeding often leads to the loss of bark, poor health, and also susceptible to fungal infections and other insect damage (Remadevi, 2012).

Fig. 10.7 Termite attack in stored sandalwood logs

Fig. 10.8 (**a**, **b**) Heartwood rot decay of sandalwood; (**c**) *Ganoderma* outgrowth on sandalwood

10.4 Fungal Decay on Sandalwood

10.4.1 In Sandal Logs

Sandalwood after removal or extraction from the natural stands is stored in depots for sale or rarely before transportation to depots; they are left in forest damp soil. During the intervening period of stacking and final clearing at sandal kotis, they are exposed to various elements and environmental conditions, which provide ideal condition for attack of decaying organisms like fungi, bacteria, slime molds, and insects resulting in damage of sapwood and heartwood in various levels (Fig. 10.8a, b). Various fungal species collected from sandalwood in log and also from extracted trees from forest before transportation to depot are listed below (Nayar et al., 1980):

1. ***Hexagonia discopoda* Pat. et Har.** (Fungi: Basidiomycetes, Aphyllophorales): This causes brown cubical rot, a common cause of decay of timber exposed to weather, but can occur as a wound parasite of weak trees, growing in unfavorable localities. It produces a dark brown stain in the initial stages of the attack and thin papery sheets of mycelium are formed continuously, in parallel strands along the radial cleavages. The wood separates with mycelia sheets attacked to the radial surfaces. The sporophores are formed on the stem of the dead tree, are sessile, semicircular, 10 to 25 cm across, and corky when wet but hard and brittle on drying, crusty above, of brown shades. Hymenium is pinkish with hexagonal pores.
2. ***Polyporus sulphureus* (Fr.) Murril.** (Fungi: Basidiomycetes, Aphyllophorales): It causes brown cubical rot and a parasitic decay organism is felled timber and on wood in service. During early stage, yellowish to red discolouration develops, and later, the wood turns deep reddish-brown and breaks up into cubical pieces, with cracks filled with mycelium. Sporophores are annual, imbricated in groups, thin, bracket-shaped with wavy margins, 5 to 20 cm across, orange above, and color fading with age. Flesh is soft, soon decomposes, and pores are rounded to dentate.
3. ***Polyporus sanguineus* Klotzch.** (Fungi: Basidiomycetes, Aphyllophorales): This causes white rot; it is saprophyte on the wood but occasionally, and it is reported as a wound parasite.
4. ***Ganoderma applanatum* (Wallr.) Pat**. (Fungi: Basidiomycetes, Aphyllophorales): This causes white mottled rot and is a common saprophyte but has also been reported as a wound parasite in various perennial crops causing decay. During early stages, the decay is seen as white mottle. The sporophore is a broad, flat, bracket, 10 to 40 cm, imbricated or zoned, gray to rusty brown; spores ferruginous; growing margin white; flesh brown, firm silky, fibrous.
5. ***Ganoderma lucidum* (Leyss.) Karst.** (Fungi: Basidiomycetes, Aphyllophorales): It causes white spongy rot, attacking roots and spreading to the basal part of stem; sporophore develops mostly when tree is killed and is recognized by red color and shining varnish-like crust.
6. ***Trametes corrugata* (Pers.) Bres.** (Fungi: Basidiomycetes, Aphyllophorales): This causes white spongy rot; sporophores are conchate, overlapping, 10 to 12 cm, glabrous, rugose, dark reddish-brown with fertile margins.
7. ***Irpex flavus* Klotzsch** (Fungi: Basidiomycetes, Aphyllophorales): It is a common saprophyte, but rarely found wound parasite, causing a soft decay of heartwood.
8. ***Poria incressata* (Berk. and Curt.)** (Fungi: Basidiomycetes, Aphyllophorales): It causes root rot, forming effuse mats, hard and brittle on drying, white above; wood becomes soft and crumbles to the touch.
9. ***Auricula tiales*** (Fungi: Basidiomycetes, Auriculariales): It is commonly known as wood ear. Sporophore russet red when fresh and are grouped on the surface of the wood. They emerge through borer holes, and only the sapwood is affected.

10.4.2 In Standing Tree

Most heartwood rots arise by the invasion of the heartwood fungi that decompose and utilize cellulose and lignin. They generally form prominent fruit bodies from which air-borne spores are liberated and invade the hosts frequently through wounds. There are many fungi causing decay in the heartwood of standing trees (Soni et al., 2010). Overgenerous irrigation to mature sandalwood trees will harbor the fungal diseases *Phytophthora* and *Pythium*. *Phytophthora* infects only roots, but not other tree tissues. The dieback fungus infects tree roots and kills trees by cutting off their water supply. The tree responds initially by dropping its leaves and then slowly dies of drought (Done et al., 2004). Dieback fungus can be controlled by conservative applications of water based on soil moisture monitoring and aerial application of suitable fungicide to more susceptible areas (TFS Sandalwood Project, 2007).

Soni et al. (2010) noticed fruiting body of the causal heartwood rot fungus *Phellinus caryophylli* on the surface of punk knots. Major symptoms of heartwood rot are appearance of punk knots on main stem originating from different depths of sapwood and heartwood. Barbour et al. (2010) studied the heartwood rot and its impact on oil levels in the heartwood of sandalwood and isolated two groups of fungi belonging to Basidiomycetes and Ascomycetes from infected area. They were closely related to *Ceriporia* and *Irpex, Fomes,* and *Ganoderma* (Fig. 10.8c)*, and Phellinus* or *Peniophora* of Basidiomycetes. Ascomycetes are *Fusarium solani, Lasiodiplodia, Neoscytalidium dimidiatum,* and *Pseudofusicoccum adansonia.* They concluded that fungi entered either from root infection via the primary wood or from wounds made during pruning or when branches are damaged due to sunscald and mechanical damage. The fungal disease via the primary wood from the base of the tree appeared to have a positive effect on sandalwood oil production. However, infection via the sapwood reduces the economic viability of the tree crop. Following entry, the heartwood rot infection spreads and reduces the economic viability of the tree crop. The inner region of the infected wood degraded to such an extent that hallow often formed to provide an entry point for other pathogens and pests viz. ants and termites. Fungal infection hypothesized that primary infection does not kill the tree but, secondary infection damages the tree and kill, particularly termites.

The presence of heartwood rot can have both economic and environmental impacts. Initially, the infected wood is discoloured as the fungi grow, cellulose is broken down, and wood tissues become soft and weak. The tree can still grow around decayed wood. As such, sandalwood trees are hard and wood-rot killing is very rare, and care should be taken for the protection of the bark, especially near the base of the tree to reduce the risk of bark damage (Barbour et al., 2010). Though such trees may continue to live for some time, yet heartwood may not be available for extraction. In central India, these factors included as a decline factor and most of the material sandalwood trees are died due to canker and heartwood rot problems (Soni et al., 2010).

Sandalwood trees appear to have second mechanism to protect itself against fungal attack. Trees appeared to respond to fungal infection by encapsulating the area with darker ring of aromatic wood. Oil analysis using gas chromatography has confirmed that the tree responds to fungal attack by trying to encapsulate the fungal infection with sesquiterpenes, the key constituent of sandalwood oil. The sesquiterpenes produce tree and help in protection from fungi. As these compounds only develop as the tree matures, early care of Indian sandalwood trees until sandalwood oil is deposited in the heartwood is a key factor affording fungal disease resistance and maintaining the commercial potential of the plantations (Barbour et al., 2010).

Burgess et al. (2014) reported that pruning provides easy entering of fungal pathogens on sandalwood and potentially compromises the heartwood as the tree grows. The presence of the pathogens can have a strong economic impact, by limiting the growth of the tree and subsequently reducing heartwood development and also oil production. Smaller the pruning wound, there is a less chance of infection. Wounds on younger trees were rapidly occluded. However, within occluded pruning wounds, canker fungi were isolated in 70% of samples and rot fungi were isolated in 10% of samples. Therefore, an occluded wound is not necessarily pathogen-free and rot may develop in time. It also confirmed that pruning wounds are an entry pathway for canker and rot fungi, and even if the wound is occluded, the rot may already be well established internally.

10.5 Economic Losses Due to Biodeterioration of Sandalwood

Sandalwood is sold by weight but not by volume and the present value of sandalwood (Arun Kumar et al., 2012), and presently, it is second costliest wood in the world, and hence, during extraction even the sawdust is systematically collected.

The increase in the incidence of stem borers is of great concern as it causes very extensive and serious damage in perennial trees like sandalwood. Once they are infested with stem borers, it pays way for the infection of decay fungi. Most of the time, their infestation goes unnoticed, until the tree dies or shows external signs of damage. The affected trees show poor growth and poor quality of timber, which will affect the revenue directly (Sundararaj et al., 2019b). The affected trees show less resistance to diseases and natural calamities. Breaking of shoots by winds often facilitates entry of pathogens/microorganisms (Sundararaj, 2014). Sundararaj (2011) commented that the continued influx of insect pest on sandalwood from agricultural and horticultural environments forms a major threat to conservation and protection of sandalwood trees. Chemical, physical, and morphological modifications produced by unfavorable environmental conditions along with biodeterioration can result in loss of wood quality (Blanchette, 2000; Ciferri, 2002; Huismana et al., 2008).

The annual global sandalwood production is estimated to be approximately 5610 tones, which has declined markedly over the past 20 to 30 years. India's production during 1930s through 1950s was around 4000 tons of heartwood per year, which had decreased to meager 400 tons of wood per year (Gowda et al., 2008). Maximum quantity of 27,930 kg sandalwood oil has been exported in 1997–98, which has been reduced to 2330 kg in 2019–20 (Export Import Data Bank Version, 2021). It was estimated that an average of 198.6 kg of heartwood was lost for every tone of wood produced by sandal trees and more than 25% of logs reaching the depot are with hollow wood (Remadevi & Muthukrishnan, 1998). In India, it has been estimated that 33% of the timber produced is lost due to various biodegrading agents (Sen-Sarma et al., 1975). The heartwood loss ranging from 22.6 to 34.5% was reported during extraction, and this loss might be attributed due to the adverse effect of pruning and other mechanical injuries inducing infection of decay fungi and infestation of stem borers (Sundararaj et al., 2019b).

10.6 Management of Biodeteriorating Agents

Many trees in plantation or natural forest are less susceptible to pest attacks. It is pragmatic to choose resistant trees, either in the plantations or in the natural forest to raise new plantations, and thus, the damage in plantations can be minimized (Mannakkara, 2006). Injured and stressed trees are more susceptible to pest attacks, so it is essential to maintain healthy trees through proper water and nutrient management. Removal of larvae in the initial stage of attack and destroying egg masses and caterpillars and also removal of excess weeds are recommended. Avoiding pruning and any mechanical damage (Fig. 10.9a, b, c), since these wounds attract more damaging pest for egg laying, acts as a site of oviposition (Howard, 2001; Sundararaj et al., 2019b). Harvesting a deteriorated tree by proper and timely diagnosis can prevent further loss of wood. Stocking the sandal logs on cemented dry platforms where termites/fungi cannot attack the wood is essential (Remadevi, 2012).

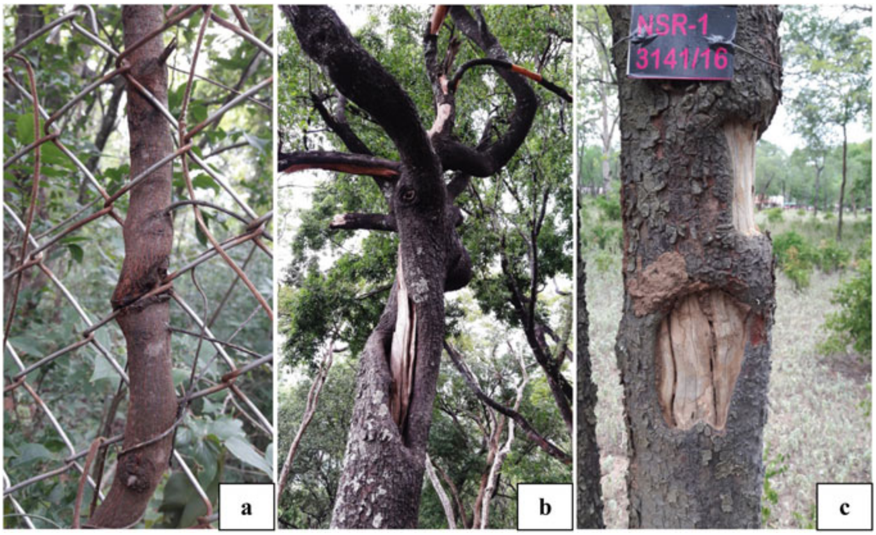

Fig. 10.9 Mechanical damage-inducing fungal decay. (**a**) Wire fencing; (**b**) pruning; (**c**) bark scrapping for numbering

Many pesticides and insecticides are used to control the pest population. Plants in affected pocket may be sprayed with a systematic insecticide recommended for stem boring caterpillars. The spray should be directed to the main stem and the thicker branches. Two or three repeated applications are required (Mannakkara, 2006). Some systemic insecticides have proven effective against some boring insects, but most will not kill larvae already in the tree, especially most destructive wood-boring larvae. Chemical control is usually limited to the short period of time when the adult or newly hatched larvae are exposed on the bark and before they enter the tree. In most of the cases, spraying chemicals will not control wood-decaying fungi. Eliminating moisture sources and replacing decayed wood, mostly the removal of moistened bark, air drying, and removal of sapwood, are recommended (Remadevi, 2012). Rawat et al. (2018) reported neem oil containing azadirachtin, and it is recommended as a main antifungal compound against *Fusarium* sp.

Biological mode of control of borers is more encouraged in order to attain sustainable and environmentally compatible pest management. It includes the use of natural enemies like predators, parasitoids, or even entomopathogens. Caterpillars are less exposed to predators because they live and feed inside the stem. But certain spiders and insects may prey on eggs and newly hatched larvae before they enter to the host plant. Insectivorous birds may help to reduce the adult population (Mannakkara, 2006).

10.7 Conclusion

In India, viable sandalwood trees are commercially extinct due to illegal harvesting and overexploitation. Commercially utilizable trees are hardly available, and it is also experiencing considerable loss of valuable heartwood of sandalwood due to biodeteriorating agents like borers, termites, and fungi combined with extreme climatic conditions and poor maintenance of sandalwood both in plantation and in stored logs. Sandalwood being a second most costly and high-valued wood in the world adequate attention needs to be taken, to prevent loss of sandalwood by managing biodeteriorating agents in living trees and in storage. Protection of trees from termite, fungal, and borer attack employing physical and biological methods needs greater attention to reduce the wood deterioration in trees. The policy of leaving trees for harvesting only after a certain age has to be reviewed as the retention of affected trees in situ only aggravates the deterioration. Harvesting a deteriorated tree by proper and timely diagnosis can prevent further loss of wood. The stocking conditions also contribute to termite and fungal decay. Hence, stocking sandal logs should be on cemented dry platforms where termites/fungi cannot attack the wood. Prevention and protection from biodeterioration and proper maintenance can contribute to better yield and quality of the valuable sandalwood.

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Insect Borers of Bamboo and Their Management

11

George Mathew

Contents

Abstract

Information pertaining to the insect borers of bamboos is presented. Of the various borers infesting live bamboo, the weevils, *Cyrtotrachelus buqueti* Guer., *C. longimanus* Fb., *C. dux* Boheman, and the bamboo Hispine borer, *Estigmena chinensis* Hope were the most important. Regarding borers associated with harvested culms, the powder-post beetles, *Dinoderus minutus* Fb. and *D. ocellaris* Stephens, caused severe damage to stored culms. Information pertaining to the biology, ecology, and possible management of various bamboo borers is presented.

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_11

Keywords

Bamboo borers · Bamboo borer management · India

11.1 Introduction

In India and in many other Asian countries, bamboos are extensively planted to meet rural and industrial raw material requirements. Bamboos have great ecological significance since they provide habitats for a variety of organisms including insects, spiders, reptiles, birds, and mammals. Of these, insects form the major group with over 800 species being recorded from bamboo from Asian countries. From India, over 270 species of insects have been reported (Browne, 1968; Singh, 1988; Chakrabarti & Maity, 1980; Sohi et al., 1980). Remadevi and Revathi (2013) listed a total of 272 species of herbivores falling in 56 families of 9 orders on growing bamboos in India. Although several insect species have been reported on bamboo, very rarely they cause any serious damage in the natural bamboo stands although the plantations are often affected by various insect pests that feed on foliage, suck sap from the plants, or bore into the shoots or culms. Infestation by insects may affect plant vigor leading to mortality of plants thus affecting the productivity. Stored culms and various bamboo products are also affected by various borers. Of the various categories of insects attacking bamboo, the shoot or culm borers are economically very important. Insect borers affecting bamboos can be broadly divided into two categories – those attacking live plants and those attacking harvested culms or various finished products. An account of important insect borers of bamboos in India and their possible management is presented in this paper.

11.2 Insect Borers Associated with Live Bamboo

Beetles are the important stem borers of bamboo. Four species of Curculionidae and two of Chrysomelidae are associated with live bamboo. The former includes the weevils *Cyrtotrachelus buqueti* Guer., *C. longimanus* Fb., *C. dux* Boheman, and *Myocalandra exarata* Boheman, and the latter include the Bamboo Hispine borer (*Estigmena chinensis* Hope) and the Bamboo stem beetle (*Sagra femorata* Lichtenstein). Brief accounts of these beetles are given below:

11.2.1 Bamboo Shoot Weevils

About 18 species of weevils have been recorded to attack bamboo shoots. Of these, *Cyrtotrachelus buqueti* Guer., *C. longimanus* Fb., *C. dux* Boheman, and *Myocalandra exarata* Boheman are the important weevils attacking live bamboo shoots in India (Fig. 11.1a,b,c). While *C. buqueti* prefers culms of smaller diameter (less than 2 cm), *C. longimanus* prefers larger culms. Both larvae and adults bore

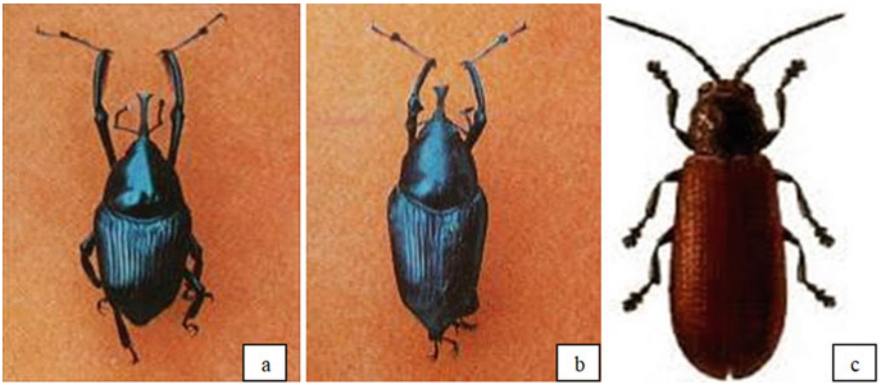

Fig. 11.1 Insect borers attacking live bamboo: (**a**) *Cyrtotrachelus buqueti*; (**b**) *Cyrtotrachelus longimanus*; (**c**) *Estigmena chinensis.* Courtesy: Haojie et al. (1998)

holes on bamboo shoots and the damage caused by them usually leads to mortality of shoots, deformation, or stunting. These weevils which are commonly found on bamboo shoots during May to October are brownish in color with cream-white, apodus grubs. Larvae bore vertical tunnels within the culms starting beneath or near the culm sheath passing internally through several internodes and ending in a hollowed and dead terminal shoot. A single larva can destroy a culm and induce development of multiple shoots of little commercial value (Haojie et al., 1998). Fully mature larvae drop to ground and undergo pupation in the soil. The life cycle is annual with the adults over-wintering in cocoons in the soil. Digging and removal of damaged culms have been recommended to control the weevils (Dayun & Shaojin, 1987). Keeping the culm density low has also been suggested since the infestation is less in well-thinned areas (Singh & Bhandari, 1988). Mechanical control by collection and destruction of beetles at the beginning of Monsoon has been suggested by Beeson (1941). Nanxing et al. (1988, 1989) have recommended the use of nematodes. *M. exarata* which attack *Bambusa polymorpha* and *Dendrocalamus strictus* is considered as a pest of minor importance. The weevils that emerge during February to June bore longitudinal tunnels in the intermodal region. Culms already damaged by other borers are generally attacked. Cutting and disposal of attacked culms has been recommended for its control (Beeson, 1941).

11.2.2 Bamboo Hispine Borer

The bamboo Hispine beetle *Estigmena chinensis* Hope is an important culm borer of live bamboo (http://www.csdyzx.com). This insect, distributed in India, Bangladesh, Malaysia, and Myanmar, has been reported on *Bambusa bambos, B. burmanica, B. nutans, Gigantochloa scortechinii, Schizostachyum pergracile,* and *Dendrocalamus strictus.* This is an important pest of bamboo shoots and young culms in natural stands and plantations. Attack generally occurs during the initial stages of culms growth and there is one generation in a year (Beeson, 1941; Roonwal, 1977). Eggs are deposited on the surface of internodes in groups and the larvae feed beneath sheaths and later bore into the inner wall of the shoot, boring downwards and excavating tunnels. The beetles on emergence remain within the tunnels till the onset of the monsoon. Removal of damaged culms, maintaining low culms density and manual destruction of beetles, has been suggested for its control. Removal of dead or split bamboos that provide shelter to the beetle has also been suggested to minimize attack by this borer.

11.3 Post-Harvest Pests of Bamboo

In the context of acute short supply of timber in India, bamboo is being looked upon as a potential alternative to wood for many applications. Besides paper and rayon pulp, bamboo has also proven its suitability for other industrial products such as boards, paneling, furniture, and handicrafts. The ligno-cellulose material of bamboo resembles wood in many technical properties and hence can be utilized as a substitute to wood for the manufacture of many of these products. However, the major problem with bamboo in contrast with durable woods is perhaps its high susceptibility to beetle borers and termites during post-harvest period.

11.3.1 Powder-Post Beetles

Harvested culms and finished products are often heavily attacked by insect borers leading to considerable economic loss. In general, infestation of beetle borers is dependent on the technical properties of the culms. It is generally found that the maturation changes involving cell wall thickening and lignification of tissues are complete when the culms attain 3–4 years of age. The insects attack the culms for the nourishment it contains. Starch, carbohydrates, and proteins are the substances that attract insect borers. Of the various insects attacking harvested bamboo, the bostrychid and lyctid borers are the most important. *Dinoderus minutus* Fb., *D. ocellaris* Stephens, *D. brevis* Horn., and *Heterobostrychus aequlis* Waterhouse belonging to Bostrychidae (http://www.plantwise.org; http://www.nqccs.com.au) as well as *Lyctus africanus* Lesne, *L. brunneus* Steph., and *Minthea rugicollis* Walker belonging to Lyctidae (http://www.city.nagoya.jp) are the important post-harvest pests of bamboos in India (Fig. 11.2a,b,c,d). Although all these beetles have similar habits, the *Dinoderus* beetles cause the major damage and are responsible for 90% of damage to stored bamboos. Adult beetles enter the culms through the cut ends. The beetles make horizontal tunnels in which the eggs are deposited. Larvae bore longitudinally in the culms with the tunnels crisscrossing in heavy infestation. Pupation occurs within the tunnels in pupal chambers and the adults that hatch out bore their way out. Both adults and larvae of this insect feed inside felled culms feeding on starch stored in culm tissues reducing a stack of bamboos into a powdery mass of frass within a few weeks.

Fig. 11.2 Some important powder-post beetles attacking bamboo: (**a**) *Dinoderus minutus. B*y Desmond W. Helmore – Manaaki Whenua – Landcare Research, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=72865519; (**b**) cross section of bamboo showing damage by Dinoderus beetles; (**c**) *Lyctus africanus,* Courtesy: Ken Walker, Museum Victoria; (**d**) *Minthea rugicollis,* Courtesy: Wisut et al. (2009)

Investigations on infestation by *Dinoderus* beetles have shown that starch content of the culm is a predisposing factor for borer attack. The damage caused is proportional to starch stored in the culms which is detected by the beetles immediately after the culms are felled and assembled for drying and storage. *Bambusa vulgaris* which has the highest amount of starch is highly susceptible. Culm age was found to influence the abundance of starch in the tissues. Usually, young growing culms contain higher levels of starch while flowered bamboo with starch completely depleted is found to be resistant to borers. On the contrary, there are some reports to show the absence of a definite relationship between culm age and accumulation of starch in the tissues (Bhat, 2003). Similarly, different portions of the culms show different levels of susceptibility on account of differences in the starch content. Generally, the nodal portions of the culms and the septa contain higher level of starch. Similarly, the upper parts of the culms contain higher quantities of starch compared to the lower parts. It is found that bamboo harvested during summer is more rapidly destroyed than those felled after the rainy season as the latter has less starch (Liese, 1985, 1988). Some workers have suggested suitable 'low starch periods' for harvesting bamboos with a view to minimize the borer problem (Beeson, 1941). Observations by Sulthoni (1996) on traditional harvesting period of April–May in East Java also support this finding. Similarly, some observations have been made in India which shows that the beetle damage is lower during the rainy season mainly because of the unsuitability of the season for borer establishment. Besides the low starch periods which offer higher resistance to bamboo, there are also some popular beliefs in rural areas regarding timing of the harvesting to minimize borer damage. In Bihar and Orissa, it is commonly believed that bamboo felled in the bright phase of the moon is less susceptible than when it is felled during the dark phase. In some places, the opposite is the belief. Experiments conducted in India showed that there is a cycle of moisture percentage increasing from full to new moon and decreasing from new to full moon. The starch content, on the other hand, did not show any change with respect to lunar month. Experiments have shown that there is no scientific proof to this belief.

The most striking feature of *Dinoderus* infestation brought out by observations over several years is that their infestation is highly unpredictable. Infestation has been reported practically in all the months of the year, at one place or another, but not continuously in the same place. Often within a storage yard, infestation may be confined only to some of the stacks. Some of the infested stacks that contained fresh-cut reeds may not be attacked at all while the older stacks may be attacked, thereby showing that the freshness of the material was not the sole factor promoting borer infestation. It has been generally observed that infestations at particular sites declined in intensity and almost disappeared in about 2 or 3 months after their first appearance, although this was not always the case. In addition to stacked whole reed culms, finished products made of reed or bamboo are also often damaged by *Dinoderus.* These included reed mats stored in godowns, reed or bamboo baskets stored in retail shops and houses as well as various handicrafts made of bamboo.

Besides *D. minutes,* another bostrychid, *Heterobostrychus aequalis* also occasionally attacks freshly cut culms and the pattern of tunneling is more or less similar to that of *Dinoderus.* Finished products are often affected by the lyctids *Minthea rugicollis* and *Lyctus africanus* making rambling tunnels and causing serious damage (Beeson, 1941). Fumigation of infested material using sulfuryl fluoride at the rate of 30–35 g/cum for 24 h will be effective to control infestation of these beetles.

11.4 Management of Infestation by Powder-Post Beetles

11.4.1 Conventional Methods

As has been stated earlier, starch, carbohydrates, and proteins are essential for the establishment of *Dinoderus* beetles. The borer incidence has strong correlation with the amount of nutrients available in felled culms which vary significantly with the bamboo species, growing sites, culm age, felling season, and the mode of transport. Considering these aspects, some preventive measures have been developed against these borers. As they get older, culms will have less soluble carbohydrates, proteins, and moisture. Similarly, culms will be physiologically less active during winter or during rains when they are more resistant to borer attack (Nair et al., 1983). Hence, harvesting of 3–4 years old culms and felling at winter or rainy season are generally recommended. In Indonesia, harvesting of culms, 1 week after full moon is practiced since it is believed that during this period the nutrient flow will be less. Mathur (1961) reported clump curing which involves cutting the culms at the base and leaving them vertically leaning against other culms in the clump for 4 weeks to bring down the starch level. Other traditional methods include heating of culms in fire or boiling water, smoking, burying the culms in beach sand, curing in sea water, or application of slaked lime. Submersion in water and curing in the clump are reported to decrease the starch content stored in culms tissues. Immersion in water for 4–12 weeks leads to leaching out of soluble materials in the culms that make it unacceptable to borers. In Bangladesh, a method of mud curing is practiced in which freshly cut culms are soaked in muddy pond for 1–8 weeks and then slowly dried in the shade (Chowdhury, 1993). Treating the culms in boiling water for 15–60 min is reported to be effective in leaching out starch. In China, treating bamboos infested with *D. japonicus* under high pressure steam (5 lb. at 108 ° C for 10 min) or soaking in hot water was effective in controlling the beetle. In Japan, the culms are smoked at 50–60 °C usually using the leaves of felled bamboo. Smoking is believed to deposit toxic substances and destroy the starch in the culm tissue and thus resisting degradation (Hidalgo-Lopez, 2003). Prior to smoking, the culms are perforated in such a way that the holes are scattered and not in a line. Heating the culms in open fire or in special heating chambers can also be carried out (http://www.trada.co.uk/-). Momentary exposure of culms to temperature as high as 150 ° C has been suggested, but there is a risk of culms splitting due to heat.

11.4.2 Chemical Treatments

Application of various preservatives, repellents, and pesticides has been tried for bamboo protection. Traditional chemical methods of treatments are mostly intended to ward off the insects either due to repellent or toxic nature of the chemicals used. Slaked lime, mud, cow dung, motor oil, diesel, kerosene, varnish, tar dissolved in wax, naphthalene, formalin, etc., have been used to prevent borer infestation. Various pesticides such as BHC, DDT, dieldrin, Metacid (Methyl parathion), 0.5% Thiodan (Endosulphan) 0.75% with diesel oil have been tried in the past to control bamboo borers. Varma et al. (1988) tested the effectiveness of various commercial formulations of insecticides and concluded that BHC and two pyrethroids – cypermethrin and permethrin – were effective. Semi-finished bamboo products can be treated by soaking in 2% aqueous solution of boric acid, 0.5% pentachlorophenate,and 5% alcohol (Haojie et al., 1998). Mori and Hideo (1979) reported that prothiophos and phoxim – two low-toxicity organophosphides – were more effective than organochlorine ones for preservation of bamboo materials. Treating bamboo splits by immersing in 0.2% phoxim for 3 min can result in total mortality of *Dinoderus* beetles present inside and will afford protection for nearly 1 year. Soaking in an aqueous solution of methamidophos or 0.033–0.001% trichlorphon (Dipterex) for 8 h is recommended for controlling *D. japonicus* in China (Chang, 1979). Application of neem oil or cypermethrin 0.4% in diesel oil at the cut ends and on the surface has been reported to be effective. Chemical treatments using various wood preservatives have also been recommended.

Various chemicals such as borax:boric acid in 5:1 ratio, 5% water solution of copper-chrome-arsenic (CCA), copper-potassium dichromate-borax (CCB), boric acid-borax-sodium chlorophenate (BBP) (in 1:1:5 ratio), 2–3% solution of borax: boric acid in 5:1 ratio, or 10% or 20–25% water solution of copper sulfate are used in preservative treatments. In the Boucherie method, the preservative chemical is pumped into the culms. For this, the septa of culm segments (except the last septum) are pierced with a long, pointed iron rod and the preservative is pumped into the cavity (http://www.guaduabamboo.com). The treated poles are stacked vertically for 7–8 days after which they can get dried in the open. Usually, 2–3% solution of borax:boric acid in 5:1 ratio is used for treatment. Bamboo can be treated by immersing in the treatment solutions kept in a treatment tank under normal temperature. For efficient uptake of the preservatives, the solutions may be heated, or treatment carried out under high pressure (Singh & Tewari, 1979). Remadevi et al. (2013) reported fumigation with phosphine to be effective in managing *D. minutus* infestation in finished products. Fumigation of infested material using sulfuryl fluoride at the rate of 30–50 g/cum for 24 h has also been undertaken for protection from borers. Microwaving and infra-red techniques are also in use.

11.5 Termites

Apart from beetles, termites are also often a serious problem to stored bamboo and bamboo products. Termites are of two major types – subterranean termites which form nests in the soil or dry wood termites which nest in various woodworks. The subterranean termites live in nests formed below ground and reach woodwork through earthen tunnels. The wood inhabiting termites make nest within cavities formed in the wood. One of the signs of infestation by dry wood termites is the tiny, round particles coming out of the affected wood. The American powder-post termite, *Cryptotermes dudleyi* Banks (Isoptera: Kalotermitidae) is an introduced species found in several parts of India. *Odontotermes feae* Wasm. (Macrotermitidae), *Coptotermes heimi* Wasm., and *Microtermes fletcheri* Holmg. (Rhinotermitidae) are some of the termites causing damage to bamboo.

11.6 Management of Termite Infestation

Adoption culms of preventive measures such as storing bamboo on raised platforms without touching the soil and carrying out prophylactic treatment to avoid termite infestation. Various termiticides such as Chlorpyriphos (15–20%), Imidacloprid (Premise 30.50 SC) 5 ml/lit, or *Metarhizium* suspension are available to prevent termite infestation. Various ready-to-use oil-based chlorpyriphos formulations such as "Wood Guard, Terminator", etc., are available for direct application on borer-infested bamboo products.

11.7 Conclusions

Although several insect borers have been reported on bamboos, the potential pests are only a few. The borers associated with live shoots are often not a serious problem. Regarding the post-harvest pests, the bamboo borers *Dinoderus minutus* and *D. ocellaris* are the most important. By adopting appropriate pest management strategies, incidence of these pests can be avoided.

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Wood Biodeterioration in Marine Environment

12

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Contents

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_12

Abstract

The biological processes a wood undergoes on exposure to use or otherwise in marine environment are comprehensively briefed up. Biofilm development on material surfaces in seawater followed by the biocorrosion phenomenon in general is narrated. Biofouling menace common to all anthropogenic installations and particularly to wooden structures is outlined. Wood and borer hazard with reference to its material qualities, resources, utility, biodeterioration by fungi and higher organisms in marine environment are detailed. Employment of prime timbers for various end uses, their availability and alternative substitute species are discussed. Timber protection in seawater realm for movable assemblies and immovable fabrications, advantages of technology adoption for such purposes, hurdles in achieving the aims and goals are highlighted. Finally, the future of wood is emphasized in view of the many soothing qualities it confers on man kind for the sustainability of the globe.

Keywords

Seawater · Biofilm · Biocorrosion · Biofouling · Wood boring · Timber Protection

12.1 Introduction

Wood or timber or lumber is habitually a most cherished engineering material for umpteen fabrications on land, freshwater and seawater even during the current era despite the advent of quite a lot of alternative advanced substances. Even today, wood remains the unique choice because of its innumerable distinct affirmative characters that rate it as a material *par excellence*, marvellously meeting with the chief favourable feature of robustness in the case of almost all built structures either big or small (Purushotham, 1988; Satish Kumar, 1978). But inopportunely, wood is liable to decay and disintegration exclusively in seawater in contrast to that in freshwater or even that on land especially with enormous rapidity due to its biological origin and recyclable nature.

Such decay and disintegration of wood in seawater is popularly termed as ‘marine biodeterioration’ and the phenomenon attains international significance because it drains away the national exchequers the entire world over and depletes off the natural resources internationally. In fact, this highly complex issue includes three equally intricate major components, namely, biocorrosion, biofouling and bioboring while the causatives are referred to as biodeteriogens (Turner, 1988). While the first constituent, although ubiquitous affecting many substances in other realms too, is primarily concerned with metals and alloys exposed in marine environment. The second one related to all kinds of age-old or modern material appliances put to use at sea is universal to all materials. The last one pertains to concrete, corals, floating nuts, mangroves, rocks, (sometimes rubber), wood and sea weeds.

All these three marine biodeterioration processes in fact are dependent on the initial settlers consisting of bacteria, protists and other microorganisms which together form a ‘biofilm’ on the substratum. This biofilm conditions the surface of the substratum for subsequent recruits by providing them food and foothold. Sometimes the film even serves as a protective layer over any original hostile surface underlying it and helps other flora and fauna to develop there subsequently. Thus, the development of a biofilm is a precursor for the promotion of marine biodeterioration reliant on the nature and quality of the substratum (Rao et al., 2007).

12.2 Biofilm, the Precursor

Any material including wood freshly placed in sea is rapidly and randomly covered with a very thin layer of mud, sand, suspended particulates and organic detritus together with bacteria, their extracellular products, diatoms, algal spores and sometimes even protozoans (Fig. 12.1). This layer or rather matrix is called as ‘slime film’ or ‘primary film’ or ‘biofilm’.

A sequence of discrete events (Corpe, 1972; Marshall et al., 1971) that can be recognized into five stages (Mitchell & Kirchman, 1984) are involved in biofilm formation.

12.2.1 Initial Conditioning

Thermodynamic forces developed across the solid and water interface due to differences in physical properties of the substratum and seawater promote adsorption of organic macromolecules, mostly glycoproteins, polysaccharides, and proteoglycans on to the substratum (Dexter, 1976; Wahl, 1997). This initial formation of a viscous layer is known as ‘conditioning film’ (Fig. 12.2). Adsorption of macromolecules in conditioning film is purely physical and spontaneous beginning within seconds to minutes of material immersion in seawater (Baier, 1984). The physical, chemical and biochemical characteristics of this macromolecular film are quite different from that of the bulk water (water in surrounding environment).

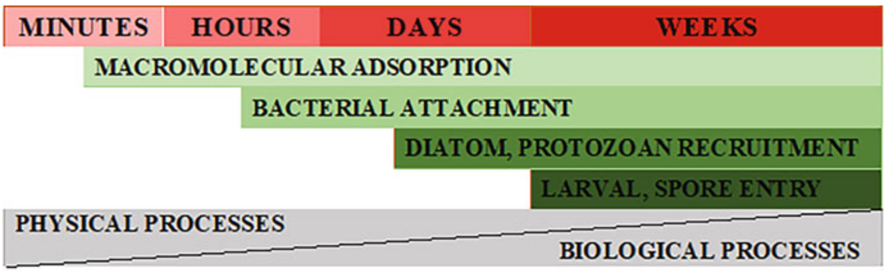


Fig. 12.1 Schematic of biofilm formation sequence (Wahl, 1989)

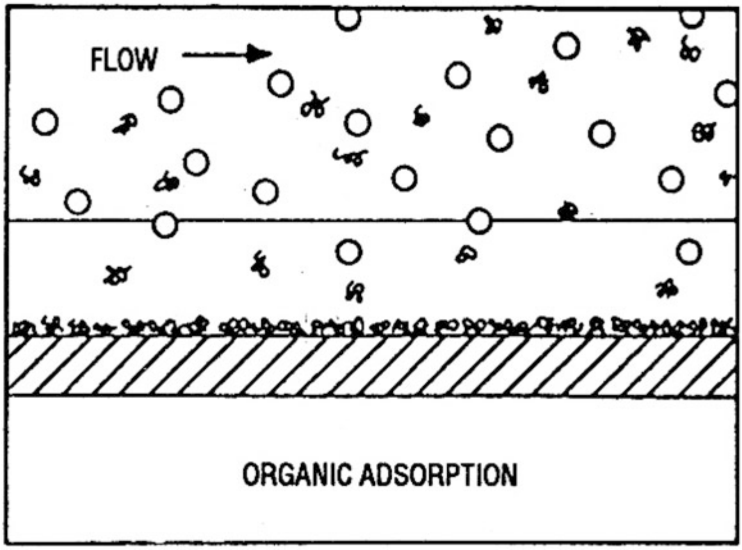


Fig. 12.2 Formation of a 'conditioning film' (Characklis, 1981)

However, conditioning films formed on different substrata kept under identical conditions are surprisingly similar (Little, 1985).

12.2.2 Attraction of Bacteria

Concentration of molecular nutrients in the conditioning film is believed to influence subsequent steps in biofilm formation (Wardell et al., 1983). Formation of conditioning film on a substratum lowers critical surface tension of the material facilitating bacterial attachment onto the solid. The macromolecules present on the surface of the substratum attract bacteria towards them mostly through chemotaxis within hours of material immersion in seawater. This is a mixed phenomenon of physical and biological nature (Fig. 12.3). Attachment of these bacteria having smaller sizes and low Reynold's numbers is comparable to that of colloidal particles (Characklis, 1981; Marshall, 1972). But bacterial motility and chemotaxis characters play significant role in their attachment to the substratum (Chet & Mitchell, 1976; Mitchell & Kirchman, 1984).

12.2.3 Reversible Adhesion

The nature of forces involved in bacterial transport to the substratum varies with distance between the cell and the surface. Long-range transport of cells up to the outer border of the viscous layer is mostly governed by water currents. Then,

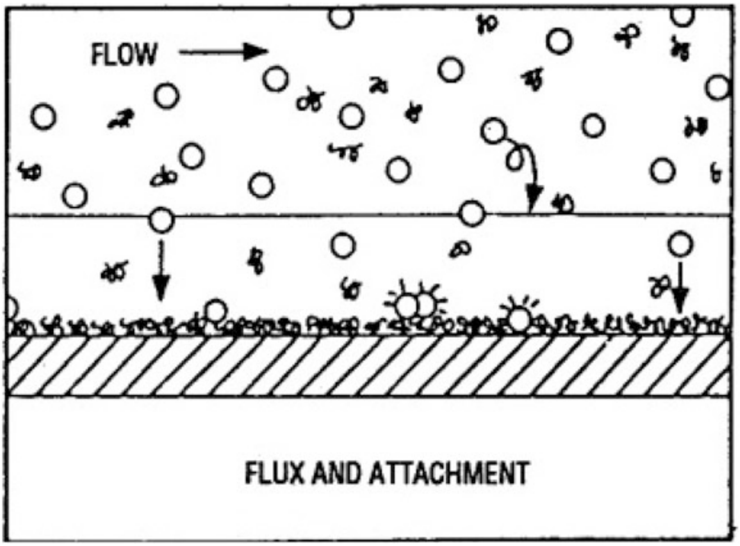


Fig. 12.3 Attachment of bacteria and reversible adhesion (Characklis, 1981)

approach to substratum takes place due to cell motility and/or chemotaxis, Brownian motion or microturbulence that occasionally breaks the viscous layer (Characklis & Cooksey, 1983). All motile bacteria possess chemoreceptors that aid them to move either towards or away from attractants or repellents. These receptors can detect chemicals as low as 10^{-6} molar. During this phase, adsorbed cells may be surrounded by relatively small quantity of glycocalyces. Most of the bacterial cells as well as substrata are predominantly negatively charged. On further approach to the substratum, the antagonistic forces of electric repulsion and Van der Waal attraction between the cell and the solid tend to immobilize cells at 3–20 nm distance from the surface. Thus, the bacteria are held only weakly to the immersed object and can be easily removed by mere mechanical shaking.

12.2.4 Irreversible Adhesion

Finally, rearrangement of glycocalyx polymers (Schneider, 1994) and/or production of fibrils, their attachment and subsequent enzymatic shortening (Fletcher & McEldowney, 1984) aid the cell in overcoming the repulsion and establishing contact with the surfaces. This settlement is facilitated by opposite charges of the cell and the substratum because of a hydrophobic cell surface or reduced cell diameter (Absolom et al., 1983; Fattom & Shilo, 1984; Pringle & Fletcher, 1983). Further firm attachment of bacteria to the substratum is achieved by covalent bonding between glycocalyx polysaccharides and binding sites on substratum/conditioning film, often through divalent cations or lectins (Costerton et al., 1978).

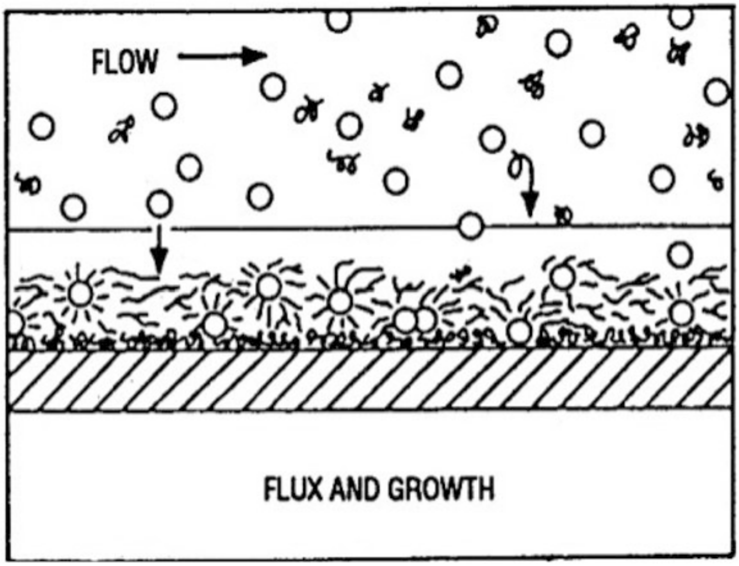


Fig. 12.4 Formation of 'biofilm' (Source: Characklis, 1981)

Generally, rod-shaped bacteria (bacillus) settle first followed by sphericals (coccus) and stalked/spiral forms (spirillus). These initial colonizers are also known as primary periphytes and generally possess chemoorganotrophic, gram (−) ve nature. They are capable of colonizing wood both under aerobic and anaerobic conditions and show indirect influence on decay processes. While obligate aerobes require oxygen for growth, obligate anaerobes grow only in the absence of oxygen and facultative anaerobes grow with or without oxygen. Subsequent copious production of extracellular polymeric substances (EPS) or exopolymers and continued bacterial settlement lead to the formation of an intricate 'film' (of 30–40 μm thin) with separate matrix compartments for live or dead cells interconnected by a branching channel network that circulates nutrients and wastes (Gunn et al., 1987; Schneider, 1994) (Figs. 12.4 and 12.5).

All this surface formation together constitutes the 'slime film' or primary film' or 'biofilm' (Zahauranec, 1988; ZoBell, 1938). Chemical species like calcium, magnesium and silica are believed to influence the formation of extracellular matrix (Characklis, 1981). This matrix thus creates distinct microhabitats suitable to meet the physiological requirements of the bacteria and as well provide them with mechanical support.

In general, the biofilm does not necessarily cover the entire surface uniformly. Usually, the microorganisms settle as individuals on the surface leading to localized patches of biofilm or discrete colonies. It normally takes relatively long time for a continuous coherent film to be formed. This biofilm acts as a bacterial reservoir capable of repopulation under favourable growth conditions and continues to evolve

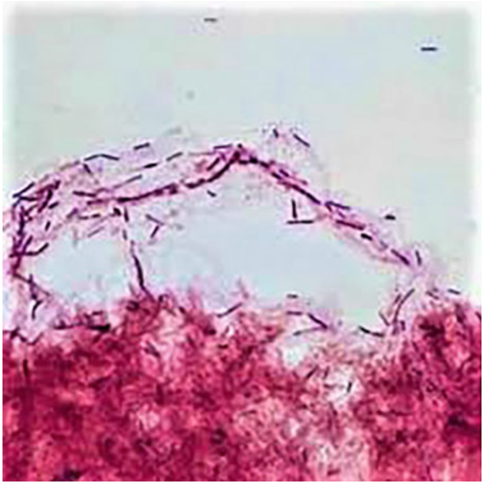


Fig. 12.5 Profile of a 'biofilm' (Source: Benetton, 2007)

through recruitment, predation, competition and disturbances (Little, 1984). A few important primary colonizers are *Alcaligens, Flavobacterium* and *Pseudomonas*.

Some of the primary colonizers can also control the relative extent of attachment and the rate of detachment by altering their cell surface hydrophobicity. Physico-chemical conditions such as solute concentration, oxygen tension, pH, redox potential, etc. of the biofilm thus formed are usually different from that of the bulk water (Dexter, 1993). However, microorganisms can survive, grow and reproduce under a wide range of temperatures (−10 to 100 °C), pH (0 to 10.5), dissolved oxygen concentration (0 to saturation), pressure (vacuum to 31 MPa) and salinity (0 to 30 PSU) although individual species tolerate much narrower ranges. Microorganisms are said to be viable when they can produce spores resistant to a variety of environmental extremes. The spores that are dormant with respect to chemical activity germinate and start/restart their activity on return of favourable growth conditions.

12.2.5 Colonization of Unicellulars

Settlement of eukaryotic unicellular forms begins within days to weeks of material immersion in sea. These cells are also subjected to the same physical forces like bacteria, but to a lesser extent because of larger cell dimension and higher motility. After coming in contact with the immersed object, the cells attach themselves with polysaccharide/protein glues to substratum's surface or biofilm or conditioning film (Cooksey et al., 1984; Tosteson et al., 1983).

The rate of growth, development and composition of this secondary microbial population mainly depends on the nutrient status of the bulk water and its variables besides substratum nature. Two of the major classes of nutrients are those that provide a source of carbon (and often energy too) and nitrogen. Autotrophs use natural and artificial light (and the catalytic action of the chlorophyll pigment to reduce atmospheric carbon and water) to produce oxygen and sugar phosphate while chemolithotrophs oxidize inorganic compounds and couple them to the reduction of carbon dioxide in a way analogous to photosynthesis. It takes weeks for the biofilm to develop in Open Ocean, but only days in coastal waters.

A fully developed secondary microbial population is dominated by shallow and filamentous bacteria such as *Bacillus, Flavobacterium, Aerobacter, Pseudomonas*, etc. (Kelley, 1965) followed by diatoms such as *Coscinodiscus, Licmophora, Asterionella, Synedra, Achnanthes, Cocconeis, Navicula, Nitzschia* and *Amphora* and sessile protozoans such as foraminiferans and ciliates such as *Folliculina, Vorticella, Zoothamnion* and *Suctoria*. These eukaryotic forms also exhibit succession and evolution with the passage of time (Ferreira & Seeliger, 1985; O'Neill & Wilcox, 1971).

12.2.6 Colonization of Multicellulars

Formation of biofilm on the surface of an object or structure immersed in sea further leads to the final phase of colonization by higher groups of multicellular organisms resulting in the establishment of a complex biotic web, usually known as 'biodeteriogen community' consisting of foulers and also borers in the case of wood and few other substrata. Thus, biofilms play an important role in mediating settlement and metamorphosis of invertebrate larvae (Kirchman et al., 1982a, b; Kirchman & Mitchell, 1981, 1983; Maki et al., 1994; Mitchell & Kirchman, 1984; Rodriguez et al., 1995).

Unlike unicellulars, settlement in the case of multicellular forms takes place not during adult life, but during their 'gene-vehicle' stage, that is spore or larval phase. Many larvae (and spores?) are attracted to the substratum by a set of specific chemicals referred to as 'cues' that indicate an object for 'right' attachment (Corpe, 1972; Little & Lavoie, 1980; Merzalek et al., 1979). On reaching the 'right' object, larvae probe the surface, settle at a particular spot, attach there and then metamorphose into adults.

Cues for larval settlement are numerous and may be positive or negative besides light levels, hydrodynamics, gravity, surface texture, roughness, colour, wettability, surface chemistry, presence of conspecifics or associatives, exuded secondary metabolites, etc. (Burke, 1986; Butman, 1986; Chabot & Bourget, 1986; Crisp, 1984; Kirchman & Mitchell, 1983; Leitz & Wagner, 1993; Morse, 1984, 1992; Neumann, 1979; Olson, 1980; Rittschof et al., 1984; Roberts et al., 1991; Todd & Doyle, 1981; Wethey, 1986). Negative cues may be as important as positive ones and their continuous absence is likely to prolong the larval phase, lower cueing threshold, induce metamorphosis without settlement and causes mortality.

Thus, biofilm formation very soon is followed by settlement and growth of multicellular organisms in several spells (Crisp & Ryland, 1960). Finally, all metamorphosed forms together give rise to a complex of biota on the substratum and build up a 'biodeteriogen community'.

12.3 Biocorrosion

Biocorrosion, also known as 'microbiologically influenced corrosion', is a process provoked by a variety of metabolic reactions of microorganisms on material surfaces, predominantly on metals and alloys introduced in seawater (and other mediums) in several forms to serve various anthropogenic purposes (Turner, 1988). Nevertheless, biocorrosion to some extent or the other also affects many other materials such as concrete, plastics, nylon, etc.

Prominent bacteria contributing to the process are *Acidithiobacillus thiooxidans* (Kelley and Wood), *Desulfovibrio africans* Campbell et al., *D. vulgaris* Hildenborough, *Desulfoto-maculum orientis* Campbell and Postgate, *D. nigrificans* (Werkman and Weaver), *Ferrobacillus ferrooxidans* Leathen and Braley, *Thiobacillus concretivorus* Kelly and Harrison, *T. thioparus* Beijerinck, etc.

Generally, a consortium of metal or sulphide reducing bacteria, rather than a single species, settling on different metal or alloy surfaces produce metal oxides or metal hydroxides or hydrogen sulphide or organic/inorganic acids or ammonia thereby causing any or a combination of biocorrosion processes often known as uniform attack, galvanic corrosion, crevice corrosion, pitting corrosion, intergranular corrosion, selective leaching, erosion corrosion and stress-corrosion cracking (https, 2021a).

Biocorrosion is several decades old problem affecting a variety of industries such as petrochemical facilities, power plants, pulp and paper mills, refineries, steel mills and general shore-based manufacturing industries. Biocorrosion can be prevented through regular mechanical cleaning, biocidal treatment or complete drainage and dry storage of the systems involved. Even then, India is losing up to $100 billion per annum due to corrosion as per 2016 year reports of 'The Economic Times' (https, 2021b).

12.4 Biofouling

As mentioned above, biofilm development also constitutes recruitment of microorganisms such as bacteria, protists and other microorganisms on material surfaces. This phenomenon as such is recognized as microbiofouling while the processes further leading to the recruitment and growth of multicellulars into a 'complex of biota' is designated as macrofouling, generally referred as biofouling in this text.

The main issue, however, in the present instance is about wood in seawater and hence 'marine wood biodeterioration' that inevitably encompasses biofouling and wood-boring and can be represented as different entities as depicted in Fig. 12.6 and marine fouling cycle (Fig. 12.7).

Any solid natural substance or synthetic material in its original or engineered form put to (or reaching) seawater either as an entire entity or dismantled component or fragmented bit provides an additional and new substratum for myriads of life forms. So, certain plants and several creatures soon make wise use of this fresh

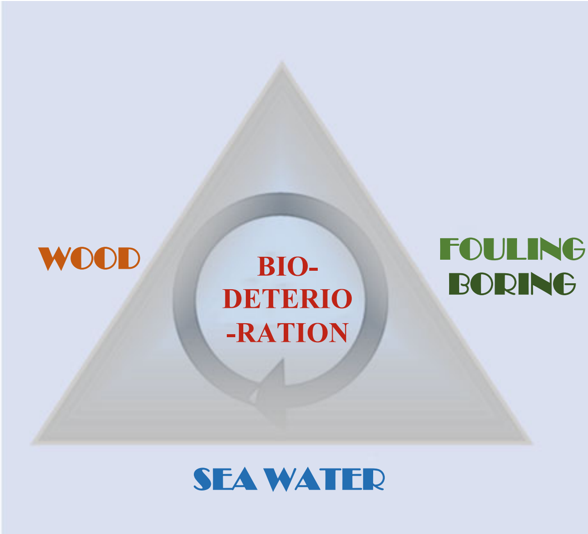


Fig. 12.6 Marine wood biodeterioration (Source: Thomas, 2002)

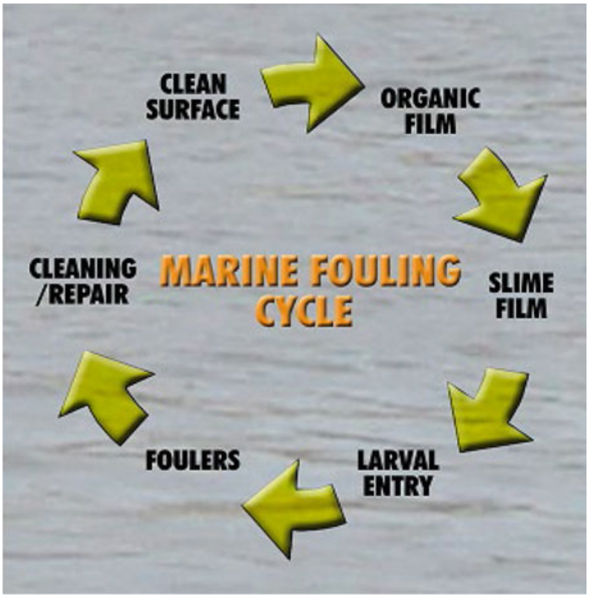


Fig. 12.7 Marine fouling cycle

opportunity and settle on it as attached (sedentary) organisms inhabiting over it for life time or dwell over it as free animals (associates or occasional visitors). This first category of animals is called as 'primary fouling assemblage (PFA)' while the second set as 'secondary fouling assemblage (SFA)' (Field, 1982). This phenomenon taking place over human introduced stationary or moving marine fabrications is designated as biofouling.

As biofouling involves wood and several materials, structures, plants, animals and geographical localities, the issue as such is absolutely complex and manifold to deal with, understand, prevent and remediate. Several materials in this instance imply substances such as cement, concrete, plastics, rubber, metals and various composites such as absorbent concrete, carbon fibre, composite honeycomb, engineered bamboo, fibreglass, kevlar, mud bricks, plywood, pykrete, translucent concrete and wood plastics that all have varied nature, properties and behaviour. Similarly, structures denote stake-net poles, fish-net poles, aquaculture poles, jetty poles, fixed fenders, floating fenders, jetty piles, wharves, bulkheads, groynes, pontoons, canoes, catamarans, dinghies, barges, dredgers, boats, vessels, ships, submarines, fish cages, culture cages, heat exchange conduits, derricks, seawater conduits, submersibles, etc. that have different sizes, shapes, textures and colours. Plants of the cluster represent Bacillariophyta (diatoms), Phaeophyta (brown algae), Chlorophyta (green algae) and Rhodophyta (red algae). Animals of the assemblage signify numerous types of multicellular organisms belonging to all phyla right from Coelenterata to Prochordata and Pisces. Geographical localities cover all the shore areas including bays, bights, coves, fjords, gulfs, inlets, sounds, backwaters, creeks, estuaries, straits, etc.

The progress of biofouling further to biofilm formation involves replacement of pioneer species, their sturdy growth, dominance of some biofoulers, etc. depending upon a number of biotic interactions such as competition for space, antagonism, symbiosis, mutualism, parasitism, prey-predator relationship, etc. and numerous abiotic factors besides structure and composition of the very substratum (Balaji, 1988).

The ‘primary fouling assemblage’ chiefly comprises of both solitary and colonial forms such as hydroids, poriferans, bryozoans, entoprocts, sabellids, serpulids, barnacles, mussels and ascidians. The ‘secondary fouling assemblage’ consists mainly of nematodes, turbellarians, polychaetes, amphipods, copepods, tanaids, isopods, nudibranchs, gastropods, echinoderms and fishes.

Recruitment and establishment of various biofouling species on the surfaces of different devices varies depending on the nature, property and behaviour of the substance of its make. Biofouling formations on non-metallic substrata are rich both qualitatively and quantitatively compared to that on metallic surfaces. Generally, wood and asbestos accumulate biofouling species quite copiously to the maximum extent followed by glass, mild steel, aluminium, asphalt and rubber in that order. Least fouling in terms of both species and bimoss occurs on copper and brass. Usually, biofouling development is observed to be substantial on hard surfaces (Barnes & Powell, 1950; Corlet, 1948; Pomerat & Weiss, 1946). In contrast, certain groups of animals such as serpulids and bryozoans are recognized to be apathetic to hard surfaces and instead mostly prefer smooth surfaces. Poor recruitment of biofoulers on copper and brass surfaces might be due to their elemental leaching that proves toxic to many biota. Rubber and asphalt being soft and flexible materials exhibit moderate degree of biofouling formations. However, between these two, asphalt harbours more fouling than rubber perhaps due to the presence of ridges, depressions and undulations on the surface that provide more foothold to the organisms. Interruptions in the surface contour of a substratum probably promote better aggregation of sessile organisms. Even in the case wood, most of these facts hold good as the strength, texture, colour and finish of timber varies from species to species and many times even within a species depending upon its position in the extracted tree and its maturity, though it is normally assumed to be homogenous (Rao et al., 2007).

Biofouling phenomenon is influenced by various colours in nature and substrata surfaces having black, red and white colours normally attract large number of biofoulers for recruitment over them compared to substrata exteriors with blue, green and grey colours. The degree of attraction of biofoulers also reduces from blue to green to grey (Dahlem et al., 1984).

Biofouling is extremely complicated as mentioned earlier because of the multitude of organisms and processes involved in the phenomenon. The composition of biofouling assemblages varies among different geographical localities as well as regions within a geographical locality (spatial variation) chiefly depending upon its environmental characteristics (abiotic features) such as currents, waves, tides, turbulence, temperature, salinity, *potentio hydrogeni*, dissolved oxygen, turbidity, nutrients, eutrophication, etc. In fact, the warm tropical waters of India provide excellent support for the development, growth and survival of varied plant and animal life including biofouling fauna and flora (Nagabhushanam & Alam, 1988a, b). However, though vast, no two situations in marine environment exist exactly similar as the biota, physical circumstances and chemical conditions are quite divergent from one another (Turner, 1988). Further, biofouling is also depth-dependent with most population's prevailing in the intertidal region than subtidal levels and below due to several advantages, the first of them being food.

Occurrence of different biofouling forms may be often continuous with one to two peaks in a year and at times sporadic but mostly varies from time to time, particularly season to season and even year to year (temporal disparity) depending upon the reproductive strategies of the individual species present in the assemblage. Also, while some biofoules prefer fresh surfaces, others opt preoccupied planes.

Biofouling species are also diversified in their consistency and outline. Besides straight plants, some forms are erect plant-like (e.g. hydroids) while others are creeping (e.g. sabellids), spreading (e.g. sponges), encrusting (e.g. some bryozoans) or blocks (balanids). As regards built of these biofoulers, some species are bare, soft or gelatinous while others build soft detritus tubes (e.g. sabellids) or calcareous tubes (e.g. spirorbids) or calcareous plates (e.g. barnacles) or calcareous shells (e.g. mussels) (Purushotham & Satyanarayana Rao, 1971).

Several inventories on biofouling organisms from various marine localities in the country are available but the latest inquiry on this aspect exclusively confined to wood material reveals the existence of 56 species in primary biofouling assemblages (Table 12.1 and Figs. 12.8, 12.9, 12.10, 12.11, 12.12, 12.13, 12.14, 12.15, 12.16, 12.17, 12.18 and 12.19) and 44 species in secondary fouling assemblages (Table 12.2, Figs. 12.20, 12.21 and 12.22) as listed below (Pati, 2011).

An exclusive investigation carried out on biofouling formations on twenty species of Indian timber disclosed that biofouling composition followed by biomass on

Table 12.1 Organisms in primary biofouling assemblages on wood

Primary biofouling species	Family	Order	Class	Phylum
1. Sponge-1 (unidentified)	–	–	–	Porifera
2. *Bimeria vestita* (Wright, 1857)	Bougainvilliidae	Anthoathecata	Hydrozoa	Cnidaria
3. *Clytia gracilis* (Sars, 1850)	Campanulariidae	Leptothecata	"	"
4. *Clytia hendersoni* (Torrey, 1904)	"	"	"	"
5. *Clytia linearis* (Thornely, 1900)	"	"	"	"
6. *Clytia noliformis* (McCrady, 1858)	"	"	"	"
7. *Obelia bidentata* Clarke, 1876	"	"	"	"
8. *Obelia dichotoma* (Linnaeus, 1758)	"	"	"	"
9. *Halecium* sp.	Haleciidae	"	"	"
10. Hydrozoan-1 (unidentified)	–	–	"	"
11. Hydrozoan-2 (unidentified)	–	–	"	"
12. *Anthopleura* sp.	Actiniidae	Actiniaria	Anthozoa	"
13. *Aiptasia* sp.	Aiptasiidae	"	"	"
14. *Diadumene* sp.	Diadumenidae	"	"	"
15. *Metridium* sp.	Metridiidae	"	"	"
16. *Pedicellina cernua* (Pallas, 1774)	Pedicellinidae	Coloniales	Turbellaria	Entoprocta
17. *Bugula neritina* (Linnaeus, 1758)	Bugulidae	Cheilostomatida	Gymnolaemata	"
18. *Hippoporina americana* (Verrill, 1875)	Bitectiporidae	"	"	"
19. *Hippopodina feegeenensis* (Busk, 1884)	Hippopodinidae	"	"	"
20. *Jellyella tuberculata* (Bosc, 1802)	Membraniporidae	"	"	"
21. *Membranipora* sp.	"	"	"	"
22. *Thalamoporella gothica* (Busk) var. *indica* (Hincks, 1880)	Thalamoporellidae	"	"	"

(continued)

Table 12.1 (continued)

Primary biofouling species	Family	Order	Class	Phylum
23. Bryozoan-1 (unidentified)	–	"	"	"
24. Bryozoan-2 (unidentified)	–	"	"	"
25. *Bowerbankia gracilis* (Leidy, 1855)	Vesiculariidae	"	"	"
26. *Zoobotryon verticillatum* (delle Chiaje, 1828)	"	"	"	"
27. *Polydora* sp.	Spionidae	Spionida	Polychaeta	Annelida
28. *Dasychone cingulata* Grube, 1878	Sabellidae	Sabellida	"	"
29. Sabellid-1 (unidentified)	"	"	"	"
30. Sabellid-2 (unidentified)	"	"	"	"
31. *Serpula vermicularis* (Linnaeus, 1758)	Serpulidae	"	"	"
32. *Hydroides brachyacanthus* (Rioja, 1863)	"	"	"	"
33. *Hydroides diramphus* (Mörch, 1863)	"	"	"	"
34. *Hydroides elegans* (Haswell, 1883)	"	"	"	"
35. *Hydroides operculatus* (Treadwell, 1929)	"	"	"	"
36. *Hydroides vizagensis* (Lakshamana Rao, 1969	"	"	"	"
37. *Hydroides* sp.-1	"	"	"	"
38. *Hydroides* sp.-2	"	"	"	"
39. *Ficopomatus enigmaticus* (Fauvel, 1923)	"	"	"	"
40. *Balanus amphitrite amphitrite* (Darwin, 1854)	Balanidae	Sessilia	Maxillopoda	Arthropoda

(continued)

Table 12.1 (continued)

Primary biofouling species	Family	Order	Class	Phylum
41. *Balanus variegatus* (Darwin, 1854)	"	"	"	"
42. Vermetid-1 (unidentified)	Vermetidae	Mesogastropoda	Gastropoda	Mollusca
43. *Perna viridis* (Linnaeus)	Mytilidae	Mytiloida	Bivalvia	"
44. *Modiolus philippinarum* (Hanley, 1844)	"	"	"	"
45. *Modiolus striatulus* (Hanley, 1844)	"	"	"	"
46. *Pinctada fucata* (Gould, 1850)	Pteriidae	Pterioida	"	"
47. *Pinna* sp.	"	"	"	"
48. *Crassostrea cuttackensis* (Newton and Smith, 1912)	Ostreidae	Ostreoida	"	"
49. *Saccostrea cucullata* (Born, 1778)	"	"	"	"
50. *Anomia achaeus* (Gray, 1850)	Anomiidae	"	"	"
51. *Anomia* sp.	"	"	"	"
52. *Mytilopsis sallei* (Recluz, 1849)	Dreissenidae	Veneroida	"	"
53. *Ascidia gemmata* (Sluiter, 1895)	Ascidiidae	Enterogona	Ascidiacea	Chordata
54. *Styela canopus* (Savigny, 1816)	Styelidae	Pleurogona	"	"
55. *Symplegma oceania* (Tokioka, 1961)	"	"	"	"
56. Ascidian-1 (unidentified)	–	–	"	"

different species varied remarkably. Barnacles recruitment was dominant on all panels but maximum on *Sideroxylon longepetiolatum* and minimum on *Tetrameles nudiflora*. Tunicates were next dominant biofouling group with maximum recruits on *Tectona grandis,* least numbers on *Pterocarpus dalbergioides* and absent on *Artocarpus gomeziana*, *Hopea odorata*, *Lagerstroemia hypoleuca* and *Terminalia bialata*. Bryozoans were the least recruited assembly with highest formations on *Tetrameles nudiflora*, least recruited on *Artocarpus chaplasha*/*Terminalia bialata*

Fig. 12.8 Biofouling on FRP-coated wooden boat

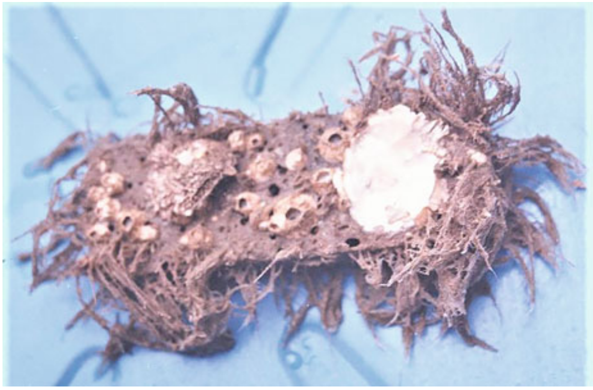


Fig. 12.9 Hydoid biofouling from wood

but lacking on *Mimusops* sp./*Lannea coromandelica*. As regards biomass, the build-up was maximum on *Artocarpus chaplasha/Hopea odorata* but least on *Artocarpus gomeziana/Lagerstroemia hypoleuca*. Thus, superior antibiofouling qualities were exhibited by some of the above timbers and may prove beneficial under practical situations (Raveendran & Wagh, 1993) further to the development of eco-friendly antifouling formulations.

The organisms in a biofouling community can be viewed from very many different angles such as frequency, abundance, density, diversity, evenness, etc. and expressed normally as different statistical measurements viz. Marglef index (d), Shannon-Weiner index (H′), Jacccard index (J'), Simpson index I, etc.

The biomass built up by biofoulers on various substrata in marine environment in general increases gradually with the progression of time. However, in the case of mild steel, the biomass initially increases but declines subsequently. Such reduction in biomass might be due to periodical sloughing off of foulers along with the

Fig. 12.10 Sponge biofouling from wood

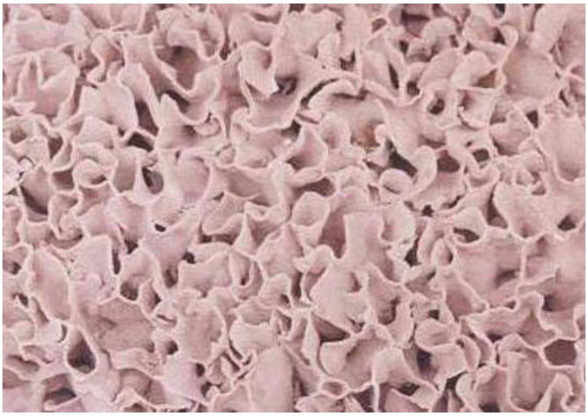


Fig. 12.11 Ectoproct biofouling from wood

Fig. 12.12 Sabellid biofouling from wood

Fig. 12.13 Serpulid biofouling from wood

Fig. 12.14 Spirorbids from a biofouling assemblage

Fig. 12.15 Balanid biofouling from wood

Fig. 12.16 Lepas from a biofouling assemblage

Fig. 12.17 Oyster biofouling from wood

Fig. 12.18 Mussel biofouling from wood

Fig. 12.19 Ascidians from a biofouling assemblage

corrosion product. During the initial period of exposure, corrosion product forms very quickly on mild steel and sloughs off soon. Similar phenomena of ‘throwing out’ of biological material from highly corrodable metals were reported by Elfird (1975), Srinivasa Rao (1977).

Generally, progressive development ensues in the biofouling communities formed on a substratum. Initially, a number of organisms belonging to hydroids, bryozoans, entoprocts, sabellids, serpulids and balanids along with free forms colonize the panels. Subsequently, all these forms grow well and additional recruitment of some of them along with certain bivalves takes place further to increase in diversity of free-living associates. However, the abundance of hydroids, etc., dwindles down. With more advancement of time, hydroids and spirorbids largely get reduced, but bryozoans, entoprocts, sabellids, serpulids and balanids flourish very well gradually improving in their size and number. During the succeeding period, extra development of animals occurs but new recruitment becomes scarce and occasional (Jackson, 1984).

Biofouling affects all installations and flotilla in marine environment to different degrees depending upon their resident time. The structural and functional integrity of stationary structures are affected due to corrosion and erosion. The hydrodynamic properties of all types of craft are impacted because of added weight, enlarged volume, increased roughness and hindered propulsion. The water flow in conduits of ships and industries is affected owing to reduced diameter and ruggedness. The signals of underwater acoustic devices and mine actuators are interrupted due to physical interference. However, in the case of static timber erections, biofouling is assumed to offer protection from wood-borer colonization. Similarly, in the instance of underwater sea mines, the bioaccumulations provide camouflage making them less visible to the enemy. Biofouling assemblages, although enhance local biodiversity, act as possible sources of introduction of alien species to native environment, potentially through ballast water of ships. Bioactive compounds from various biofouling species can also be made use of in several sectors for achieving eco-friendly applications (Anil et al., 2002; Yan & Yan, 2003).

Table 12.2 Organisms in secondary biofouling assemblages on wood

Secondary biofouling species	Family	Order	Class	Phylum
1. Polyclad-1 (unidentified)	–	Polycladida	Turbellaria	Platyhelminthes
2. Nereid-1 (unidentified)	Nereidae	Phylodocida	Polychaeta	Annelida
3. *Eunice afra* Peters, 1854	Eunicidae	Eunicida	"	"
4. *Eunice laticeps* Ehlers, 1868	"	"	"	"
5. *Cirratulus* sp.	Cirratulidae	Spionida	"	"
6. Cirratulid-1 (unidentified)	"	"	"	"
7. *Tanais philetaerus* Stebbing, 1904	Tanaidae	Tanaidacea	–	Arthropoda
8. *Corophium triaenonyx* Stebbing, 1904	Corophiidae	Amphipoda	Malacostraca	"
9. *Cirolana* (*Anopsilana*) *willeyi* (Stebbing, 1904)	Cirolanidae	Isopoda	"	"
10. *Cirolana bovina* Barnard, 1940	"	"	"	"
11. *Cirolana fluviatilis* Stebbing, 1902	"	"	"	"
12. *Cirolana* sp.	"	"	"	"
13. *Sphaeroma walkeri* Stebbing, 1905	Sphaeromatidae	"	"	"
14. *Paracerceis* sp.	"	"	"	"
15.*Calappa* sp.-2	Calappidae	Decapoda	"	"
16. *Doclea* sp.	Majidae	"	"	"
17. *Platylambrus prensor* (Herbst, 1803)	Parthenopidae	"	"	"
18. *Scylla* sp.-1	Portunidae	"	"	"
19. *Portunus pelagicus*(Linnaeus, 1758)	"	"	"	"
20.*Charybdis helleri* (A. Milne Edwards, 1867)	"	"	"	"
21.*Charybdis* sp.	"	"	"	"
22. *Thalamita crenata* (Latreille, 1829)	"	"	"	"
23.*Macromedaeus crassimanus* (A. Milne Edwards, 1867)	Xanthidae	"	"	"
24.*Myomenippe hardwicki* (Gray, 1831)	Menippidae	"	"	"
25. Pinnotherid-1 (unidentified)	Pinnotheridae	"	"	"
26. Crab-1 (unidentified)	–	"	"	"

(continued)

Table 12.2 (continued)

Secondary biofouling species	Family	Order	Class	Phylum
27. Crab-3 (unidentified)	–	"	"	"
28. *Synalpheus brevicarpus* (Herrick, 1891)	Alpheidae	"	"	"
29. *Pycnogonum* sp.	Pycnogonidae	Pantopoda	Pycnogonida	"
30. Nudibranch-1 (unidentified)	–	–	Aplacophora	Mollusca
31. *Littoraria* (*Littorinopsis*) *scabra scabra* (Linneus, 1758)	Littorinidae	Mesogastropoda	Gastropoda	"
32. *Assiminea* sp.	Assimineidae	"	"	"
33. *Cypraea arabica* Linnaeus, 1758	Cypraeidae	"	"	"
34. *Anachis terpsichore* Sowerby, 1832	Columbellidae	Neogastropoda	"	"
35. *Thais* (*Stramonita*) *rugosa* (Born, 1778)	Muricidae	"	"	"
36. *Nassarius* sp.	Buccinidae	"	"	"
37. Gastropod-1 (unidentified)	–	–	"	"
38. Gastropod-2 (unidentified)	–	–	"	"
39. *Trapezium sublaevigatum* (Lamarck, 1819)	Trapeziidae	Veneroida	Bivalvia	"
40. *Trapezium* sp.	"	"	"	"
41. *Laternula* sp.	Laternulidae	Pholadomyoida	"	"
42. Ophiurid-1 (unidentified)	Ohiuridae	Ophiurida	Ophiuroidea	Echinodermata
43. Gobiid-1 (unidentified)	Gobiidae	Perciformes	Actinopterygii	Chordata
44. Gobiid-2 (unidentified)	"	"	"	"

Fig. 12.20 Cirolinid (SFA)

Fig. 12.21 Decapod (SFA)

In the light of the aforesaid impacts, losses and damages, biofouling in the vast Indian marine environment is certainly substantial in terms of materials, time, human resources, power and money. But no reliable estimates are available in recent literature for any of them.

In order to prevent and control marine biofouling in a variety of situations, numerous methods are in vogue for a very long time. Such practices, however, get improvised from time to time with the advancement of knowledge and technology. Initially, inorganic paints were used for the purposes, but subsequently they were replaced by toxic paints, next by environmentally-benign paints, later on by biocidal coatings followed by neutral foul-release coatings at present.

Fig. 12.22 Gastropod (SFA)

12.5 Wood Boring

In order to understand wood boring, the unique qualities of timber, its status among different structural materials of the day, availability, applications, etc. need to be familiarized at first.

12.5.1 Timber, Its Excellence

Among various goods originating from forests, timber constitutes an important and indispensable raw material for diverse industrial and structural applications including maritime enterprise (Anon, 1970; Bosshard, 1969). Due to many inherent qualities such as ready availability, relative cheapness, light weight, good strength, easy workability, resistance to seawater corrosion, amenability to fabrication of structures of different lengths, breadths, heights and shapes, etc. further to its renewability, salvage worth, carbon foorprint value and eco-friendly nature, timber stands as a material *par excellence* so far used in marine environment.

Even after the emergence of several modern constructional materials such as reinforced cement concrete (RCC), ferro cement, rubber, asbestos, plastics, polyvinyl chloride (PVC), polyurethane (PU), polystyrene (PS), low-density polyethylene

(LDPE), high-density polyethylene (HDPE), fibreglass reinforced plastic (FRP), perspex, teflon, metals, alloys and other composites, timber is continuously used in large quantities for various structural purposes in terrestrial, aquatic and marine conditions there by occupying a prime position among different structural commodities because of unique characteristics it possesses and umpteen advantages it offers as mentioned above (Rao et al., 2007; Santhakumaran, 1994b; Satyanarayana Rao, 2002).

12.5.2 Timber, Its Resources

Indian forests were copious with many varieties of trees that yield good dimension timber useful for structural fabrication (Anonymous, 1950; Srivastava, 1985). Among good dimension timbers, durable species (prime timbers) such as teak (*Tectona grandis* L. f.), sal (*Shorea robusta* Gaertn.), deodar (*Cedrus deodara* (Roxb.) G. Don f.) and mathi (*Terminalia arjuna* (Roxb.) Wight & Arn.) were abundantly available earlier for long and hence used liberally. Unchecked population explosion coupled with improving living conditions and expanding enterprise have lead to ever-growing demand for wood resulting in irrational exploitation, haphazard consumption and unscientific utilization of the invaluable natural product that in turn resulted in severe resource crunch and steep cost escalation of timber ultimately draining off the national exchequer to a great extent annually. This forced common populace as well as entrepreneurs to turn indiscriminately to various timbers belonging to lesser durability groups as substitutes. A good number of such substitutes are augmented either from avenues, homesteads, shade trees and commercial plantations or far off Andaman-Nicobar Islands or foreign countries through imports. Except for a few species, all such timbers of varied genesis though put to a wide range of needs and services are not scientifically explored with reference to their utility. Most of these alternate species render relatively short service than prime timbers because either they are soft wood species or short rotation timbers with easy susceptibility to deterioration from biological agencies, besides strength related issues. Quick timber damages of the kind invite frequent repair, regular replacement and repeated substitution resulting again in heavy pressure on tree resources.

12.5.3 Timber, Its Marine Utility

In respect of marine applications, timber is perhaps the very first material used in sea by man for almost all his needs right from merchandise, transport, voyages, explorations, fishing, whaling and prospecting for precious materials to waging wars. In the modern world, coastal entrepreneurs like boat operators, coast guard, dock yards, fishermen, fish farmers, fishing harbours, fish landing centres, mariculturists (marine farmers), naval forces, offshore explorers, sea ports, ship breaking units, ship yards, aqua tourism and other shore-based industrial establishments use lot of timber for water front stationary installations such as

Fig. 12.23 Fixed fenders

Fig. 12.24 Fishing jetty

bulk heads, dock blocks, fenders, jetties, piles, fishnet poles, farm sluices, feed posts and wharves and moving structures such as barges, boats, catamarans, canoes, dinghies, dugouts, fishing vessels and other fishing craft (Rao et al., 2007) (Figs. 12.23, 12.24, 12.25, 12.26, 12.27, 12.28, 12.29, 12.30, 12.31, 12.32, 12.33 and 12.34).

In coastal cum marine situations, scores of poor traditional fishermen chiefly depend on wood for their craft as well as for creating most of their basic amenities. India with an extensive sea board of 8118 km, continental shelf of 0.53 million km^2 and exclusive economic zone (EEZ) of 2.02 million km^2 has 7 major fishing harbours, 62 minor harbours and 1457 fish landing centres (Fig. 12.35). The shore line harbours 4,945,717 traditional fishers dispersed in 3461 fishing villages spread over 10 states and 4 Union territories including the sub-oceanic islands of Andaman-Nicobar Islands and Lakshadweep Archipelago. A majority of members of this fishing community is solely dependent upon 0.2 million artisanal fishing units to venture into the seas as a full-time occupation merely to make an eking (Anonymous, 2020).

Fig. 12.25 Fishnet poles

Fig. 12.26 Stakenet poles

Fig. 12.27 Feed posts

Fig. 12.28 Wharf

Fig. 12.29 Barge

Fig. 12.30 Boat

Fig. 12.31 Catamaran

Fig. 12.32 Canoes

Fig. 12.33 Fishing craft

Fig. 12.34 Fishing vessels

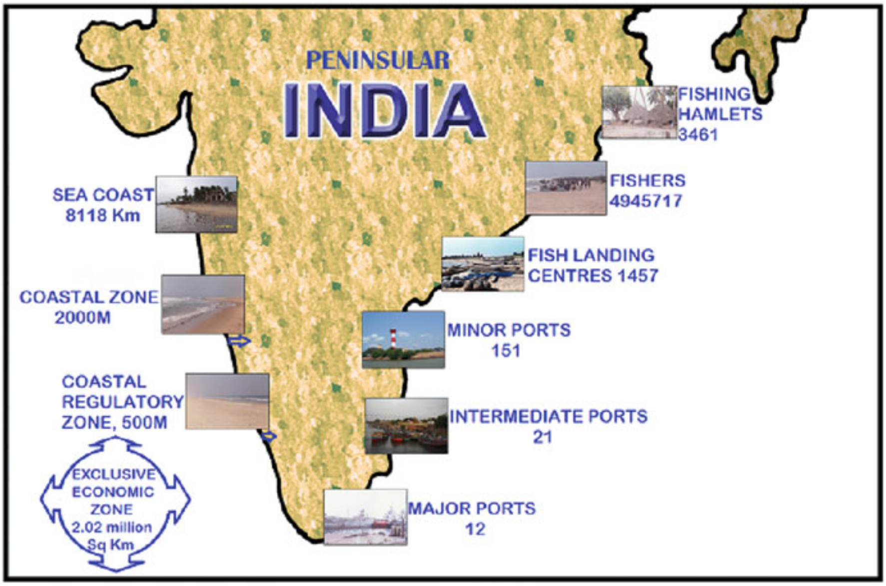


Fig. 12.35 Coast, port and fisheries statistics of India

12.5.4 Timber Fleet, the Mainstay

In spite of the continued mechanization of fishing craft, marine fishing industry in India is dominated by traditional ways of catching sea fish. Artisanal marine fishery in India contributes to ~54% of the sea landings by deploying a vast fleet (202,796 units) of different types to reap the seas besides 67,254 mechanised boats and deep sea vessels (Anonymous, 2020).

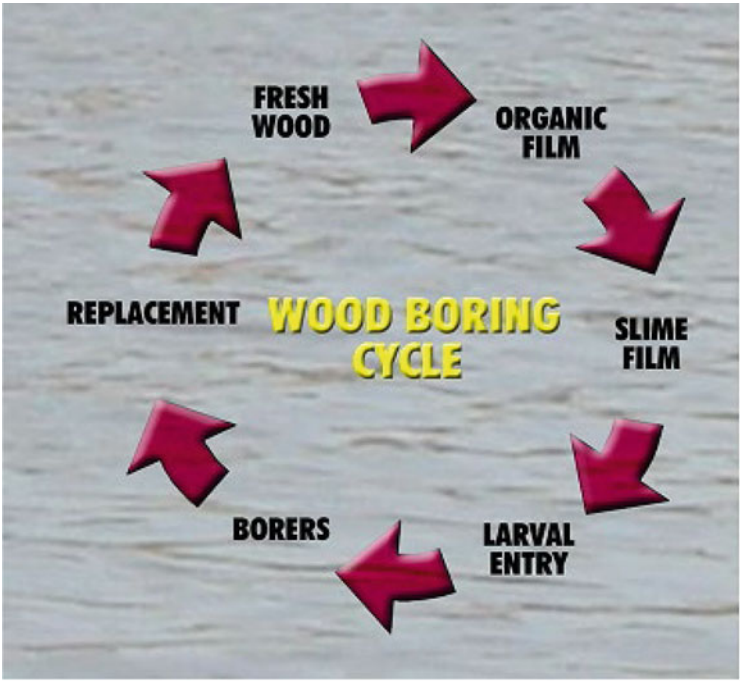


Fig. 12.36 Wood boring in sea

12.5.5 Timber, Its Deterioration at Sea

Marine wood borers are a rich and varied assemblage of invertebrate organisms well known for ages to invade and damage wood with enormous rapidity in oceans, seas, estuaries, back waters and brackish waters all around the world with a life cycle as depicted in Fig. 12.36 and as such are of great economical and ecological importance throughout the globe (Distel et al., 2011; Sen et al., 2010; Weigelt et al., 2017).

Different biological agencies causing rapid timber deterioration in marine *milieu* are bacteria, biofoulers, lignicolous fungi and wood borers. These organisms impair the functional integrity of various wood structures either by sheer colonization over the surface (biofoulers) or effecting biocorrosion (bacteria) or softening the exteriors (lignicolous fungi) or drilling deep to different depths (marine borers) finally leading to overall deterioration of the fabrications and erections, both stationary and motile. The nature and composition of these deteriogens, the mode and intensity of their attack and the type and severity of damage they inflict to wood are greatly governed by bio-physico-chemical features of the environment and their variability that often differs from place to place. These organisms also attack dead and live trees in the most valuable mangrove ecosystems and cause great loss to the vegetation. Wood deterioration in marine environment is several times faster than that on land. Usually no unprotected timber, however durable on land, serves for a year or two at sea as wood borers particularly take lead in diminishing its longevity.

At present, no statistics are available on marine timber utility in India. However, Indian total annual timber consumption is reported to be 68.99 million m^3 between the years 2011 and 2016 (Shrivastava & Saxena, 2017). Conservatively considering that just 10% of this quantity (6.9 million m^3) as wood used in marine sector in India, total annual value (estimated @ Rs.2500 per cft) approximates at Rs.0.6 billion while a minimum of 10% annual timber losses would amount to Rs.0.06 billion.

Therefore, it is very vital to have an insight into various marine biodeteriogens in the country and their activities.

12.5.6 Timber, Its Decay Fungi at Sea

Timber biodeterioration by fungi is chiefly due to species belonging to Ascomycota and Deuteromycota and occasionally to Basidiomycota. Fungi exhibit a wide range of capabilities in decaying wood causing serious damage up to 70 mm depth (Jones et al., 1986; Satyanarayana Rao et al., 1985). A few species utilize only cellulose [e.g. *Corollospora maritima* Werdermann, *Lulworthia purpurea* (Wilson) Johnson and *Monodictys pelagica* (Johnson) Jones] while others utilize both lignin and cellulose [e.g. *Digitatispora marina* Doguet, *Hylocyphina villosa* Kohlm and Kohlmand *Nia vibrissa* Moore and Meyers] but certain others utilize only readily available sugars or starch present in ray parenchyma [e.g. *Dendryphiella salina* (Suth.) Nicot and Pugh, *Leptosphaeria* spp. and *Pleospora* spp.] (Mouzouras et al., 1988). In addition, the fungi aid in successful colonization of wood by marine wood-borers. Only very limited work is done on fungal decay of wood in Indian marine environment (Balaji, 2013; Nagaveni et al., 2007; Santhakumaran et al., 1994; Tiwari et al., 1984).

12.5.6.1 Fungi on Test Timber

A total of 40 identified species and 18 unidentified taxa of marine fungi (in) were reported from various untreated and treated [copper-chrome-arsenic (CCA), copper-chrome-boric (CCB) and creosote-fuel oil (CFO)] wood exposed for testing in Indian marine environment (Balaji, 2013; Nagaveni et al., 2007; Tiwari et al., 1984) (Tables 12.3 and 12.4; Figs. 12.37, 12.38, 12.39 and 12.40). The incidence of fungal taxa associated with each timber species varied differentially depending upon the diversity of the biota, preservative employed, treatment given and coupon exposure depth.

An electron microscopic examination of Brazilian Jack-Wood and African Rose-Wood panels exposed for 7 months at Goa showed colonization of wood by several soft-rot species followed by tunnelling bacteria. Initially, only the fungi produced small cavities in the secondary cell walls while the middle lamella was intact. Subsequently, the fungi proliferated while tunnelling bacteria made an entry. Later, the secondary cell wall was filled with soft-rot cavities whereas middle lamella and secondary cell wall got tunnelled by bacteria. With the advancement of time,

Table 12.3 Marine fungal deteriogens

Kingdom Fungi; Phylum Basidiomycota			
Class	Order	Family	Species
Agaricomycetes	Agaricales	Niaceae	1. *Halocyphina villosa* Kohlm. & E. Kholm. 1965
Dothideomycetes	Capnodiales	Cladosporiaceae	2. *Cladosporium herbarum* (Pers.) Link 1821
			3. *Cladosporium oxysporum* Berk.&M. A. Curtis 1868
	Pleosporales	Pleosporaceae	4. *Cochliobolus lunatus* R.R. Nelson & Haasis, (1964)
			5. *Clavariopsis bulbosa* Anastasiou 1962
			6. *Periconia prolifica* Anastasiou, 1963
		Sporormiaceae	7. *Sporormiella minima* (Auersw.) S.I. Ahmed & Cain, 1970
		Didymosphaeriaceae	8. *Verruculina enalia* (Kohlm.) Kohlm. & Volkm.-Kohlm. 1990
	Dothideomycetes Incertae sedis	Parabambusicolaceae	9. *Monodictys pelagica* (T.W. Johnson) E.B.G. Jones, 1963
Eurotiomycetes	Eurotiales	Trichocomaceae	10. *Aspergillus flavus* Link 1809
			11. *Aspergillus fumigatus* Fresenius 1863
			12. *Aspergillus niger* van Tieghem 1867
			13. *Aspergillus nidulans* G Winter 1884
			14. *Aspergillus terreus* Thom. 1918
			15. *Aspergillus wentii* Wehmer 1896
			16. *Emericella nidulans* (Eidam) Vuill. 1927
			17. *Paecilomyces variotii* Bainier 1907
			18. *Penicillium aurantiogriseum* Dierckx 1901
			19. *Pencillium spinulosum*Thom, C. 1910

(continued)

Table 12.3 (continued)

Kingdom Fungi; Phylum Basidiomycota			
Class	Order	Family	Species
Sordariomycetes	Sordariales	Chaetomiaceae	20. *Humicola alopallonella* Meyers & R.T. Moore, 1960
		Sordariaeceae	21. *Neurospora sitophila* Shear & Dodge 1927
	Sordariomycetidae Incertae sedis	Savoryellaceae	22. *Savoryella lignicola* E.B.G. and Eaton 1969
	Lulworthiales	Lulworthiaceae	23. *Zalerion maritimum* (Linder) Anastasiou 1963
			24. *Zalerion varium* Anastasiou 1963
	Trichosphaeriales	Trichosphaeriaceae	25. *Nigrospora oryzae* (Berk. and Br.) Petch. 1924
	Microascales	Halosphaeriaceae	26. *Cirrenalia tropicalis* Kohlm. 1968
			27. *Culcitalna achraspora* Meyers and Moore 1960
			28. *Halosphaeria quadricornuta* Cribb & J.W. Cribb, 1956
			29. *Lignincola laevis* Hohnk 1955
		Microascaceae	30. *Scopulariopsis brevicaulis* (Sacc.) Bainier, 1907
			31. *Scopulariopsis croci* van Beyma 1945
	Hypocreales	Hypocreales incertae sedis	32. *Emericellopsis minima* Stolk 1955
			33. *Gliomastix murorum* var. *polychroma* (Corda) Hughes 1958
			34. *Payosphaeria minuta* H.Y.M. Leung 1990
			35. *Torpedospora radiata* Meyers 1957
		Nectriaceae	36. *Fusarium incarnatum* (Desm.) Sacc. 1886
			37. *Fusarium solani* (Mart.) Sacc. 1881
			38. *Neocosmospora vasinfecta* Smith 1859
		Stachybotryaceae	39. *Stachybotrys chartarum* (Ehrenb.) S. Hughes, 1958
		Hypocreaceae	40. *Trichoderma viride* Pers.:Fr., 1829

Table 12.4 Marine fungal genera

Alternaria sp.	*Corollospora* sp.	*Nia* sp.
Aniptodera sp.	*Fusarium* sp.	*Pencillium* sp.
Arthobotrys sp.	*Halosphaeria* sp	*Philophora* sp.
Aspergillus spp.	*Humicola* sp.	*Phoma* sp.
Botrysporium sp.	*Leptosphaeria* sp.	*Podospora* sp.
Cirrenalia sp.	*Lulworthia* sp.	*Zalerion* sp.

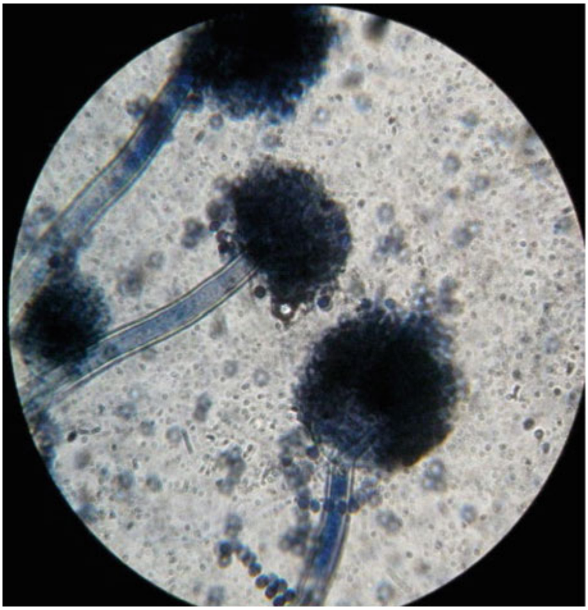


Fig. 12.37 *Aspergillus* sp.

both tunnelling bacteria and fungi caused heavy biodegradation of cell walls resulting in their complete collapse (Santhakumaran & Singh, 1992).

12.5.6.2 Fungi on Catamarans

Preliminary investigations on two untreated and two CCA treated catamarans made of *Albizia chinensis* (Osbeck) Merr. in service for 10 years at Visakhapatnam portrayed severe soft-rot fungal infestation, though differing between the two categories (Fig. 12.41). Screw-like tunnels were produced in less lignified secondary cell walls of the wood logs with broad and brown hyphae in cell lumina of the rays. Occasionally, small, black perithecae and fruiting bodies were also noticed and the infestation had extended quite deep up to 7 cm (Fig. 12.42) (Satyanarayana Rao et al., 1985).

Fig. 12.38 *Fusarium* sp.

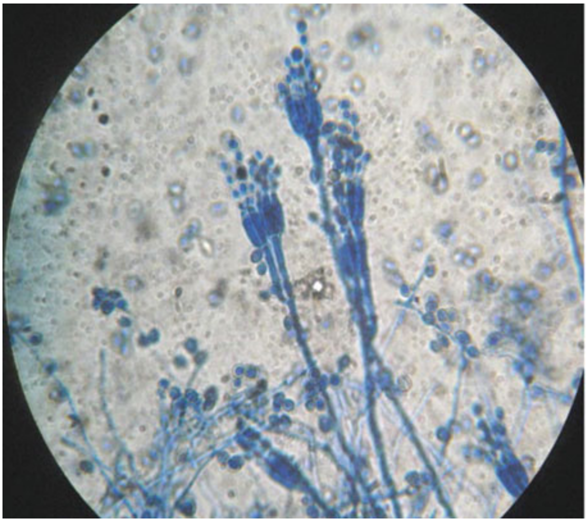


Fig. 12.39 *Pencillium* sp.

12.5.7 Timber, Its Main Enemy at Sea

Early documentary evidence on marine wood borers of India dates back to the eighteenth century (Adanson, 1765). Mentions of these organisms from India are

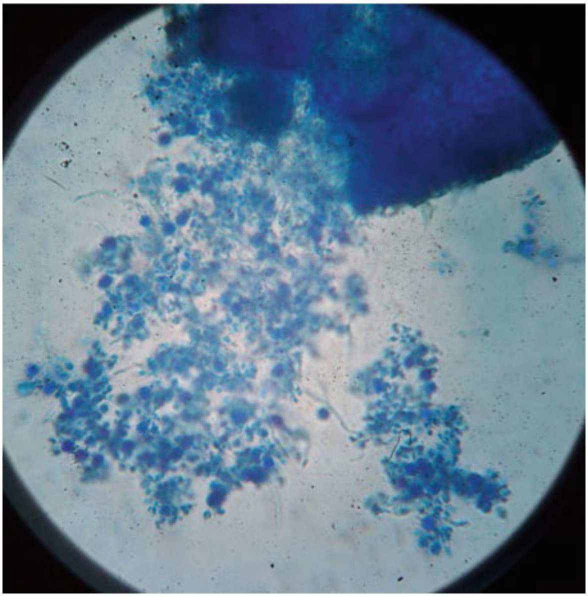
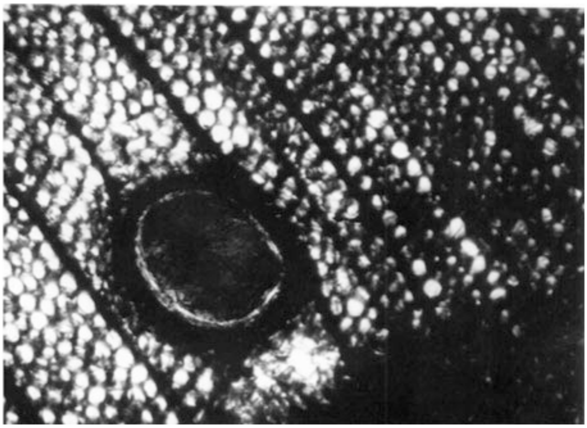


Fig. 12.40 *Philophora* sp.

Fig. 12.41 Biodeterioration of catamaran timber by fungi

also available in Walch (1777), Spengler (1779), Gmelin (1791), Latham and Davis (1791). However, Erlanson (1936) was the first to conduct a survey on marine wood-boring organisms in India at the Travancore-Kochi coast. During nineteenth and early twentieth centuries also, some wood-boring species from India were listed, described or reviewed (Santhakumaran, 1994b). So far, around 150 publications dealing exclusively with systematics, occurrence or distribution of wood borers have emanated from various coastal localities of the country. Of these, important publications of the last decade are mentioned here.

Fig. 12.42 Fungal perithecae and fruiting bodies in catamaran timber



Kumar et al. (2000) viewed marine wood borers as a menace in the making along the Gujarat coast of India. Spatial and temporal distribution of fungi and wood borers in the coastal tropical waters of Goa, India was assessed by Vishwakiran et al. (2001). Dev Roy (2006) gave an account of the marine wood borers of the Andaman-Nicobar Islands and provided a key to identify the species. Seasonal settlement of wood borers in Krishnapatnam harbour in Andhra Pradesh along the east coast of India was studied by Tarakanadha and Rao (2007). Pachu et al. (2009) have reported marine wood borer species from the mangroves of the Krishna estuary. Nayak et al. (2012) studied the incidence of molluscan wood-borers of Chilika Lagoon in Odisha on the East coast of India in addition to mentioning their control measures. Marine wood borer communities of Visakhapatnam harbour in India were investigated by Pati et al. (2013) in relation to their spatio-temporal patterns and different environmental drivers of the ambient. Rao et al. (2013) studied the occurrence and species diversity of marine wood borer species at Kothakoduru and Bangarammapalem minor mangrove habitats of Andhra Pradesh in India. A new record of the marine wood borer, *Spathoteredo obtusa* (Sivickis), belonging to the family Teredinidae; from the mangroves of Andaman Archipelago of India was reported by Marimuthu et al. (2015). Macintosh (2012) added a new teredinid species *Lyrodus turnerae* found from eastern Australia and the Coral Sea that is perhaps present in India also. Velasquez and Shipway (2018) and Shipway et al. (2019) respectively described two more new teredinid genera with one species each, *viz*., *Nivanteredo coronata* from Southwest Pacific and *Tamilokus mabinia* from Philippines.

Marine wood borer fauna belongs to two distantly related Classes, viz., Crustacea in Phylum Arthropoda and Bivalvia in Phylum Mollusca (Jones et al., 2001).

Crustaceans comprise of six genera, namely, *Chelura* of the family Cheluridae, *Paralimnoria* and *Limnoria* of the family Limnoriidae and *Cymodoce, Exosphaeroma* and *Sphaeroma* of the family Sphaeromatidae.

Bivalves include ten genera, namely, *Barnea, Diplothyra, Lignopholas, Martesia, Pholadidea, Pholas, Xylophaga, Xylopholas, Xyloredo* and *Zirfea* of the

Table 12.5 Limnoriids in India

	Phylum: Arthropoda
	Class: Malacostraca
	Order: Isopoda
	Family: Limnoriidae
1.	*Limnoria andamanensis* Lakshmana Rao and Ganapati, 1969
2.	*Limnoria bombayensis* Krishna Pillai, 1961
3.	*Limnoria indica* Kampf and Becker 1958
4.	*Limnoria insulae* Menzies, 1957
5.	*Limnoria pfefferi* Stebbing, 1904
6.	*Limnoria platycauda* Menzies, 1957
7.	*Limnoria septima* Barnard, 1936
8.	*Limnoria tripunctata* Menzies, 1951
9.	*Limnoria unicornis* Menzies, 1957

family Pholadidae and fourteen genera, namely, *Bactronophorus, Bankia, Dicyathifer, Kuphus, Lyrodus, Neoteredo, Nototeredo, Nausitora, Psiloteredo, Spathoteredo, Teredo, Terodora, Teredothrya* and *Uperotus* of the family Teredinidae.

In general, Chelurids are pests of minor economic importance while *Barnea, Diplothyra, Pholas* and *Zirfea* rarely attack wood and *Pholadidea, Xylophaga,*

Fig. 12.43 Limnoriid

Fig. 12.44 Limnoriid attack

Xylopholas and *Xyloredo* mostly are confined to temperate regions, particularly deep seas (Jones et al., 2001).

12.5.7.1 Limnoriids

Limnoriids, commonly known as gribbles, enter wood in juvenile stages both for food and shelter and make longitudinally cylindrical burrows (20–40 mm) parallel to grain leaving a series of ventilation holes (12–26 mm deep) on the superficial surface of timber, especially at deeper levels but up to mid-tide zone. Gribbles grow to a maximum size of 7 mm and riddle wood usually look like lace with a spongy texture. Male and female organisms live in pairs at the end of the burrow and frequently come out to start fresh attack. Normally, juveniles burrow from the original parent tunnel itself, and from these the third generation makes burrows giving rise to tertiary branches. The genera also infesting wood through fresh attack or migration are most destructive particularly in temperate regions of the world in shallow coastal waters, sometimes superseding the damage caused by shipworms. In India, this family shows limited distribution along the coasts represented by 9 species (Palma & Santhakumaran, 2014; Santhakumaran, 2005) (Table 12.5; Figs. 12.43 and 12.44).

Table 12.6 Sphaeromatids in India

	Phylum: Arthropoda
	Class: Malacostraca
	Order: Isopoda
	Family: Sphaeromatidae
1.	*Sphaeroma annandalei* Stebbing, 1911
1a.	*Sphaeroma annandalei travencorensis* Pillai, 1955
2.	*Sphaeroma terebrans* Bate, 1866
3.	*Sphaeroma triste* Heller, 1868
4.	*Sphaeroma tuberculatum* George, 1963

Fig. 12.45 Sphaeromatid

Fig. 12.46 Sphaeromatid attack

12.5.7.2 Sphaeromatids

Sphaeromatids, commonly known as pillbugs, get into wood usually in juvenile stages mainly for shelter and make several, relatively small (~ 15 mm) cylindrical burrows up to 15 mm in sub-surface portion of the timber perpendicularly, especially at intertidal level, but sparsely even down to mud level. These organisms tolerate

Table 12.7 Pholadids in India

	Phylum: Mollusca
	Class: Bivalvia
	Order: Myoida
	Family: Pholadidae
	Subfamily: Pholadinae
1.	*Barnea birmanica* (Phillippi), 1849
2.	*Barnea candida* (Linnaeus), 1758
3.	*Barnea manillensis* (Phillippi), 1849
4.	*Pholas chiloensis* Molina, 1782
5.	*Pholas orientalis* Gmelin, 1791
	Subfamily: Martesiinae
6.	*Lignopholas fluminalis* (Blanford), 1867
7.	*Martesia fragilis* Verrill and Bush, 1898
8.	*Martesia nairi* Turner and Santhakumaran, 1989
9.	*Martesia striata* (Linnaeus), 1758
	Subfamily: Xylophaginae*
10.	*Xylophaga indica* Smith, 1904
11.	*Xylophaga globosa* Sowerby, 1835
12.	*Xylophaga mexicana* Dall, 1908

* According to MolluscaBase (https, 2021c) and Pournou (2020), the Subfamily Xylophaginae has recently been elevated to the "Family" rank as "Xylophagaidae" based on evidences from the ancestral state, cladistic and phylogenetic analyses (Monari 2009; Distel et al., 2011; Haga & Kase, 2013) followed by acceptance through spelling amendment by IUZN (2018)

salinities as low as 1 psu and withstand freshwater conditions as well as aerial exposure for several days. The genera infesting wood through fresh attack or migration are most destructive almost throughout the world in shallow water bodies, especially estuaries, backwaters, lagoons and allied domains. In India, this family is well distributed in all the estuaries and backwaters represented by 4 species and a variety, namely, *S. annandalei* Stebbings, *S. a. travancorensis* Pillai, *Sphaeroma terebrans* Bate, *S. triste* Heller and *S. tuberculatum* George (Palma & Santhakumaran, 2014; Santhakumaran, 2005) (Table 12.6; Figs. 12.45 and 12.46).

12.5.7.3 Pholadids

Pholadids generally termed as piddocks invade into wood in larval stage mainly for shelter leaving minute entry ports outside but make several relatively large, pear-shaped burrows up to 40 mm in sub-surface portion of the timber almost at all depths from intertidal level. The animals are immobile lying inside wood, projecting a pair of siphons into water, but withdraw them (during unfavourable conditions) and remain alive for several days. Different pholadid species possess different salinity tolerances from freshwater to seawater. The species are most destructive in shallow warm waters from temperate to tropical regions, both in marine and brackish water

Fig. 12.47 Pholadid

Fig. 12.48 Pholadid attack

regimes. In India, this community is widely spread all along the coasts represented by 12 species (Palma & Santhakumaran, 2014; Santhakumaran, 2005) (Table 12.7; Figs. 12.47 and 12.48).

12.5.7.4 Teredinids

Like Pholadids, teredinids usually referred to as shipworms having worm-like body also enter into wood in larval stages, but for both food and shelter, although they could also filter feed. Leaving a minute entry port on the surface of timber, these

Table 12.8 Teredinids in India

	Phylum: Mollusca
	Class: Bivalvia
	Order: Myoida
	Family: Teredinidae
	Subfamily: Teredininae
1.	*Bactronophorus thoracites* (Gould), 1856 (Fig. 12.51)
2.	? *Neoteredo reynei* (Bartsch), 1920
3.	*Dicyathifer manni* (Wright), 1866 (Fig. 12.52)
4.	*Teredothyra excavata* (Jeffreys), 1860
5.	*Teredothyra matocotana* (Bartsch), 1927 (Fig. 12.53)
6.	*Teredothyra smithi* (Bartsch), 1927
7.	*Teredora malleolus* (Turton), 1822 (Fig. 12.54)
8.	*Teredora palauensis* (Edmondson), 1959
9.	*Teredora princesae* (Sivickis), 1928
10.	*Uperotus clavus* (Gmelin), 1791
11.	*Uperotus liberkindi* (Roch), 1931 (Fig. 12.55)
12.	*Uperotus panamensis* (Bartsch), 1922
13.	*Uperotus rehderi* (Nair), 1956
14.	*Psiloteredo senegalensis* (Blainville), 1828
15.	*Teredo aegypos* Moll, 1941
16.	*Teredo bartschi* Clapp, 1923
17.	*Teredo clappi* Bartsch, 1923
18.	*Teredo fulleri* Clapp, 1924
19.	*Teredo furcifera* von Martens, 1894
20.	*Teredo indomalaiica* Roch, 1935
21.	*Teredo mindanensis* Bartsch, 1923
22.	*Teredo navalis* Linnaeus, 1758
23.	*Teredo parksi* Bartsch, 1921
24.	*Teredo poculifer* Iredale 1936 (Fig. 12.56)
25.	*Teredo portoricensis* Clapp, 1924
26.	*Teredo somersi* Clapp, 1924
27.	*Teredo triangularis* Edmondson, 1924
28.	*Lyrodus affinis* (Deshayes), 1863
29.	*Lyrodus bipartitus* (Jeffreys), 1860 (Fig. 12.57)
30.	*Lyrodus massa* (Lamy), 1923
31.	*Lyrodus medilobatus* (Edmondson), 1942
32.	*Lyrodus pedicellatus* (Quatrefages), 1849
33.	*Lyrodus singaporeana* Roch, 1935
34.	*Lyrodus takanoshimensis* (Roch) 1929s
35.	*Lyrodus triste* (Iredale), 1936
	Subfamily: Bankiinae
36.	*Nototeredo edax* (Hedley), 1895
37.	*Nototeredo knoxi* (Bartsch), 1917
38.	*Nototeredo norvagica* (Spengler), 1792 (Fig. 12.58)

(continued)

Table 12.8 (continued)

	Phylum: Mollusca
	Class: Bivalvia
	Order: Myoida
	Family: Teredinidae
	Subfamily: Teredininae
39.	*Spathoteredo obtusa* (Sivickis), 1928
40.	*Nausitora dunlopei* Wright, 1864
41.	*Nausitora fusticula* (Jeffreys), 1860
42.	*Nausitora globosa* (Sivickis), 1928
43.	*Nausitora hedleyi* Schepman, 1919 (Fig. 12.59)
44.	*Nausitora oahuensis* (Edmondson), 1942
45.	*Bankia australis* (Calman), 1920
46.	*Bankia bipalmulata* (Lamarck), 1801
47.	*Bankia bipennata* (Turton), 1819
48.	*Bankia brevis* (Deshayes) 1863
49.	*Bankia campanellata* Moll and Roch, 1931(Fig. 12.60)
50.	*Bankia carinata* (Gray), 1827
51.	*Bankia destructa* Clench and Turner, 1946
52.	*Bankia fimbriatula* Moll and Roch, 1931
53.	*Bankia gracilis* Moll, 1935
54.	*Bankia gouldi* (Bartsch) 1908
55.	*Bankia martensi* (Stempell) 1819
56.	*Bankia nordi* Moll, 1935
57.	*Bankia philippinensis* Bartsch, 1927
58.	*Bankia rochi* Moll, 1931
59.	*Bankia zeteki* Bartsch 1921

animals penetrate deep into the core of timber making numerous long, tubular or serpentine and intricate tunnels parallel to grain, but never cross one another. The destruction vigour of these forms is amazing. These organisms attack wood at all depths although the intensity increases from intertidal region to mud-level. These animals are also immobile residing inside wood projecting a pair of siphons into water, but withdraw them and plug the entrance hole with a pair of unique and specialized calcareous organelle known as ‘pallets’ to remain alive for several days during unfavourable conditions. Interestingly, these pallets are typical to each species and help serve in identification rather than shells (Fig. 12.61), body or siphons. (So, pallets of different species are featured in figures.) Various species prefer various salinities from brackish water to seawater and generally tolerate very low salinities. These bivalves are gravely destructive throughout the world. In India, the group is highly prevalent in all coastal waters being represented by 59 species belonging to 13 genera (Rao et al., 2011) (Table 12.8; Figs. 12.49 and 12.50).

Fig. 12.49 Teredinid (Whole animal)

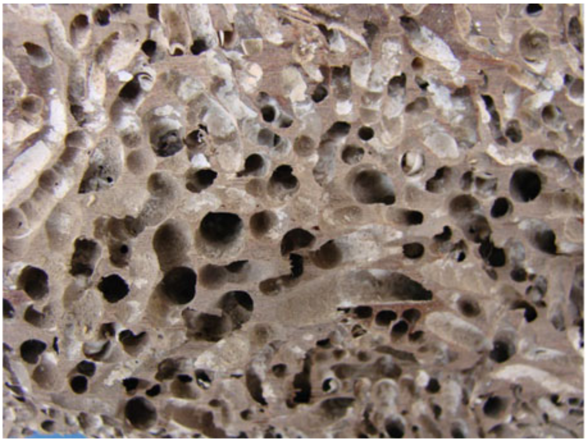


Fig. 12.50 Teredinid attack

12.5.8 Timber, Its Bioresistance at Sea

After understanding the nature and voracity of various deteriogens, evaluation of the bioresistance of various timbers for consumption under marine conditions is very much essential. Such an assessment leads to pin-pointing the appropriate suitability of a timber for the intended purpose and aids in ascertaining its potential as an

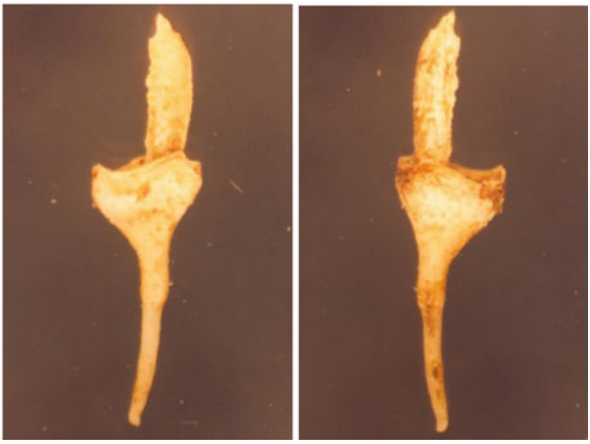


Fig. 12.51 *Bactronophorus thoracites*

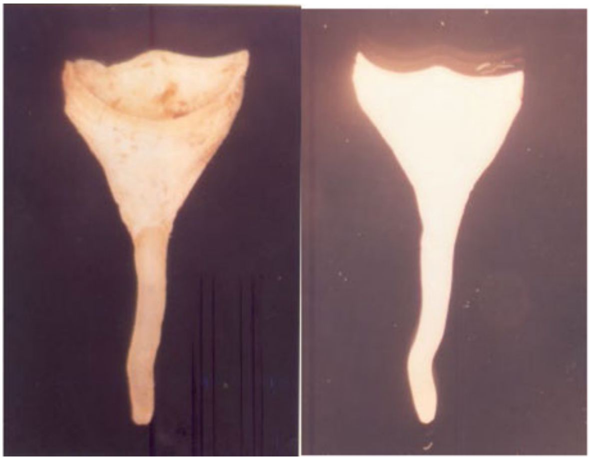


Fig. 12.52 *Dicyathifer manni*

alternative to the lesser-used taxa, under-utilized species and imported varieties thereby easing the pressure on limited choices generally available.

The inherent character or ability of a timber to resist deterioration caused by bacteria, fungi and marine borers is considered as the bioresistance or natural resistance or natural durability of that species in marine environment. Stevenson (1874) was the first to study the natural resistance of timber under marine conditions. Subsequently, several workers all over the world had studied this aspect. All such findings till 1957 were bibliographed in Clapp and Kenk (1956, 1957). Cunningham (1908), Messent (1920), Howard (1920, 1922), Pearson and Brown (1932) made some of the earliest reports mentioning about marine borer attack and timber use in

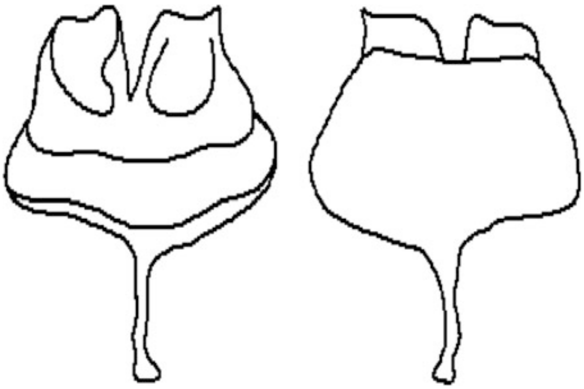


Fig. 12.53 *Teredothyra matocotana*

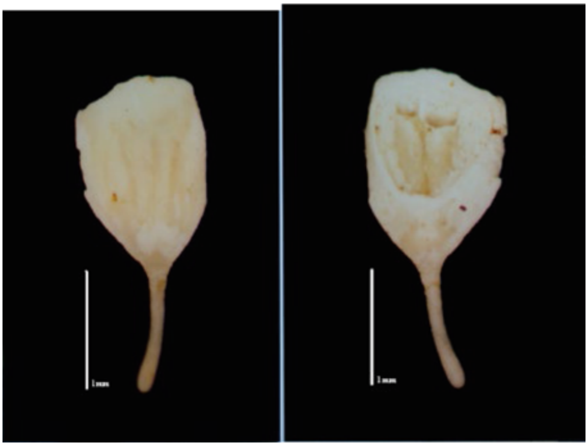


Fig. 12.54 *Teredora malleolus*

Indian waters. Further investigations carried out in the country are specific and more detailed in nature. Several publications had also emanated during the last century and the past two decades of the current century.

Realizing the importance of these studies in the Indian context, Wood Preservation Branch of the Forest Research Institute and Colleges (now Indian Council of Forestry Research and Education, ICFRE) at Dehradun initiated field tests in 1953 at Visakhapatnam, Madras (now Chennai), Trivandrum (now Thiruvananthapuram), Cochin (now Kochi) and Bombay (now Mumbai) harbours. Santhakumaran (1994b) listed out 77 publications on this subject in an annotated bibliography on Indian marine wood borers while results of the findings were summarized from time to time as consolidated reports (Purushotham & Satyanarayana Rao, 1971; Tiwari et al., 1984).

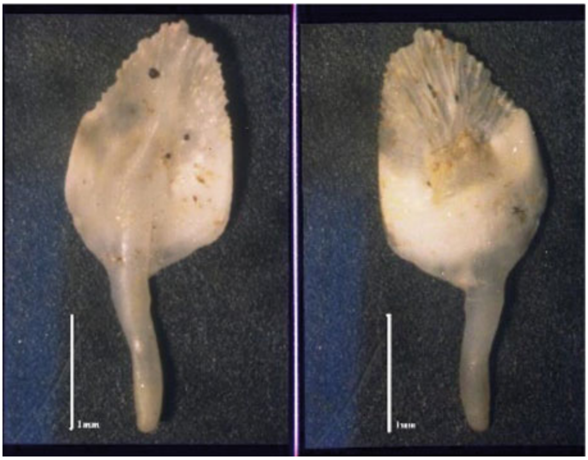


Fig. 12.55 *Uperotus lieberkindi*

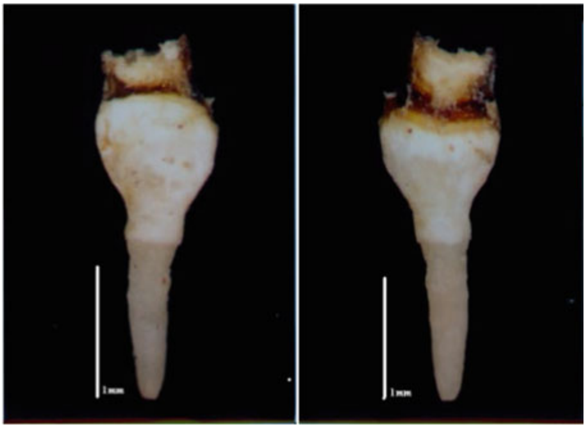


Fig. 12.56 *Teredo poculifer*

Among other workers, Nair (1956) studied bioresistance of 16 species in Madras and Kayamkulam waters. Balasubramanyan and Menon (1963), Balasubramanyan (1970a, b), Nair and Saraswathy (1971), Cherian et al. (1992) worked on the natural durability of various timbers in Kochi harbour and its vicinities. Karande (1967, 1968) evaluated the resistance of a few timbers in Bombay harbour. Kalyanasundaram and Ganti (1974, 1975b, c) assessed the longevity of 28 to 43 timber species at Port Blair (Andaman Islands), Visakhapatnam, Madras, Cochin, Marmugao and Bombay harbours. Karande (1978) tested a few Andaman timbers for their natural durability at Port Blair. Chandramohan et al. (1979) evaluated the performance of five timbers at Mangalore fishing harbour. Raveendran and Wagh (1990) studied the resistance of Andaman timbers in Marmugao waters.

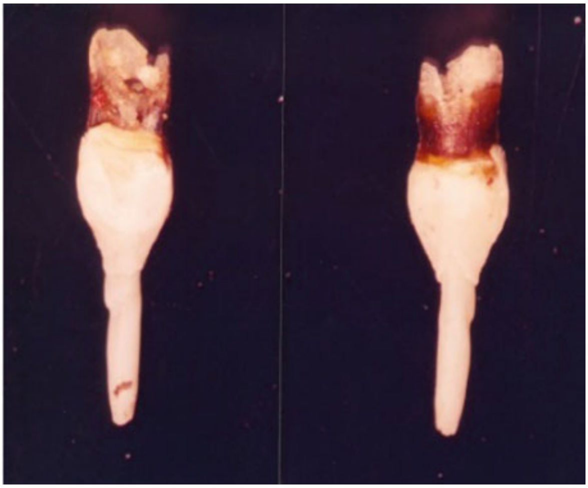


Fig. 12.57 *Lyrodus bipartitus*

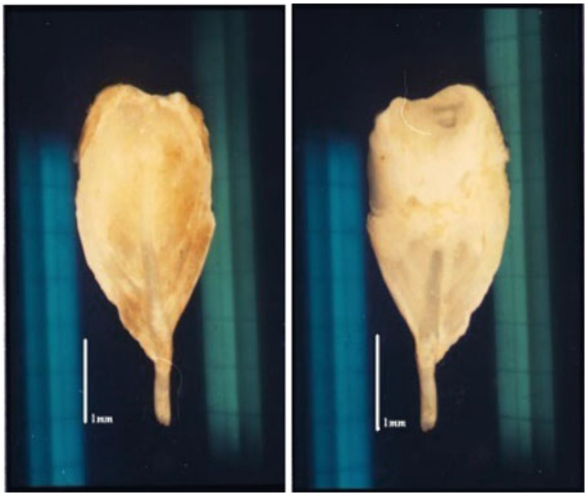


Fig. 12.58 *Nototeredo norvagica*

12.5.9 Timber, Its End Uses at Sea

So, such investigations on the natural resistance of various timbers from different quarters in marine regime came handy in identifying comparatively durable species useful for different constructions (Santhakumaran, 1994a). However, the natural resistance of a timber in a particular marine station, i.e., sea port, naval base, dockyard, shipyard, fishing harbour, marina, transport jetty or other seaboard point of interest is governed by a combination of physico-chemical properties of a timber species (Bultman et al., 1980; Rao et al., 2007; Santhakumaran, 1991) coupled with

Fig. 12.59 *Nausitora dunlopei*

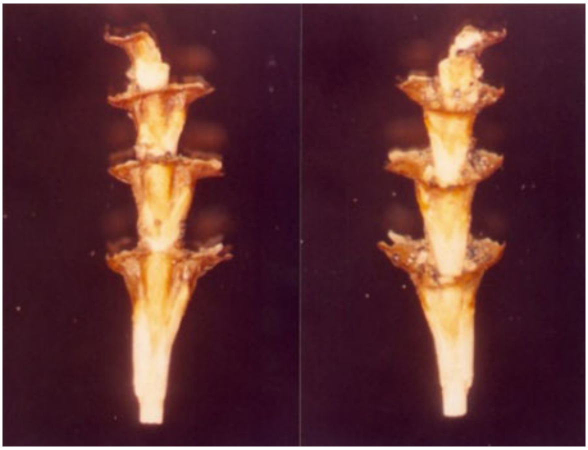


Fig. 12.60 *Bankia campanellata*

abiotic factors (Kalyanasundaram & Ganti, 1975a; Raveendran & Wagh, 1988; Santhakumaran, 1989) and biotic conditions (Dharmaraj & Nair, 1983; Santhakumaran, 1994a) of the ambient medium. For example, the performance of the same species of timber even in the same locality is not uniform. This is attributable to the composition of wood-boring fauna in a locality, their dependence

Fig. 12.61 Teredinid shells

on wood for food and reproductive seasons and variations in the time of the year and depths at which the structures are installed (depending on the vertical distribution, breeding strategies and seasonal intensity of the borers existing there).

Accordingly, locality specific trials and resultant findings play a pivotal role in finalising any recommendations. Incidentally, Chennai, Krishnapatnam and Visakhapatnam ports located along the east coast adjoining the Bay of Bengal and Kochi, Goa and Mumbai ports situated on the west coast abutting the Arabian Sea (except Krishnapatnam harbour) use timber in considerable quantity in dockyards, shipyards and naval establishments situated there (Rao et al., 2007).

Timber in the said marine domains is chiefly employed to fabricate life boats and rafts and to install a gamut of stationary structures such as beams, dock blocks, fenders, keel blocks, launching ways, piers, piles, shores, stage planks and wharves. In order to aid in guiding port, dockyard, shipyard and naval establishments in the country in selecting suitable timber species for fabricating the aforesaid structures, the following recommendations are brought out based on the publications of Sharma et al. (1974). Wood Explorer Data Base (2005), Rao et al. (2007). The list given consists of scientific nomenclature of each timber followed by author citation with year, trade name and its family affiliation.

12.5.10 Prime Timbers, their Alternatives

In fact, full-proof bioresistant timbers are not at all available anywhere for utility under marine conditions and almost all species exhibiting best bioresistance in the country became scarce. Conventional craft fabricating artisans and even many engineers constructing boats and other marine structures often limit their choice of material to traditionally used and well-established durable timber varieties. Thus, potential alternatives equated with eminent species from among lesser-known timbers for use in marine constructions are often turned down from acceptance both by the makers and end users (Borges et al., 2008; Palanti et al., 2015; Rosenbusch et al., 2006; Santhakumaran & Sneli, 1978; Sen et al., 2009). So, in order to promote the use of alternatives in various marine constructions (for that matter, in other situations also), ample knowledge and enormous awareness needs to be created till valid information is caught up among all the concerned (supplier, middlemen, maker and end user) (Williams et al., 2005). Conversely, the use of well-established durable timber varieties, though scarce is also gradually decreasing because their supply suffers from illegal logging, transportation, sales and socio-political issues in the wake of implementation of certification procedures (Treu et al., 2019).

Despite being world's top producer of tropical wood, India is importing several species of timber from at least 20 countries to a tune of 18.01 million m^3 worth 6701.3 million US$ to meet the gap between demand and supply as on the year 2015 (Shrivastava & Saxena, 2017). And marine timber utilities for sure take a considerable share of it necessitating compulsory search for native alternatives.

To date, over 250 native species were screened out for their natural resistance under marine conditions and certain potential timbers were identified as alternatives to presently used species and listed for use in marine environment, possibly after due preservative protection (Tarakanadha et al., 2005).

Potential alternatives for catamarans are *Ailanthus excelsa* Roxb. 1795, India tree of heaven, Simaroubaceae; *Ailanthus triphysa* (Dennst.) Alston 1818, Maharukh, Simaroubaceae; *Albizia odorotissima* (L. f.) Benth. 1806, Black siris, Fabaceae;

Fig. 12.62 Natural durability of timber for catamarans (1-*Albizia chinensis*, 2-*Albizia procera*, 3-*Alstonia scholaris*, 7-*Bischofia javanica*, 6-*Bombax ceiba*, 9-*Elaeocarpus recurvatus*, 10-*Erythrina stricta*, 20-*Lagerstroemia parviflora*, 21-*Lagerstroemia reginae*, 22-*Lannea coromandelica*, 23-*Paraserianthes falcataria*, 25-*Samanea saman*, 28-*Tetrameles nudiflora*)

Bombax ceiba L. 1753, Cotton tree, Malvaceae; *Elaeocarpus recurvatus* Corner 1871, Rudrak, Elaeocarpaceae; *Erythrina variegata* L. 1786, Coral tree, Fabaceae; *Kydia calycina* L. 1786, Coral tree, Fabaceae; *Macaranga peltata* (Roxb.) Mull.Arg. 1866, Macaranga, Euphorbiaceae; *Maesopsis eminii* Engler 1895, Umbrealla tree, Rhamnaceae; *Melia dubia* Cav.1789, Malabar neem, Meliaceae; *Toona ciliata* M. Roem.1846, Toon tree, Meliaceae and *Trema orientalis* (L.) Bl. 1856, Indian mettle, Ulmaceae. Balan (1980) also recommended several alternate timbers such as *Ailanthus triphysa* (Dennst.) Alston 1818, Maharukh, Simaroubaceae; *Albizia stipulata* Auct.Non DC 1825, Silk plant, Fabaceae; *Artocarpus chaplasha* Roxb. 1814, Chaplash, Moraceae; *Bombax insigne* Wall. 1830, Guiana chestnut, Malvaceae; *Canarium euphyllum* Kurz.1872, White Dhup, Burseraceae; *Endospermum malaccense* Benn.& Muell. Arg. 1864, Bakotta, Euphorbiaceae; *Parishia insignis* Hook. f. 1860, Lelayang, Anacardiaceae; *Planchonella longipetiolata* (King & Prain) H.J.Lam. 1925, Lambapatti, Sapotaceae; *Pterocymbium tinctorium javanicum* (R. Br.) Kosterm. 1969, Amberoi, Malvaceae and *Tetrameles nudiflora* R. Br. ex Benn. 1838, Maina, Datiscaceae from Andaman-Nicobar Islands for catamarans (Fig. 12.62).

Prospective species for canoes and mechanized craft are *Acacia nilotica* (L.) Willd. ex Del. 1812, Babul, Fabaceae; *Albizia chinensis* (Osbeck) Merr. 1825, Chinese Albizia, Fabaceae; *Albizia procera* (Roxb.) Benth. 1844, White siris, Fabaceae; *Albizia amara* (Roxb.) B. Boivin 1806, Bitter Albizia, Fabaceae; *Albizia lebbeck* (L.) Benth. 1844, Indian siris, Fabaceae; *Ailanthus excelsa* Roxb. 1795,

Fig. 12.63 Natural durability of timber for canoes (6-*Bombax ceiba,* 36-*Calophyllum inophyllum,* 10-*Erythrina variegata,* 20-*Lagerstroemia reginae,* 45-*Mangifera indica,* 28-*Tetrameles nudiflora,* 29-*Trewia polycarpa*) and Port/ Harbour structures (6-*Albizia odoratissima*, 2-*Albizia procera*, 88-*Artocarpus hirsutus*, 64-*Casuarina equisetifolia*, 46-*Mesua ferrea*, 109-*Pinus roxburghii*, 48-*Pterocarpus dalbergioides*, 78-*Terminalia arjuna*, 60-*Xylia xylocarpa*)

Fig. 12.64 Natural durability of timber for canoes and mechanised craft (31-*Acacia nilotica*, 1-*Albizia chinensis*, 88-*Artocarpus hirsutus*, 62-*Azadirachta indica*,7-*Bischofia javanica*, 36-*Calophyllum inophyllum,* 64-*Casuarina equisetifolia*, 20-*Lagerstroemia parviflora*, 21-*L. reginae*, 45-*Mangifera indica,* 46-*Mesua ferrea*, 109-*Pinus roxburghii*, 48-*Pterocarpus dalbergioides*)

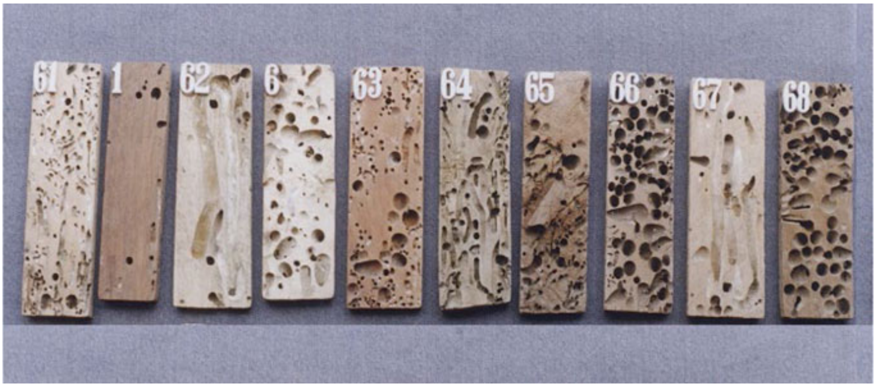


Fig. 12.65 Natural durability of timbers for port/harbour structures (61-*Acacia auriculiformis*, 1-*Albizia chinensis*, 62-*Azadirachta indica*, 6-*Bombax ceiba*, 64-*Casuarina equisetifolia*, 65-*Dalbergia latifolia*, 67-*Eucalyptus grandis*, 68-*Eucalyptus tereticornis*)

India tree of heaven, Simaroubaceae; *Ailanthus triphysa* (Dennst.) Alston 1818, Maharukh, Simaroubaceae; *Anogeissus acuminata* (Roxb. ex DC.) Wall. ex Guill. & Perr. 1832, Dhaura, Combretaceae; *Artocarpus heterophyllus* Lam. 1789, Jack-fruit, Moraceae; *Artocarpus hirsutus* Lam. 1789, Wild jack, Moraceae; *Azadirachta indica* A. Juss. 1830, Indian lilac, Meliaceae; *Bischofia javanica* Blume 1826, Bishop wood, Phyllanthaceae; *Erythrina variegata* L. 1786, Coral tree, Fabaceae;

Mangifera indica L. 1753, Mango, Anacardiaceae; *Melia dubia* Cav.1789, Malabar neem, Meliaceae; *Paraserianthes falcataria* (L.) Neilsen 1754, Batai, Fabaceae; *Samanea saman* (Jacq.) Merr. 1844, Rain tree, Fabaceae; *Thespesia populnea* (L.) Soland. Ex Correa. 1807, Bendy tree, Malvaceaeand *Toona ciliata* M. Roem. 1846, Toon tree, Meliaceae (Figs. 12.63 and 12.64).

Possible alternative species for port/harbour structures are *Acacia auriculiformis* A.Cunn. ex Benth. 1842, Black wattle, Fabaceae; *Acacia nilotica* (L.) Willd. ex Del. 1812, Babul, Fabaceae; *Artocarpus heterophyllus* Lam. 1789, Jackfruit, Moraceae; *Artocarpus hirsutus* Lam. 1789, Wild jack, Moraceae; *Calophyllum polyanthum* Wall. Ex Choisy 1869, Poonspar tree, Calophyllaceae; *Chloroxylon swietenia* (Roxb.) DC. 1824, Satin wood, Rutaceae; *Eucalyptus grandis* W. Hill ex Maiden 1903, Flooded gum, Myrtaceae; *Eucalyptus tereticornis* Sm.1795, Mysore gum, Myrtaceae; *Lagerstroemia lanceolata* Wall. 1839, Nandi tree, Lythraceae; *Lannea coromandelica* (Houtt.) Merr.1774, Jhingam, Anacardiaceae and *Syzygium gardneri* Thw. 1874, Kari njaval, Myrtaceae (Fig. 12.65).

Most of the above-mentioned alternative timbers are grown in either home-steads or avenues or shade trees or plantations or compensatory forests and as such available in plenty.

Now that the causatives and casualties are understood, the means to circumvent or overcome the precarious situation needs to be considered seriously on well-found scientific facts and streamlined technical lines.

12.5.11 Timber, Its Protection at Sea

In order to curtail marine wood biodeterioration, several preventive or protective or control measures are in vogue for centuries (Tarakanadha et al., 2005). Basically they belong to five categories, viz., indigenous approaches, mechanical barriers, bioresistant timbers, chemical preservatives and botanical preservatives.

Fig. 12.66 Indigenously protected traditional craft

Fig. 12.67 Indigenously protected mechanized fishing boats

12.5.11.1 Indigenous Approaches

Coatings of several formulations made of indigenous substances/products such as animal (buffalo or camel) fat, crude fish oil, hunnai oil, shark liver oil, groundnut oil, calophyllum oil, cashew nut shell oil, castor oil, coconut oil, karanjel oil, neem oil, poon oil, plant resins, vegetable tannins, chandrus, dammar battu, ketch, lime, pitch, coal tar, bitumen, sand and cement are applied mainly to non-motorized traditional wooden craft such as canoes, catamarans, dhoes, dhonies, dinghies, dugouts, machuwas, masulas, navas, rampanis, vallams, vendis, etc. (Sreekrishna, 2002).

For example, a layer of thoroughly mixed castor oil and lime is initially applied to the exterior as well as interior of a boat with the help of a torch (diviti). After its drying, a coating of dammar battu oleo-resin dissolved in ground-nut oil is given as a second stratum. Finally, second coating is repeated and later the craft is put to use. Sometimes other oils mentioned above are employed in place of castor oil. In another method, well powdered solidified plant resin (chandrus) is dissolved in karanjel oil by boiling it and then made into a paste by adding fine lime powder. The preparation is applied to the boat in the above said fashion followed by a final coat of cashew nut shell oil (Figs. 12.66 and 12.67).

These methods, however, provide protection for short durations and hence are applied repeatedly at regular intervals. On testing along scientific lines, none of the said procedures proved dependable (Purushotham & Satyanarayana Rao, 1971; Santhakumaran et al., 1982; Tiwari et al., 1984) except cement plastering of wooden poles over iron nails and winding wire and coir rope matrices (Rao et al., 1993). Nonetheless, most of the said applications are faith bestowed ethnic systems widely practised in the majority of fishing hamlets along the Indian coasts even today because of casual material accessibility, easy human resources availability, void skill involvement (barefoot technology) and cost-effective procedures.

Fig. 12.68 Metal sheathing of a boat as a mechanical barrier (damaged)

Fig. 12.69 Fibre-reinforced plastic coating to a boat as a mechanical barrier

12.5.11.2 Mechanical Barriers

Studding of timber all over the surface with iron nails (scupper nailing) or embedding the structures in concrete in the instance of stationary structures such as fishnet poles, stake net posts, fender piles, jetty piles, feed posts and groynes (hydraulic shore structures) are some defensive measures used to control marine wood biodeterioration. Similarly, in the case of moving flotilla such as trawlers, seiners, lift netters, gill netters and tuna liners a sheathing over their exterior is provided employing plastic or metal sheet of copper, zinc, aluminium or alloys or fibre reinforced plastic coating as a protective technique against marine wood biodeterioration (Purushotham & Satyanarayana Rao, 1971; Tiwari et al., 1984; Unnikrishnan Nair et al., 1987). Of these, scupper nailing is found effective in the case of stationary structures (Rao et al., 1991) and metallic sheathing, though costly, for mechanized

Fig. 12.70 Durable timbers for boat building

craft for reasonably long periods. But of late, the latter is substituted mostly by fibre reinforced plastic coating because of monetary benefits (Figs. 12.68 and 12.69).

However, any slightest damage due to mechanical abrasion or wear and tear of the barriers provides access of timber to millions of borer larvae through the void (s) so created thereby providing ample choice for the borers to colonize and destroy the wood without slightest external sign of the internal sabotage inflicted. Metal sheathing may also require frequent replacement due to corrosion in seawater. Of course, biofouling cannot be avoided and co-exists increasing the weight of the vessel. Therefore, several kinds of anticorrosive and anitfouling paints are applied over them for protection from time to time. In the case of damage to fibre-reinforced plastic no repair is possible than completely peeling the sheath and redoing it. In either case, repair, maintenance and allied costs prove heavy.

12.5.11.3 Bioresistant Timbers

Biodeterioration control through the use of timbers endowed with comparatively better bioresistance against marine organisms attack to obtain maximum longevity of the structures for use in seawater environment is another preventive measure to tackle the issue. India is blessed with several tropical hardwood species well known for their many affirmative properties including high immunity against marine wood borer attack for making umpteen items and hence were preferred as choice material for many marine fabrications too during many yester years. The country was famous world over for building great armada from such timbers and supplied them to many foreign nations. But over the centuries, such mighty timbers have become quite rare and the existing species of the kind did not attain the required maturity to be relatively as immune as they were earlier. Specifically, population explosion after industrial revolution made the situation deteriorate further. Nevertheless, out of the now available hard woods, some of the best taxa dependable for their natural bioresistance are *Artocarpus hirsutus* (Aini), *Cleistanthus collinus* (Oduvan), *Dalbergia latifolia* (Rosewood), *Dipterocarpus indicus* (Gurjan), *Hardwickia*

Fig. 12.71 Prime species for repairing boats

binata (Anjan), *Hopea parviflora* (Hopea), *Lannea coromandelica* (Jhingan) *Lagerstroemia microcarpa* (Ben teak), *Madhuca longifolia* (Mahua), *Mimusops littoralis* (Bullet wood), *Pterocarpus dalbergioides* (Andaman Padauk), *Pterocarpus marsupium* (Bijasal), *Schelichera oleosa* (Kusum), Shorea *robusta* (Sal), *Tectona grandis* (Teak), *Terminalia paniculata* (Kindal) and *Xylia xylocarpa* (Irul) (Purushotham & Satyanarayana Rao, 1971; Rao et al., 2007; Santhakumaran, 1997; Santhakumaran & Jain, 1983; Satyanarayana Rao et al., 1994a). During repair and maintenance of marine craft also timber of these famous species are used (Figs. 12.70 and 12.71).

The said procedure has been practised for a considerable period of time and the said prime varieties put to use even when no necessity exists for their use in certain situations just to fulfil self-satisfaction, rather than need. Yet, this is not a promotional method as stocks of relatively resistant timbers quickly get exhausted and further dependence on such preferences in all likelihood poses serious threat to the resources, their conservation, sustainability and ultimately the forest biodiversity itself.

12.5.11.4 Chemical Preservatives

Among the first four options, the last technology is advanced, well developed, highly efficient and thoroughly established. In this option, wood is treated with selected chemical compounds (inorganic or organic or a combination of both) through pressure impregnation for preserving it from the menace of various biodeteriogens and thereby improving its durability and enhancing its service performance. Thus, a substance or chemical that delays biodeterioration of timber in utility and prolongs longevity of the structure is known as a wood preservative. Since the benefits accrued from the treatment of wood with preservatives are superb and cost-effective, particularly in risky areas like cooling towers, mines and marine environment; this technology is now widely used in many countries around the world specifically in hazardous situations like seawater.

The use of chemical preservatives for wood treatment had started in India during the nineteenth century. Unlike in other countries, oil borne preservatives, namely, creosote and pentachlorophenol were vividly used in the country initially. But after the invention of water-borne preservatives, their use had declined considerably. Particularly, the water-borne preservative copper-chrome-arsenic (CCA or Ascu) invented in India during 1933 proved to be the best chemical highly effective against biodeterioration on land as well as under marine conditions. Usually, a pre-fabricated timber structure dismantled is vacuum-cum-pressure treated with CCA of required strength to the targeted preservative retention level depending upon the end use prerequisite to achieve finally desired quantity of chemical in timber components that are reassembled for application. The efficacy of a treated structure depends on the quantity of preservative entering the wood and its permanence inside. CCA being water soluble but fixed type wood preservative, gradually leaches out of treated installations as constituent elements into marine environment in nano quantities thereby preventing wood deteriorating biological agencies in their infancy from invading the wood substance and in turn protecting it from their ravages.

Balan (1980) recommended several physical (reinforced plastic sheathing over the logs) and chemical (copper-chrome-arsenic, coal tar creosote, etc.) treatment methods to increase the service life of fishing craft. Other simple methods like dipping, soaking and diffusion are also recommended for treatment of fishing craft made especially of sawn timber, as the methods need no special skill, instruments or space.

Apart from CCA, other preservatives such as copper-chrome-boric (CCB), borax-boric acid and organic solvent type preservatives are used to some extent in India while ammonical copper arsenate (ACA), copper zinc chrome (CZC), ammoniacal zinc borate (AZB), trichlorophenol, copper naphthenate and copper resinates are used sparsely (Satish Kumar, 1991, 1998; Inder Dev & Bhojvaid, 2003). In recent decades, several copper-based new preservatives, namely, ammoniacal copper borate (ACB), copper zinc borate (CZB), borated copper chrome arsenic (BCCA), copperised cashew nut shell liquid (CCNSL), copper resinate mixtures, ammoniacal compound quaternary (ACQ), ammoniacal copper citrate (CC), ammoniacal copper zinc arsenate (ACZA) and copper dimethyl dithio carbamate (CDDC) and micronized copper, etc. were developed to contain growing environmental concerns of arsenical use in CCA (Inder Dev & Bhojvaid, 2003; Tripathi & Dev, 2003).

Over 40 timber species were treated to various retentions with chemical preservatives, namely, creosote, creosant, creosote:coal tar, creosote:fuel oil, pentachlorophenol, copper resinate, trichlorophenol, CCA and CCB and tested in different harbours of the country (Purushotham & Satyanarayana Rao, 1971; Rao et al., 2007; Santhakumaran & Krishnan, 1991; Satish Kumar, 1998; Satyanarayana Rao et al., 1994b; Tiwari et al., 1984). Early this century, four new preservative formulations, namely, ammoniacal compound quaternary (ACQ), ammoniacal copper citrate (CC), ammoniacal copper zinc arsenate (ACZA) and copper dimethyl dithio carbamate (CDDC) were tested for the first time in Indian waters at Visakhapatnam and Krishnapatnam harbours. Of these, ACZA, especially at

Fig. 12.72 Control, *A. lebbeck*

Fig. 12.73 CCA, *A. lebbeck*

Fig. 12.74 CCB, *lebbeck*

Fig. 12.75 Control, *T. nudiflora*

Fig. 12.76 CCA, *T. nudiflora*

Fig. 12.77 CCB, *T. nudiflora*

Fig. 12.78 *Anogeissus acuminata* (1) Control, (2) CCA-treated and (3) CCB-treated panels

retentions approximating 40 kg.m^{-3} has shown promising results comparable to CCA (Rao, 2001; Tarakanadha, 2003).

In an attempt to prepare preservative-treated catamarans out of *Albizia lebbeck* and *Tetrameles nudiflora*, their marine evaluation in untreated form revealed the natural bioresistance to be less than 11 and 14 months, respectively, while the durability of both CCA and CCB treated panels to be about 1½ years suggesting higher target levels of retentions for obtaining satisfactory performance from them (Rao, 2008) (Figs. 12.72, 12.73, 12.74, 12.75, 12.76 and 12.77).

In another earlier attempt, marine evaluation of plank-built catamaran timber, *Anogeissus acuminata* (Yon) in untreated and CCB and CCA preserved conditions disclosed that it exhibited 15, 21 and 27 months durability, respectively signifying its satisfactory performance (Rao & Balaji, 2010) (Fig. 12.78).

Adaptability of tributyl tin methacrylate-methyl methacrylate (subsequently banned of course), basically used as an antifoulant over ship exteriors, as a wood preservative in warding off marine borer attack was simultaneously assessed at Visakhapatnam and Kochi harbours. Timber panels of *Paraserianthes falcataria* (Albizia) and *Bombax ceiba* (Semul) pressure impregnated with the formulation were exposed to marine borer hazard at the two places for 36 months. At the end of the testing period at the former place, both treated species effectively prevented wood borer attack and kept the wood in sound condition. On the contrary, treated panels of both the species at Kochi succumbed to slight (4%) to moderate (32%) destruction depending upon the chemical retentions. Intrusion of timber by sphaeromatids followed by gradual entry of a couple of teredinid taxa was found to be the cause of such damage that perhaps resulted from the loss of surface wood layers rich in preservative due to repeated rubbing of panels against RCC wharf piers (Balaji & Rao, 2013).

Generally, in Indian waters, most of the native timber species last for a year or so in untreated condition, whereas they fare well four to five times better than that in preservative-treated condition.

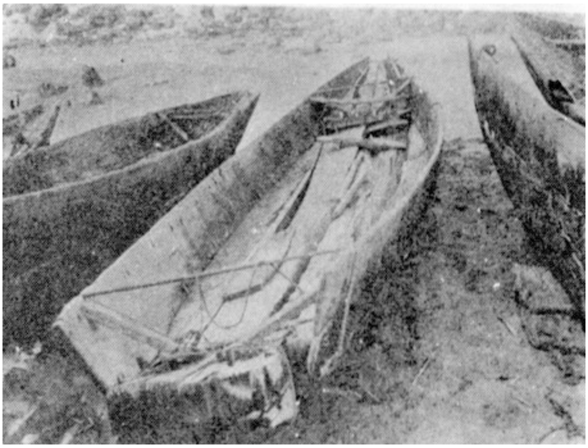


Fig. 12.79 Preservative protected *Albizia chinensis* catamaran

Fig. 12.80 Preservative protected *Paraserianthes falcataria* catamaran

Fig. 12.81 Preservative protected *Bombax ceiba* catamarans for distribution

Fig. 12.82 Preservative protected plank-built catamarans of *Anogeissus acuminata*

12.5.12 Timber, Its Treated Structures at Sea

Authentic service trials were also conducted with original structures (fenders, piles, canoes and catamarans treated with CCA or CFO or both). These trials amply demonstrated the benefits of chemical wood preservation in marine environment (Purushotham & Satyanarayana Rao, 1971; Rao et al., 2007; Tiwari et al., 1984). In these trials, CCA, CFO and CCA cum CFO-treated fender piles ($18 \times 0.6 \times 0.3$ m) of *Terminalia arjuna* (Arjun) were installed in Cochin harbour and the structures largely retained serviceability at the end of their removal after 5 years under modernization spree (Cheriyan et al., 1991). In trials on traditional craft, CCA treated *Albizia chinensis* (Siris) catamarans lasted for 26 years as against a normal service life of 5–7 years at Visakhapatnam (Fig. 12.79). CCA-treated *Paraserianthes falcataria* (Albizia) catamarans launched at Chennai during 1990 performed well for 15 years (Fig. 12.80).

CCA-treated catamarans made of a highly perishable (<6 months of natural durability) timber, namely, *Bombax ceiba* (Semul) gave an actual service of 17 years at Visakhapatnam. (Fig. 12.81). During the end of last century, 85 CCA-treated *B. ceiba* catamarans were distributed to fishermen in Andhra Pradesh and Tamil Nadu states under a World Bank sponsored project along with another five plank-built catamarans made of CCA-treated timber of *Anogeissus acuminata* (Yon) (Fig. 12.82) (Rao et al., 2007).

Thus, even highly non-durable timber species could profitably be used after suitable chemical protection to make service structures of very long durability at a very low additional investment. The chemical treatment of such cheap and alternate species also widens the choice of timber leading to ease the pressure on conventional species and indirect conservation of valuable forest resources to gain on sustainability.

A couple of decades ago, Central Institute of Fisheries Technology, Kochi also launched two CCA cum CFO treated (by diffusion method) canoes made of quickly

Fig. 12.83 Adoption of preservation technology

perishable, relatively cheap, mostly unutilized and easily available rubber wood (*Hevea brasiliensis*) timber. The cost of each such treated canoe was 35–40% less than the conventionally used Aini (*Artocarpus hirsutus*) canoe (Saleem, 2003). Later on, this technology is reportedly popularized among the needed sectors resulting in the use of treated craft by them.

12.5.13 Timber, Constraints to Protect It

Though CCA and CCB originated in India, they are extensively used elsewhere than at home and at present an overall decline in their use exists due to shifting of railway, telecommunication and allied users from timber to other products for a long time. In spite of excellent performance of CCA-treated timber under adverse conditions, a few countries have recently limited it to selected applications while a few other countries totally banned it fearing certain environmental risks. In India, no such steps are initiated so far (but for the ban of pentachlorophenol) most probably because of the comparatively lesser amount of preservative impregnated into the timbers. The quantity of chemical imparted into the wood for use especially under marine situations in the country is far less (25%–50% less as per Bharat Standards) than that used by other nations. Although over 200 treatment plants with an annual capacity of about three million m^3 reportedly exist in India, the facilities are very much underutilized. And only a few industries resort to the preservative treatment of wood that too chiefly for cooling towers, plywood, some furniture and packing material meant for export goods.

Timber utility in the Indian marine environment is gradually increasing due to ever-expanding shore-based activities, marine exploration and sea exploitation, but goes unnoticed. Timber availability together with competitive cost and eco-benign quality make wood a preferred structural material for many marine end uses even now. Though timber treatment technology is well tested under marine conditions and readily available, very negligible volume of wood is preserved either chemically or otherwise leading to rapid destruction of service structures, loss of valuable commodity and decline of tree cover. The advantages of wood preservation and adoption of proper technologies will save enormous quantity of wood by enhancing the service life of structures by several fold under different situations (Satish Kumar, 1998) (Fig. 12.83).

Owing to several socio-economic and technical constraints, transfer of technology is found rather difficult in this sector. Therefore, there is an urgent need to make strict legislation for propagating the use of treated timber to drive away the negligence and ignorance prevailing in the implementation of wood protection technology including marine aspect. Only then the colossal loss of timber resources, drain of forest wealth, loss of ecological diversity and damage to environment could be averted in addition to foreign exchange savings. In a breakthrough judgment some time ago, the Supreme Court of India directed the forest department of Andaman-Nicobar Islands to sell only treated timber (Aggarwal, 2003). Implementation nationwide of the same direction would instantly boost wood preservative treatment. In addition, stringent measures are to be drawn out to encourage and ensure the use of treated wood especially in harsh and aggressive environments by formulating proper policies and regulations involving administrators, wood scientists, timber technologists, traders in the field, and the very consumers themselves.

12.5.13.1 Botanical Preservatives

Increased environmental awareness demands eco-benign third generation wood preservative formulations and eco-efficient treated wood products in place of conventional risky chemical systems. Therefore, research is geared up recently to bring out environmentally sound and safe new generation 'green' wood guards. In order to develop these alternatives, products of plant origin are exploited and utilized.

In this maiden attempt, extractives were prepared from the leaf biomass of *Ageratum conyzoides* L. (Goat Weed), *Croton bonplandianum* Baill. (Rush Foil), *Lantana camara* L. (Spanish Flag) and *Parthenium hysterophorous* L. (Santa Maria Feverfew) plants (Rao, 2013).

The four plant species yielded different quantities of extractives in different solvents (acetone, benzene-alcohol and water). Mango (*Mangifera indica* L.) timber was pressure treated with (i) copper, (ii) copper-chrome, (iii) aqueous extractive and (iv) copper-chrome-extractive solutions while extractives obtained in organic solvents were incorporated plant-wise and solvent-wise in varnish medium and brush coated to the panels.

Panels of different treatments with *L. camara* extractive lasted up to 12 months, but treated panels of *C. bonplandianum* exhibited relatively superior performance whereas the performance of *A. conizoides* and *P. hysterophorous* could not be evaluated due to logistic issues. The panels put to marine trials after treatment with extractive(s) fortified varnish continued in the field for 4 to 6 months without undergoing any serious damage from marine wood-boring organisms.

These preliminary investigations underline the need to further explore the many botanicals available in the country to arrive at many dependable eco-friendly marine wood preservative formulations.

12.6 Conclusion

Important contributions over the last two decades from elsewhere continue to deal with the bioresistance of several conventional hard wood species, imported timbers, lesser-used species, composite wood and even parallel strand lumber, though this aspect in the country has met with disdain in recent years. Although relegated to back stage for some time now due to the advent of several modern materials such as fibreglass, fibre reinforced plastic, ferrocement, high-density polyethylene/polystyrene, metals, plastics, rubber and an array of composites; timber in all likelihood is going to stage a comeback soon in a bigway in the wake of environmental concerns, especially related to climate change as it does not leave any carbon footprint thereby sparing the world from global warming and allied threats. Further, in order to achieve 'green economy', the role of wood as a renewable material needs to be appreciated and emphasised through 'green growth frameworks' in all the sectors concerned.

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Natural Durability of Timber in Terrestrial and Marine Realms of India: A Contrasting Feature

13

Rashmi Ramesh Shanbhag, R. Sundararaj, and M. V. Rao

Contents

Abstract

Natural durability is the important factor, which determines the usefulness and the proper utilization of wood resources for the appropriate purposes. The wood that used in land and water may characteristically differ in their buoyancy but the durability is innate property and is always considered as key factor to fight against the wood deteriorating agents those are fungi and insects such as termites on land and marine borers and foulers in aquatic regime. In this paper, we performed the detailed literature review of the wood species which are tested in the terrestrial and aquatic realms of Indian continent and its waters, their utility in marine so that a comparative or the contrasting features can be drawn between the woods.

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https://doi.org/10.1007/978-981-16-8797-6_13

Keywords

Natural durability · Terrestrial · Marine · Wood destroying organisms

13.1 Introduction

Wood was the most important material, next to stone, used by primeval man to explore new frontiers of life and exploit food, particularly in aquatic regimes. Even after the passage of several millennia and the advent of modern construction materials such as cement, metals, alloys, rubber, plastic, perspex, and fiber-reinforced plastics, timber, a renewable resource available in the form it can be readily put to use, still retained its status as a pristine structural material due to its many other virtues, such as light weight, high strength, non-corrosiveness, non--magnetic nature, and amenability to be shaped, bent, or joined (Cragg et al., 1999; Oevering et al., 2001; Borges et al., 2009). Even during this twenty-first century, wood is the most preferred structural material in both terrestrial and aquatic regimes. In terrestrial conditions, wood is used for many major construction purposes and in marine regime for harbor structures such as piles, piers, wharves, floating/static fenders, dock blocks; different types of fishing craft known as dinghies, canoes, catamarans, pontoons, boats, and several cruising/transport vessels; groins and marinas. In the absence of perfect alternatives, wood is used in the country for many marine constructions and a total of 270,050 fishing craft constructed out of locally available timber species are in use in India.

Timber, being an organic material; is susceptible to bio-deterioration by a variety of organisms, namely, microbes such as fungi (McCarthy et al., 2009) and bacteria (Edlund & Nilsson, 1998), insects such as termites (Scheffrahn, 1991), beetles, and marine borers (Tsunoda, 1990; Highley, 1999) that turn to be major threats to the service life of wood. However, some timbers possess comparatively high inherent capacity to resist this bio-deterioration (Harris, 1961). Such in-built property of wood is known as natural durability or natural bio-resistance. Durability is one of the key performance factors used to assess the suitability of a timber species for a specific end application. Most of the timbers contain peripheral sapwood and interior heartwood that possess contrasting features. While sapwood usually displays poor strength qualities coupled with low resistance that prohibits its use in the construction of various structures, heartwood generally presents relatively higher physical as well as durability properties that facilitate its utility in the fabrication of different facilities and hence "natural durability ratings" imply grading of timbers according to the quality of heartwood of a tree (Wong et al., 2005). Due to commonly prevailing hot and humid environmental conditions, biological hazard is normally very high in the tropics.

Among various biological agents, termites are a major menace to the service life of wood in terrestrial conditions in India, as these agencies mainly feed on cellulose. Wood, being a complex compound and heterogeneous aggregate composed of cellulose, hemicellulose, and lignocellulosic matrix, fulfills the subsistence need of termites for cellulose (Scheffrahn, 1991). Of the various groups of termites, the subterranean type accounts for 80% of the world's economically dominant variety (Su & Scheffrahn, 1998) causing 95% of damage to wood (Rawat, 2004). In India, 33% of the total timber in use is lost mainly due to termite attack and annually 35.12 million US $ are spent toward anti-termite treatment (Verma et al., 2009), whereas in marine environment inclusive of mangrove habitats, marine borers as major causatives effect wood deterioration resulting in an approximate annual monetary loss of 805 million US $. Wood destruction varies among different timbers depending upon the species and sometimes within the species, place of origin, utility zone, and end-use (Rao et al., 2007). In India, extensive investigations were carried out to assess the durability of various timber species at different geographical localities on land (Purushotham & Mascarenhas, 1952; Das et al., 1965; Purushotham et al., 1968; Sen-sarma & Chatterjee, 1965; Rao et al., 1982; Krishnan, 1989; Muthukrishnan et al., 2004; Thakur, 2009; Shanbhag & Sundararaj, 2013a, b) and along peninsular and Andaman-Nicobar Island coasts of the sea resulting in substantial data generation (Purushotham & Satyanarayana Rao, 1971; Tiwari et al., 1984; Rao et al., 2007, 2016). The present attempt, however, is an effort to compare the natural durability or bio-resistance of some timbers under terrestrial and marine environments as such knowledge on wood bio-deterioration under different environmental regimes lays the prerequisite for their appropriate use in respective spheres while elucidating their performance in Indian tropical terrestrial and marine environmental realms.

13.2 Material and Methods

For analysis, primary data on timber durability, rating, and causes, with special reference to field trials conducted on different wood species under terrestrial and marine realms of India were obtained from several records published by various investigators from year 1965 to 2015 in Dissertations, Journals and Books and tabulated as secondary data for comparison. As such, evaluation is based entirely on the response of various timbers to macro borers attack (termites on land and marine borers in sea) besides inclusion of any other relevant information. Though fungi are also major agents of wood degradation on land, natural durability studies on wood species against them are mainly performed under laboratory conditions, particularly for obvious reasons and hence, data on fungal decay are not considered in this review. The data were also discussed in the light of similar works done abroad so as to pinpoint the probable factors responsible for imparting the inherent resistance to wood.

Generally, natural durability evaluation on land is carried out following the specifications laid down in Bureau of Indian Standards (BIS-4833, 1993; BIS-401, 1982). According to which field evaluation of natural durability of timber will be conducted using wooden stakes measuring 60 cm $\times$ 5 cm $\times$ 5 or 30.5 cm $\times$ 3.8 cm $\times$ 3.8 cm implanted in the ground to half of their lengths (Fig. 13.1). Before laying the experiment setup in the ground it is must and should

Fig. 13.1 Termite test yards—exposure trial set up for natural durability evaluation of timber under terrestrial conditions

Fig. 13.2 Termite infestation on test stakes implanted in ground

Fig. 13.3 Visual observation and rating of termite test stakes

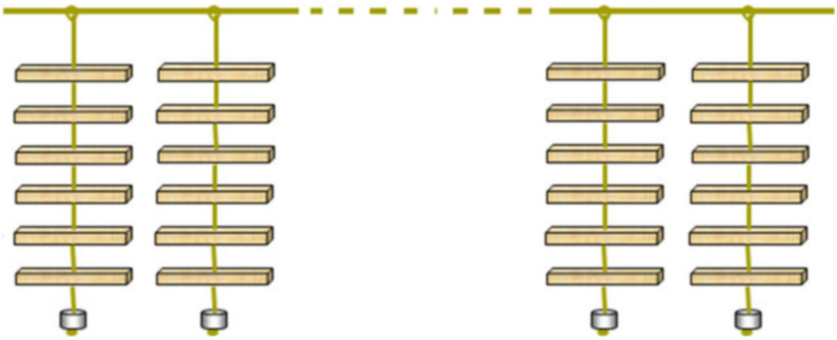

Fig. 13.4 Schematic of exposure trial set up for natural durability evaluation of timber under marine conditions

that the specimens selected for study should be free from any 5 arbor 5s, fungal infection, and knots. After lying, the experiment specimens will be examined at frequent intervals mostly visual observations (Figs. 13.2 and 13.3) and average useful life is calculated from these observations. Based on the observations we have to categorize wood into 3 durability classes: class-I (life span of over 120 months), class-II (life span between 60 and 120 months), and class-III (life span up to 36–60 months). Those species that fail or crumble to degradation before 36 months of implantation are perishable or nondurable species possessing no natural resistance at all.

Whereas in case of marine trials, timbers of size 305 × 38 × 38 mm as prescribed in BIS: 6791 (1973) or other convenient dimensions are selected for durability evaluation as per under marine conditions. The stakes of each species in triplicate attested with suitable identities are drilled at midlength cum midwidth employing a 4 mm drill bit. Then 3–6 panels are randomly tied through the holes 100 mm apart from one another into a ladder using a 4 mm nylon rope and provided with a suitable sink (weight) at the bottom end (Fig. 13.4). All such ladders in turn are fastened side by side longitudinally at 40 mm intervals to a 25 mm dia main horizontal rope. The entire set is finally suspended into seawater well below the lowest water mark from the jetty or wharf piles in an arbor or a test site in other place and thus subjected to marine exposure trials.

Inspection schedules for assessing the condition of the panels are generally fixed at quarterly intervals. At the end of each quarter, the test ladders are removed from the arbor waters and examined for their soundness. The timber stakes are thoroughly scrapped of all surface fouling and qualitative/quantitative abundance of the marine wood-boring organisms together with the damage inflicted by them to the timber panels is recorded. These observations are continued until apparent destruction of each panel reaches ~50% after which it is removed from the field and finally assessed for internal destruction. Average performance of the three panels in months is considered as a timber's marine natural durability or bio resistance. As almost all timber species get pulverized by marine wood-boring organisms usually within a year; as such no specific grading is adopted so far to classify timbers in marine environment unlike that on land.

13.3 Results and Discussion

The data compiled brought to light that so far a total of 255 timber species are evaluated in marine environment in India, though at different localities along the shoreline (Table 13.1). However, particular specifications or guidelines to categorize "marine natural durability of timbers" into different classes or groups do not exist in India and perhaps elsewhere in the world also. On the contrary, natural durability of timbers under terrestrial conditions is distinguished into 3 categories viz., Class-I timbers having a field permanence of above 120 months, Class-II timbers having a field life of 60–120 months, and Class-III timbers having less than 60 months as per Bureau of Indian Standards. Of the 255 timbers mentioned above, 124 species were also tested in terrestrial conditions at various places all over the country. The natural durability of 28 of these species belongs to Class-I category; 18 taxa to Class-II and 78 species to Class-III, based on appropriate grading done as per the above standards.

All materials including wood under marine conditions are affected by another troublesome phenomenon called biofouling, i.e., accumulation of several sedentary as well as motile life forms such as microfoulers comprising of bacteria, diatoms, algal spores, and fungi, forming a biofilm on the substratum; soft macrofoulers, namely, macroalgae and hydroids and hard macrofoulers, viz., bryozoans, tubeworms, barnacles, oysters, mussels, tunicates, etc., that altogether exert up to 50% additional frictional drag to moving craft (Maréchal & Hellio, 2009). As maritime transportation accounts for 90% exchange of goods globally, control of biofouling on boats and ships is essential for their operational efficiency besides prevention of economic losses (Hellio et al., 2004). In addition, wood in particular is infested and damaged by several primary agencies called wood-boring organisms encompassing crustaceans of the families Limnoriidae, Sphaeromatidae, and Cheluridae and bivalves of the families Teredinidae and Pholadidae (Cragg et al., 1999; Daniel et al., 2011).

In view of the extreme biological hazard posed by wood borers, first of all it is preferable to use naturally durable timbers for marine constructions. Such naturally durable timbers, screened out after field exposure trials, are likely to possess desirable strength to weight ratio, resilience to withstand sudden loads, and reasonable resistance to abrasion. Moreover, these timbers are relatively cheap and easily amenable for fabrication into desired structures with readily available tools (Cragg et al., 1999). Although treated wood is a better option for use in seawater, some species of borers, particularly *Limnoria* spp. are found to tolerate creosote since the early reports of Stephenson in 1862 (Becker, 1971). This tolerance is reportedly imparted by the presence of creosote-degrading bacteria in the guts of *Limnoriids* (Zachary & Colwell, 1979; Zachary et al., 1983).

Table 13.1 Natural durability of timbers in marine and terrestrial conditions

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
1.	*Abies pindrow*	Fir	63.75 (13.00)	III	Minor traditional fishing craft, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Purushotham et al. (1973), Tewari (1978), Rao et al. (2007)
2.	*Acacia auriculiformis*	Akashmuni	59.50 (5.00)	II	Perhaps not put to use in seawater so far	Nagaveni et al. (2007), Remadevi and Muthukrishnan (2007), Rao et al. (2007)
3.	*Acacia nilotica*	Babul	64.25 (7.50)	III	Non-mechanized and mechanized boats, marine structures	Tewari (1978), Indra Dev and Chauhan (2004), Bakshi (1976), Tewari (1978), Rao et al. (2007)
4.	*Acacia leucophlea*[a]	Distiller's acacia	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
5.	*Acacia pennata*	Biswai	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
6.	*Acer campbellii*	Maple	64.67 (8.33)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Rao et al. (2007)
7.	*Acer negundo*	Acer	r (8.00)		Non-mechanized and mechanized boats	Rao et al. (2007)
8.	*Acer pseudoplatanus*	Maple	89.50 (7.50)	III	Boat building, life boats, minor traditional fishing craft	Rao et al. (2016), TWED (2009)
9.	*Adenanthera pavoniana*	Ywegi	63.50 (8.00)		Boat building	Rao et al. (2007), TWED (2009)
10.	*Adina cordifolia*	Haldu	63.50 (8.00)		Non-mechanized and mechanized boats	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
11.	*Aglaia anamallayana*	Chennagil	80.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
12.	*Aglaia elaegnoidea*	Chokla	57.50 (5.75)		Perhaps not put to use in seawater so far	Rao et al. (2007)
13.	*Aglaia hernia*	Amari	58.75 (6.60)		Perhaps not put to use in seawater so far	Rao et al. (2007)
14.	*Ailanthus excelsa*	Maharuch	72.00 (6.00)	III	Boat building	Venmalar et al. (2011), Rao et al. (2007), TWED (2009)
15.	*Ailanthus triphysa*	Maharuch	74.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
16.	*Albizia amara*	Lallei	63.00 (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
17.	*Albizia chinensis*	Siris	69.00 (7.50)	III	Catamarans, non-mechanized and mechanized boats	Bakshi (1976), Rao et al. (2007)
18.	*Albizia lebbeck*	Kokko	63.75 (7.00)	I	Non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), Jain and Narayan (1998), Rao et al. (2007)
19.	*Albizia odoratissima*	Kalasiris	64.20 (6.60)	I	Marine structures	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), Purushotham et al. (1973), Puri and Khan (1970), Tewari (1978), Jain and Narayan (1998), Rao et al. (2007)
20.	*Albizia procera*	Safed siris	63.00 (8.75)	II	Catamarans, marine structures	Rao et al. (2007)
21.	*Alstonia kurzii*	Chattiyan	70.00 (6.00)		Catamarans	Rao et al. (2007)

22.	*Alstonia scholaris*	Saptaparna	R (8.00)	III	Catamarans	Masani (1961), Das et al. (1965), Tewari (1978), Rao et al. (1982), Rao et al. (2007)
23.	*Anacardium occidentale*	Cashew	48.33 (7.00)		Boat building	Rao et al. (2007), TWED (2009)
24.	*Anogeissus acuminata*	Yon	R (6.00)	II	Boat building, plank-built catamarans	Das et al. (1965), Tewari (1978), Rao et al. (2007), TWED (2009)
25.	*Anogeissus latifolia*	Axle wood	46.83 (11.33)	III	Marine structures	Masani (1961), Das et al. (1965), Bakshi (1967), Masani (1961), Rao et al. (2007)
26.	*Anthocephalus chinensis*	Kadam	R (5.50)		Catamarans	Rao et al. (2007)
27.	*Antiaris toxicaria*	Arana	70.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
28.	*Antidesma acidum*	Carpenters tamarind	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
29.	*Apanthe cuspidata*	Koditani	60.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
30.	*Aphanamixis polystachya* (Syn. *Amoora rohituka*)	Pitraj	59.67 (9.00)	I	Perhaps not put to use in seawater so far	Das et al. (1965), Bakshi (1967, 1976), Tewari (1978), Rao et al. (2007)
31.	*Areca catechu*	Beetle nut	75.00 (6.00)	III	Marine structures	Das et al. (1965), Rao et al. (2007)
32.	*Artocarpus chama*	Chaplash	62.58 (5.50)		Catamarans, non-mechanized and mechanized boats	Rao et al. (2007)
33.	*Artocarpus fraxinifolius*	Mundani	65.20 (11.60)		Non-mechanized and mechanized boats	Rao et al. (2007)
34.	*Artocarpus gomezianus*	Lakooch	41.00 (6.75)		Marine structures, non-mechanized and mechanized boats	Rao et al. (2007)
35.		Kathal	48.60 (7.80)	I		

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
	Artocarpus heterophyllus				Perhaps not put to use in seawater so far	Masani (1961), Tewari (1978), BIS-401 (1982), Muthukrishnan et al. (2004), Rao et al. (2007)
36.	*Artocarpus hirsutus*	Aini	59.75 (8.00)	III	Marine structures, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Rao et al. (2007)
37.	*Avicennia officinalis*	White mangrove	57.50 (6.00)			Rao et al. (2007)
38.	*Azardirachta indica*	Neem	66.25 (7.75)		Non-mechanized and mechanized boats	Rao et al. (2007)
39.	*Barringtonia acutangula*	Ijal	R (5.50)	III	Boat building	BIS-401 (2001), Rao et al. (2007), TWED (2009)
40.	*Bauhinia Roxburghiana* (Syn. *Phanera retusa*)	Roxburgh's bauhinia	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
41.	*Bauhinia vahlii*	Malo	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
42.	*Benkara malabarica*	Pudan	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
43.	*Betula alnoides*	Himalayan birch	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
44.	*Bischofia javanica*	Urium	64.40 (6.00)	III	Catamarans, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)

45.	*Bombax ceiba* (Syn. *Salmalia malabarica*)	Semul	64.17 (9.84)	III	Catamarans, minor traditional fishing craft	Bakshi (1976), Masani (1961), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
46.	*Bombax insigne*	Didu	74.00 (10.00)	III	Catamarans, minor traditional fishing craft	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
47.	*Borassus flabellifer*	Palmyra palm	28.33 (10.00)	III	Marine structures, minor traditional fishing craft	Masani (1961), Das et al. (1965), Rao et al. (2007)
48.	*Boswellia glabra*	Salai	50.75 (8.80)		Perhaps not put to use in seawater so far	Rao et al. (2007)
49.	*Bridelia squamosa*	Kasi	52.75 (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
50.	*Buchanania axillaris*	Cuddapah almond	62.50 (4.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
51.	*Buchanania lanzan*	Calumpang nut tree	70.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
52.	*Butea monosperma* (Syn. *B. frondosa*)	Palas	68.00 (6.00)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
53.	*Calophyllum inophyllum*	Poon	56.25 (6.50)		Minor traditional fishing craft, non-mechanized and mechanized boats	Rao et al. (2007)
54.	*Calophyllum polyanthum* (Syn *C. elatum*)	Poonspar	35.33 (14.33)		Minor traditional fishing craft, non-mechanized and mechanized boats	Rao et al. (2007)
55.	*Canarium euphyllum*	White Dhup	70.00 (6.00)	III	Catamarans	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
56.	*Canarium strictum*	Black dammar	64.67 (6.00)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Tewari (1978), BIS-401 (1982), Rao et al. (1982), Scheffer and Morrell (1998), Rao et al. (2007)
57.	*Canthium dicocum*	Balasu	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
58.	*Carallia brachiata*	Carallia	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
59.	*Careya arborea*	Kumbi	56.00 (9.67)	I	Non-mechanized and mechanized boats	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
60.	*Cassia fistula*	Rajbrikh	65.33 (6.30)	II	Perhaps not put to use in seawater so far	Das et al. (1965), Puri and Khan (1970), BIS-401 (1982), Masani (1961), Bakshi (1967, 1976), Rao et al. (2007)
61.	*Cassia siamea*	Kassad tree	R (6.00)		Boat building	Rao et al. (2007), TWED (2009)
62.	*Castanopsis hystrix*	Indian chestnut	57.50 (8.00)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), Rao et al. (2007)
63.	*Casuarina equisetifolia*	Casurina	61.80 (7.40)	III	Marine structures, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Indra Dev and Chauhan (2004), Rao et al. (2007)

64.	*Cedrus deodara*	Deodar	67.33 (7.67)	I	Marine structures, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Purushotham et al. (1973), BIS-401 (1982), Jain and Narayan (1998), Rao et al. (2007)
65.	*Ceiba pent & ra*	Kapak	76.67 (5.00)		Catamarans	Rao et al. (2007)
66.	*Chlorophora excelsa*	African teak	65.00 (6.00)		Boat building; life boats; marine constructions, minor traditional fishing craft	Rao et al. (2007), TWED (2009)
67.	*Chloroxylon swietenia*	Satinwood	60.67 (5.70)	III	Boat building, marine constructions	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
68.	*Chukrasia tubularis*	Chikrassy	53.33 (8.00)		Boat building, minor traditional fishing craft	Rao et al. (2007), TWED (2009)
69.	*Cinnamomum cecicodaphne*	Sugangh kokila	R (7.00)	III	Perhaps not put to use in seawater so far	Das et al. (1965), BIS-401 (1982), Rao et al. (2007)
70.	*Cinnamomum verum*	Cinnamon	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
71.	*Cinnamomumm malabatrum*	Wild Cinnamon	67.50 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
72.	*Cipadessa baccifera*	Nalbila	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
73.	*Cleistanthus collinus*	Karada	62.50 (13.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
74.	*Cocus nucifera*	Coconut	57.50 (7.50)		Marine structures	Rao et al. (2007)
75.	*Combretum roxburghii*	Roel	69.00 (4.30)		Perhaps not put to use in seawater so far	Rao et al. (2007)
76.	*Cordia macleodii*	Ganni	R (8.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
77.	*Cryptomeria japonica*	Sugi	R.67.00 (5.70)	III	Boat building, fishnet floats	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
78.	*Cullenia rosayraona*	Karanai	60.00 (6.00)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
79.	*Dalbergia lanceolaria*	Bithua	52.50 (5.80)		Perhaps not put to use in seawater so far	Rao et al. (2007)
80.	*Dalbergia latifolia*	Rosewood	48.00 (10.00)	I	Non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Jain and Narayan (1998), Rao et al. (2007)
81.	*Dalbergia sissoo*	Sissoo	62.67 (0.007)	II	Non-mechanized and mechanized boats	Masani (1961), Bakshi (1967, 1976), Tewari (1978), Scheffer and Morrell (1998), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
82.	*Dillenia indica*	Sandpaper tree	49.00 (8.70)	III	Stringers	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)

83.	*Dillenia pentagyna*	Dillenia; dog teak	R (6.00)	III	Stringers	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
84.	*Diospyros ebenum*	Ceylon ebony	52.50 (5.00)	II	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
85.	*Diospyros malabarica*	Gaub	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
86.	*Diospyros melanoxylon*	Ebony	58.00 (6.50)	III	Perhaps not put to use in seawater so far	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Bakshi (1976), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
87.	*Diospyros montana*	Mountain ebony	66.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
88.	*Dipterocarpus indicus*	Gurjan	60.00 (7.80)	III	Minor traditional fishing craft, non-mechanized and mechanized boats, Marine structures	Purushotham et al. (1973), Jain and Narayan (1998), Gillah et al. (2004), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
89.	*Dipterocarpus turbinatus*	Teli gurjan	52.00 (5.20)	III	Non-mechanized and mechanized boats	Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
90.	*Dryobalanops aromatica*	Kapoor	50.00 (18.00)		Catamarans, minor traditional fishing craft	Rao et al. (2016)
91.	*Duabanga gr & iflora*	Lampati	65.00 (6.50)	III	Boat building; minor traditional craft	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)

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Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
92.	*Dysoxylum binectariferum*	Devdam	R (8.00)	II	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998)
93.	*Dysoxylum malabaricum*	White cedar	60.60 (6.40)	II	Non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Purushotham et al. (1968), Jain and Narayan (1998), Rao et al. (2007)
94.	*Ehretia laevis*	Ivory wood	53.33 (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
95.	*Elaeocarpus recurvatus*	Nilgiri rudraksh	79.00 (7.50)		Catamarans	Rao et al. (2007)
96.	*Elaeocarpus tuberculatus*	Rudrak	50.00 (6.00)	III	Catamarans	Rao et al. (1982, 2007)
97.	*Eriolaena c & ollei*	Salman Wood	R (6.50)	I	Boat building, oars	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
98.	*Erythrina stricta*	Coral tree	R (6.00)		Catamarans, minor traditional fishing craft	Rao et al. (2007)
99.	*Erythrina variegata*	Pangara	63.33 (6.00)		Catamarans	Rao et al. (2007)
100.	*Eucalyptus camaldulensis*	Eucaly	R (7.00)	I	Perhaps not put to use in seawater so far	Dobriyal and Intradev (1992), Rao et al. (2007)
101.	*Eucalyptus gr & is*	Rose gum	61.67 (4.70)	II	Perhaps not put to use in seawater so far	Dobriyal and Intradev (1992), Rao et al. (2007)
102.	*Eucalyptus tereticornis*	Mysore gum	63.75 (8.00)	II	Perhaps not put to use in seawater so far	Dobriyal and Intradev (1992), Rao et al. (2007)

103.	*Eugenia hemispherica*		79.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
104.	*Euodia lunu-ankenda*	Kambli	67.50 (3.00)		Catamarans	Rao et al. (2007)
105.	*Euodia speciosa* (Syn. *Melicope bonwickii*)	Evodia	R (3.00)		Catamarans	Rao et al. (2007)
106.	*Exbuckl & ia populnea* (*Buckl & ia populnea*)	Pipli	57.50 (7.00)	III	Perhaps not put to use in seawater so far	BIS-401 (2001), Rao et al. (2007)
107.	*Excoecaria agallocha*	Geon	70.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
108.	*Fagus gr & ifolia*	Beech	95.00 (9.00)	III	Perhaps not put to use in seawater so far	Rao et al. (2016)
109.	*Fagus sylvatica*	Beech	90.00 (8.50)	III	Boat building, marine constructions	Rao et al. (2016), TWED (2009)
110.	*Ficus benghalensis*	Banyan	62.50 (6.00)	III	Catamarans	BIS-401 (1982), Rao et al. (2007)
111.	*Ficus drupacea (Syn. F. mysorensis)*	Gonimara	62.50 (.003)		Catamarans	Rao et al. (2007)
112.	*Ficus exasperata (Syn. F. asperrima)*	Sandpaper fig	R (3.00)		Catamarans	Rao et al. (2007)
113.	*Ficus hispida*	Wild fig	66.50 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
114.	*Ficus racemosa (Syn. F. glomerata)*	Country fig	65.00 (6.00)		Catamarans	Rao et al. (2007)
115.	*Ficus religiosa*	Pipal	68.75 (5.50)		Catamarans	Rao et al. (2007)
116.	*Flacourtia indica*	Ramantchi	R (5.50)			Rao et al. (2007)
117.	*Fraxinus angustifolia*	Ash	68 (5.30)	III	Perhaps not put to use in seawater so far	Rao et al. (2016)

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Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
118.	*Fraxinus excelsior*	Ash	R (7.00)	III	Non-mechanized and mechanized boats	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Shanbhag and Sundararaj (2013a b), Rao et al. (2007)
119.	*Garcinia indica*	Mangosteen	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
120.	*Gardenia latifolia*	Indian box wood	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
121.	*Gardenia turgida*	Khurur	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
122.	*Garuga pinnata*	Garuga	56.67 (8.80)	III	Rafters	Masani (1961), Das et al. (1965), BIS-401 (1982), Rao et al. (2007), TWED (2009)
123.	*Gliricidia maculata*	Gliricidia	R (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
124.	*Gluta travancorica*	Gluta	R (7.00)	I	Perhaps not put to use in seawater so far	Das et al. (1965), BIS-401 (1982), Rao et al. (2007)
125.	*Gmelina arborea*	Gamari	56.25 (7.75)	I	Catamarans, minor traditional fishing craft, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Bakshi (1967), Rao et al. (2007)
126.	*Grevillea robusta*	Silver-oak	84.00 (5.60)	III	Catamarans	Masani (1961), BIS-401 (1982), Rao et al. (2007)

127.	*Grewia tiliiaefolia*	Dhaman	68.25 (7.00)	II	Non-mechanized and mechanized boats	Das et al. (1965), Puri and Khan (1970), Purushotham et al. (1973), Bakshi (1967, 1976), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
128.	*Gyrocarpus asiaticus*	Tanaku	71.67 (6.00)		Catamarans	Rao et al. (2007)
129.	*Hardwickia binata*	Anjan	42.00 (9.30)	I	Boat building	Masani (1961), Das et al. (1965), Bakshi (1976), Puri and Khan (1970), Tewari (1978), BIS-401 (1982), Jain and Narayan (1998), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
130.	*Heritiera littoralis*	Sundri	R (8.00)	I	Non-mechanized and mechanized boats	BIS-401 (1982), Rao et al. (2007)
131.	*Hevea brasiliensis*	Rubber wood	68.00 (4.30)	III	Perhaps not put to use in seawater so far	Ananthapadmanabha et al. (1990), Indra Dev and Chauhan (2004), Remadevi and Muthukrishnan (2007), Shanbhag and Sundararaj (2013a, b), Rao et al. (2007)
132.	*Holarrhena pubescens*	Easter tree	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
133.	*Holigarna arnottiana*	Cheru	70.00 (6.00)		Catamarans	Rao et al. (2007)
134.	*Holigarna caustra*	Cheru	68.00 (3.00)		Catamarans	Rao et al. (2007)
135.	*Holoptelea integrifolia*	Kanju	42.00 (7.30)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Purushotham et al. (1973), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)

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Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
136.	*Hopea odorata*	Thingan	65.00 (9.00)	II	Boat building; Minor traditional fishing craft	Das et al. (1965), Rao et al. (2007), TWED (2009)
137.	*Hopea parviflora*	Hopea	42.20 (14.40)	I	Non-mechanized and mechanized boats, marine structures	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
138.	*Hopea utilis*	Kongu	62.50 (5.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
139.	*Hydnocarpus pent & ra*	Marotti	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
140.	*Kingiodendron pinnatum*	Piney	65.00 (8.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
141.	*Kydia calycina*	Pula	75.0 (5.67)	III	Boat building, catamarans, oars	BIS:401 (2001), Rao et al. (2007), TWED (2009)
142.	*Lagerstroemia hypoleuca*	Pyinma	75.00 (9.00)	I	Non-mechanized and mechanized boats, marine structures	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
143.	*Lagerstroemia microcarpa* (Syn. *L. lanceolata*)	Benteak	48.83 (10.67)	II	Non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Purushotham et al. (1973), BIS:401 (2001), Rao et al. (2007)
144.	*Lagerstroemia parviflora*	Lendi	43.33 (6.65)	III	Catamarans, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Bakshi (1976), Tewari (1978), Scheffer and Morrell (1998), BIS:401 (2001), Rao et al. (2007)

145.	*Lagerstroemia speciosa*	Jarul	48.00 (8.33)		Catamarans, non-mechanized and mechanized boats, minor traditional fishing craft	Rao et al. (2007)
146.	*Lannea corom & elica*	Jhingam	47.60 (7.20)	III	Catamarans	Rao et al. (1982, 2007)
147.	*Leucaena leucocephala*	Sababul	r (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
148.	*Limonia acidissima*	Wood apple	60.00 (9.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
149.	*Litsea glutinosa*	Common tallow laurel	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
150.	*Lophopetalum wightianum*	Banati	85.00 (6.00)	III	Catamarans	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
151.	*Macaranga peltata*	Ch & akal	64.50 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
152.	*Madhuca longifolia* (Syn. *Bassia latifolia*)	Mahua	36.00 (8.67)	I	Non-mechanized and mechanized boats	BIS: 401 (2001), Rao et al. (2007)
153.	*Mangifera indica*	Mango	65.00 (6.43)	III	Minor traditional fishing craft, non-mechanized and mechanized boats	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), Rao et al. (1982), BIS-401 (1982), Rao et al. (1982), Scheffer and Morrell (1998), Muthukrishnan et al. (2004), Rao et al. (2007)
154.	*Manilkara hex & ra*	Ceylon iron wood	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
155.	*Manilkara zapota*	Sapota	R (9.00)		Wharf and marine construction	Rao et al. (2007), TWED (2009)
156.	*Mastixia pent & ra chinensis*	Bolong-jigri	90 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
157.	*Melia azedarach*	Persian lilac	R (6.00)	III	Boat building, rafters	BIS-401 (1982), Indra Dev and Chauhan (2004), Rao et al. (2007), TWED (2009)
158.	*Melia dubia*	Malabar neem	66.00 (5.89)	III	Catamarans, Non-mechanized and mechanized boats, minor traditional fishing craft	Masani (1961), Rao et al. (2007)
159.	*Mesua nagassarium*	Mesua	44.25 (11.75)		Non-mechanized and mechanized boats, marine structures	Rao et al. (2007)
160.	*Michelia cathcartii*	Champ	59.00 (8.00)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
161.	*Michelia champaca*	Champ	64.75 (6.80)	III	Boat building, catamarans, minor traditional fishing craft	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Indra Dev and Chauhan (2004), Bakshi (1967), Rao et al. (2007), TWED (2009)
162.	*Michelia doltsopa* (Syn. *Magnolia doltsopa*)	Manipur Magnolia	64.75 (6.80)	III	Perhaps not put to use in seawater so far	BIS-401 (1982), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
163.	*Miliusa tomentosa* (Syn. *Saccopetalum tomentosum*)	Hoom	R (7.50)	III	Perhaps not put to use in seawater so far	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)

164.	*Mimusops elengi*	Bullet wood	54.33 (6.00)	I	Perhaps not put to use in seawater so far	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
165.	*Mimusops littoralis*	Bullet wood	R (24.00)	I	Perhaps not put to use in seawater so far	Masani (1961), Rao et al. (2007)
166.	*Minolta poly & a*	Ping	70.00 (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
167.	*Mitragyna parvifolia* (Syn. *Stephegyna parvifolia*)	Kalim	61.00 (8.00)	III	Boat building	Purushotham et al. (1973), BIS-401 (2001), Rao et al. (2007), TWED (2009)
168.	*Morinda pubescens*	Togaru	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
169.	*Morus alba*	Mulberry	59.50 (4.75)	III	Boat building	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), Rao et al. (2007), TWED (2009)
170.	*Murraya paniculata*	Satin wood	67.50 (5.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
171.	*Olea dioica*	Olive	R (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
172.	*Oroxylum indicum*	Indian calosanthes	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
173.	*Ougeinia oojeinsis* (Syn. *O. dalbergioides*)	S & an	72.50 (10.50)	I	Boat building	Masani (1961), Das et al. (1965), Bakshi (1967, 1976), BIS-401 (1982), BIS:401 (2001), Rao et al. (2007), TWED (2009)
174.	*Pajanelia longifolia*	Pajanelia	60.00 (8.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
175.	*Pajanelia rheedii* (Syn *P. longifolia*)	& aman Jhingan	R (6.00)	III	Boat building, minor traditional fishing craft	BIS:401 (2001), Rao et al. (2007), TWED (2009)
176.	*Palaquium ellipticum* (Syn. *Dichopsis elliptica*)	Pali	71.50 (5.30)	II	Boat building, life boats	Bakshi (1967, 1976), BIS-401 (1982), Rao et al. (2007), TWED (2009)
177.	*Paraartrocarpus Bracteatus*[b]	Tibung	63.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
178.	*Paraserianthes falcataria*	Albisia	67.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
179.	*Peltophorum pterocarpum*	Copper pod	68.50 (5.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
180.	*Persea macrantha*	Machilus	56.50 (6.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
181.	*Phyllanthus emblica*	Amla	R (6.00)	III	Perhaps not put to use in seawater so far	BIS:401 (2001), Rao et al. (2007)
182.	*Picea smithiana* (Syn. *P. morinda*)	Spruce	66.33 (7.33)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Purushotham et al. (1973), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
183.	*Piliostigma malabaricum*	Kanchan	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
184.	*Pinus insigne*	Pine	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

185.	*Pinus roxburghii* (Syn. *P. longifolia*)	Chir	63.75 (7.25)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Purushotham et al. (1968), Bakshi (1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
186.	*Pinus wallichiana*	Kail	88.50 (6.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
187.	*Pinus wallichiana (Syn. P. excelsa)*	Kail	R (3.00)	III	Perhaps not put to use in seawater so far	Bakshi (1967, 1976), BIS:401 (2001), Rao et al. (2007)
188.	*Planchonella longipetiolata*	Lambapatti	62.50 (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
189.	*Planchonia & amanica*	Red bombwe	68.00 (8.00)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
190.	*Poeciloneuron indicum*	Ballagi	51.67 (8.70)	II	Boat building	Masani (1961), Das et al. (1965), Tewari (1978), Rao et al. (1982), Scheffer and Morrell (1998), Bakshi (1967, 1976), BIS-401 (1982), Rao et al. (2007), TWED (2009)
191.	*Polyalthia cerasoides*	Debdaru	R (6.80)		Perhaps not put to use in seawater so far	Rao et al. (2007)
192.	*Polyalthia fragrans*	Nedunar	59.50 (6.46)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
193.	*Pongamia pinnata*	Indian Birch	62.50 (4.50)	III	Boat building	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
194.	*Populus ciliata*	Poplar	83.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
195.	*Prosopis chilensis*	Algaroba	70.00 (3.00)	II	Boat building	Indra Dev and Chauhan (2004), Rao et al. (2007)
196.	*Protium serratum* (Syn. *Bursera serrata*)	Indian red pear	R (12.00)		Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), Rao et al. (2007)
197.	*Psidium guajava*	Amarud	58.33 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
198.	*Pterocarpus dalbergiodies*	& aman paduk	39.00 (7.67)	I	Perhaps not put to use in seawater so far	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Jain and Narayan (1998), Muthukrishnan et al. (2004), Masani (1961), Rao et al. (2007)
199.	*Pterocarpus marsupium*	Bijasal	46.50 (10.34)	I	Perhaps not put to use in seawater so far	Purushotham et al. (1968), Puri and Khan (1970), BIS-401 (1982), Jain and Narayan (1998), Rao et al. (2007)
200.	*Pterocarpus soyauxii*	Honnai	r (18.00)	I	Boat building, minor traditional fishing craft, stationary structures	TWED (2009), Rao et al. (2016)
201.	*Pterocymbium tinctorium*	Papita	70.00 (7.50)	III	Perhaps not put to use in seawater so far	Tewari (1978), Scheffer and Morrell (1998), BIS:401 (2001), Rao et al. (2007)
202.	*Pterospermum diversifolium*	Mathi paila	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
203.	*Pterospermum xylocarpum*	Lolugu	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

204.	*Pterygota alata* (Syn. *Sterculia alata)*	Buddha Coconut	74.00 (3.00)		Perhaps not put to use in seawater so far	BIS-401 (1982), Rao et al. (2007)
205.	*Quercus robur*	Oak	68.00 (10.00)	III	Boat building, marine constructions, minor traditional fishing craft	TWED (2009)
206.	*Quercus semecarpifolia*	Oak	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
207.	*Rhizophora apiculata*	Tall-stilt mangrove	70.00 (6.00)		Boat building, marine constructions, minor traditional fishing craft	Rao et al. (2007), TWED (2009)
208.	*Rhizophora mucronata*	Asiatic Mangrove	65.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
209.	*Sagerea liseri*	Chooi	60.00 (9.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
210.	*Samanea saman*	Rain tree	70.00 (5.50)	III	Perhaps not put to use in seawater so far	Muthukrishnan et al. (2004), Rao et al. (2007)
211.	*Sapindus laurifolia*	Soap nut	70.67(4.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
212.	*Sapium baccatum*	Seleng	R (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
213.	*Schima wallichii*	Chilawni	49.00 (9.50)	III	Rafters	Masani (1961), Das et al. (1965), Purushotham et al. (1973), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
214.	*Schleichera oleosa* (Syn. *S. trijuga*)	Kusum	39.50 (7.50)	III	Boat building	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), BIS: 401 (2001), Rao et al. (2007), TWED (2009)
215.	*Schrebera swietenoides*	Molcha	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
216.	*Shorea laevis*	Honnai	75.00 (18.00)		Perhaps not put to use in seawater so far	Rao et al. (2016)
217.	*Shorea macroptera*	Maranti	60.33 (8.00)		Perhaps not put to use in seawater so far	Rao et al. (2016)
218.	*Shorea robusta*	Sal	70.00 (6.00)	I	Boat building	Das et al. (1965), Purushotham et al. (1973), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Jain and Narayan (1998), Masani (1961), Bakshi (1967, 1976), Rao et al. (2007), TWED (2009)
219.	*Sonneratia alba*	Sweet-scented Apple Mangrove	70.00 (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
220.	*Sonneratia apetala*	Keora	84.00 (7.50)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), BIS:401 (2001), Rao et al. (2007)
221.	*Soymida febrifuga*	Rohini	77.50 (7.50)	I	Perhaps not put to use in seawater so far	Das et al. (1965), BIS-401 (1982), Rao et al. (2007)
222.	*Spondias pinnata* (Syn. *S. mangifera*)	Amra	R (3.00)	III	Perhaps not put to use in seawater so far	BIS: 401 (2001), Rao et al. (2007)
223.	*Sterculia foetida*	Jangal Balsum, pinari	64.50 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)

224.	*Sterculia urens*	Karar	r (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
225.	*Sterculia villosa*	Udal	R (6.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
226.	*Stereospermum chelonoides* (Syn. *S. Suaveolens*)	Padri	47.33 (6.90)	III	Boat building, minor traditional fishing craft, oars	Das et al. (1965), BIS-401 (1982), Rao et al. (2007), TWED (2009)
227.	*Stereospermum colais*	Padri	R (8.50)	III	Perhaps not put to use in seawater so far	Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), Rao et al. (2007)
228.	*Streblus asper*	Sandpaper mulberry	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
229.	*Strychnos nux vomica*	Kuchla	57.50 (6.00)		Boat building	Rao et al. (2007), TWED (2009)
230.	*Swietenia mahagoni*	Mahagoni	77.00 (4.50)		Boat building, life boats, minor traditionl fishing craft	Rao et al. (2007), TWED (2009)
231.	*Symplocos cochinchinensis*	Laurel Sapphire berrry	76.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
232.	*Symplocos laurina*	Lodh; Chunga	R (3.00)	III	Perhaps not put to use in seawater so far	Rao et al. (1982, 2007)
233.	*Tamarindus indicus*	Imli	68.75 (7.50)		Boat building, barge fenders, harbour works, marine constructions, naval architecture rafts, raft floats, ship building	Rao et al. (2007), TWED (2009)
234.	*Taxus baccata*	Yew	r (12.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
235.	*Tecomella undulata*	Roheda	71.00 (3.00)	Timber is strong after 30 months.	Perhaps not put to use in seawater so far	Nagaveni et al. (2002), Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
236.	*Tectona gr & is*	Teak	65.00 (18.00)	I	Boat building, life boats, minor traditional fishing craft, oars, ship building	Rao et al. (2016)
237.	*Terminalia alata* (Syn. *T. crenulata* and *T. elliptica*)	Laurel	49.33 (11.33)	II	Boat building	BIS-401 (1982), Bakshi (1976). Rao et al. (2007), TWED (2009)
238.	*Terminalia arjuna*	Arjun	59.25 (7.50)	II	Rafters	Jain and Narayan (1998), Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Indra Dev and Chauhan (2004), Rao et al. (2007), TWED (2009)
239.	*Terminalia bellerica*	Bahera	63.60 (8.40)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Purushotham et al. (1968), Bakshi (1967, 1976), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007)
240.	*Terminalia bialata*	White chugalam	62.50 (9.00)	III	Boat building, oars	Masani (1961), Das et al. (1965), Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Rao et al. (2007), TWED (2009)
241.	*Terminalia chebula*	Myrobalan	53.00 (10.00)	III	Boat building, oars	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), Rao et al. (2007), TWED (2009)

242.	*Terminalia manii*	Black chuglam	R (8.00)	III	Perhaps not put to use in seawater so far	Masani (1961), Das et al. (1965), Tewari (1978), Scheffer and Morrell (1998), BIS-401 (1982), Rao et al. (2007)
243.	*Tetrameles nudiflora*	Maina	r (7.50)	III	Boat building, fishnet floats, minor traditional fishing craft	Masani (1961), Das et al. (1965), Rao et al. (2007), TWED (2009)
244.	*Toona ciliata*	Toon	58.80 (8.60)	III	Perhaps not put to use in seawater so far	Tewari (1978), BIS-401 (1982), Scheffer and Morrell (1998), Indra Dev and Chauhan (2004), Bakshi (1976), Rao et al. (2007)
245.	*Trema orientalis*	Indian mettle	62.50 (5.00)		Boat building, fishnet floats, minor traditional fishing craft	Rao et al. (2007), TWED (2009)
246.	*Trewia polycarpa*	Gutel	R (7.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
247.	*Vatica chinensis*	Vella payin	71.00 (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
248.	*Ventilago calyculata*	Surul	R (3.00)		Perhaps not put to use in seawater so far	Rao et al. (2007)
249.	*Ventilago denticulata*	Surul	R (4.30)		Perhaps not put to use in seawater so far	Rao et al. (2007)
250.	*Ventilago maderaspatana*	Vembadam	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
251.	*Vitex pinnata*	Mayiladi	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
252.	*Wrightia arborea*	Dharauli	R (5.50)		Perhaps not put to use in seawater so far	Rao et al. (2007)
253.	*Wrightia tinctoria*	Dudhi	44.00 (10.80)		Perhaps not put to use in seawater so far	Rao et al. (2007)

(continued)

Table 13.1 (continued)

Sl. no.	Timber species	Trade Name	Destruction (%)/ marine bio-resistance (months)	Durability class on land	Marine utility	References
254.	*Xylia dolabriformis*	Pyinkado	r (18.00)	I	Perhaps not put to use in seawater so far	Rao et al. (2016)
255.	*Xylia xylocarpa*	Irul	r (9.80)	I	Boat building, barge fenders, harbour work, life boats, naval architecture, marine construction, minor traditional fishing craft, raft floats, ship building, wharf construction	Das et al. (1965), Jain and Narayan (1998), Rao et al. (2007), TWED (2009)

R—Destruction >50%; r—Destruction <50%; TWED (2009)—The Wood Explorer Database, 2009; *Syn.* synonym

[a] By oversight written earlier as *Acacia oenoplia*

[b] Doubtful identity

Natural durability of wood is a measure of its ability to resist the attack of fungi, insects, and marine borers. Although no native wood is entirely immune to the attack of such organisms, some of them possess comparatively superior bio-resistance (Deb & Roy, 2021). Timber resistance to fungal infestation or insect attack on land may not be durable when subjected to marine wood borer attack. Worldwide, a considerable number of timber species have already been tested. Over 350 species were tested in Hawaiian waters (Edmondson, 1955) and 115 in Panamanian waters (Bultman & Southwell, 1976). In India, several investigators have attempted to assess the durability and other aspects of different species at various localities along the coast from time to time (Purushotham & Satyanarayana Rao, 1971; Kalyanasundaram & Ganti 1974, 1975; Tiwari et al., 1984; Santhkumaran, 1994; Satyanarayana Rao et al., 1994; Balaji & Satyanarayana Rao, 1998; Rao et al., 2003, 2005, 2007; Tarakanadha et al., 2005).

Traditionally, highly durable wood species like teak (*Tectona grandis*), aini (*Artocarpus hirsutus*), and sal (*Shorea robusta*) are preferred for marine structures in India. But drastic decline in the availability of naturally durable timber species toward the end of the twentieth century resulted in the import of timber from different countries such as Australia, Belgium, Burma, Cameroon, France, Ghana, Indonesia, Ivory Coast, Malaysia, South Africa, and Tanzania in order to bridge the gap between supply and demand. However, the performance of such imported timber under various service conditions in different Indian environments is evaluated recently. In addition, information on these lines is desirable to select a timber to its best end-use.

Resistance is a critical determinant of life span of a tree species. Many heartwood species are known for their resistance against degradation (Deb & Roy, 2021) and this feature is exploited to fabricate sound and long-lasting structures on extraction of wood (Harris, 1961). In this particular study, a general trend noticed was that the tropical tree species exhibited more bio-resistance and durability against marine wood borers. The resistance of some of these tropical tree species, such as *T. grandis* (Karnade et al., 1993; Muslich & Hadjib, 2008), *Shorea robusta* (Karnade et al., 1993), *Shorea* sp. (Borges et al., 2008), *Shorea macroptera*, *Dryobalanops* sp., *Xylia dolabriformis,* and *Pterocarpus soyauxii* (TRADA, 2010) against marine biodegrading organisms, is well known. Such resistance is either due to differences in timber hardness or presence of lignin, extractives of toxic/anti-feedant nature, or both (Cragg et al., 2007; Borges et al., 2008).

Extractives confer durability to wood in a variety of ways. They may be toxic to biodeteriogens; disrupt lingo-cellulose breakdown systems by scavenging free radicals and may even deter feeding (Ohmura et al., 2000; Schultz & Nicholas, 2000; Chang et al., 2000; Wang et al., 2004). Extractives may also affect enzyme-producing microorganisms within the guts of wood borers (Boyle & Mitchell, 1981). Borges et al. (2008) have demonstrated that marine borer *Limnoria quadripunctata* showed reduced pellet production, when forced to feed on tropical hardwoods under laboratory screening tests and this might be due to higher wood density or abundant extractive content in these tropical hard woods. Moreover, extractive substances like nositol and sito-sterol (King & Jurd, 1953); alkaloids (Hochman, 1973); quinones in

Tectona grandis (Eslyn et al., 1981); glycoside esters (Messanga et al., 1998); minquartynoic acid (Rasmussen et al., 2000); tropalone derivatives (Mesa-Siverio et al., 2003); phenolics as in *Quercus robur* (Aloui et al., 2004); terpenoids (Han et al., 2005), and napthoquinones in *Pterocarpus soyauxii* (Anon, 2008) are known to enhance timber resistance against marine wood borers.

Several workers have suggested that various chemical deposits in the heartwood zone could provide natural durability to a timber (Dilip, 1963). Silica content in teak wood is variable with a reported value of up to 1.4%, whereas the same in *Dryobalanops* spp. ranges from 0.12 to 0.91% (Chudnoff, 1984), offering a blunt effect resulting in reduced scraping activity. But there are some exceptions also, for example, *Shorea* spp. contain abundant amount of silica in ray tissues, but found to be non-resistant to marine borer invasion (Chudnoff, 1984). Silica, when present in sufficiently large quantities, makes the wood resistant to marine borers provided the wood has compact texture. Bozkurt and Erdin (1989) reported that wood species with high silica and calcium crystal contents show high blunt effects and will be resistant to marine borers. For example, wood species *Pterocarpus soyauxii* contain calcium oxalate deposits, which account for their higher natural durability under marine conditions (Şen et al., 2009), just like the case of dense fibers of *Xylia dolabriformis* plugged with gum (Adeniyi et al., 2012). In addition, some of these woods are reported to be denser making it difficult for the marine borers to file and grind the substratum for food (Berkel, 1970).

The rate and type of wood bio-deterioration in marine environment is influenced by geographical location, nature of substratum, and position of timber in relation to mean sea level and other physicochemical parameters of water (Eaton, 1985). Optimal hydrographical features at the test stations quickly promote abundant recruitment of fouling organisms on timber surfaces and good colonization of marine wood-boring organisms in the core substance of wood.

13.4 Conclusion

In comparing the wood performance between terrestrial and marine realms, it is to be borne in mind that destruction inflicted to a timber by marine borers is neither evident externally nor assessable from outside unlike the damage pattern perpetrated by most of the land borers and destruction instigated by terrestrial organisms. There is no match in the bio-deterioration affected by the organisms in the two situations and internal loss of wood in the sea cannot be generally predicted unless a timber section is sliced out. The intensity of attack and the rapidity of devastation of wood by marine borers are such that even the highly preferred, durable, and Class I (remains durable for more than120 months) species such as teak (*Tectona grandis*), irul (*Xylia xylocarpa*), and Andaman padauk (*Pterocarpus dalbergioides*) under terrestrial circumstances are sabotaged within a short span of 6–8 months in the sea. Further, microorganisms are dominant destructive agents on land compared to macroorganisms whereas in marine realm the scenario is quite opposite making macro-organisms of Crustacea and Bivalvia accountable for bringing about major ruin relegating micro-organisms to take role in surface conditioning and superficial softening of the wood facilitating penetration of the lignocellulosic material by bivalve borer larvae. Additionally, in the sea, the depth zone of greatest hazard varies from intertidal zone to mud level depending on the ecological preferences and requirements of dominant borers in a locality. On the contrary, such complex strategies in deteriogens do not arise on land. Ecological conditions that largely govern the activities of destructive organisms are more with wide-ranging variations in the sea than on land thereby influencing the vigor and magnitude of wood damage in marine realm.

Marine biodeteriogens are morphologically, physiologically, and ecologically well adapted to the burrowing mode of life within wood. Highly chitinous mandibles in crustaceans and sharply toothed shell valves in lamelli branches are the powerful modified bio drilling organs of the borers to achieve excavation of the substratum. The plate-like posterior segments of crustaceans, pholadid shells with hinge ligamentation, and specifically evolved posterior calcareous sculpted accessories (called "pallets" that strangely are species-specific) of shipworm said in temporarily closing the respective entries of their holes in protecting the animals from predators and environmental extremes. Cellulose digestion, fast growth, early maturity, large brood, prodigious production, and reproductive strategies are some of the important physiological adjustments accomplished by the borers to meet with the short sedentary life they lead. Wide tolerance to temperature, salinity, dissolved oxygen pressure, and changes in the ambient are a few ecological adaptations attained by the deteriogens for successful existence in the unpredictable surroundings they exist.

Especially, the numerical superiority established by the wood boing community as whole in the sea (besides certain planktonic copepods) through production of enormous number of larvae in each brood results in the infestation of fresh timbers, boles, roots, nuts, and other lignocellulosic constituents in heavy intensity ultimately leading to their destruction with apparent vigor and insatiable craving making the agencies man's formidable enemy at sea. At least for over 300 years, scientists all around the globe are trotting to lodge upon an effective answer to prevent or control marine wood bio-deterioration on a permanent basis, rather than opting for alternative constructional materials than wood and adding fresh problems to elude them. Yet, the solution remains a distant dream because of the many complications involved in the issue.

Acknowledgments The authors are grateful to the Director and Coordinator (Research), Institute of Wood Science and Technology, Bangalore for providing facilities. We thank Dr. (Late) L.N. Santhakumaran, Scientist (Retd.), Institute of Wood Science and Technology for his suggestions, which significantly improved the manuscript. Financial assistance is provided by the Indian Council of Forestry Research and Education(IWST/WBD/XI/139) for conducting this research work.

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Degradation of Wood and Wooden Products by Insects and Their Management 14

Raja Muthukrishnan and R. Sundararaj

Contents

Abstract

In India, around 72 timber species were being utilized in the Handicraft and Furniture industries, while the Packing industries were found to consume 71 timber species. These timbers were found infested by different insect borers and

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_14

some of them were found common in many timber species used in untreated raw material and finished products. The economically important insect borers are *Lyctus africanus* Lesne, *Sinoxylon anale* Lesne, *Heterobostrychus aequalis* Waterhouse, and *Stromatium barbatum* Fabricius. Further, due to the lack of supply of traditional wood alternate timbers are being used as raw material, the insect pest problems are an added threat to these wood-based industries. The sapwood of traditional and alternate timbers, containing adequate starch/food reserves were found prone to insect pest damage. Many of the finished wooden handicraft and furniture products are inferior in quality due to the use of untreated raw material, which is susceptible to insect pests. This affects its value, both in the national and international market. Infestation by insect pests usually starts in the raw material at the felling site and may continue in the timber depot and thereafter in the finished product or even after being passed on to the consumer. A revenue loss of approximately 25% or more is estimated, due to beetle pest damage to the raw wood material and to the finished product stage. This revenue loss could be further enhanced over a period of time. This chapter deals with the different insect borers recorded on the timber species on both the raw material and finished products used for handicraft, furniture, and packing case industries, and the effective management measures are discussed.

Keywords

Insect borers · Traditional and alternate timber species · Protection and management

14.1 Introduction

Wood is one of the most important renewable natural resources and is perhaps the first material used by man since time memorial. It is the prime product of forests which continues to be one of the most widely used raw materials for diverse industrial and structural applications like construction, furniture, handicrafts, etc., in spite of the introduction of many modern alternate materials. In India, the handicraft and furniture industry is considered an ancient cottage industry, representing the rich heritage of India. It is the second largest industry next to agriculture and its existence is known since the beginning of civilization and also described as a material symbol of the cultural heritage of India. It is also represented as an important social, economic and cultural activity. Earlier reports indicated that the exports of handicrafts products have increased from Rs. 1065 crores in 1991–1992 to Rs. 6769 crores in 2001–2002. In the Wooden Handicraft sector alone the export figures in crores during the Year 2005–2006 was Rs. 853 crores, during 2006–2007 it was Rs. 1180 crores. 2007–2008 it was 1039 crores and 2008–2009 it was 672 crores. During 2020–2021 it is USD 611.48 million for Wood-ware alone and for Furniture USD 575.77 million. Presently, there is an acute shortage of conventional timbers resulting in escalating cost of handicraft and furniture products. This condition has necessitated the use of alternate indigenous and imported timbers possessing properties in handicraft and furniture profession. Added to this, several fast-growing plantation timbers are also being used by these industries. Apart from lack of supply, insect pest problems on wood are an added threat to these industries. The sapwood of traditional and alternate timbers, containing adequate starch/food reserves were found prone to insect pest damage. Many of the finished wooden handicraft and furniture products are inferior in quality due to the use of untreated raw material, and they are susceptible to insect pests. This affects their value of wooden products in both the national and international markets. All insect-infested handicraft and furniture products are returned by the wholesale dealers to the concerned artisans themselves, as they are not willing to shoulder the loss of revenue due to its biodegradation by insects.

The furniture industry relies extensively on wood and wood-based materials as it excels in performance, manufacturing, appearance characteristics, and ease of assembly of wood pieces with other materials and it can be readily available with varnishes and paints. Wooden furniture is the most common consumer choice because of its innate stability and reliability, pleasant appearance, sustainability, and good economic value over the long term (Pakarinen, 2001). The growth in wooden furniture is foreseen as wood is one of the raw materials that is naturally available in abundance and can be used in the production of almost all types of furniture. In India, wood accounts for 65% of the Indian furniture, and of that teak accounts for almost 50% while Sal and Deodar account for about 20% and the balance includes Mahogany, Cedar, and other tree types. Hardwoods are preferred more over softwoods because the higher density wood has superior manufacturing characteristics such as better machining and finishing, and higher strength. Solid wood is widely preferred in furniture manufacturing owing to its durability and resistance characteristics in the longer term (Anon, 2020). Solid wood is the primary form used but there has been an increased use of veneer, plywood and composite panels, high density engineered products such as laminated veneer lumber and parallel strand lumber are picking up pace. The increased and cheaper imports along with plantations promote the market for engineered woods. Although much of the low-to-medium value furniture produced may use vinyl or other polymer materials as face laminates, high-grade hardwood veneers are the laminate choice for high-value furniture. Furniture industry uses composite materials with laminates and has the advantage over solid wood of being cheaper and providing better dimensional stability in the interior environment.

Packing case industry utilizes a lion share of the timber produced in India. The wood packing industries in India consume 5.6, 0.36, 0.2, 0.15, 0.2, and 0.3 million m^3 respectively for packing fruits, vegetables, tea, tobacco, textiles, machinery, etc., amounting to a staggering figure of 6.81 million m^3 (Tandon et al., 1988). Although Packing case industry is considered a less economic trade, the quantity of timber used in this sector is huge. Here again, it has been observed that many fabricators are facing acute shortage of traditional timber for the fabrication of packing cases and have started consumption of alternate/plantation timbers, to cater to the needs of the consumer. Since the government has imposed a ban on the felling of trees in the natural forests, many short-rotation timbers/plantation and exotic timbers are being used both for the domestic and industrial sectors. Packing is one of the important end uses for the industrial/horticultural sector. Wooden packing cases are required for transport of the finished product to the consumer in safe and original condition. Here again the demand for timber is rising every year. From the all-India figure, it is inferred that the percentage of timber requirement in the packaging sector is about 30% of the sawn timbers. Recycling of used wooden packing cases is also employed in certain sectors, to reduce costs for transport of their goods.

14.2 Timbers Used in Handicraft and Furniture Industries

In India, about 1800 commercially valuable timber species with biological diversity have been recorded in which many timbers are traditionally being used in the handicraft, furniture, and packing industries. Studies indicated that about 72 timber species were being utilized in the Handicraft industries and almost all timber species used in the Handicraft industries are used in the Furniture sector depending upon its availability, while the Packing industries were found to consume 71 timber species. A detailed list of the traditional, alternate/plantation, exotic, imported timber species used in handicraft and furniture industries for fabricating different handicraft and furniture products is shown in Table 14.1 and the different insect borers collected from these handicrafts, furniture, packing cases, and timber species are shown in Table 14.2. However, during a passage of time it has been observed that a large gap exists between the demand and supply position of traditional timbers being used by the handicraft, furniture, and packing case industries as a whole. This situation has been raised due to the Government of India policies on the conservation of forest resources, over exploitation and ban of felling of natural forests. To bridge this gap, between the demand and supply, increasing the availability of raw material through the plantation of short-rotation timbers and import of timbers on a short-term basis is the other substitute (Joshi et al., 2011).

14.3 Wood Packing Case Industries

The most common timber species used in packing cases is *Hevea brasiliensis* and its consumption in many of the packing case industries is around 70%. The consumption of the other timber species used for packing cases is around 30% which includes *Grevillea robusta, Ficus bengalensis, F. infectoria, F. religiosa, Pongamia glabra, Samanea saman,* and *Eucalyptus hybrid.* The detail of timber species used in packing case industries is shown in Table 14.2. The insect species reported on these timber species are added in Table 14.3.

Table 14.1 Traditional, alternate/plantation, exotic, imported timber species used for different handicraft and furniture

	Timber species	Common/Trade Name	Wood handicraft/furniture products
1	*Acacia arabica*	Gobbadi Karijali	Toy-making, turnery, furniture
2	*Acacia auriculaeformis*	Bengal Jali	Turnery, carving and lacquer work, furniture
3	*Adina cordifolia*	Yethiga, Heddi, Haldu	Inlay work, turnery, carving, furniture toys, pen holders, combs, rulers, handles, ornamental caskets, and picture frames
4	*Ailanthus excelsa*	Maharukh	Toys
5	*Artocarpus integrifolia*	Halasu, Jackfruit tree	Inlay work
6	*A. heterophyllus*	Kathal	Turnery
7	*Artocarpus integrifolia*	Aini	Carving, furniture turnery, toys, and picture frames
8	*Albizia lebbek*	Kokko	Toy making
9	*Alstonia scolaris*	Chatian, Maddale, Hale, Satin wood	Turnery, furniture
10	*Anogeissus pendula*	Kardahi	Carpentry work, and turnery, furniture
11	*Azadirachta indica*	Bevu, Neem	Wood carving of gods, furniture, and toys
12	*Bauhinia malabarica*	Kanchan	Toys
13	*Boehmeria rugulosa*	Genthi	Toys, turnery for making jars for clarified butter and domestic utensils, spoons, small boxes, and carved bowls
14	*Buxus wallichiana*	Boxwood	Turnery, carving and making toys, combs, mathematical instruments, and fancy boxes for butter, honey, snuff, etc.
15	*Cedrus deodara*	Deodar cedar	Furniture
16	*Chloroxylon swietenia*	Satin wood	Prized for cabinet work, picture frames, interior decorative work, carving, turnery, furniture, and other fancy goods
17	*Cinnamomum zeylanicum*	Cinnamon	Turnery articles
18	*Cordia macleodii*	Daigan and Dhengan	Highly decorative timber use for turnery articles, carved picture frames, and toys
19	*Dalbergia latifolia*	Beete, Shisham, Rosewood	Wood carving, turnery, and furniture
20	*D. sisso*	Agaru, Sisso	Handicraft items and furniture
21	*Diospyros ebenum*	Ebony, Karimara, Ebony, Bale	Highly prized ornamental articles, toys, and furniture. Sapwood used for picture frames, turnery articles, and inlay work
22	*Dysoxylum malabaricum*	White cedar	Carving, engraving work, turnery articles, and toys
23	*Enterolobium contorisiliquim*	Pacara earpod	Toys, boxes, and picture frames

(continued)

Table 14.1 (continued)

	Timber species	Common/Trade Name	Wood handicraft/furniture products
24	*Eriodendron anfractuosum*	Pania	Inlay work
25	*Eucalyptus camaldulensis*	Neelgiri	Wood carving, turnery articles, and furniture
26	*E. citriodora*	Neelgiri	Handicraft items
27	*E. tereticornis*	Mysore gum	Turnery, furniture
28	*E. hybrid*	Hybrid Neelgiri	Turnery, furniture
29	*Euonymus crenulatus*	Spindle tree	Carving, turnery and used to substitute for boxwood
30	*Ficus infectoria*	Basan, Karibasari	Turnery, furniture
31	*Ficus religiosa*	Arali	Inlay work
32	*Gardenia latifolia*	Gardonia	Valuable substitute for boxwood and all types of turnery articles such as combs, rulers, toys, penholders, brush backs, etc., and engraving
33	*Gmelina arborea*	Gamari, Shivana	Wood carving, bent wood articles, turnery articles, and toys
34	*Grevillea robusta*	Silver oak	Wood carving furniture
35	*Gyrocarpus americanus*	Tanaku	Toys, imitation fruits, carved animals, and other utility items
36	*G. jacquini*	Helicopter tree	Toys, handicraft items
37	*Hardwickia pinnata*	Piney	Turnery articles, furniture
38	*Hevea brasiliensis*	Rubber wood	Wood carving, turnery, handicraft items, furniture
39	*Holoptelea integrifolia*	Kanju	Carving articles
40	*Hymenodictyon excelsum*	Kuthan	Toy making
41	*Juglans regia*	Walnut	Fancy goods, turnery articles, and furniture
42	*Lagerstroemia microcarpa*	Ben-teak	Turnery articles, furniture
43	*Leucaena leucocephala*	Subabul, White Lead Tree	Wood carving, turnery furniture
44	*Linociera malaharica*		Boxwood, turnery articles, and toys
45	*Maeopsis emini*	Musizi	Wood carving, toys, and export artifacts
46	*Mangifera indica*	Mavu	Wood carving, furniture
47	*Melia azedarach*	Persian Lilac	Toys, small articles, turnery articles, and furniture
48	*Michelia champaka*	Sampige, Champa	Inlay work
49	*Mitragyna parvifolia*	Kaim	Lord Buddha images, making drums and other musical instruments
50	*Pithecellobium dulce*	Dakhanibabal, VilayatiImli-	Wood carving

(continued)

Table 14.1 (continued)

	Timber species	Common/Trade Name	Wood handicraft/furniture products
51	*P. saman*	Rain tree	Wood carving
52	*Polyalthia fragrans*	Kekechapaya, Gouri	Photo frames
53	*Protium serratum*	Indian Red Pear	Photo and mirror frames
54	*Pterocarpus dalbergioides*	Rakta Chandan	Decorative articles, inlay work
55	*P. marsupium*	Bijasal, Honne	Wood carving, inlay work
56	*Santalum album*	Srigandha, Gandha, Chandana	Wood carving
57	*Shorea robusta*	Sal	Furniture
58	*Simarouba glauca*	Paradise tree	Handicraft items
59	*Sterculia urens*	Gular and Tapsi	Carving toys
60	*Swietenia mahagoni*	Mahogany	Turnery, toys, inlay work, jewelry boxes, cabinet making and carved wood work and furniture
61	*Syzygium cuminii*	Nerale, Jambul, Jamun	Inlay work
62	*Tamarindus indica*	Hunase, Imli	Inlay work
63	*Tecomella undulata*	Rakhta rohita (Rohida Tree)	Handicraft items
64	*Tectona grandis*	Saguvani, Tega, Teak	Wood carving, turnery furniture, etc.
65	*Terminalia arjuna*	Thoramathi, Neeramathi, Holemathi	Inlay work
66	*Terminalia chebula*	Alale, Gallnut, Harda	Inlay work
67	*Toona ciliata*	Toon	Toy making, musical instruments, carvings, and cigar boxes
68	*Trewia nudiflora*	Gutel	Carved images
69	*Terminalia chebula*	Hole-lakki, Sankani, Holenacei	Inlay work
70	*Wrightia tinctoria*	Dudhi, Hale, Kadumurkha	Turnery articles including toys
71	*Zanthoxylum ovalifolium*	–	Toy making and carved articles
72	*Z. rhetsa*	Mullilam	Turnery articles and ornamental purposes

Table 14.2 Traditional and alternative timber species (raw material) used in wood packing case industries

	Timber species	Common/Trade Name	Wood packing case products
1	*Acacia auriculaeformis*	Bengal Jali	Light Veneer Packing cases for horticultural produce
2	*Adina cordifolia*	Yethiga, Heddi, Haldu	Packing cases with low durability
3	*Ailanthus excelsa*	Maharukh	Packing cases with low durability
4	*Albizzia chirensis*	Siris	Packing cases with low durability
5	*A. falcataria*	Batai, Molucca albizzia	Light Packing cases
6	*A. lebbek*	Kokko	Packing cases with high durability
7	*A. procera*	Safed siris	Packing cases with moderate durability
8	*Alstonia scolaris*	Chatian, Maddale, Hale, Satin wood	Packing cases with low durability
9	*Alnus* sp.	Alder	Packing cases
10	*Anthocephalus chinensis*	Kadam	Packing cases with low durability
11	*Aphanamixis polystechya*	Pitraj	Packing cases with high durability
12	*Artocarpus heterophyllus*	Kathal	Packing cases with high durability
13	*A. fraxinifolius*	Mundani	Packing cases with low durability
14	*A. hisutus*	Aini	Heavy packing cases with high durability
15	*A. incisus*	Bread fruit	Packing cases
16	*A. lakoocha*	Lakooch	Packing cases with high durability
17	*Bischofa javanica*	Uriam	Packing cases with low durability
18	*Boehmeria rugulosa*	Genthi	
19	*Bombax ceiba*	Semul	Packing casers with low durability
20	*Bridelia* sp.	Kassi	Packing cases with moderate durability
21	*Calophyllum elatum*	Siruponne, Ponne	Heavy packing cases
22	*Callophyllum* sp.	Poon	Packing cases with moderate durability
23	*Canarium strictum*	Kaighupa, Dhup mara, Raidhupa	Packing cases
24	*Cararium* sp.	White Dhup	Packing cases with low durability

(continued)

Table 14.2 (continued)

	Timber species	Common/Trade Name	Wood packing case products
25	*Careya arborea*	Gawla, Kaval	Packing cases
26	*Ceiba pentandra*	Seemaburguga, Silk cotton, SermSel	Light packing cases
27	*Cullenia excelsa*	Karani	Packing cases with low durability
28	*Cupressus goveniana*	California cypress	Packing cases
29	*C. lusitanica*	Mexican white cedar	Light packing cases
30	*Dalbergia lanceolaria*	Takoli, Pachadi, Bastard Rosewood	Light packing cases
31	*Dysoxylum malabaricum*	White cedar	Packing cases with high durability
32	*Elaeocarpus tuberculatus*	Rudrak	Packing case boards
33	*Eucalyptus camaldulensis*	Neelgiri	Packing cases
34	*Eucalyptus tereticornis*	Mysore gum	Heavy packing cases
35	*E. terticornis* (Clones)	Mysore gum	Light Veneer Packing cases for horticultural produce
36	*E. hybrid*	Hybrid Neelgiri	Packing cases
37	*Ficus hispida*	Dodathmara, Kad-aati	Light packing cases
38	*F. religiosa*	Arali	Packing cases
39	*Gironnera reticulata*	–	Packing cases, crates
40	*Gmelina arborea*	Gamari	Packing cases with high durability
41	*Grevillea robusta*	Silver oak	Packing cases, pallets
42	*Grewia tiliaefolia*	Tadagana, Dadsala, Dhanwara, Toda	Heavy packing cases
43	*Guruga pinnata*	Garuga	Packing cases with low durability
44	*G. jacquini*	–	Light packing cases
45	*Hevea brasiliensis*	Rubber wood	Packing cases, pallets
46	*Holoptelea integrifolia*	Kanju	Packing cases with low durability
47	*Kydia calycina*	Pula	Packing cases
48	*Lagerstroemia microcarpasyn. L. rhornosonii*	Benteak	Heavy packing cases
49	*L. parviflora*	Lendi	Packing cases with low durability
50	*L. reginae*	Mani Marutu, Pride of India	Heavy packing cases
51	*L. speciosa*	Jarul	Packing cases with moderate durability
52	*Lannea coramandelica*	Jhingan	Packing cases with low durability
53	*Lophopetalum wightianum*	Banati	Packing cases with low durability

(continued)

Table 14.2 (continued)

	Timber species	Common/Trade Name	Wood packing case products
54	*Machilus* sp.	Machilus	Packing cases with low durability
55	*Mangifera indica*	Mavu	Packing cases with low durability
56	*Mastixia arborea*	Kumbalamara, Gulla	Light packing cases
57	*Michelia champaka*	Sampige, Champa	Packing cases with low durability
58	*Mitragyna parvifolia*	Kaim	Packing cases with low durability
59	*Palaquium elipticum*	Pali	Packing cases with moderate durability
60	*Pithecolobium saman*	Rain tree	Packing cases
61	*Polyalthia* sp.	Debdaru	Packing cases with low durability
62	*Pterygota alata*	Narikel	Packing cases
63	*Simarouba glauca*	Bitter Wood, Paradise Tree	Light packing cases
64	*Stereospermum* sp.	Padri	Packing cases with low durability
65	*Syzygium cuminii*	Nerale, Jambul, Jamun	Packing cases with moderate durability
66	*Terminalia bellerica*	Bahera	Heavy packing cases with low durability
67	*Tetromeles nudiflora*	Maina	Packing cases with low durability
68	*Toona ciliate*	Toon	Packing cases with low durability
69	*Trewia nudiflora*	Gutel	Packing cases with low durability
70	*Vateria indica*	Vellapine	Packing cases with low durability
71	*Zanthoxylum rhetsa*	Mullilam	Packing cases with high durability

14.4 Biological Degradation of Timber by Insects

Different insect pests with different damage potential could be causing bio-degradation to wood and wooden products in different areas. Infestation by insect pests usually starts in the raw material at the felling site and may continue in the timber depot and thereafter in the finished product or even after being passed on to the consumer. A revenue loss of approximately 25% or more is estimated, due to beetle pest damage to the raw wood material to the finished product stage. This revenue loss could be further enhanced over a period of time. Some insect borers

Table 14.3 Insects infesting traditional, alternate/plantation, exotic/imported timber species (raw and finished products) used in handicraft, furniture and packing case industries

Timber species	Insect pests
Acacia arabica	**Bostrychidae**: *Sinoxylon anale* Lesne, *S. sudanicum* Lesne
	Cerambycidae: *Aeolesthes holosericea* Fab., *Stromatium barbatum* Fab.
	Lyctidae: *Lyctus africanus* Lesne
	Scolytidae: *Xyleborus noxius* Sampson
A. auriculaeformis	**Lyctidae**: *L. africanus* Lesne, *Minthea rugicollis* Walker
Adina cordifolia	**Bostrychidae**: *H. aequalis* Waterhouse, *S. anale* Lesne, *Sinoxylon conigerum* Gerst
	Lyctidae: *L. africanus* Lesne
	Platypodidae: *Platypus solidus* Walker
	Scolytidae: *Xyleborus* sp.
Ailanthus excelsa	**Buprestidae**: *Sphenoptera mediocris* Kerremans
Albizzia chirensis	–
A. falcataria	**Bostrychidae:** *Sinoxylon anale* Lesne, *S. atratum* Lesne
	Cerambycidae: *Xystrocera globosa* Oliver
	Curculionidae: *Mecistocerus fluctiger* Faust, *M. concretus* Faust, *Cossonus canarensis* Faust
A. lebbek	**Anobiidae**: *Gastrallus birmanicusinsulcatus* Pic, *G. plicaticollis* Pic
	Anthribidae: *Acorynus laenatus* Jordan, *Eucorynus crassicornis* Fab.
A. procera	**Anobiidae**: *Ptilinus binodulus* Motschulsky
	Bostrychidae: *Lyctoxylon japonum* Reitter, *Lyctus africanus* Lesne, *Sinoxylon anale* Lesne, *S. capillatum* Lesne, *S. crassum crissum* Lesne, *S. crassumdekkanense* Lesne, *S. pugnax* Lesne, *S. pygameum* Lesne, *S. sudanicum* Lesne, *Xylodectes ornatus* Lesne
	Brenthidae: *Caenorycho desplanicollis* Walker, *Cerobates sexsulcatus* Motschulsky, *Jonthocerus carinensis* Senna
	Buprestidae: *Agrilus beesoni* Obenberger, *A. grewiae* Thery
	Cerambycidae: *Chlorophorus sacrocarpi* Gardner, *Coptop sleucostictica* White
	Curculionidae: *Mecistocerus fluctiger* Faust
	Platypodidae: *Crossotarsus saundersi* Chapuis, *C. squamulatus squamuloides* Beeson, *Platypus solidus* Walker
	Scolytidae: *Dryocoetes coffeae* Eggers, *Xyleborus minor* Stebbing
Alnus sp.	–
Alstonia scolaris	**Bostrychidae**: *Heterobostrychus aequalis* Waterhouse, *M. rugicollis* Walker, *S. anale* Lesne, *Xylothrips flavipes* Illiger, *Heterobostrychus aequalis* Waterhouse,

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	M. rugicollis Walker, *S. anale* Lesne, Xylothrips *flavipes* Illiger
	Lyctidae: *L. africanus* Lesne, *L. africanus* Lesne
Anogeissus pendula	**Bostrychidae**: *Schistocerus anobiodes* Waterhouse
	Buprestidae: *Chrysobothris beesoni* Obenberberger, *C. indica* Cast & Gory Obenberberger
Anthocephalus chinensis	–
Aphanamixis polystechya/ Amoorarohituka	**Platypodidae**: *C. saundersi* Chapuis, *C. squamulatus squamuloides* Beeson, *Platypus cupulifer* Wich
	Scolytidae: *Thamnurgides vulgaris* Eggers
Artocarpus. fraxinifolius	**–**
A. *hetrophyllus*	**Anthribidae**: *Sintor* sp.
	Brenthidae: *Cerobates sexmaculatus* Motschulsky, *C. sumatranus* Senna, *C. tristriatus* Lund, *Eupsalis truncate* Boheman, *Hormoecerus reticulatus* Fab., *Jonthocerus cremates* Lacordaire, *Prophthalmus bourgeoisi* Power
	Cerambycidae*: Batocera rubus* Linn, *B. rufomaculata* De Geer, *Dihammus rusticator* Fab., Epepeotes *luscus* Fab., *E. unicinatusvar. salvazai* Pic, *Glenea belli* Gahan, *Macrochenusti grinus* Olivier, *Mesosa columba* Pascoe, *Obereaarto carpi* Gardener, *Olenecamptus bilobus* Fab., *Pterlophia infirmier*Breuning
	Curculionidae: *Cossonus disciferus* Walker, *C. divisus* Mischl
	Lyctidae: *Lyctus brunneus* Stephens
	Platypodidae: *Platypus indicus* Strohmeyer, *P. solidus* Walker
	Scolytidae: *Diamerus curvifer* Walker, *Xyleborus badius* Eichhoff, *X. fornicates* Eichhoff, *X. indicus* Eichhoff, *X. interjectus* Blandford, *X. parvulus* Eichhoff, *X. rudis* Eggers, *X. similis* Ferr, *X. semigranosus* Blandford
A. hirsutus	**Anthribidae**: *Tropideres bolinus* Jordan
	Bostrychidae: *Sinoxylon anale* Lesne, *S. atratum* Lesne, Xylosocus *capucinus* Fab., *Xylothrips flavipes* Illiger
	Cerambycidae*: Batocera rufomaculata* DeGeer, *Macrochenus tigrinus* Olivier, *Olenecamptus bilobus* Fab., *Pterolophia occidentalis* Schwarzer
	Curculionidae: *Aclees birmanus* Faust
	Lyctidae: *Lyctus africanus* Lesne
	Scolytidae: *Xyleborus interjectus* Blandford, *X. testaceus* Walker
A. incises	**Scolytidae**: *Xyleborus interjectus* Blandford
A. integrifolia/A. integra	**Brenthidae**: *Cerobates sexsulctus* Motschulsky, *C. sumatranus* Senna, *C. tristriatus* Lund, *Eupsalis truncate* Boheman, *Hormoecerus reticulatus* Fab.,

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Jonthocerus cremates Lacordaire, *Prophthalmus bourgeoisi* Power
	Cerambycidae: *Batocera rubus* Linn, *B. rufomaculata* De Geer, *Dihammus rusticator* Fab., *Epepeotes luscus* Fab., *E. unicinatus var. salvazai* Pic, *Glenea belli* Gahan, *Macrochenus tigrinus* Olivier, *Mesosa columba* Pascoe, *Obereaarto carpi* Gardener, *Olenecamptus biliobus* Fab., *Pterlophia infirmior* Breuning
	Curculionidae: *Cossonus disciferus* Walker, n *C. divisus* Mischl
	Lyctidae: *Lyctus brunneus* Stephens
	Platypodidae: *Platypus indicus* Strohmeyer, *P. solidus* Walker
	Scolytidae: *Diamerus curvifer* Walker, *Xyleborus badius* Eichhoff, *X. fornicatus* Eichhoff, *X. indicus* Eichhoff, *X. interjectus* Blandford, *X. parvulus* Eichhoff, *X. rudis* Eggers, *X. similis* Ferr, *X.semigranosus* Blandford
A. lakoocha	**Anobiidae**: *Gastrallus birmanicusinsulcatus* Pic, *Basitropis nitidicutis* Jekel, *Eucorynus crassicornis* Fab., *Unciferstigmosus* Jordan, *Xenoceru srectilineatus* Jordan
	Brenthidae: *Cerobates fossulatus* Motschulsky
	Buprestidae: *Agrilus fici* Thery
	Cerambycidae: *Stromatium barbatum* Fab.
	Platypodidae: *Crossotarsus squamulatus* Chapuis, *Platypus curtatus* Sampson, *P. signatus* Chapuis, *Ericryphalus indicus* Eichhoff, *Ozopermon cylindricus* Eggers, *Thamnurgides indicus* Eggers, *T. opacifrons* Beeson, *Xyleboru sdihingensis* Beeson, *X. interjectus* Blandford, *X. intextus* Beeson, *X. ovalicollis* Eggers, *X. pumilus* Eggers, *X. sulcatus* Eggers
Azadirachta indica	**Bostrychidae**: *S. anale* Lesne
	Platypodidae: *Crossotarsus saudersi* Chapuis
Bauhinia malabarica	**Platypodidae:** *Crossotarsus emorsus* Beeson, *C. fractus* Sampson, *C. saundersi* Chapuis, *C. squamulatus squamuloides* Beeson
Bischofa javanica	**Cerambycidae**: *Stromatium barbatum* Fab. (Cerambycidae)
	Platypodidae: *Platypus cuplifer* Wichmann
	Scolytidae: *Hypothenemuas aroriensis* Beeson (Scoytidae)
Boehmeria rugulosa	**Curculionidae:** *Peribleptusdealbatus* Boisduval
Bombax ceiba/Bombax malabaricum/Salmalia malabarica	**Anthribidae**: *Basitropis hamate* Jordan, *Exechesops triangularis* Jordan, *Rhaphitropis carbo* Jordan, *Tropideres paviei* Lesne, *T. securus* Boheman
	Bostrychidae: *Dinoderus bifoveolatus* Wollaston, *D. brevis* Horn, *D. minutus* Fab., *Heterobostrychus aequalis* Waterhouse, *H. hamatipennis* Lesne, *H. pileatus*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Lesne, *Lyctoxylon japonum* Reitter, *Lyctus africanus* Lesne, *L. brunneus* Stephens, *Minthea rugicollis* Walker, *Schistoceros anobioides* Waterhouse, *Sinoxylon anale* Lesne, *S. atratum* Ces., *S. capillatum* Lesne, *S. crassum* Lesne, *Trgoxylon spinifrons* Lesne, *Xylothrips flavipes*Illiger, *X. ornatus* Lesne, *X. tortilicornis* Lesne
	Brenthidae: *Caenorrychodes planicollis* Walker, *Cerbates adustus* Sennav, *C. sexulcatus* Motschoulsky, *C. tristriatus* Fab., *Cyphagogus corporally* Kleine, *C. eichhorni* Kleine, *Eupsalis truncata* Boheman, *Hormocerus reticulatus* Fab., *Mesoderes aberrans* Kleine, *Microtrachelizus apertus* Kleine, *Trachelizus bivalcatus* Fab.
	Cerambycidae: *Aesopida malasica* Thompson, *Artimpaza obscura* Gardner, *Batocera rufomaculata* De Geer, *Coptops aedificator* Fab., *Derolus volvulus* Fab., *Dihammus griseoplagiatus* Breuning, *Glenea homonospila* Thomson, *G. multiguttata* Guerin, *G. spilota* Thomson, *Glenea* sp., *Macrohenus guerini* White, *Mesosa bifasciata* Breuning, *M. indica* Breuning, *Niphona malaccensis* Breuning, *Plocaederus ferrugineus* Linn., *Rhaphipodus obesus* Gahan, *Stromatium barbatum* Fab.
	Curculionidae: *Dystropicus clitellae* Faust, *D. dorsalis* Faust, *Mecistocerus bardus* Faust, *M. fluctiger* Faust, *Osphiliabombacis* Marshall, *O. odinae* Marshall, *Rhadinomerus bombacis* Marshall, Sipalus hypocrite Boheman, *Tomicoproctus machili* Marshall
	Platypodidae: *Crossotarsus minax* Walker, *C. saundersi* Chap, *Platypus cupulifer* Wichmann, *P. latifinis* Walker, *P. solidus* Walker, *P. uncinatus* Blandford
	Scolytidae: *Hypothenemuseu polyphagus* Beeson, *Xyleborus andrewesi* Blandford, *X. compactus* Eichhoff, *X. dilatatus* Eichhoff, *X. fornicates* Eichhoff, *X. interjectus* Blandford, *X. minor* Stebbing, *X. noxius* Sampson, *X. parvulus* Eichhoff, *X. similis* Ferrari, *X. testaceus* Walker
Bridelia sp.	–
Buxus wallichiana	–
C. lusitanica	–
Calophyllum elatum	**Bostrychidae**: *Sinoxylon anale* Lesne, *Heterobostrychus aequalis* Waterhouse
Canarium strictum	**Bostrychidae**: *Heterobostrychus hamatipenni* Lesne, *Trgoxylon spinifrons* Lesne, *Xylothrips flavipes* Illiger and *Stromatium barbatum* Fab.
	Lyctidae: *Minthea rugicollis* Walker
	Platypodidae: *Crossotarsus quadricandatus* Strohmeyer, *Platypus nilgiricus* Bees and *P. solidus* Walker

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Scolytidae: *Xyleborus granulipennis* Eggers and *X. testaceus* Walker
Cararium sp.	**Bostrychidae**: *Xylothrips flavipes* Illiger
	Lyctidae: *Minthea rugicollis* Walker
	Platypodidae: *Platypus nilgiricu* Bees
Careya arborea	**Cerarmbycidae**: *Batocera rufumoculata* De Geer and *B. rubus* Linn
Cedrus deodara	**Anobiidae**: *Priobium (Trypopirys) luteopilos* Pic
	Buprestidae: *Anthaxia baconis* Thomson, *Sphenoptera aterrima* Kerremanand, *Sphenoptera lafirtei* Thomson
	Cerambycidae: *Criocephalus tibetanus* Sharp, *Leptura rubriola* Bates, *Stromatium barbatum* Fab., *Tetropium oreinum* Gahan
	Curculionidae: *S. tenosceis himaltfyensis* Stebbing, *Xenotllimetes himalqyensis* Stebbing, *Xerodermus himalqyanus* Marshall
	Platypodidae: *Crossotarsus coniferae* Stebbing, *Crossotarsus jairmairei* Chapuis, *Crossotarsus wilhloti* Stebbing, *Diapus quadrispinatus* Chapuis
	Scolytidae: *Crypturgfls beesoni* Eggers, *Gypflrgus minimfls* Stebbing, *Ips longifolia* Stebbing, *Piryogenes scitus* Blandford, *Piryophthorus deodara* Stebbing, *Piryophthorus himalqyensis* Stebbing, *Polygraphus aterrimus* Strohmeyer, *Polygrapbus major* Stebbing, *Polygraphus pini* Stebbing, *Seolytoplatypus rqja* Blandford, *Scolytus major* Stebbing and *S. minor* Stebbing
Ceiba pentandra	**Bostrychidae**: *Sinoxylon anale* Lesne, *Dinoderus* sp. and *Xylothrips flavipes* Illiger
	Cerambycidae: *Batocera rufomaculata* De Geer, Batocera sp.
	Platypodidae: *P. latifinis* Walker, *P. solidus* Walker, *Platypus cavus* Strohm
	Scolytidae: *Xyleborus interjectus* Bland
Chloroxylon swietenia	**Anthribidae**: *Basitropis affinis* Jordan, *Dendrotrogus colligens* Walker
	Cerambycidae: *Aeolesthes holosericea* Fab., *Stromatium barbatum* Fab., *Tetraommatus filiformis* Perroud, *Xylotrechus carinifrons* Laporte et Gory, *X. smei* Laporte et Gory
	Platypodidae: *Platypus solidus* Walker
	Scolytidae: *Xyleborus parvulus* Eichhoff
Cinnamomum zeylanicum	**Scolytidae**: *Xyleborus arquatus* Sampson
Cordia macleodii	–
Cullenia excelsa	**Platypodidae**: *Platypus solidus* Walker
	Scolytidae: *Xyleborus noxius* Sampson

(continued)

Table 14.3 (continued)

Timber species	Insect pests
Cupressus goveniana	–
C. lusitanica	
Dalbergia lanceolaria	**Bostrychidae:** *Sinoxylon anale* Lesne
	Lyctidae: *Minthea rugicollis* Walker
	Scolytidae: *Xyleborus similis* Ferr.
	Cerambycidae: *Stromatium barbatum* Fab.
D. latifolia	**Bostrychidae**: *S. anale* Lesne
	Lyctidae: *M. rugicollis* Walker
	Scolytidae: *Xyleborus interjectus* Bland
D. sissoo	**Anthribidae**: *Tropideres secures* Boheman, *Xylinades plagiatus* Jordan
	Bostrychidae: *Heterobostrychu shematipennis* Lesne, *Lyctoderma ambiguum* Lesne, *Lyctus africanus* Lesne, *Sinoxylon anale* Lesne, *S. capillatum* Lesne, *S. crassum crassum* Lesne, *S. crassum dekkanense* Lesne, *S. indicum* Lesne, *S. oleare* Lesne
	Buprestidae: *Acmaeodera keremansi* Stebbing, *Agrilus birmanicus* Kerremans, *A. dalbergiae* Thery, *Anthaxia marshalli* Stebbing
	Cerambycidae: *Acanthophorus* sp., *Batocera rubus* Hope, *Cacia cretifera* Hope, *Celosterna scabrator* Fab., *Diorthu scinerus* Fab., *Monochamus bimaculatus* Gahan, *Perissus dalbergiae* Gardner, *Rhaphum abimaculata* Schwarzer, *Stromatium barbatum* Fab., *Xylotrechussmei* Laporte & Gory
	Curculionidae: *Acinemisbauhiniae* Marshall, *Mecistocerus fluctiger* Faust, *Phaenomeres sundevalli* Boheman, *Sipalus hypocrita* Boheman, *Tomico proctusmachili* Marshall
	Platypodidae: *Crossotarsu ssaundersi* Chapuis, *Platypus solidus* Walker
Diospyrous ebonum	–
Dysoxylum malabaricum	**Scolytidae**: *Xyleborus interjectus* Blandford, *X. similis* Ferr.
Elaeocarpus tuberculatus	**Bostrychidae**: *Xylothrips flavipes* Illiger
	Cerambycidae: *Epepeote suncinatus var salvazi* Pic.
	Platypodidae: *Platypus solidus* Walker
	Scolytidae: *Thamnurgides cardamom* Schaufuss
Enteriobium contorisiliquim	–
Eriodendron anfractuosum	**Bostrychidae**: *S. anale* Lesne, *Dinoderus* sp., *X. flavipes* Illiger
	Platypodidae: *P. solidus* Walker
	Scolytidae: *X. interjectus* Bland
Eucalyptus camaldulensis	**Bostrychidae**: *Sinoxylon anale* Lesne
	Cerambycidae: *Celosterna scabrator* Fab., *Eucommato ceravittata* White

(continued)

Table 14.3 (continued)

Timber species	Insect pests
E.citriodora	**Bostrychidae:***Sinoxylon anale* Lesne
	Cerambycidae: *Celosterna scabrator* Fab., *Eucommato ceravittata* White
E. hybrid	**Bostrychidae**: *Sinoxylon anale* Lesne
	Cerambycidae: *Celosterna scabrator* Fab., *Eucommato ceravittata* White
E. tereticornis (clones)	**Bostrychidae**: *Sinoxylon anale* Lesne
	Cerambycidae: *Celosterna scabrator* Fab., *Eucommato ceravittata* White
Euonymus crenulatus	–
Ficus hispida	**Anthribidae**: *Basitropis nitidicutis* Jekel
	Bostrychidae: *Lyctus africanus* Lee, *Schistocerus anoboides* Waterhouse
	Cerambycidae: *Apriona germari* Hope, *Batocera rubus* Linneaus, *Epepeotes luscus* Fab., *Exocentrus ficicola* Fisher, *Rapica rufecens* Pic, *Stromatium barbatum* Fab.
	Scolytidae: *Xyleborus fornicates* Eichhoff
F. lacor (Ficus infectoria)	**Platypodidae***: Platypus* sp.
	Bostrychidae: *L. africanus* Lesne
Ficus religiosa	**Anthribidae**: *Eucorynu scrassicornis* Fab., *Gibber callistus* Jordan, *Phaeochrotes cineromaculatus* Motschulsky
	Bostrychidae: *Lyctus africanus* Lesne, *Minthea rugicollis* Walker, *Sinoxylon anale* Lesne, *Xylodectes ornatus* Lesne
	Brenthidae: *Caenorychodes planicollis* Walker, *Trachelizus bisulcatus* Fab.
	Buprestidae: *Acmaeodera interupta* Kerremans, *Melanophila coriacea* Kerremans
	Cerambycidae: *Batocera rufomaculata* De Geer, *Captops aedificator* Fab., *Epepeotes unicinatus* Gahan, *Macrochenus guerinii* White, *M. bimaculatus* Gahan, *Olenecamptus bilobus* Fab., *O. bilobusvar*. 5 *maculatus* Breuning, *O. bilobus* Fab. var. (new), *Pterolophia occidentalis* Schwarzer, *Xylo trechussmei* Laporte and Gory
	Curculionidae: *Aclees birmanus* Faust, *Alcides westermanni* Boheman, *Mecistocerus fluctiger* Faust, *Mecopus bispinosus* Weber, *Pagiophloeus macilentus* Boheman
	Platypodidae: *Crossotarsus saundersi* Chapuis, *Platypus solidus* Walker
	Scolytidae: *Orthotomicus perexiguus* Blandford, *Xyleborus eugeniae* Eggers, *X. interjectus* Bandford, *X. similis* Ferrari *(syn X. submarginatus)* Blandford, *X. testaceus* Walker *syn. X, kraatzi* Eichhoff
Gardenia latifolia	–

(continued)

Table 14.3 (continued)

Timber species	Insect pests
Gironnera reticulata	–
Gmelina arborea	**Anthribidae**: *Phloeobius pilipes* Jordan, *Tropideres bolinus* Jordan, *Zygeanodes molitor* Jordan
	Bostrychidae: *Lyctus africanus* Lesne, *Sinoxylon anale* Lesne, *S. crissum crissum* Lesne
	Buprestidae: *Sambus gmelinae* Thery, S. *nigritus* Kerremans
	Cerambycidae: *Dihammus elongatus* Breuning, *D. gardeneri* Breuning, *Glenea galathea* Thomson, *G. indiana* Thomson, *Nupserha variabilis* Gahan, *Plocaederu sobesus* Gahan, *Pothynemo ringae* Aurivillius, *Xylotrechus buqueti* Laporte & Gory, *X. smei* Laporte & Gory, *Xylotrechus* sp.
	Curculionidae: *Cercidocerus lateralis* Fab., *Osphilia gmelinae* Marshall
	Platypodidae: *Platypus uncinatus* Blandford
	Scolytidae: *Xyleborus asperipennis* Beeson, *X. assamennis* Eggers, *X. difficilis* Eggers, *X. fornicatus* Eichhoff, *X. indicus* Eichhoff, *X. interjectus* Blandford, *X. intextus* Beeson, *X. lantanae* Eggers, *X. mus* Eggers, *X. pseudopilifer* Schedl., *X. testaceus* Walker, *Setenis furva* Geb, *Strongylium* sp.
Grevillea robusta	**Anthribidae/Ptinidae**: *Ptilinus binodulus* Motschulsky
	Bostrychidae: *Dinoderus minutus* Fab., *Sinoxylon anale* Lesne
	Cerambycidae: *Stromatium barbatum* Fab.
	Curculionidae: *Pagiophloeus umbricidus* Marshall
	Lyctidae: *L. africanus* Lesne, *L. brunneus* Stephens
	Scolytidae: *Xyleborus fornicates* Eichhoff, *X. perforans* Wollaston, *X. semiopacus* Eichhoff, *X. ornatus* Lesne, *Ptilinus binodulus* Motschulsky
Grewia tiliaefolia	**Bostrychidae**: *Heterobostrychus aequalis* Waterhouse, *Sinoxylon anale* Lesne, *S. pygmaeorn* Lesne.
	Curculionidae: *Mecopus* sp.
	Cerambycidae: *Stromatium barbatum* Fab.
	Scolytidae: *Pagiophiloeus umbricidus* Marshall, *Xyleborus fornicates* Eichhofff, *X.perforans* Wollaston, *X. semiopacus* Eichhoff
Guruga pinnata	–
G. jacuini	–
Gyrocarpus americanus	–
Hardwickia pinnata	**Lyctidae**: *Lyctus brunneus* Stephens, *L. malayanus* Lesne, *Minthea rugicollis* Walker, *Trogoxylon spinifrons* Lesne
Hevea brasiliensis	**Bostrychidae**: *Dinoderus minutus* Fab., *D. ocellari* Stephens, *S. anale* Lesne, *Sinoxylon atratum* Lesne,

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	S. conigerum Gerst, *S. pygmaeum* Lesne, *S. crassum* Lesne, *Heterobostrychus aequalis* Waterhouse, *Xyloperha mutilate* Walker, *Xylothrips flavipes* Illiger
	Cerambycidae: *Agelasta cristata* Breuning, *A. nigromaculata* Gahan, *Batacera rufomaculata* De Geer, *Coptops aedificator* Fab., *Dihammus rusticator* Fab., *Mocchotypxver rucicillis* Gahan, *Pterolophis annulate* Chevrolat, *Stromatium barbatum* Fab., *Xystocera globosa*-Oliver
	Curculionidae: *Phaenomerus sundevalli Boh.*
	Lyctidae: *L. africanus* Lesne, *L. brunneus* Stephens, *M. rugicollis* Lesne, *P. solidus* Walker
	Platypodidae: *Crossotarsus minax* Walker, *C. venustus* Chapuis, *Platypus cupulatus* Chapuis, *Platypus latifinis* Walker, *P. lepidus* Chapuis, *P. solidus* Walker, *Platypus parallelus* Fab., *S. conigerum* Gerst, *S. pygmaeum* Lesne, *S. crassum* Lesne, *Heterobostrychus aequalis* Waterhouse
	Scolytidae: *Xyleborus* sp. *n. r similes, Xyleborus similis* Ferr, *Xylothrips flavipes* Illiger, *Xystocera globosa*-Oliver
Holoptelea integrifolia	**Bostrychidae**: *Lyctoxylon beesonianum* Lesne, *Sinoxylon conigerum* Gerstacker, *Meanophila coriacca* erremans
	Cerambycidae: *Coptops aedificator* Fab., *Xylotrochus smei* Laporte and Gory, *Xylotrochus* sp.
	Platypodidae: *Platypus solidus* Walker
Hymeno dictyonexcelsum	**Brenthidae**: *Caenorychodes planicollis* Walker, *Hormocerus reticulatus* Fab.
	Cerambycidae: *Aeolesthes induta* Newman, *Batocera* sp., *Dihammus gardeneri* Breuning, *Xylo trechussmei* Laporte & Gory
	Mordellidae: *Glipa tricolor* Wiedemann
	Platypodidae: *Platypus secretus* Sampson, *P. suffodiens* Sampson, *Xyleborus interjectus* Blandford, *X. minutissimus* Eggers, *X. pumilis* Eggers, *X. simils* Eggers
Juglans regia	**Anthribidae**: *Litocerus khasianus* Jordan, *Tropideres vigens* Jordan
	Buprestidae: *Agrilus* sp.
	Cerambycidae: *Aeolesthes sarta* Solsky, *Aglaophis humerosus* Caevrolat, *Dihamamus elongates* Breuning
	Curculionidae: *Cossonus binolosus* Marshall, *D. in sequalis* Gardner, *Exocentrus parrotiae* Fisher, *Dryophthoroides paroungulis* Marshall, *Stenoscelia gracilitarsis* Wollaston, *Glenea beesoni* Heller, *Macrotoma plagiata* Waterhouse, *Mesos asetulosa* Breuning, *Morimopsis lacrymans* Thomson, *Paraleprodera stephana* Waterhouse, *Pterolophia*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	granulosa Breuning, *P. obscuroides* Breuning, *P. rosacea* Breuning
	Platypodidae: *Crossotarsus fairmairei* Chapuis, *Rhaphuma horifieldi* White, *Xenomimetes sikkimensis* Marshall
Kydia calycina	**Anobiidae**: *Ptilineurus elegans* Fairmaire
	Anthribidae: *Deropyguschaerilus* Jordan, *Phloebius gigas* Horn
	Bostrychidae: *Dinoderus bifoveolatus* Wollaston, *D. brevis* Horn, *D. minutus* Fab., *Hetrobostrychus aequalis* Waterhouse, *Trogoxylon auriculatum* Lesne, *Xylodectes ornatus* Lesne
	Brenthidae: *Opistheno pluscavus* Walker, *Trachelizus bisulcatus* Fab., *Agrilus pastoralis* Thery
	Cerambycidae: *Aeolesthes holosericca* Fab., *Aesopida malasiaca* Thomson, *Glenea nigrolincata* Gahan, *G. vaga* Thomson, *G. vagaflavocolorata* Breuning, *Monochamus nivosus* White, *Olenecamptus indianus* Thomson, *Plaocaedrus obesus* Gahan, *Stromatium barbatum* Fab., *Xylotrechus buqueti* Laporte & Gory, *X. smei* Laporte & Gory, *X. subscutellatus* Chevrolat, *Desmidophorus hebes* Fab.
	Curculionidae: *Mecistocerus fluctiger* Faust, *Rhadinopus buteae* Marshall, *Sipalus hypocrite* Boheman
	Lyctidae: *Lyctus africanus* Lesne, *L. brunneus* Lesne, *Minthea rugicolis* Walker
	Scolytidae: *Ernoporus corpulentus* Sampson, *Hypothenemuseu polyphagous* Beeson, *Xyleborus fallax* Eichhoff, *X. interjectus* Blandford, *X. similis* Ferrari, *X. testaceus* Walker
Lagerstroemia microcarpa syn. L. rhornosonii, L. lanceata	**Anobiidae (Ptinidae):** *Ptilinus binodulus* Motschoulsky
	Anthribidae: *Basitropis rotundata* Jordan, *Dendrotrogus augustipennis* Jordan, *Uncifer* sp., *Xylinodes plagiatus* Jordan
	Bostrychidae: *Dinoderus brevis* Horn, *Heterobostrychus aequalis* Waterhouse, *H. pileatus* Lesne, *Lyctus africanus* Lesne, *Micrapate simplicipennis* Lesne, *Sinoxylon anale* Lesne, *S. atratum atratum* Lesne, *S. conigerum* Lesne, *Schistocerus anoboides* Waterhouse, *Sinoxylon anale* Lesne, *S. crassum dekkanense* Lesne, *Tropideres secures* Boheman, *Xylodectes ornatus* Lesne, *Xylothrips flavipes* IIliger
	Brenthidae: *Caenorycho desplanicollis* Walker, *Cyphagogus westwoodi* Parry, *Opisthenopluscavus* Walker
	Buprestiae: *Anthaxia acutipennis* Thery, *A. basei* Thery, *Belionota prasina* Thunberg, Sphenoptera *andamanensis* Waterhouse

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Cerambycidae: *Aeolesthes holosericea* Fab., *Aesopida malasiaca* Thomson, *Ceresium leucosticticum* White, *Coptops aedifactor* Fab., *C. leucostictica* White, *C. pascoei* Gahan, *Derelus volvulus* Fab., *Dihammus griseoplagiatus* Breuning, *D. longiscapus* Gahan, *D. punctifrons* Gahan, *D.cinereus* Fab., *Epepeote sgardneri* Breuning, *Exocentrus alboguttatus* Fisher, *E. dalbergiae* Fisher, *Gleneamulti guttata* Guerin, *G. vaga* Thomson, *Macrotoma spinosa* Fab., *Mesosa indica* Breuning, *Monochamus bimaculatus* Gahan, *Olenecamptus bilobus* Fab., *Palimna annulata* Olivier, *P. annulatanebulosa* Breuning, *Plocaederus obesus* Gahan, *Ropica rufescens* Pic, *Stromatium barbatum* Fab.
	Curculionidae: *Camptorrhinus affinis* Faust, *C. dorsalis* Boisduval, *C. scrobicollis* Faust, *Mecistocerus fluctiger* Faust, *Osphilia odinae* Marshall, *Rhadino pusbutae* Marshall
	Eucnemidae: *Fornax vestitus* Fleutiaus
	Lyctidae: *Lyctus africanus* Lesne
	Lymexylonidae: *Atractocerus reversus* Walker
	Mordellidae: *Glipa tricolor* Wiedmann
	Platypodidae: *Crossotarsus minax* Walker, *Xyleborus testaceus* Walker, *Eucorynus crassicornis* Fab., *Exillis asper* Jordan, *Crossotarsus bonvouloiri* Chapuis, *C. fractus* Sampson, *C. minax* Walker, *C. saundersi* Chapuis, *C. saundersisubmontanus* Beeson, *C. squamulatus* Chapuis, *C. squamulatus squamuloides* Beeson, *Platypus cupulatus* Chapuis, *P. forfex* Beeson, *P. latifinis* Walker, *P. rectangulatus* Sampson, *P. secretus* Sampson, *P. solidus* Walker
	Scolytidae: *Xyleborus andrewsi* Blandford, *X. fornicatus* Eichhoff, *X. interjectus* Blanford, *X. laticollis* Blandford, *X. minor* Stebbing, *X. noxius* Sampson, *X. parvalus* Eichhoff, *X. semigranosus* Blandford, *X. shoreae* Stebbing, *X. similis* Ferrari
L. parviflora	**Anthribidae**: *Basitropis hamate* Jordan
	Bostrychidae: *Lyctus africanus* Lesne, *Sinoxylon atratum kohlarianum* Lesne, *S. crassam dekkanense* Lesne, *Xylodectes ornatus* Lesne
	Buprestidae: *Agrilus aurociliatus* Thery
	Curculionidae: *Aeolesthes holosericea* Fab., *Ceresium leucosticticum* White, *C. zeylanicum* White, *Epipedocera affinis* Chevrolat, *Pterolophia occidentalis* Schwarzner, *Sarothrocera lowi* White, *Xylotrechus brueti* Laporte & Gory

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Platypodidae: *Crossotarsus saundersi* Chapuis, *C. saundersi submontanus* Beeson, *Platypus cuplifer* Wichmann
	Scolytidae: *Xyleborus testaceus* Walker
L. reginae	**Bostrychidae**: *Sinoxylon anale* Les.
	Cerambycidae: *Olenecamptus signaticoilis*
	Lyctidae: *Minthea rugicollis*
	Platypodidae: *Platypus uncinatus* Bland.
	Scolytidae: *Sphaerotrypes* sp.
L. speciosa	**Anthribidae**: *Phloebius pilipes* Jordan
	Buprestidae: *Chrysochroao pulen ta* Gory, *C. vittata* Fab.
	Cerambycidae: *Ceresium rufum* Lameere, *Macrochenus guerinsii* White, *Nothopeus fulus* Bates, *Olenecampus signaticollis* Heller
	Lyctidae: *Minthea rugicollis* Walker
	Solytidae: *Xyleborus semigranosus* Blandford
Lannea coramandelica	**Anthribidae**: *Basitropis rotundata* Jordan, *Dendrotrogus augustipennis* Jordan, *Eucorynus crassicornis* Fab., *Exillis asper* Jordan, *Uncifer* sp., *Xylinodes plagiatus* Jordan
	Bostrychidae: *Dinoderus brevis* Horn, *Heterobostrychus aequalis* Waterhouse, *H. pileatus* Lesne, *Lyctus africanus* Lesne, *Micrapate simplicipennis* Lesne, *Schistocerus anoboides* Waterhouse, *Sinoxylon anale* Lesne, *S. crassum dekkanense* Lesne, *Tropideres secures* Boheman, *Xylodectes ornatus* Lesne, *Xylothrips flavipes* IIIiger
	Brenthidae: *Caenorycho desplanicollis* Walker, *Cyphagogus westwoodi* Parry, *Opisthenopluscavus* Walker
	Buprestiae: *Anthaxia acutipennis* Thery
	Buprestidae: *Abasei* Thery, *Belionota prasina* Thunberg, *Sphenoptera andamanensis* Waterhouse
	Cerambycidae: *Aeolesthes holosericea* Fab., *Aesopida malasiaca* Thomson, *Ceresium leucosticticum* White, *Coptops aedifactor* Fab., *C. leucostictica* White, *C. pascoei* Gahan, *Derelus volvulus* Fab., *Dihammus griseoplagiatus* Breuning, *D. longiscapus* Gahan, *D. punctifrons* Gahan, *D. cinereus* Fab., *Epepeote sgardneri* Breuning, *Exocentrus alboguttatus* Fisher, *E. dalbergiae* Fisher, *Gleneamulti guttata* Guerin, *G. vaga* Thomson, *Macrotoma spinosa* Fab., *Mesosa indica* Breuning, *Monochamus bimaculatus* Gahan, *Palimna annulata* Olivier, *P. annulatanebulosa* Breuning, *Plocaederus obesus* Gahan, *Ropica rufescens* Pic, *Stromatium barbatum* Fab.

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Curculionidae: *Camptorrhinus affinis* Faust, *C. dorsalis* Boisduval, *C. scrobicollis* Faust, *Mecistocerus fluctiger* Faust, *Osphilia odinae* Marshall *Rhadino pusbutae* Marshall
	Eucnemidae: *Fornax vestitus* Fleutiaus
	Lymexylonidae: *Atractocerus reversus* Walker
	Mordellidae: *Glipa tricolor* Wiedmann
	Platypodidae: *Crossotarsus bonvouloiri* Chapuis, *C. fractus* Sampson, *C. minax* Walker, *C. saundersi* Chapuis, *C. saundersisubmontanus* Beeson, *C. squamulatus* Chapuis, *C. squamulatus squamuloides* Beeson, *Platypus cupulatus* Chapuis, *P. forfex* Beeson, *P. latifinis* Walker, *P. rectangulatus* Sampson, *P. secretus* Sampson, *P. solidus* Walker
	Ptinidae: *Ptilinus binodulus* Motschoulsky
	Scolytidae: *Xyleborus andrewsi* Blandford, *X. fornicatus* Eichhoff,*X. interjectus* Blanford, *X. laticollis* Blandford, *X. minor* Stebbing, *X. noxius* Sampson, *X. parvalus* Eichhoff, *X. semigranosus* Blandford, *X. shoreae* Stebbing, *X. similis* Ferrari, *X. sordicauda* Motschoulsky, *X. testaceus* Walker
Lophopetalum wightianum	**Platypodidae**: *Platypus andrewesi* Strohm
Leucaena leucocephala	**Bostrychidae**: *H. aequalis* Waterhouse, *S. anale* Lesne, *S. atratum* Lesne
	Scolytidae: *Xyleborus* sp.
Linociera malaharica	–
Machilus sp.	**Bostrychidae**: *Bostrychopsis parallela* Lesne, *Heterobostrychus hamatipennis* Lesne
	Cerambycidae: *Anaches dorsalis* Pascoe
	Curculionidae: *Dryophthoroides parvungulis* Marshall, *Rhadinomerus diversipes* Marshall, *R. granulicollis* Faust, *R. machili* Marshall
	Platypodidae: *Crossotarsus cinnamomi* Beeson, *C. saundersi* Chapuis, *Scolytoplatypus pubscens* Hagedorn, *S. raja* Blandford, *S. saxeseni* Ratzburg, *S. tegalensis* Eggers
Maesopsis eminii	–
Mangifera indica	**Anodiidae**: *Gastrallus birmanicus insulcatus* Pic, *Basitropis nitidicutis* Jekel, *Eucorynus crassicornis* Fab.
	Anthribidae: *Ozotomerus maculosus* Perroud, *Phaeochrotescinero maculatus* Motschoulsky
	Bostrychidae: *Bostrychopsis parallela* Lesne, *Dinoderus bifoveolatus* Wollaton, *D. brevis* Horn, *Heterobostrychus aequalis* Waterhouse, *H. hamatipennis* Lesne, *H. pileatus* Lesne, *Lyctus africanus* Lesne, *L. brunneus* Stephens, *Minthea rugicollis* Walker, *Parabostrychus elongates* Lesne, *Rhizopertha dominica* Fab., *Schistoceros*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	anobioides Waterhouse, *Sinoxylon anale* Lesne, *S. atratum kohlarianum* Lesne, *S. crassum crassum* Lesne, *S. crassum dekkanense* Lesne, *S. indicum* Lesne, *S. oleare* Lesne, *Xylopsocus capucinus* Fab., *Xylothrips flavipes* IIIiger
	Brenthdae: *Opistheno puscavus* Walker
	Buprestidae: *Belinota prasine* Thunberg
	Cerambycidae: *B. rubus* Linnaeus, *Batocera rufomaculata* De Geer, *Camptocnema lateralis* White, *Clyzomedus transversefasciatus* Breuning, *Dihammus griseoplagiatus* Breuning, *Distenia dravidiana* Gahan, *Glenea multiguttata* Guerin, *Macrotoma crenata* Fab., *Olenecampus bilobus* Fab., *Pharsalia proxima* Gahan, *P. proxima var intermedia* Heller, *Plocaederus obesus* Gahan, *P. pedestris* White, *P. ruficornis* Aurivillius, *Pseudanaesthetis languna* Pic, *Pterolophia occidentalis* Schwarzer, *Stromatium barbatum* Fab., *Xylotrechus smei* Laporte & Gory
	Curculionidae: *Mecistocerus fluctiger* Faust, *Phaenomerus sundevalli* Bohrman
	Lyctidae: *L. africanus* Lesne
	Mordellidae: *Mordellistena glipodes* Blair
	Platypodidae: *Platypus solidus* Walker
	Scolytidae*:* *Xyleborus* sp., *Crossotarsus minax* Walker, *C. saundersi* Chapuis, *C. saundersi submontanus* Beeson, *Platypus latifinus* Walker, *P. solidus* Walker, *P. uncinatus* Bland*, Xyleborus andrewsi* Blandford, *X. discolor* Blandford, *X. haberkorni Eggers*, *X. lantanae* Eggers, *X. noxius* Sampson, *X. semigranosus* Blandford, *X. similis* Ferrari *(syn. X. submarginatus* Blandford), *X. testaceus* Walker *(syn. X. kraatzi* Eichhoff), *Xyleborus* sp.
Mastixia arborea	–
Melia azedarach	**Bostrychidae**: *Sinoxylon anale* Lesne
	Cerambycidae: *Melamauster chinensis* Forster
	Platypodidae: *Crossotarsus saundersi* Chapuis, *C. squamulatus squamuloides* Beeson
Michelia champaka	**Anthribidae**: *Exechesops (Zygaenodes molitor)* Jordan
	Brenthidae: *Baryrrhynchus miles* Boheman
	Cerambycidae: *Pothyne distincta* Breuning, *Dihammus* sp., *Stromatium barbatum* Fab.
	Curculionidae: *Acicnemis bauhinae* Marshall, *Astycus lateralis* Fab., *Exillis asper* Jordan, *Gibber callistus* Jordan, *Melanopsacus nanellus* Jordan, *Rhaphitropis cosmia* Jordan, *R. incanus* Jordan, *Tropideres luteago* Jordan
	Lyctidae: *L. africanus* Lesne, *Lyctus brunneus* Stephens, *P. persimilis* Gahan, *Pterolophia macromorata* Breuning

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Platypodidae: *Diapus bruchus* Beeson, *D. spatulifer* Beeson
	Scolytidae: *Hyorrhynchus samsinghensis* Beeson, *Uncifer myodes* Jordan, *Xyleborus lantanae* Eggers, *X. mus* Eggers
Mitragyna parvifolia	**Anthribidae**: *Dendrotrogus augustipennis* Jordan
Palaquium elipticum	**Scolytidae**: *Scolytomimus assamensis* Schel.
Pithecolibium dulce	**Cerambycidae**: *Celosterna scrabrator* Fab.
	Lyctidae: *L. africanus* Lesne, *Trogoxylon spinifrons* Lesne
P. saman	**Cerambycidae**: *Pterolophia andamanica* Breuning, *P. gardeneriana* Breuning, *Platypus suffodiens* Sampson
	Lyctidae: *L. africanus* Lesne
Polyalthia fragrans	**Platypodidae**: *Platypus indicus* Strohmeyer, *P. latifinis* Walker, *P. solidus* Walker
	Scolytidae: *Xyleborus semigranosus* Blandford
Protium sp.	**Brenthidae**: *Cyphagogus westwoodi* Parry
	Bupretidae: *Lampra magnifera* Kerremans
	Cerambycidae: *Monochammus bimaculatus* Gahan, *Plocaederus obesus* Gahan
	Platypodidae: *Crossotarsus fractus* Sampson
Pterocarpous dalbergiodes	**Cerambycidae**: *Dihammus admixtus* Gahan, *Xenolea tomentosa* Pascoe, *Xylotrechus buqueti* Laporte & Gory
	Curculionidae: *Sipalus hypocrite* Boheman
	Platypodidae: *Crossotarsus andamamanus* Beeson, *C. latelunatus* Beeson, *C. saundersi* Chapuis, *C. verelunatus* Beeson, *Xyleborus adumbrates* Blandford, *X. andamanensis* Blandford, *X. (Progenius) bidentatus* Eichhoff, *X. (Progenius) brevidentatus* Eggers, *X. cognatus* Blandford, *X. incurvus* Eggers, *X. interjectus* Blandford, *X. niligirensis* Hagedorn, *X. noxius* Sampson, *X. (Eccoptopterus) sexspinosus* Motschulsky, *X. similis* Ferrari, *X. testaceus* Walker, *X. vicarious* Eichhoff
P. marsupium	**Anobiidae/Ptinidae**: *Gastrallus birmanicus insulates* Pic
	Bostrychidae: *S. anale* Lesne, *S. capillatum* Lesne
	Buprestidae: *Chrysobothris* sp., *C. saundersi* Chapuis
	Cerambycidae: *Aeolesthes holosericea* Fab., *Cacia cretifera* Hope, *Clytocera chionospila* Gahan, *Derolus volvulus* Fab., *Diorthus sericeus* Gardener, *Glenea multiguttata* Guerin, *Pterolophia occidentalis* Schwarzer, *Stromatium barbatum* Fab., *Xylotrechus smei* Laporte & Gory, *X. subscutellatus* Chevrolat
	Curculionidae: *Mecistocerus fluctiger* Faust, *Litocerus philippinensis crucicollis* Jordan, *Xenocerus rectilineatus* Jordan, *Xylinades beesoni* Jordan
	Lyctidae: *L. africanus* Lesne

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Platypodidae: *Crossotarsus minax*, *Rhadinopus buteae* Marshall, *S. crassum* Lesne, *S. crassum crassum* Lesne, *S. crassum dekkanense* Lesne, *S. indicum* Lesne, *S. oleare* Lesne
	Scolytidae: *Xyleborus exiguus* Walker, *X. interjectus* Blandford, *X. noxious* Sampson, *X. similis* Ferrari (syn. *X. submarginatus)* Blandford, *X. testaceus* Walker (syn. *X. kraatzi* Eichhoff), *Xylocisto rtilicornis* Lesne
Pterygota alata	–
Santalum album	**Brenthidae**: *Cero bates sexsulcatus* Motschoulsky
	Bostrychidae: *Heterobostrychus pileatus* Lesne, *S. atratum atratum* Lesne, *Xylopsocus capucinus* Fab.
	Lyctidae: *L. africanus* Lesne, *S. anale* Lesne
Shorea robusta	**Bostrychidae**: *Dinoderusbrevis* Hom., *Dinoderus minutus* abricius, *Dinoderue ocellaris* Stephens, *Heterobostrychus aequalis* Waterhouse, *H. hamatipennis* Lesne, *H. pileatus* Lesne, *H. unicornis* Lesne, *Lyctoxywn beesonianum* Lesne, *Lyctus africanus* Lesne, *Rhizopertha dominica* Fabrioius, *R. dominica granulipennis* Lesne, *Schistoceros anobioides* Waterhouse, *Sinoxylon anale* Lesne, *S. atratum* Lesne, *S. atratum atratum* Lesne, *S. atratum kohlarianum* Lesne, *S. capillatum* Lesne, *S. crassum* Lesne, *S. crassum crassum* Lesne, *S. crassum dekkanense* Lesne, *S. pygmaeum* Lesne, *Trogoxylon auriculatum* Lesne, *T. spinifrons* Lesne, *Xylocis tortilicornis* Lesne, *Xylodectes ornatus* Lesne, *Xylopsocus cupucinus* Fab., *Xylothrips flavipes* Illiger
	Brenthidae: *Allaeometrus breviceps* Senna, *Allaeometrus deformis* Kleine, *Cyphagogus buccatus* Kleine, *Higonius crux* Olliff, *Microtrachelizus beneficus* Kleine, *Opisthenoplus cavus* Walker, *Suborychodes intermedius* Kleine
	Buprestidae: *Acmaeodera gardneri* Obenberger, *A. interrupta* Kerremans, *A. stictipennis* Castelnau & Gory, *Agrilus beesoni* Obenberger, *Catoxantha bicolor* Fab., *Chrysobothris andamana* Kerremans, *C. beesoni* Obenberger, *C. indica* Castelnau & Gory, *Chrueobothris sexnotata* Gory, *Jlelanophila coriacea* Kerremans, *Psiloptera cupreoepiendens* Saunders, *P. fastuosa* Fab., *P. viridans* Kerremans
	Cerambycidae: *Acomihophorue setrtuicornis* Olivier, *Aeolesthee holosericea* Fab., *Anaqelasta apicalis* Pic, *Batocera rufornaculata* De Geer, *Cacia cretifera* Hope, *Ceresium nilgiriense* Gahan, *C. zeylanicurn* White, *Chlorophorus annularis* Fab., *C. amllifer* Heller, *C. hederatus* Heller, *C. shoreae* Gardner, *Clyzornedus tramsoerseiasciatus* Breuning, *Coptops aedifiicator* Fab., *C. leucostictica* White, *C. lichenea* Pascoe, *Demonax ascendens* Pasooe, *Derolus volvulus* Fab., *Dioleqes*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	pauper Pascoe, *Diastocera wallichi* Hope, *Diorthus cinereus* Fab., *Epipedocera zona* Chevrolat, *Euryphagus lund,i* Fab., *Glenea rnuitiguttata* Guerin, *Gnatholea simplex* Gahan, *Hoplocerarnbyx spinicornis* Newman
	Cuculionidae: *Camptorrhinus albizziae* Marshall, *C. scrobicollis* Faust, *Conarthrus jansoni* Wollaston, *Himatinum asperum* Marshall, *Mecistocerus jhwtiger* Faust, *Phaenomerue brevrostris* Marshall, *Phaenomerus sundevalli* Boheman, *Rhadinomerus diversipes* Marshall, *Rhadinomerus subfasciatus* Marshall
	Eucnemidae/Melasidae: *Dendrocharis intermedia* Fleutiaux
	Lyemxylonidae: *Atractocerue emorqinatus* Castelnau
	Mordellidae: *Mordellistena daturae* Blair
	Platypodidae: *Crossotarsus bonvouloiri* Chapuis, *C. saundersi* Chapuis, *C. saundersi submontanus* Beeson, *Diaoaous furtivus* Sampson, *Diapus quinquespinatus* Chapuis, *Platypus oavus* Strohmeyer, *P. cupulatus* Chapuis, *P. cupulifer* Wichmann, *P. curtatus* Sampson, *P. ourtus* Chapuis, *P. perrisi* Chapuis, *P. pilifrons* Chapuis, *P. solidus* Walker, *P. uncinatus* Blandford
	Scolytidae: *Cryphalus mangiferae* Stebbing, *C. ptoxyleborus turbineus* Sampson, *Sphaerotrypes globulus* Blandford, *S. siwalikensis* Stebbing, *Tamnurgides corticis* Beeson, *T. parvus* Beeson, *Ifebbia pabo* Sampson, *Xyleborus alpha* Sampson, *X. andrewesi* Blandford, *X. aplanatus* Wichmann, *X. bicolor* Blandford, *X. dilatatus* Eichhoff, *X. elegans* Sampson, *X. glabratus* Eichhoff, *X. haberkomi* Eggers, *X. interjectus* Blandford, *X. laticollis* Blandford, *X. maJor* Stebbing, *X. minor* Stebbing, *X. noxius* Sampson, *X. patvulus* Eichhoff, *X. perparvus* Sampson, *X. recidens* Sampson, *X. schlichi* Stebbing, *X. semigranosus* Blandford, *X. sexpinosus* Motschoulsky, *X. shoreae* Stebbing, *X. similis* Ferrari , *X. testaceus* Walker , *X. turbincus* Sampson, *X.ndulatus* Sampson
Simarouba glauca	–
Sterculia urens	**Bostrychidae**: *Dinoderus ocellaris* Stephens
	Cerambycidae: *Batocera* sp., *Plocaederus obesus* Gahan
Stereospermum sp.	**Scolytidae**: *Xyleborus incurcus* Eggers, *X. sordicauda* Motschoulsky, *X. testaceus* Walker
Swietenia mahagoni	**Bostrychidae**: *Xylocis tortilicornis* Lesne, *Xylopeocus capucinus* Fab.
	Lyctidae: *Lyctus africanus* Lesne, *Minthea rugicollis* Walker
	Scolytidae: *Cnestus magnus* Sampson, *Scolytoplatypus brahma* Blandford, Webbia *canalifer* Schedl, *Xyleborus discolor* Blandford, *X. duplicatus* Schedl, *X. gravidus*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Blandford, *X. mancus* Blandford, *X. origerus Blanford*, *X. morstatti* Hagedorn, *X. philippinensis* Eichhoff
Syzygium cuminii	**Bostrychidae**: *S. anale* Lesne
	Cerambycidae: *Batocera rufomaculata* De Geer
	Platypodidae: *P. solidus* Walker
	Scolytidae: *Xyleborus* sp., *Sphaerotrypes* sp.
Tamarindus indica	–
Tecomelia undulata	–
Tectona grandis	**Anobiidae**: *Gilibium* sp.
	Anthribidae: *Acorynu slabidus* Jordan, *Tropideres bolinus* Jordan, *T. luteago* Jordan*, T. notabilis* Jordan*, T. securus* Boheman
	Bostrychidae: *Dinoderus brevis* Horn, *D. minutus* Fab., *D. ocellaris* Stephens, *Heterobostrychus aequalis* Waterhouse, *Lyctus africanus* Lesne, *Minthea rugicollis* Walker, *Schistocerus anobiodes* Waterhouse, *S. anale* Lesne, *S. crissum* Lesne sub, sp. *Dekkanense* Lesne, *S. cucumella* Lesne, *S. parviclava* Lesne, *S. pygmacum* Lesne, *Trogoxylonspini frons* Lesne, *Xylion bifer* Lesne, *Xylocistortili cornis* Lesne, *Xylopsocus capucinus* Fab.
	Brenthidae: *Araiorrhinus beesoni* Kleine, *Cyphagogus buccatus* Kleine, *C. corporaali* Kleine, *Higonius crux* Olliff, *Trachelizus bisulcatus* Fab.
	Cerambycidae: *Aeolesthe sholoserica* Fab., *Apriona swainsoni* Hope, *Ceresium leucosticticum* White, *Chlorophorus annularis* Fab., *Clytus minutus* Gardner, *Dihammus elongatus* Breuning, *D. gardneri* Breuning, *D. punctifrons* Gahan, *D. rusticator* Fab., *Gelonaetha hirta* Fairnaire, *Gleneaga lathea* Thomson, *G. Indiana* Thomson, *G. vaga* Thomson, *Niphona malaccensis* Breuning, *Ostedes pauperata* Pascoe, *Pterolophiaper similis* Gahan, *P. transversefasciata* Breuning, *P. tubercula* Breuning, *P. tuberculata* Breuning var. subobsoleta Breuning, *Stromatium barbatum* Fab., *Xylotrechus buqueti* Laporte & Gory, *X. carinifrons* Laporte & Gory, *X. quadripes* Chevrolat, *X. smei* Laporte & Gory, *Xylotrechus subscutellatus* Chevrolat
	Platypodidae: *Crossotarsus emorsus* Beeson, *C. minax* Walker, *C. saundersi* Chapuis, *C. squamulatus* Chapuis, *Diapus quinquespintus* Chapuis, *Platypus cupulatus* Chapuisn, *P. errans* Sampson, *P. solidus Walker*, *Platypus* sp.
	Scolytidae: *Xyleborus andrewsi* Blandford, *X. burmanicus* Beeson, *X. butamali* Beeson, *X. fallax* Eichhoff, *X. fornicatus* Eichhoff, *X. gravidus* Blandford, *X. hagdorni* Stebbing, *X. incurvus* Egger, *X. interjectus* Beeson, *X. intextus* Beeson, *X. minor* Stebbing, *X. morigerus* Blandford, *X. noxius* Sampson, *X. parvulus*

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Eichhoff, *X. phillippinensis* Eichhoff, *X. semigranosus* Blanford, *X. sexpinosus* Motschulsky, *X. similis* Ferrari, *X. sordicauda* Motschulsky, *X. subsimilis* Eggers, *X. testaceus* Walker, *X. velatus* Sampson
Terminalia arjuna	**Anthribidae**: *Caranistesa boreus* Jordan, *C. variegatus* Boheman
	Bostrychidae: *S. anale* Lesne, *S. atratum atratum* Lesne, *S. crassum crassum* Lesne, *S. crassum dekkanense* Lesne
	Buprestidae: *Sphenoptera konbirensis* Kerramans
	Lyctidae: *L. africanus* Lesne
	Platypodidae: *Crossotarsus minax* Walker
Terminalia bellerica	**Anobiidae**: *Ptilinus binodulus* Motschulsky
	Anthribidae: *Mecocerusallectus elegans* Jordan, *Tropideres notabilis* Jordan
	Bostrychidae: *Dinoderus gardenri* Lesne, *D. minutus* Fab., *Hetrobostrychus aequelis* Waterhouse, *H. hamatipennis* Lense, *H. pileatus* Lesne, *Lyctoxylon japonum* Reitter, *Lyctus africanus* Lesne, *L.brunneus* Stephens, *L. malyanus* Lesne, *Micrapate simplicipennis* Lesne, *Minthea rugicollis* Walker, *Sinoxylon anale* Lesne, *S. atratum atratum* Lesne, *S. atratum kohlarianum* Lesne, *S. capillatum* Lesne, *S. conegerum* Gerstacker, *S. crissum crissum* Lesne, *S. crassum dekkanenense* Lesne, *S. pygamaem* Lesne, Trogoxylon *spinifrons* Lesne, *Xylodectes ornatus* Lesne, *Xylopsocus capucinus* Fab., *Xylothrips flavipes* IIIiger
	Brenthidae: *Baryrrhycnhus miles* Boheman, *Caenorychodes planicollis* Walker, *Cyphagogus westwoodi* Parry, *Opisthenoplus cavus* Walker, *O. fascinotus* Kleine
	Buprestridae: *Belionota prasine* Thunberg
	Brenthidae: *Sphenoptera konbirensis* Kerremans
	Cerambycidae: *Aeolesthes holoserica* Fab., *Coptops aedificator* Fab., *C. annulipes* Gahan, *C. lichenea* Pascoe, *Dihammus griseoplagiatus* Breuning, *D. punctifrons* Gahan, *Exocentrus terminaliae* Fisher, *Margites modicus* Gahan, *Monochamus bimaculatus* Gahan, *Olenecamptus indianus* Thomson, *Paripocregyes fascovittatus* Breuning, *Pharsalia intermedia* Heller, *P. proxima* Gahan, *Pterolophia* sp., *Stromatium barbatum* Fab.
	Curculionidae: *Cossonus binodosus* Marshall, *Mecistocerus fluctiger* Faust
	Curculionidae: *Mecobaris terminaliae* Marshall, *Phaenomerus sundevali* Boheman, *Sipalis hypocrite* Boheman
	Platypodidae: *Crossotarsus bonvouloiri* Chapuis, *C. minax* Walker, *C. saundersi* Chapuis, *C. saundersi submintanus* Beeson, *Diapusquinqu espinatus* Chapuis,

(continued)

Table 14.3 (continued)

Timber species	Insect pests
	Platypus cupulatus Chapuis, *P. latifinis* Walker, *P. secretus* Sampson, *P. solidus*Walker, *P. uncinatus* Blandford
	Scolytidae: *Thamnurgides indicus* Eggers, *T. opacifrons* Beeson, *Xyleborus bicolor* Blandford, *X. interjectus* Bandford, *X. minor* Stebbing, *X. noxius* Sampson, *X. shoreae* Stebbing, *X. similis* Ferrari *(syn. X. submarginatus* Blandford), *X. testaceus* Walker
Terminalia chebula	**Bostrychidae**: *Sinoxylon anale* Lesne, *S. crassum* Lesne, *S. oleare* Lesne
	Buprestidae: *Opisthenoplus cavus* Walker, *O. fascinatus* Kleine, *Anthaxia sericata* Thery
	Cerambycidae: *Margites modicus* Gahan
	Curculionidae: *Rhadinomerus diversipes* Marshall, *R. subfasciatus* Marshall
	Scolytidae: *Xyleborus shoreae* Stebbing, *X. sordicauda* Motschulsky, *X. testaceus* Walker, *Xyleborus* sp.
Tetromeles nudiflora	**Platypodidae**: *Platypus solidus* Walker
Toona celiata	**Curculionidae**: *Pagiophloeus longiclavis* Marshl
Trewia nudiflora	**Bostrychidae**: *Micrapate simplicipennis* Lesne, *Minthea rugicolis* Walker, *Sinoxylon atratum atratum* Lesne
	Cerambycidae: *Exocentrus dalbergiae* Fisher, *Pterolophia servilis* Breuning, *Stromatium barbatum* Fab.
Vateria indica	**Bostrychidae**: *Sinoxylon anale* Lesne, *S. conigerum* Lesne, *Heterobostrychus aequalis* Waterhouse, *Xylothrips flavipes* Illiger
	Platypodidae: *Platypus andrewesi* Strohm, *P. solidus* Walker, *Crosso tarsussaundersi* Chap, *Diacavusas samensis* Br.
	Scolytidae: *Scolytomimusa assamensis* Schl., *Sphaerotrypes* sp., *Xyleborus similis* Ferr., *X. interjectus* Bland
Vitex leucoxylon	–
Wrightia tinctoria	**Bostrychidae**: *Lyctus africanus*-Lesne, *Minthea rugicollis* Walker, *Sinoxylon* sp.
	Cerambycidae: *Coptops aedificator* Fab.
	Curculionidae: *Mecistocerus fluctiger* Faust
	Scolytidae: *Dryoco etessp, Xyleborus noxius* Sampson, *X. semigranosus* Blandford
Zanthoxylum ovalifolium	–
Z. rhetsa	**Cerambycidae**: *Glenea indiona* Thomson, *G. homonospila* Thomson, *Neocallia pubescens* Fischer
	Scolytidae: *Xyleborus interjectus* Bland, *X. noxius* Sampson, *X. similis* Ferr

Source: Bhasin and Roonwal (1954), Mathur and Singh (1960a, b, c, d), Mathur and Singh (1961a, b) were found common in many timber species used in untreated raw material and finished products in handicraft, furniture, and packing case industries.

Innovative work was undertaken on the economic importance of different Coleopterous insects on Indian timbers by Stebbing (1914). The biology of some of these important borers was examined and reported by Beeson et al (1936) in his book on the Indian Forest records. Stebbing (1914) work was later abridged by Beeson (1941) in his standard work on the ecology and control of the forest insects of the Indian sub-region. Extensive survey was undertaken in various Government Timber Depots of Kerala, making observations, collections, identification, and documentation of over 50 species of Coleopterous borers from these timber depots (George, 1982). Most of these coleopterous borers belonged to the families Cerambycidae, Bostrychidae, Lyctidae, Platypodidae, Scolytidae, and Curculionidae. Some species belonging to the families Anthribidae and Brentidae were also recorded during the study (Booth et al., 1990).

All the insect pests collected on the traditional, alternate/plantation, imported and exotics timbers presently being used and recommended for use, for the handicraft, furniture, and packing case industries were documented. This documentation of the insect pests was undertaken on all the timbers used both as a raw material and as a finished product, in the handicraft, furniture, and packing case industries. Available literature on the diversity of insect borers damaging the above timber species, in the felling sites and under storage is listed in Table 14.3.

14.4.1 Insect Infestation in Wood Carving or Statue Making

Carved images are usually created using half girth of a timber log usually with sap and heartwood. The inner half girth was used as the back of the carved image and the curved outer half or semi-circle of the bole was used as the portion for carving. The event of more sapwood being present on the outer half of the carved portion (Fig. 14.1a, b) caused many wood vessels being open/exposed for bostrychids viz. *Heterobostrychus aequalis* and *Sinoxylon anale*. The rough surface or unpolished carved product and the delay to sand and polish the carved material in the handicraft and furniture industry make it further susceptible to Lyctid and Bostrychid attack (Muthukrishnan et al., 2002). The godowns containing insect borer-infested handicraft and furniture finished products were found to be a breeding ground for both Lyctid and Bostrychid beetles' infestations (Fig. 14.2a, b). Timely detection and isolation of borer-infested material and preservative treatment is very essential to save these finished handicraft and furniture products from future destruction and spread of these timber pests to other uninfected finished handicraft and furniture products (Muthukrishnan & Remadevi, 2017). Also, timely treatment and polishing handicraft and furniture products prior to insect attack made the product immune to fresh attack and could prevent seasonal re-absorption of moisture required for larval development. The use of linseed oil for polishing was observed to give a higher protection against moisture and attained moisture curbing properties (Badoni et al., 1990). The alternate plantation timber found suitable for handicraft and furniture

Fig. 14.1 (**a**, **b**) Sapwood wood of *Dalbergia sissoo* (Rose wood) included in fabricating handicraft and furniture products

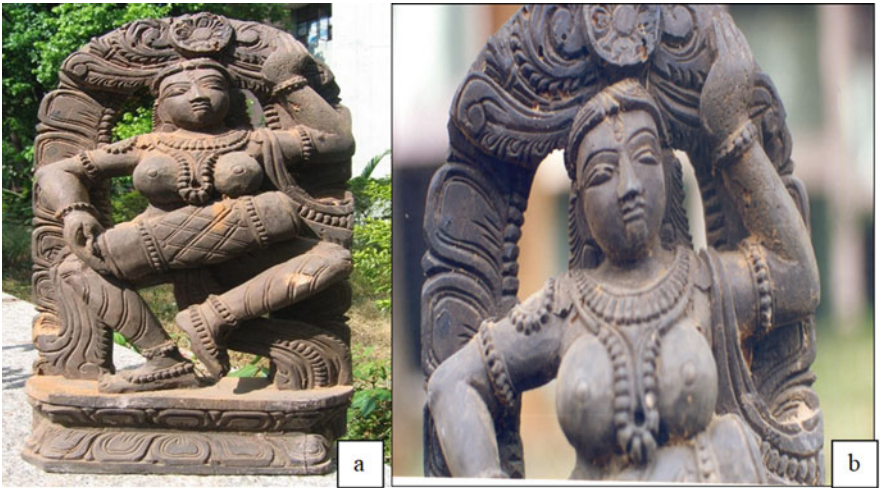


Fig. 14.2 (**a**, **b**) Wood sculpture carved out of *Mangifera indica* (Mango wood) infested by *Lyctus africanus* and *Sinoxylon* sp.

Fig. 14.3 (**a**) Packing cases fabricated with untreated *Hevea brasiliensis* (Rubber wood) and (**b**) untreated *Hevea brasiliensis* (Rubber wood) pallet heavily infested by *Sinoxylon* sp.

products is *Hevea brasiliensis* (Krishna Rao et al., 1993). This untreated timber was found to be highly susceptible to heavy insect borers (Fig. 14.3a, b). *Sinoxylon anale* was also observed to cause severe economic loss (Gnanaharan et al., 1983) and *L. africanus*.

14.4.2 Inlay/Relief or Patch-Work

Earlier the inlay-work, relief-work, or patch-work was done, using decorative veneers of different timber species with different colors pasted onto solid wood base namely, *Dalbergia latifolia*—Rosewood. Presently, this same inlay-work/relief-work or patch-work is being created using the same decorative veneers of different timber species of different colors using untreated one-sided teak (O.S.T) or untreated commercial plywood or block wood as the base material, this in return has led to the infestation by powder post beetles mostly *L. africanus*, causing economic loss to the artisan and buyer (Muthukrishnan et al., 2002). The different colorful decorative veneers of different timbers used in the inlay-work/relief-work or patch-work were *Adina cordifolia, Artocarpus integrifolia, Diospyros ebenum, Eriodendronan fractuosum, Ficus religiosa, Grevillea robusta, Michelia champaka, Pterocarpus dalbergiodes, Syzygium cuminii, Swietenia mahagoni, Tamarindus* *indica, Terminalia arjuna, Terminalia chebula,* etc., which were pasted to the plywood as base material and were also found susceptible to different insect borers.

14.4.3 Wood-Turning or Toy-Making

Wood-turning or toy-making industries were found using lathe machines for turning toys and other handicraft and furniture products using an array of plantation, traditional, alternate, exotic timber species. *Wrightia tinctoria* as a raw material with bark was found infested with *Platypus s*p., *Xyleborus* sp., and *Lyctus africanus*. *Alstonia scolaris* and *Wrightia tinctoria* were found to be very susceptible to *Sinoxylon* sp*.,* (Fig. 14.4), and *Heterobostrychus aequalis*. Another timber used for turning in the toy industry, *A. cordifolia* as a raw material was found susceptible to *H. aequalis*, *S. anale*, *Platypus solidus,* and *Xyleborus* sp. Alternate timbers such as *Acacia auriculaeformis, Eucalyptus camaldulensis, Eucalyptus tereticornis, Maeopsis eminii,* and *Swietenia mahogany* are also recommended as alternate for turning purposes (Kumar et al., 1995). Sapwood of *A. auriculaeformis* was found to be attacked by *L. africanus* and *Minthea rugicollis.* The sapwood of *Eucalyptus camaldulensis, E. tereticornis,* and *Leucaena leucocephala* used for pulp, paper production, and other purposes were found to be destroyed in the timber depots in varying degrees by powder post beetles *Sinoxylon* spp. and *Heterobostrychus aequalis* (Fig. 14.5a, b).

Wood turnery is carried using machine lathes. The turned material was smoothened with sand paper and immediately coated with laquor dyes of different colors. This laquoring is carried out to add décor and also make the finished product immune to insect infestation. However, it is also observed that some finished toys and turnery products contained emergence holes after storage. This was probably due to attack by the insect borers deep in the raw material, prior to fabrication (Fig. 14.6a–c). Alternate timbers used in the wood-turning or toy-making industry are *Eucalyptus hybrid* and *Ficus lacor.* Raw wood material, *E. hybrid,* is found prone

Fig. 14.4 Wood of *Wrightia tinctoria* infested with the process of fumigation of borer-infested timber stacks

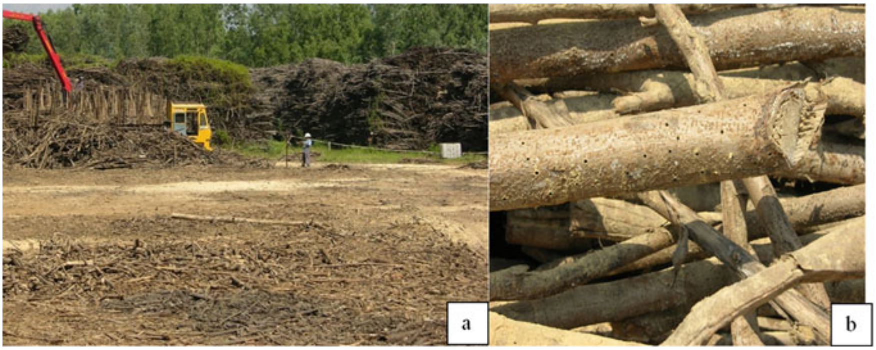


Fig. 14.5 (**a**, **b**) *Leucaena leucocephala* (Subabul) under storage showing combined infestation of *Sinoxylon* sp. and *Xyleborus* sp.

Fig. 14.6 (**a**–**c**) Finished handicraft products showing insect borer damage (*Heterobostrychus aequalis* and *Sinoxylon anale*)

to the attack by *S. anale*. *Ficus lacor* used for making rocking horses was found susceptible to *L. africanus* and *Platypus* sp. *Dalbergia latifolia* sapwood is often found infected with *Xyleborus interjectus* in the wood carving industry at Mysore. Studies have proved that the influence of pin-holes caused by ambrosia beetles definitely weakened the strength of timber (Rajput et al., 1980, 1990) and are rendered useless for decorative purposes. Sapwood portion of timbers used for making handicraft and furniture was found most susceptible to powder post beetle damage (Fig. 14.7a, b). Since traditional timbers have become scarce, six alternate handicraft and furniture plantation timbers viz. *Acacia auriculaeformis*, *Eucalyptus camaldulensis, Eucalyptus tereticornis, Leucaena leucocephala, Maesopsi seminii,*

Fig. 14.7 (**a**, **b**) Sapwood portion of handicraft product (Wall hanging) infested by *Lyctus africanus*

and *Swietenia mahogany* have been identified to be suitable for handicraft and furniture industry (Kumar et al., 1995). The raw material of these timbers is found susceptible to insect borers in varying degrees (Muthukrishnan & Remadevi, 2017).

14.4.4 Photo Frames

Picture frames have traditionally been made of wood, which is still the most common material. Wooden photo frames were usually fabricated using the timbers like *Adina cordifolia, Artocarpus integrifolia, Chloroxylon swietenia, Cordia macleodii, Diospyros ebenum, Enteriobium contorisiliquim, Polyathia fragrans, Protium serratum,* etc., some picture frames have elaborated moldings which may relate to the subject matter. Complicated older frames are often made of molded and gilded plaster over a plain wood base. In some instances, where the art in the frame is dispensable or durable, no protection may be necessary. When a picture frame is expected to be exposed to direct sunlight, or harsh lighting conditions such as fluorescent lights, UV filtering may be added to slow down the photocatalytic degradation of organic materials behind picture framing glass. Certain untreated wooden photo frames and untreated plywood, block boards were found susceptible to insect attack (Fig. 14.8).

14.5 Ecological Succession of Insect Degradation

Biological degradation by insects takes place right from the time the tree is felled and continues till its conversion to structural material/finished products and further beyond during its service life by the consumer (Purushotham, 1975). The susceptibility of different timber species varies with different species of insect borer and the

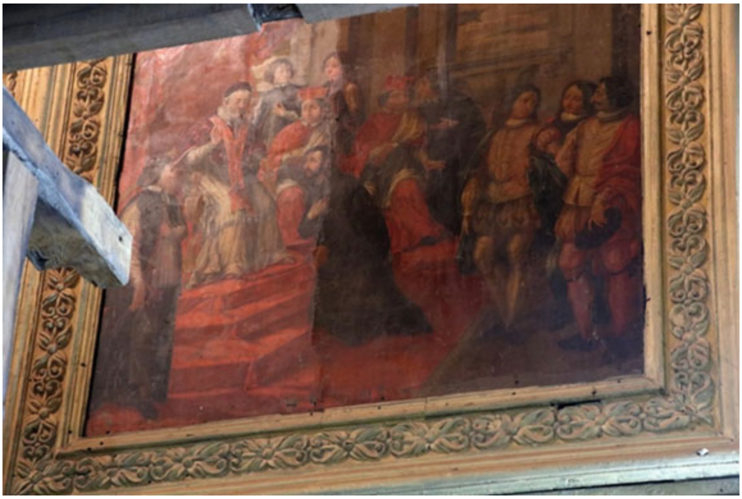


Fig. 14.8 Damage of wood frames by wood borers

Fig. 14.9 (**a**, **b**) Mixed infestation of wood borers in wooden structures

magnitude of damage depends chiefly on parameters such as starch content, climate, and locality. Starch in wood is the most preferred component by insect borers. The coleopteran insects have been observed as the most important insect borers causing damage to timber. These insect borers are found both on trees, logs, and in timber containing varying moisture content and even in dry timber (Mathur, 1961). This damage is used to start or continue after making of the finished product, or in a wooden structure of a building (Fig. 14.9a, b). Depending primarily upon the moisture gradient and other related factors in the wood, there is an ecological succession of insect borers attacking the harvested timber. Freshly felled and cut logs or planks having high moisture logs are attacked by platypodids (pin-hole borers) (Fig. 14.10a, b) and scolytids (Fig. 14.11a, b). After felling, timber is left as it is or stacked in the felling site itself for varying periods, pending transportation. When the felled logs further dry and get seasoned, the next major group of insect borers or beetles which attack and damage timber in storage are the powder-post

Fig. 14.10 (**a**, **b**) Symptoms of infestation of the platypodids

Fig. 14.11 (**a**, **b**) Symptoms of scolytid infestation

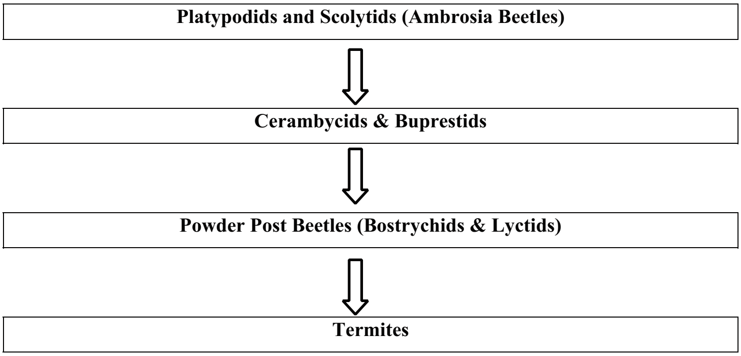
beetles (Bostrychidae and Lyctidae) (Graham, 1925). The reasons for the attack by the two families of insects was totally dependent on two conditions namely the moisture content of the timber logs, i.e., when moisture is reduced to about 30–50%. The major infestation takes place during this period. Insect borers that have already infested a log during harvesting in a forest area continue their activity during transit. Unseasoned and partially seasoned wood may have fresh infestation during transportation and storage. As much as 20–25% of wood stock is wasted due to insect

Fig. 14.12 (**a**) Symptom of cerambycid infestation in chair and (**b**) chair armrest showing the symptom of infestion by *Stromatium barbatum*

borer attacks in timber depots, sawmills, and in woodworking factories. Many times cerambycid (*Stromatium barbatum*) and bostrichid (*Sinoxylon* sp.) larvae infested trees, remain in wood, and continue to grow even after harvesting and emerge as adults in the finishing stage of wooden products (Fig. 14.12a, b). The other condition for the attack of these beetles is sapwood containing sufficient starch for the development of the larvae and it is only under this condition that adult beetles bore inside the sapwood to lay their eggs. Bostrychids being polyphagous thrive well in different timber depots containing different timber species and make the timber unfit for use.

The family Lyctidae is a major insect pest attacking dry timber, also dependent on starch for its nutrition and thrives well in sapwood with a moisture content of 10–15% and wood less than 10% moisture content is not attacked. However, higher moisture is favored for larval development (Beeson, 1941). Vessel diameter of timber was found to be a prerequisite factor for the oviposition in the case of female lyctid beetles (Altson, 1923). Vessel diameter of timber was found to be a prerequisite factor for the oviposition in the case of female lyctid beetles (Altson, 1923). Only timbers having a minimum average vessel diameter of about 60 μm are likely to be attacked by Lyctids. The reason for the above condition is that the female Lyctid beetle lays her eggs only by introducing its ovipositor measuring from 50 to 90 μm into the wood vessel of the timber. Few eggs are also laid in the lumen of wood vessels exposed by the mandibular action of the adult beetles. These tasting marks are referred to by Parkin (1934). Many handicraft and furniture timbers used were found susceptible to *Lyctus africanus*—Lesne. This Lyctid is the commonest species which is widely found and distributed throughout India. Since the emergence of Lyctids was observed throughout the year, its damage could be encountered throughout the year in the handicraft and furniture industry (Fig. 14.13a–g).

Fig. 14.13 Symptom of the infestion of *Lyctus africanus* in wood and wooden products: (**a**) sandalwood log; (**b**) stacked rubberwood; (**c**) wooden panel; (**d**) wooden cot; (**e**) laminated plywood; (**f**) patch work/inlay work handicraft (wall hanging); (**g**) untreated commercial plywood base material used for handicraft product (patch work\inlay work)



Flow chart: Succession of insects: (post harvest & storage)

14.6 Diagnosis of the Infestation of Different Insects

The insect attack on timber can be understood by the general indications shown in Table 14.4. Lyctid, bostrichid, anobid, and cerambycid attack sapwood rich in carbohydrates, starch, and soluble sugars. They are essentially polyphagous and are the most common pests in the household furniture and wardrobes, which are made of untreated plywoods and blockboards. The most economically important group of insects that attack wood in this way includes two closely related families

Table 14.4 Symptoms of infestation by a different group of insects

Sl. no	Symptom	Causative wood invader
1	Long cylindrical pellets ejecting from logs with bark on or moist debarked wood:	Platypodid beetles, e.g., *Platypus solidus*
2	Fine white powder coming out through holes from debarked wood, converted planks, doors, window frames, shutters, rafts, racks, blockboards, plywood, and furniture:	Powder post beetles, e.g., *Sinoxylon* sp., (Figs. 14.2b and 14.3b) *Lyctus* sp. (Fig. 14.2a)
3	Timber surface with holes:	
	A. Circular pin holes up to 4 mm diameter:	Ambrosia beetles (Fig. 14.10) and Scolid infestation (Fig. 14.11)
	B. Circular pinholes ca. 1.5 mm diameter:	Lyctids (Fig. 14.7)
	C. Circular shot holes ca. 6 mm:	Bostrychids (Fig. 14.9)
	D. Elliptical shot holes up to 11 mm:	Flat headed beetles (Fig. 14.9)
4	Gnawing or scratching sound from inside the wood initially, with no visible wood dust. Emergence holes with fine dust coming out on rupture of the wood:	Long horn beetle, e.g., *Stromatium barbatum* (Fig. 14.12a, b)
5	Humming sound of bees with visible big holes on the beams and rafts:	Wood wasps, e.g., *Xylocopa* sp.

viz., Lyctidae and Bostryhidae which are commonly known as powder-post beetles. The larvae of these beetles reduce timbers to a mass of very fine, talcum powder-like substance. The adults do very little damage. These insects make their presence known by exit holes. They attack dead wood almost exclusively, especially dried and cured lumber, and several generations can re-infest the same piece of wood until starch remains in the sapwood, riddled with exit holes. Beneath the surface of the infested wood are frass-filled galleries or tunnels, usually coursing along the grain of the wood. The lyctid and bostrichid beetle attacks can be diagnosed by the characteristics listed in Table 14.5.

The true powder-post beetles (Lyctidae) loosely fill their galleries with very fine powder, similar in appearance to talcum powder; the false powder-post beetles (Bostrychidae) tightly pack their galleries with a coarser boring dust, often containing small wood fragments. In a more definitive sense the term "powder-post beetles," should apply only to the lyctids, for their larvae are the only ones that produce a fine, talcum powder-like dust in their galleries. Probing or tapping the infested area of the wood will usually reveal one of the types of frass described above. In the wood structure of the building, beetle infestations occur most often in untreated hardwood cabinets, blockboards, plywood, and flooring. Lyctids attack start by depositing their eggs and are second only to termites in their destructiveness to wood and wood products, but confine their attacks to large-pored hardwoods and bamboo. The greatest lyctid beetle activity is found in wood with a moisture content of 10–20%. Lyctidae contains several genera of which the genera, *Lyctus* sp. and *Minthea* sp. are of considerable economic importance. *L. africanu*s, *L. brunneus,* and *Minthea rugicollis* are very common species found in seasoned timber. Eggs are inserted by long ovipositor of female into exposed pores or vessels on transverse or longitudinal surfaces of sapwood. Most species of timbers having vessels with minimum average diameter of about 60 μm are likely to be attacked. Wood with smaller pores and coniferous species are not attacked. Starch is the main food utilized by the larva along with certain sugars and protein. Moisture being an important factor for the development of larvae, wood with less than 10% moisture content is not attacked.

Unlike the lyctids, in most bostrychid species the head is deflexed and not visible from above, being hidden from view beneath a large thorax that gives the beetle a humpbacked appearance. They are most abundant in the tropics, they mine dead, seasoned, or cured hardwoods or hardwood furniture. Bostrychids particularly *Heterobostrychus aequalis*, *Schistocerca anoboides*, and *Sinoxylon* spp. particularly *S. anale* and *S. sudanicaum* (Fig. 14.14) and *Bostrichus unicornis* cause extensive damage to timber in service and storage. Their rate and mode of development are not uniform. The vulnerability of each species of timber to attack by these species varies and the intensity of attack depends mostly on various factors like climate, locality, time of felling, and starch content in sapwood. The other bostricids commonly known as ghoon borer viz., and *Dinoderus* spp. (*D. minutus, D. ocellaris,* and *D. brevis*) infest the Bamboos under storage, either as culms or as finished products.

Table 14.5 Distinguishing features of Lyctid and Bostrichid infestation

Lyctid attack—features (True powder-post beetles)	Bostrichid attack—features (False powder-post beetles)
Attack partially/fully seasoned timber (10–15% moisture)	Attack timber with more moisture content (30–50%)
Female inserts the ovipositor inside cuts/ exposed wood vessels (pores) to lay eggs	Female burrows into timber to lay eggs
The holes are made by emerging adults and are pinholes	The holes are made by adults to lay eggs and also while emerging. They are shot holes.
The adults are smaller and with flattened body	Adults are bigger and with cylindrical body
Galleries are almost same size and shape and loosely filled with very fine powder, similar in appearance to face powder	Galleries vary greatly in size and shape and are tightly packed with a coarser boring dust, often containing small wood fragment

Fig. 14.14 Symptom infestion of wooden product by *Sinoxylon sudanicum*

14.7 Wood Protections

Naturally durable timbers account for only 10% of the total volume of wood used in the industrial sector (Purushotham, 1975). The presence of various chemical compounds and lignin are the factors which account for the natural resistance of timbers (Wolcott, 1946, 1947; Abushama & Abdel Nur, 1973; Behr et al., 1972). Earlier studies revealed that some plantation timber species including exotics show natural resistance for more years, while some timbers showed high susceptibility to termite and fungal attack (Indra et al., 2001) *Tectona grandis* (Teak), *Shorea* sp., (Malaysian sal), *Artocarpus heterophyllus* (Jack), and *Pterocarpus dalbergioides*

(Andaman padauk) showed no damage, throughout the experimental period of 36 months against termites in the field (Muthukrishnan et al., 2003). Comparative durability of exotic timber hybrid species of young *Acacia auriculiformis* and *Acacia mangium* are more durable than mature *Hevea brasiliensis* (Rubberwood). *Acacia* hybrid was found to be the most durable timber. *A. mangium* was found to be very susceptible to termite attack (Remadevi & Muthukrishnan, 2007). Wood protection or preservation is an art through which wood can be protected against degrading agencies and its life increased 5–8 times depending upon the adversity of condition of use. Wood as a material is very durable and in sheltered environments it can last for thousands of years without sustainable changes. The saying "an ounce of prevention is better than a pound of cure" is most fitting in the case of management of wood biodeterioration.

- It is the responsibility of those who harvest, mill, or store the wood to follow appropriate preventive measures which would prevent insect attack on wood before it is used. An extremely important phase of prevention is sanitation.
- In nature and factories, beetles breed in old and dried wood, such as dead branches and limbs of trees, and material of this kind should be burned if it exists near piles of lumber. The same may be said of old lumber and other materials that are subject to infestation. Storage areas should be inspected periodically**.** Infested lumber should be burned, and pallets, stacking sticks, stakes, platforms, and shelves should be protected and sanitized against insect attack, prior to procuring fresh stocks of timber for consumption.
- The first step for purchasing timber, a thorough examination of the timber is a prerequisite to detect any active infestation. Lyctids are generally brought into factories in wood that contain their eggs or larvae. Lumber should be examined for signs of infestation. For any active infestation, borer holes and accumulating wood powder in piles near holes or on the floor below, beetles crawling on the wood or any ticking sound that is made by the feeding larvae, if detected should be rejected.
- Only a desired quantity of properly kiln or air-dried wood, or chemically treated wood (wood preservatives or insecticides) should be purchased by the consumer.
- Finished handicraft, furniture products should be immediately coated with paint, varnish, shellac, sealer, or wax, to prevent ovi-position by adult beetles. If the adults' emergence holes are found in such finished items, it may usually be assumed that the infestation began before the coating was applied.
- Infestation by lyctid beetles can be avoided merely by using only softwoods for the pallets, stacking sticks, etc.
- Green lumber can be protected against powder-post beetles by submerging it in an insecticidal cold-water emulsion. Similar protection for seasoned wood can be obtained with a solution of insecticide and deodorized kerosene. Immersion for 3 min gives protection for at least 3 years. Protection for 1 season can be obtained with only a 10-s immersion in insecticides or a 15-s dip in a 5% borax solution heated to 180 °F (82 °C). Following any of these treatments, the treated timber or

wood handicraft/furniture/packing case products can be painted or varnished after a reasonable drying period.

- The type of treatment selected for control of powder-post beetles will depend on a number of circumstances. Among them one is the size of the infested area. If the infestation is localized, the application of a toxic solution to the infested wood surface or a liquid gas volatilized under a tarpaulin may be considered. Infested furniture can be fumigated in a gas tight fumatorium. For the treatment of a large infested area, such as an entire house containing handicraft or furniture, a complete fumigation of the entire structure is the most reliable way to control the infestation. It is often difficult to locate incipient infestations. However, even with complete fumigation of a building, incomplete control of lyctid beetles occurs in about 10% of the treatments.

14.7.1 Preventive Measures

Prevention and control can be achieved by adopting (1) natural or non-chemical measures and (2) chemical measures.

1. **Natural or non-chemical measures**:
   (a) **Usage of heartwood:** Sapwood should be avoided for structural wood and other wood products as sapwood is more prone to insect attack. Heartwood of most of the timbers is resistant to borers. Partly inclusion of sapwood in the handicrafts made up of using heartwood often disliked by customers, because of its white or yellow color and also prone to powder post beetle damage.
   (b) **Safe felling period:** The safest felling period is during winter (November to March) in North India and immediately after rains in south India when most of the coleopterans do not remain on wings or are in hibernation. Procurement of raw material preferably during winter or after the rainy season and shifted at the earliest from felling site to place of fabrication/factory site.
   (c) **Debarking:** Females of longhorn borers oviposit in the bark. Debarking soon after felling along with the use of end coating of antiseptic, anti-splitting compositions with coal tar, paraffin wax, etc., will prevent ovi-position by these beetles.
   (d) **Starch depletion:** The presence of starch is compulsory for the infestation by powder post beetles. Amount of starch in sapwood depends on the species of tree, felling season, and treatment of logs after felling. High girdling of trees before felling reduces the starch content. Immersion of logs in freshwater for varying periods or continued sprinkling of water on the logs results in the depletion of starch.
   (e) **Storage:** Storage in the open is preferable to storage under shade because it reduces pin-hole borer attack. Proper hygiene in the storage areas is essential for the prevention of borer attacks. Stringent hygienic conditions to be maintained and consumption of raw material on a first come first basis and

regular inspection of godowns having raw material and finished products for diagnosing any insect infestation.

(f) **Seasoning of wood:** The process of seasoning is essentially one of removing moisture from timber. Seasoning as applied to wood is primarily a drying process. Freshly felled timber contains large quantities of moisture, the major portion of which has to be removed before the timber is fit for use for most purposes. Seasoning reduces the likelihood of mold, stain or decay; reduces weight thereby reduces transportation and handling costs; as wood dries most of its strength properties improve; strength of joints made with nails and screws is greater in dried wood than in green; and also improves finishing of wood. Low-temperature kiln drying of timber is advisable for timber used in handicrafts (Fig. 14.15a–c).

14.7.2 Prophylactic Chemical Treatments

Prophylactic treatment can be given either by spraying contact insecticides or by dipping in wood-protecting solutions. In rainy seasons it is advisable to incorporate a compatible fixative to prevent washing off of the chemical. Micro-emulsions of pyrethroid insecticides give protection from a wide range of borers and termites. Tree poisoning is a method where the tree to be felled, is treated in-situ with water-soluble insecticides and fungicides using simple pressure injection techniques. Fumigation is resorted to eradicate the existing infestation and is no cover against future infestations. Borates have low toxicity to man and are approved for interior uses of wood treatment. They protect attacks by both fungi and insects. They are the preservatives of choice for remedial treatments of wood in service. Chemical barrier is very effective in preventing the invasion by wood-boring insects. Treatment with 5% solution of borax, 0.1% sodium fluoride, 5% zinc chloride, and 50:50 solutions of creosote and fuel oil can be done by impregnation either under pressure or by open hot and cold process for the protection from timber pests. Varnishing/polishing or painting the surface and closing all fissures and holes by waxing prevent oviposition by powder post beetles and cerambycid *S. barbatum.*

14.8 Wood Preservatives

These are chemical substances, which are applied to wood to make it resistant to attack against decaying agents. Coal or Creosote, Copper and Zinc Naphthenates/Abietates, Pentachlorophenol, Benzene Hexachloride, DDT, Copper-Chrome-Arsenic (CCA) Acid Cupric-Chromate (ACC), Chromated–Zinc Chloride, Copper-Chrome-Boron are some of the important preservatives. Treatment methods include both non-pressure process and pressure process. Non-pressure processes in dry condition are by surface application and soaking treatment and in dry conditions are by sap displacement method, Boucherie process and diffusion process. In the

Fig. 14.15 Processing timber of *Wrightia tinctoria* for handicrafts (**a**) kiln drying; (**b**) stacking of wooden stakes (raw material); and (**c**) storing of handicraft parts

pressure process full cell process and empty cell process are used. The economic value of wood preservation is convincingly demonstrated by the extended service life that pressure treatment with creosote or multi-salts can impart to the original timber. Untreated railway sleepers may last 5–6 years; treated sleepers, 20–25 years; untreated transmission poles may stand for about 4–6 years; properly impregnated poles for 30 years; untreated mining timber may last for 2–3 years; treated timber up to 20 years or more; untreated timber for cooling towers may last for an average of 10 years; suitably pressure treated timber for 25–30 years (Swiderski, 1968). The preservatives used for the treatment of timber used for packing cases were Copper Chrome Boric Acid (CCB) (Fig. 14.16), Copper chrome arsenic (CCA), Cashew nut Shell Liquid or Aromine solution.

14.8.1 Surface Protection of Wood

This involves chemical modification in the surface of the wood for improving dimensional stability and photostability in wood. Modified wood has superior resistance to UV degradation, improved dimensional stability, biological resistance, and paint retention. It also helps to enhance the life of coated wood by chemical pretreatment.

Fig. 14.16 *Hevea brasiliensis* pallets dip treated with Copper Chrome Boric acid (CCB) solution prior to fabrication into packing cases

14.9 Curative Measures

- Sterilization by heat treatment in kilns at 120–150° F for 2–3 h or dipping in boiling water at 200° F for 10 min will kill all stages of borers.
- Fumigation of infested wood to control existing infestation and is no cover against future infestation. Conventionally used fumigants are methyl-bromide, sulfuryl fluoride, carbon disulfide, formaldehyde @ 400 mL per 28 m^3 of space. In the indoors, in limited area treatments, aluminum phosphide can be used for fumigation (Fig. 14.17).
- For the protection of logs at the depots, suitable insecticides can be sprayed using motorized sprayers. To affect clearing off of powder on logs for better penetration, water spray may be given a day prior to the treatment. Wood containing 0.2–0.3% boric acid equivalent (BAE) of sodium borate is also protected from powder post beetles and termites. Solid borate rods can be embedded in wood at regular intervals. Borates are good for interior applications and chemically sensitive areas. They can be used against carpenter ants, termites, and borers.

14.10 Role of Wood Protection in Conservation

India is rich in biodiversity and is one of the 12 mega biodiversity centers of the world. It occupies 2.5% of the world's land area and 1.8% of global forest area. It supports more than 15% of the human and 14% of the cattle population and therefore forests in India are under immense biotic pressure. The present forest cover is 63.7 m ha which is 19.4% of the total land area. India is essentially a bio-diversity-dependent country and the wood industry fulfills several key needs of the society (Rao, 2002). Its forests have been exploited for millennia and intensively during the past two centuries (Meena et al., 2007). The NFAP (National Forestry Action

Fig. 14.17 The process of fumigation of borer-infested timber stacks

Programme, India, Ministry of Environment & Forests, Government of India, 1998) projects the annual requirement of timber in India for housing, furniture, agriculture implements, and industrial uses to be about 64 million m^3 against a supply of 43 million m^3 (12 million m^3 from natural forests + 31 million m^3 from farm forestry and other sources). For fuel wood, which continues to be the major source of energy for rural India the projected requirement is around 201 million tons against a supply of only 95 million tons (17 million tons from forests + 78 million tons from farm forestry and other sources). Despite being bestowed with over 4000 woody species, the country is a "timber deficient country" and the gap between supply and demand is ever widening (Shashidhar & Aggarwal, 2006). There are acute shortages and phenomenal hikes in prices of conventionally preferred species of timbers like Teak, Sal, Deodar, Rosewood, Red sanders, Sandal, etc. The scenario has now become quite alarming as the productivity gap in wood biomass is far beyond the current productivity in natural forests and the expected productivity from plantation forestry. Adoption of wood preservation technologies has the potential to save approximately 2 m^3 of wood for every 3 m^3 and because of an increase in average life of timber from 5 to 15 years would save at least 5.6 m ha of forests raising the forest cover by 2% in India (Kumar, 1991). The advancements in wood protection encourage the use of secondary/fast growing/plantation timbers and these industrial plantations gradually displace wood from natural forests although the main purpose of growing such species is meant earlier to meet pulpwood demands (Kumar et al., 2004). The tree species like *Acacia auriculiformis, A. mangium, Maesopsis eminii, Eucalyptus camaldulensis, E. tereticornis, Leucaena leucocephala, Gyrocarpus americanus,* and *Swietenia mahagoni* are being utilized in furniture industry. Rubber wood is an example which is traditionally used as fuel wood finds its application in the furniture and packing case industry. Prophylactic treatments with scientific storage, conversion, seasoning, and preservative treatment of rubber wood alone meet India's timber requirement to as high as 2%. It has the potential to conserve more than 20,000 ha of rain forests. The recent development of wood polymer composites which are produced by mixing wood flour or fiber and plastics in extruders to produce a material that can be processed like a conventional plastic has the best features of wood and plastic. Wood polymer composites find application in exterior building components, railings, window profile, shutters, building profiles, automobile interiors, door panel, dashboard, trims, etc., and also in molded products. Hence production and proper use of wood form a very important part of the global level effort to conserve the tree diversity of the earth, while achieving their most economic utilization.

14.11 Conclusions

The destruction of the world's forests is a major concern in our age (John, 1989). In view of the dwindling natural forests and the logging ban in force, many countries including India have to depend more and more on "Agro-Wood" and imported wood to meet its requirements. India is importing wood and forest products to the tune of approximately US$1028 million every year (FAO, 2000). According to an International Tropical Timber Council survey, India is emerging as a major importer of tropical timber (Duncan, 2003) with the demand predicted to rise from 60 million Cu. M. in 2005 to 153 million Cu. M. in 2020, and domestic production is likely to meet only 60 million Cu. M. (Lawson & Hemery, 2007). India's annual industrial round wood imports have tripled in the last 5 years and now exceed two million m^3. The demand is expected to continue to grow and could approach ten million m^3 a year by the end of the decade (ITTO, 2004). With increasing incomes in a country that has entered the take-off stage and is poised to grow at over 9% per annum in the years ahead (Vietor, 2007), there is likely to arise still more demand for wood and wood products from the burgeoning rural populace, thereby accelerating the pressure on natural forests India's imports grew during the period of the global economic downturn, reaching 3.7 million m^3 in 2009 and rising slightly in 2010, with demand being stimulated by robust economic growth and incentives to the building industry (ITTO, 2010). Further more and more species, hitherto under-utilized, have now become necessary to be put to use and upgraded to suit different end users. The adoption of a new "National Wood Use Policy" is being advocated at many forums (Rao, 2002). To achieve this, wood science/technology interventions have now come to become very necessary. The Wood Industry as well will also be confronted with this challenge. We owe a great responsibility to our future generations and have to address this problem with a tangible and longstanding solution. As part of our commitment to intergenerational equity and Conservation of Biodiversity, we have to give serious thought for an amicable solution to these problems. The World Commission on Forests and Sustainable Development (1999) concluded, "Forests can no longer be used in the same way as they have been in the past, forest products and services must be assured through new political choices and policy decisions that ensures the survival of forests”. A report of the IUCN Working Group states that the challenge in the twenty-first century is forest resource conservation and sustainable use (Graham Bennett, 2004). Hence more conservation-oriented progressive forest policies for greening India are required for stabilization of carbon stocks in our forests and their tree diversity. These approaches need to be adopted and change with the prevailing social and economic realities of our world on local, national, and global levels.

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Basics of Wood Drying/Seasoning

15

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Contents

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_15

Abstract

Wood seasoning is one of the most important fundamental or primary processing stages for ensuring efficient utilization of wood resources as timber. The process involves reducing the moisture content of wood to a level which is in equilibrium with the atmosphere. It is also one of the most energy-intensive processing operations and has economic implications in timber products as the process has to be carried out in a controlled manner. However, the multiple benefits of seasoning in terms of quality and service life of timber products outweigh the cost and time involved in the process. The chapter deals with the fundamentals of wood seasoning, its importance in timber utilization, wood drying elements, various pre-seasoning steps and seasoning methods. The importance of seasoning schedules in controlling drying degrades has also been elaborated.

Keywords

Moisture content · Wood drying · Wood seasoning · Kiln seasoning · Drying degrades

15.1 Introduction

Wood from the freshly felled tree contains large amount of water and in many instances it can be more than the actual biomass by weight. Presence of this water is one of the major factors responsible for attracting decay organisms like insects, fungus, etc. which accelerate the degradation process. Wood is generally the most critical of all water-damaged materials as elevated moisture content can result in microbial growth and decomposition. For a wood product, it is always desirable to have a long service life which not only helps in saving wood resources but also contributes in storing carbon for a longer period which is the need of the hour in the current climate change scenario. Wood drying or seasoning plays an important role in protecting wood from biological degradation particularly fungal degradation. Wood with high moisture content provides favourable conditions for microbial

Fig. 15.1 Wood degradation due to moisture

growth which eventually leads to structural degradation of wood and complete decomposition (Fig. 15.1). Fungal growth requires the right balance of oxygen, water and temperature within the nutrient source. It is well accepted that wood having more than 20–25% moisture with respect to its dry biomass is highly susceptible for mould/fungal growth which can lead to discolouration in wood and loss in mechanical strength over a period of time.

Drying not only provides protection to wood against fungal degradation, but also imparts several favourable features to wood like improved mechanical properties, better thermal and electrical insulation properties, and increased screw and nail holding strengths, ease in transportation and handling, etc. Wood also needs to be dried in order to treat with chemical preservatives using vacuum-pressure impregnation for appropriate loadings and retention of chemicals inside wood.

However, wood needs to be dried in a specific manner in order to avoid any dimensional deformation, end cracking, surface cracking and other defects as a value addition process and is termed as wood seasoning. Any piece of wood with high moisture content when allowed to dry without any control, it tends to develop a range of defects ultimately affecting the yield of quality sawn timber. Quality drying to satisfactory gross and grade recovery levels is one of the most important challenges associated with processing of wood. In order to understand wood seasoning, knowledge of some basic concepts influencing drying process is essential.

15.1.1 Moisture Content in Wood

Moisture content in wood is defined as the ratio of mass of water present in wood to the mass of completely dried wood (in percentage). Mathematically, moisture content of wood is determined using the following equation (Eq. 15.1):

$$\mathrm{MC\%} = \frac{\text{weight of wood in green condition} - \text{ovendried weight}}{\text{ovendried weight}} \times 100 \quad (15.1)$$

The maximum moisture wood can attain depends on the anatomical structure and is the maximum amount of water possible in a piece of wood when the cell walls of structural elements of wood all completely saturated with moisture and all the cell cavities and free spaces are completely filled with water. Basic density of wood which is defined as the over dry mass with respect to swollen volume of wood is a determining factor for maximum moisture content. The maximum moisture content possible in wood with lower basic density is expected to be higher as compared to wood with higher basic density due to the availability of large volume of void spaces and cavities inside wood in low-density wood. Therefore, the maximum moisture content is inversely proportional to the basic density of wood. The density of oven-dried cell wall material is estimated to be roughly around 1.50 g/cm^3 (Walker, 2006) and the maximum moisture content (MMC) possible for a wood piece can be obtained from the following relationship (Eq. 15.2):

$$\mathrm{MMC\%} = \left[\frac{1.50 - \mathrm{BD}}{1.50 \times \mathrm{BD}}\right] \times 100 \tag{15.2}$$

where “BD” is the basic density in g/cm^3. As an example, the maximum moisture content of wood with basic density of 0.400 g/cm^3 will be about 183% whereas the same in wood with basic density of 0.750 g/cm^3 is expected to be about 67%. In general, moisture content of wood from freshly felled tree may vary depending on the season, geographical locations, position within tree and type of wood, i.e. heartwood or sapwood.

Determination of moisture content of wood/timber is an important step in deciding about the processing strategies and also in wood utilization. Several methods like oven-drying, distillation, electric resistance-based moisture measurement, capacitance-based moisture measurement, etc. All these methods have their own merits and limitations. Oven drying method is considered to be the most reliable and accurate for most of the species and has no limitations in terms of the range of moisture content that can be determined. However, it requires a laboratory set-up having an oven, has practical constraints on the size of the piece that can be tested, is time-consuming and overestimates moisture content in wood having substantial quantities of volatile extractives. The method involves drying of samples at a temperature of 100–105 °C, i.e. above the boiling point of water till the samples attain a constant weight called oven-dry weight. The moisture content can be determined using Eq. (15.1). Distillation method is a complicated process involving a closed system, requires continuous monitoring and is time-consuming. Practically, wood industry uses moisture meters for field inspection of moisture content as they provide instantaneous and reasonably accurate measurement of moisture content. The electrical resistance-based moisture meters require inserting of a pair of needles inside wood, and the electrical resistance between the needles is calibrated against the moisture content. Alternatively, moisture content in wood can be determined through dielectric constant/radio frequency principle. This type of moisture meters are completely non-destructive in nature and easy to operate. However, both these types of moisture meters are suitable for moisture content ranging from 6% to about fibre saturation point (~35% MC) and also need to be calibrated for different species. The moisture meters are extremely convenient for quality control in wood processing or wood product manufacturing units wherein large number of samples can be tested quickly (Fig. 15.2).

15.1.2 Fibre Saturation Point

It is observed that when wood is subjected to drying, though it loses moisture there is hardly any shrinkage up to certain moisture content and properties wood remain unaltered. This is linked to the manner in which moisture is attached with wood. Moisture in wood is found in two forms, i.e. free water and bound water. Free water is the moisture present in cell lumens and void spaces in liquid form whereas bound water is the moisture present in the cell walls chemically bonded with cell wall

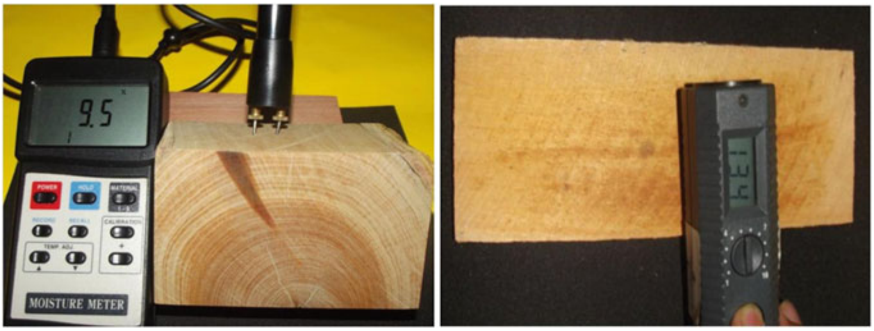

Fig. 15.2 Moisture meters for wood

elements. During drying, evaporation of the free water precedes the moisture removal from cell walls. During this stage of moisture removal, there is no change in the properties and dimensions of wood. However, as the moisture is removed from the cell walls the mechanical properties increase linearly and wood starts to shrink. The moisture content of wood at which all the free water is evaporated but the cell walls are fully saturated with bound water is called fibre saturation point (FSP). For drying operations, understanding of FSP is very important in order to control drying degrades and maintaining the quality. Also, for any vacuum-pressure impregnation of chemicals like wood preservatives, it is necessary to have empty lumens for effective penetration of chemicals. Therefore, it is prerequisite to partially dry wood at around FSP for taking up chemical impregnation. The fibre saturation has been reported to vary from 16% to 35% depending on the species and locations (Pandey & Jain, 1992).

15.1.3 Equilibrium Moisture Content

Any piece of wood, whether dried or wet, tends to attain a moisture content which is in equilibrium with the surrounding conditions in which it is kept. When dried wood is kept in humid environment for a long period, it gains moisture from the environment and moisture content rises whereas a wet piece of wood tends to lose moisture in the same environment and ultimately both the pieces of wood attain the same moisture content. When the moisture content of wood reaches a level which is in equilibrium with the environment, it is called equilibrium moisture content (EMC). EMC of wood is a function of the relative humidity and temperature of the environment. Different species of wood exhibit different EMC at a specific relative humidity and temperature condition which mainly depends on the chemical constituents, extractives content and their nature. EMC is an important parameter determining the level of moisture content to be attained in wood during drying or seasoning operation. The wood should be seasoned to a specific moisture content which is the mean of the minimum and maximum EMC of that species for a particular location where it has to be used. In Indian conditions, the average relative humidity varies from less than 40% in dry zone to more than 65% in northeast and coastal zones suggesting the desired moisture content of wood varying from 10% MC to 16% MC for furniture, doors and windows frames.

15.1.4 Swelling and Shrinkage in Wood

Swelling and shrinkage in wood with change in moisture content is one of the major impediments in wood utilization and also during processing. Repeated swelling and shrinkage leads to internal stresses in wood which result in development of cracks/surface checks and other defects which devalue wood resources. The swelling and shrinkage are also known as dimensional movement and attributes to the dimensional instability in wood. The dimensional changes take place during wood drying and during service life of wood products as a response to the fluctuating environmental conditions like relative humidity and temperature. The concept of FSP and its association with wood shrinkage has been discussed earlier and its importance in wood drying.

Swelling or shrinkage in wood does not take uniformly in all its three principal directions, i.e. longitudinal, radial and tangential (Fig. 15.3). The non-uniformity in swelling and shrinkage cannot be determined by overall volumetric changes. The total volumetric shrinkage is determined by the following equation (Eq. 15.3):

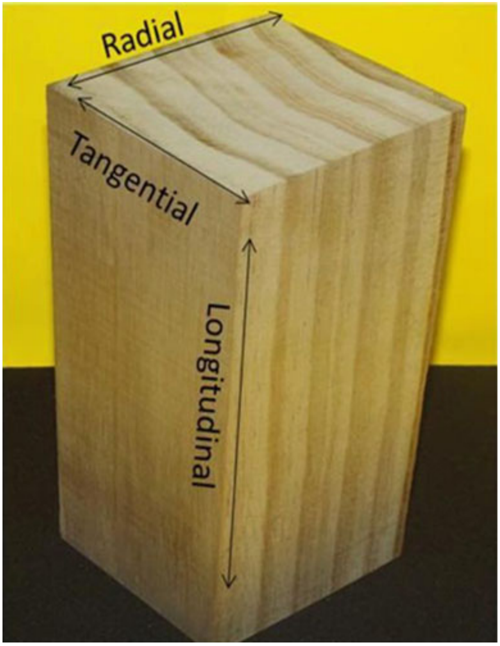

Fig. 15.3 Principal directions of wood

$$\text{Volumetric shrinkage}(\%) = \frac{\text{Swollen volume} - \text{Dried volume}}{\text{Swollen volume}} \times 100 \qquad (15.3)$$

whereas the volumetric swelling is determined using the following equation (Eq. 15.4):

$$\text{Volumetric swelling}(\%) = \frac{\text{Swollen volume} - \text{Dried volume}}{\text{Dried volume}} \times 100 \qquad (15.4)$$

Since it has been described earlier that volumetric swelling and shrinkage in wood takes place with moisture adsorption and desorption below fibre saturation point, the total volumetric shrinkage from green to dried conditions (oven dried condition) can also be estimated based on wood basic density and moisture content at fibre saturation point. The extent of volumetric shrinkage depends on anatomical structure. For high-density wood, generally the cell walls are thicker and lumen size are small therefore they exhibit relatively large volumetric shrinkage as compared to low-density wood. The total volume change is a function of change in dimensions in three directions.

Typically, dimensional changes are least in longitudinal direction followed by radial direction and tangential direction. Total shrinkage in longitudinal direction is minuscule of the order of 0.1–0.3% in normal wood and is often neglected. Whereas, typical values of radial shrinkage vary anywhere between 2 and 6% and tangential shrinkage varies between 5 and 10%. Similarly, during swelling also wood exhibit anisotropy in dimensional movements. Mathematical Equations (15.3 and 15.4) can be used for determining the directional shrinkage and swelling by putting the dimensions of the respective directions. The difference in the extent of dimensional change depending on the direction ultimately leads to dimensional distortion in wood and wooden products. The understanding of the shrinkage is important during seasoning and also during making of any product. During seasoning, wood is dried to about 12% moisture content and therefore for commercial purposes shrinkage from green condition to 12% moisture content is more relevant. In practice, not all the sawn wood pieces will have perfect radial–tangential cross section and in such case during drying a square cross section can become rhombus shape. In case of plywood, when veneers are peeled from a log in the green condition, an allowance has to be provided in veneer width considering the extent of tangential shrinkage during veneer drying. Some of the defects arising due to anisotropic shrinkage in wood are shown below (Fig. 15.4a–d).

There are a number of theories postulated to explain the differential shrinkage in different directions based on anatomical features and cell wall structure (Skaar, 1988; Spear & Walker, 2006). However, it is to be noted that anisotropy in shrinkage is very complex in nature depending on a large number of factors and no one theory can fully explain the extent of shrinkage or swelling in all species in a generalized manner. Typical values of tangential and radial shrinkage from green to oven dry conditions in few species are given in Table 15.1.

Fig. 15.4 (**a**–**d**) Shrinkage-related defects in wood on drying

Table 15.1 Typical values of tangential and radial shrinkage from green to oven dry condition in few important timber species (Rajput & Rawat, 1989)

Species	Tangential shrinkage (%)	Radial shrinkage (%)	Ratio
Rosewood	5.8	2.7	2.15
Sissoo	4.9	2.8	1.75
Ebony	8.5	5.0	1.70
White cedar	8.1	4.7	1.72
Deodar	5.2	3.6	1.44
Teak	3.9	2.2	1.77
Toon	7.3	3.4	2.14
Sal	8.8	4.2	2.09
Red sanders	4.1	3.2	1.28
Mango	4.9	3.0	1.63
Benteak	7.3	4.5	1.62
Padauk	4.4	3.3	1.33

Some of the species like eucalyptus, silver oak, casuarinas, etc. shrink excessively in both radial and tangential directions and therefore are not preferred as timber. Similarly wood with large amount of reaction wood (i.e. tension wood in hardwoods and compression wood in softwoods) tend to exhibit comparatively large longitudinal shrinkage as compared to normal wood and therefore is avoided in timber.

15.2 Precursor/Pre-emptive Steps in Wood Seasoning

A properly carried out wood seasoning operation ensures reducing the moisture content of timber to the desired level, uniform moisture content in all pieces of wood, minimal or no fungal stain, minimization of shrinkage associated defects and least drying stresses. In addition, to a great extent, the quality of the seasoned wood is predetermined by the handling of wood prior to drying. Before actual drying operations begin, several steps are important in reducing defects and degradation in wood during the process and afterwards. The precautions start with the logs. It is recommended that logs should be sawn as early as possible in order to increase recovery of quality material. The delay in sawing may lead to poor recovery of sawn timber due to end-cracks in logs due to moisture gradient and differential shrinkage. It is well known that wood dries at a rapid rate along the grain and if left unattended for a long period, end of the log dries up quickly and once the moisture content of the end portion reaches to fibre saturation point, the shrinkage starts. The differences in radial and tangential shrinkage will lead to end crack in logs (Fig. 15.5a, b). The intensity of end cracks will depend on the species and drying rate.

Exposing logs in such conditions (without proper piling) also attracts insects and pests attack and fungal degradation particularly during warm weather as it provides conducive condition for such degradations. The end-cracking can be prevented by preventing moisture loss from the ends. Storing logs under flowing water or spraying of logs continuously with water prevents any moisture loss from and also protect from fungal attack. It must be noted that logs should not be stored under stagnant water for long period and water need be changed fortnightly. For storing under water logs should also be debarked. Many times, it is not practical to store logs under water and therefore continuous water spray is practised in many cases. However, spray should be able to cover the entire surface area of logs and particularly ends to prevent any preferential drying. Cold and fresh water is more effective than is warm and recycled water. Water spray is a very common practice adopted by pulp industry and also veneering industry where logs are stored for long period and for further processing high moisture content is desired. In order to prevent end cracking in

Fig. 15.5 (**a**, **b**) End cracks in logs

Fig. 15.6 Stacking of logs in multilayer

logs, particularly meant for sawn timber, sealing of log ends for any moisture movement is more practical and economical way. Log ends are sealed either with mud, thick bitumen paint (coal tar), wax or any other coating that can prevent moisture loss from ends. The coating should be done immediately after cutting logs to specific length. End-cracking in logs can lead to substantial low recovery of quality sawn timber. Therefore, it is always recommended that the logs should be sawn as early as possible. In order to protect logs from insect/pest attacks, some standard practices in log yards need to be followed which are as follows:

- Log yard should be kept clean and free from any insects/pests.
- Logs should be stored under a shed preventing direct exposure to rain and sunlight as much as possible.
- Logs should be placed on a concrete floor or durable or preservative-treated pallet.
- Good air circulation in log yard prevents from any mould or fungal growth.
- To prevent accelerated drying from surface, bark should be retained on logs. This prevents surface checks and cracks in logs. However, this may increase the risk of insect attack.
- Logs should be stacked in closed stacks in one or more layers (Fig. 15.6).

Once logs are sawn into cut sizes, the sawn timber should be stacked properly over a raised platform avoiding direct ground contact of sawn wood (Fig. 15.7). Stickers of appropriate thickness (generally 25–40 mm cross section) should be used. The stickers are placed across the width of the stack at an equidistant spacing (450–750 mm) depending on the thickness of the sawn timber. For thinner timber, the sticker should be at close spacing whereas for thicker sections stickers can be at a longer distance (~750 mm). In general, for 20–25 mm thick boards, stickers are placed at every 600 mm distance (Fig. 15.8). The uniformity in dimensions of stickers and their proper alignment is crucial for proper stacking of sawn material

Fig. 15.7 Stacked sawn timber

Fig. 15.8 Stickers placement between boards

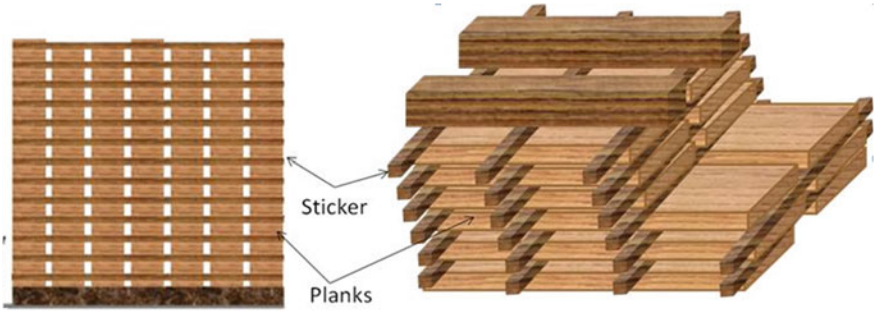

Fig. 15.9 Stacking of planks/boards

as it may affect the overall seasoning process. In case, when the sawn timber is of varying length, the longest piece should be placed at the bottom of the stack and shortest pieces should be placed on the top of the stack (Fig. 15.9).

Fig. 15.10 Improperly stacked and stored timber

When the sawn timber is not stacked properly, it is prone to develop fungal/mould growth between the wood pieces that can degrade wood apart from very slow drying. Figure 15.10 depicts an inappropriate way of stacking sawn boards in open area without any protection from sunlight and rain.

15.3 Wood Drying Elements

Three elements namely relative humidity, thermal energy and air circulation are key parameters for any drying operation (Fig. 15.11a). The combination of these three parameters defines the drying rate.

The relative humidity of air is the vapour pressure of the air in a given volume with respect to saturated vapour pressure. It expresses the relationship between the moisture content of air at a certain temperature and the moisture content of saturated air at the same temperature. The value of relative humidity ranges from 0 to 100%. Direct measurement of relative humidity is difficult and instead conventionally determined indirectly by the difference in dry-bulb and wet-bulb temperatures. The dry-bulb is a simple thermometer and wet-bulb thermometer is a thermometer whose bulb is covered with a fabric sleeve. The other end of the sleeve will be in a water reservoir. As air passes over the moist fabric sleeve water vapour is evaporated that cools the wet-bulb thermometer. Fast evaporation rate implies bigger difference between dry- and wet-bulb temperature which indicates lower relative humidity. Hygrometric chars are used to determine the relative humidity based on dry-bulb and wet-bulb temperature differences (Fig. 15.11b). Higher relative humidity at a given temperature would lead to lower water evaporation rate from wood surface and therefore slower drying. This parameter is used in controlling the seasoning of wood.

Thermal energy (heat) mainly influences the drying rate as with increased temperature moisture evaporates quickly from the surface and at the same time it accelerates the moisture movement process from inner core to the surface of

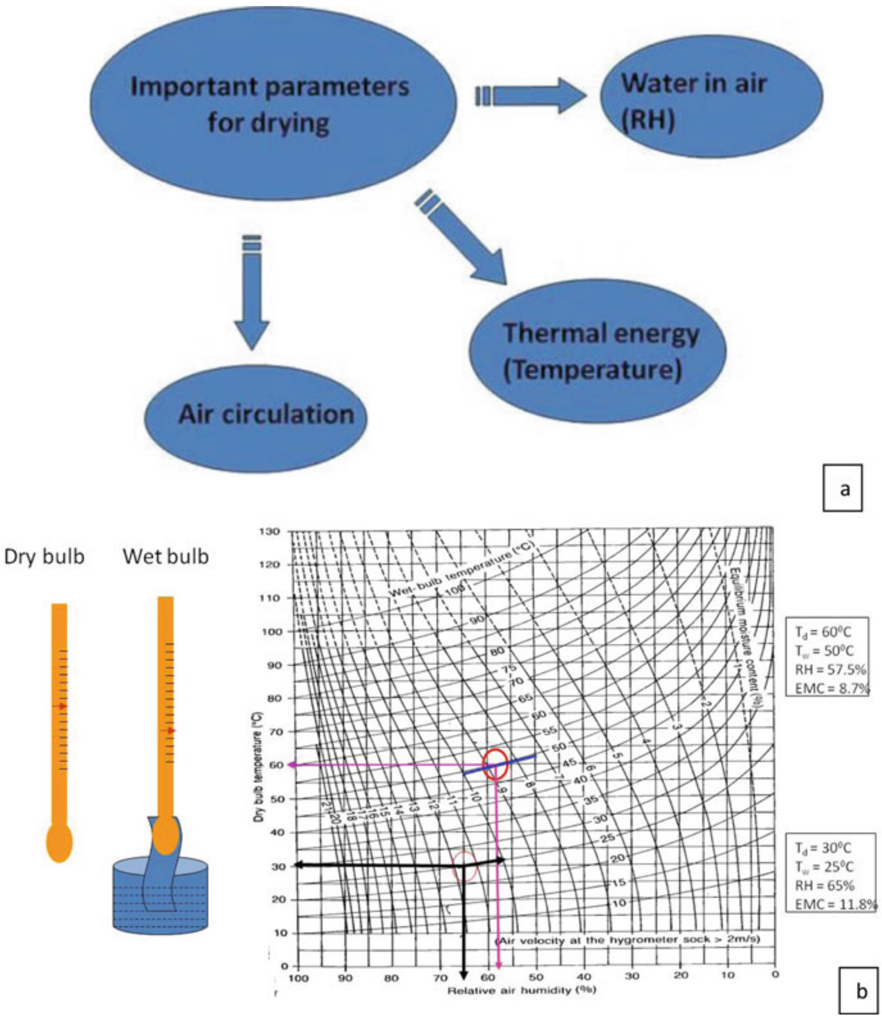

Fig. 15.11 (**a**) Three drying elements; (**b**) dry bulb, wet bulb and hygrometric chart for relative humidity

wood. Raising the temperature greatly enhances moisture diffusion rate across cell walls and therefore plays a critical role in drying process where moisture diffusion is the only mechanism for moisture loss particularly in hardwood species. Capillary movement and diffusion are the two prominent moisture movement mechanisms in wood. Capillary movement is observed predominantly in softwoods at high moisture content (>60%). Proper control of temperature during seasoning is important in maintaining the balance between surface evaporation and moisture diffusion from core to surface. Seasoning at higher temperature in the initial stages can lead to rapid evaporation of moisture from the surface resulting in steep gradient in moisture within wood, poor heat transfer from air to dried wood surface, reduced moisture loss rates and increased risks of drying stresses. The fast drying at high temperatures is often uneconomical in terms of shrinkage and distortion, particularly in hardwood species with low permeability.

Air flow within a well-stacked timber transfer the heat energy to timber and at the same time acts as the carrier for moisture evaporated from the wood surface during drying. For efficient wood seasoning, it is necessary to have proper air flow through the stack of timber. Any obstruction in smooth air flow within the stack due to improper sizes of stickers or poor arrangement of stickers may lead to substantial reduction in drying efficiencies. It is estimated that for an uneven and ragged stacking 100% air can bypass affecting drying efficiencies severely. Appropriate air velocity is important for effective drying and energy consumption. At higher moisture content (above 40%), higher air velocities can cause the outside portion of the wood to dry faster than the inner core causing degrade. For permeable species, an air velocity of at least 3 m/s is recommended whereas for slow-drying species, an air velocity of 1.5–2 m/s is essential.

15.3.1 Type of Species

Shrinkage anisotropy, susceptibility to develop drying defects and permeability are also important factors in deciding upon seasoning of specific timber species. Some species are very easy to dry whereas some species take very long time. Thus timber species are classified into three major categories according to their ease in drying and drying deformation. Based on their refractoriness in drying, these categories are

15.3.1.1 Highly Refractory

Species in this category are very slow and difficult to dry. These species are also prone to develop drying defects like end cracks, surface cracks and splitting and therefore require careful drying. These timbers should be protected from rapid drying conditions when dried from green condition. Most of the high-density timber species are under this category. Khair (*Acacia catechu*), Sal (*Shorea robusta*), laurel (*Terminalia alata*), axle wood (*Anogeissus latifolia*), etc. are some of the examples of highly refractory timber species.

15.3.1.2 Moderately Refractory

These timbers can be dried at relatively faster rate as compared to highly refractory timbers with moderate drying defects. Timber species like species like Teak (Tectona grandis), Sissoo (*Dalbergia sissoo*), Bijasal (*Pterocarpus marsupium*), Ghamari (*Gmelina arboria*), etc. are categorized in this category which are mainly used for furniture, handicrafts, and structural applications.

15.3.1.3 Non-refractory

These categories of timbers are easy to dry, can be subjected to rapid drying conditions and are generally remain free from significant drying defects. Easy drying of such timbers allows the use of higher temperatures. These timbers should be dried as early as possible as they are prone to develop mould growth and discolouration. Timbers like semul (*Bombax ceiba*), mango (*Mangifera indica*), rubber wood (*Hevea brasileinsis*), salai (*Boswellia serrata*), Poplar (*Populus* spp.), Deodar (*Cedrus deodara*), etc., belong to this category.

Proper adjustment of three basic drying parameters considering the type of species is very critical in most of the conventional wood seasoning processes to avoid any defects during seasoning and also to achieve desirable seasoned timber. The consequences of poor drying practices are considerable. It reduces the recovery of quality wood and drying degrades affect the economic value of timber. Within a stack, a large variability exists in boards in terms of moisture content, heartwood–sapwood mixture and intrinsic wood quality variation. Extra attention needs to be paid while seasoning of thicker sections as they are more prone to develop cracks and splits as compared to thinner sections and should be dried at a much lower rate. There are a number of criteria which define the quality of seasoning. The average moisture content of the timber should be at the desired level; variation in moisture content within a piece should be minimal; variation in moisture content in all the pieces should be within permissible limits with minimum variation; seasoned wood should be free from any surface checks and end cracks; seasoned wood should be free from any discolouration, fungal stain, chemical stains and warping associated defects. It should also be ensured that there is no or minimal gradient in moisture across the thickness of the wood particularly in thicker sections. These factors are important to get quality end product irrespective of seasoning method adopted.

15.4 Drying Degrades

Drying defects in timber are a result of improper drying conditions, poor stacking and refractory nature of timber, irregular grain, sawing pattern, abnormal or reaction wood and inherent gradient in properties within the wood. Defects like surface checks, end cracks, mould growth, and fungal decay can easily be observed. The major warp-associated defects are due to anisotropic shrinkage in wood.

15.4.1 Cupping

Cupping is due to difference in width-wise shrinkage of the two faces of a piece of board. The bark side will always shrink more than does the heart side; this difference is more pronounced in smaller log. Cupping is a natural tendency of flat-sawn lumber.

15.4.2 Crook/Spring

Crook or spring is side bend of a plank and is often a result of improper sawing patterns or crooked logs. This is also observed some time in radially sawn timber as the wood close to pith shrinks more longitudinally than wood near the bark.

15.4.3 Bow

Bow is caused by poor stacking, i.e. when stickers are too placed too far from each other and/or not aligned in a stack, stickers are not uniform and foundations are uneven. This can also be due to differential shrinkage of two surfaces.

15.4.4 Twist

Twist is the turning of the four corners of any face of a board so that they are no longer in the same plane. It occurs in wood containing spiral, wavy, distorted, or interlocked grain.

15.4.5 Internal Check (Honeycomb)

Internal checking, also called honeycomb, is deep surface checking which takes place due to tension failure inside the plank running across the rings. Internal check is hardly noticeable or detectable when examining the surface of dried timber and are found only when wood is further machined (crosscut, ripped, carved, or routed).

15.4.6 Collapse

Collapse is excessive shrinkage in wood during drying particularly when wood is dried at high temperature. Species like eucalyptus, oak are known to exhibit collapse. However, collapse is recoverable to a large extent by steam treatment.

15.5 Wood Seasoning Methods

Appropriate seasoning practice ensures minimizing such defects in wood during drying and thereafter. The final moisture content of wood after drying should be decided depending on the end application and the location where it has to be used. There are a number of methods for seasoning of wood. The choice of seasoning method depends on the time, cost and energy efficiency. The different methods available are:

1. Air seasoning.
2. Kiln seasoning.
3. Dehumidification drying/seasoning.
4. Vacuum seasoning.
5. Radio-frequency/microwave drying.

15.5.1 Air Seasoning

Historically, wood seasoning was carried out naturally by stacking timber under a shed at ambient temperatures and relative humidity. This was termed as air seasoning. It is one of the simplest ways of seasoning with minimum requirements. The rate at which wood dries in the air seasoning depends upon variables that involve the wood itself, the yard, the pile and climatic conditions other than wind to allow faster drying. In this method, there is no control on any of the drying parameters and therefore the drying time is highly variable. Ordinarily, timber should not be considered as fully air seasoned in less than 6 months. Seasoning of 25 mm thick planks of most of the moderate to high-density timbers may take 2–3 months to season in a moderate climate. Thicker cross sections used for door and window frames may take from 6 to 8 months. In general, air seasoning is a preferred way of pre-drying of timber when time is not a major constraint as no energy cost is involved in the process. One of the key requirements in air seasoning is to keep stacked timber under a shed in order to avoid exposure of wood to sunlight and rain. The direct exposure to sunlight results in weathering of wood surface and rain exposure results in changes in moisture content which can accelerate the overall degradation processes. In order to control the drying rates depending on the species, different types of sheds are recommended in Indian conditions. The simplest shed is only with roofing and open from all the sides allowing free movement of air within stack. This type of sheds is used for seasoning of non-refractory timbers (Fig. 15.12). In another type of shed, only north side of the shed is kept open with other three sides having walls and is generally recommended for moderately refractory species like teak, rosewood, sissoo, etc. For air seasoning and storage of seasoned refractory timber species in hot and dry climatic conditions, sheds with roof and walls on all four sides with proper cross ventilation are considered to be suitable. Roof of sheds should also have enough overhangs to protect wood from direct exposure to sunlight.

Though capital and operational costs for air seasoning irrespective of type of shed are very less and drying defects also remain within acceptable limits provided proper precautionary measures are taken care, long drying time offsets the economic advantage when industrial scale seasoning is desired with high productivity. In

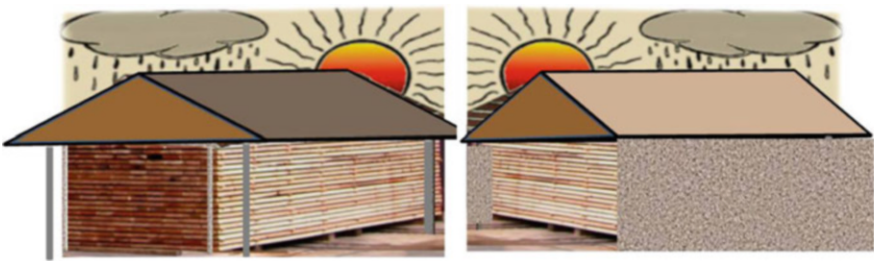

Fig. 15.12 Air drying sheds (left—open from all sides; right—open only on north side)

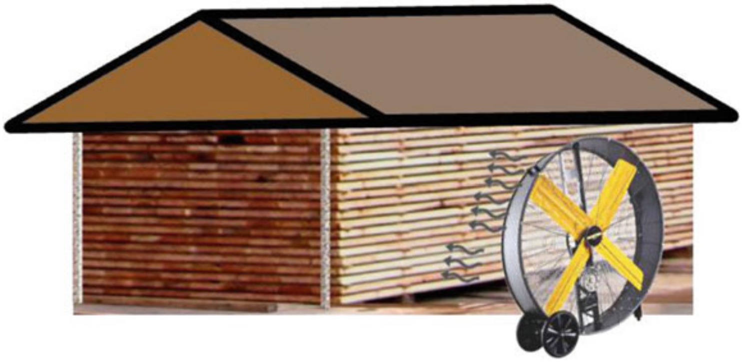

Fig. 15.13 Force air drying of timber

Table 15.2 Drying rate of different species from initial to 30% MC and from 30% to equilibrium level

Species	Initial MC (%)	Drying rate (% decrease in moisture content per day with respect to initial moisture content)			
		Forced air drying		Air drying	
		Above 30% MC	Below 30% MC	Above 30% MC	Below 30% MC
Albizia lebbek	47.1	2.02	0.32	0.57	0.58
Grevillea robusta	84.5	2.63	0.56	1.22	0.75
Eucalyptus tereticornis	57.1	1.40	0.41	0.55	0.39
Azadirachta indica	60.9	2.75	0.54	1.28	0.50
Casuarina equisetifolia	42.7	1.28	0.31	0.81	0.34

order to accelerate air seasoning, force air drying is also practised with minimal energy inputs for blowing air through the stack (Fig. 15.13). Forced air drying is very helpful in reducing the moisture above fibre saturation point and can be used efficiently as pre-kiln seasoning practice to minimize the seasoning costs. The moisture removal rate was observed to be almost two to three folds higher as compared to conventional air seasoning in forced air drying in some plantation timbers (Table 15.2) (Chauhan et al., 2006).

It is evident that above 30% moisture content, drying rate in forced air drying was significantly higher in all the species as compared to that in air drying. However, below 30% moisture content, there was no significant difference in drying behaviour in both methods.

15.5.2 Kiln Seasoning

Kiln seasoning is commercially the most acceptable and widely practised seasoning method to obtain degrade-free dried timber rapidly and economically. Kiln seasoning is conventionally carried out in a thermally insulated closed chamber having provision to control temperature, relative humidity and air flow within the chamber. A schematic diagram of a conventional steam-heated kiln is shown in Fig. 15.14. Heating in kiln can be achieved by different methods like saturated steam flowing through the heating coils, thermal fluid mainly high boiling point mineral oils, electrical heating, flue gases, etc. Relative humidity inside the chamber is controlled by controlling the air inlets/outlets also called vents. In some kilns, hot water sprays are also used to increase the humidity levels particularly for seasoning of refractory species. In steam-heated kilns, both temperature and humidity control can be controlled by steam thus avoiding any additional humidification mechanism. Air circulation is achieved by fans or blowers fixed either on overheads or on the sides. The main purpose of these fans/blowers is to obtain uniform circulation of the air through entire stack. The uniform distribution of air is very critical in order to reduce conditioning time, increase energy efficiency and uniform moisture content in the stack. The air flow reversal through the stack after a predetermined period is also necessary to achieve uniform drying of stack as unidirectional air flow can result

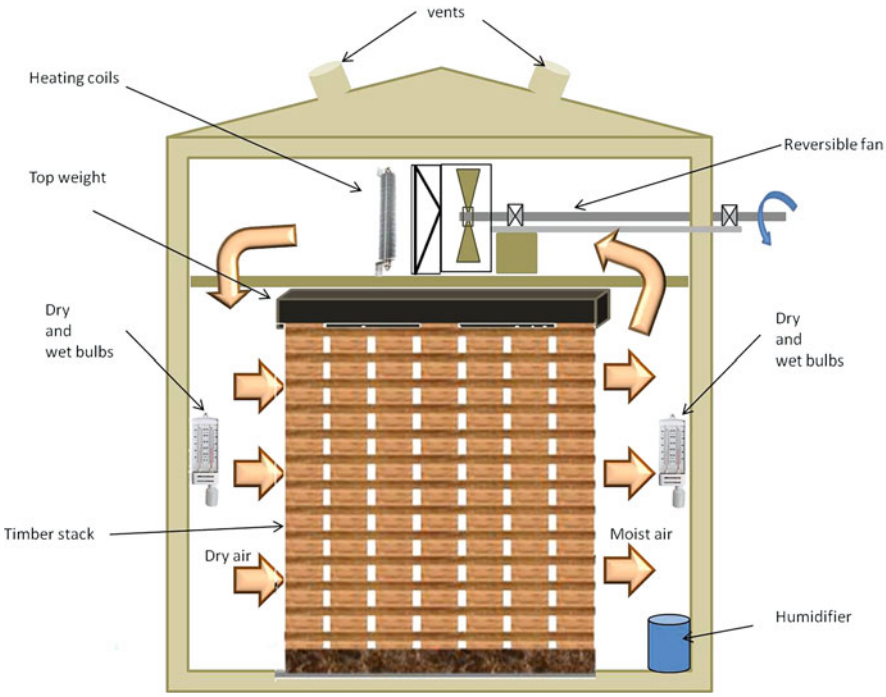

Fig. 15.14 Schematic diagram of steam-heated seasoning kiln

in faster drying at the air-inlet side and slower drying at the air-outlet side of the stack due to temperature drop in the air as it passes through the stack. The profile of the chamber is also very important as it affects the air flow circulation. The profiling of the plenum space, use of baffles/curtains, clearance of stack with false ceiling, etc. can have large implication in drying rate of timbers. It has been reported that when amount of air moving through the stack is equal to the amount of air moving around the stack can lead to substantial reduction (~25%) in drying. Even in well-aligned stack, nearly 10–25% air bypasses (Nijdam & Key, 1996).

This type of kilns uses specific sets of temperature and relative humidity conditions which are optimized for specific timber species or a group of species depending on their drying characteristics. These sets of conditions are called kiln schedules. In the seasoning schedules, initially temperature is kept low and relative humidity is maintained at higher levels to avoid quick drying of the surface. Quick drying of surface not only reduce the heat transfer rate from air to wood but also lead to moisture gradient across thickness which can result in surface checks and cracks. As the drying progresses, gradually temperature inside the kiln is raised and relative humidity is lowered in steps in order to maintain the optimum drying rates. The stepwise change in temperature and relative humidity inside the chamber has to be done considering the moisture content of wood. In general, for highly permeable timbers, drying is carried out at higher temperatures (~50 °C) right from the initial stages (green conditions). Initial temperature of about 100 °C has also been attempted in case of radiata pine species which is highly permeable timber. However, in case of refractory timbers elevated temperatures at the initial stage can lead to substantial drying degrades and therefore drying has to be initiated at very low temperature (~40 °C). During seasoning operation, it is also suggested to give steam treatment to the wood for equalization and reducing case hardening of the timber. Thus, depending on the species, an appropriate seasoning schedule has to be adopted. Bureau of Indian Standards (Annon, 1993) has recommended seven seasoning schedules (IS1141:1993) for different timber species which contain 5–9 steps. Seasoning schedules I and VII are given in Tables 15.3 and 15.4 respectively.

Schedule I is used for drying non-refractory species like pine, fir, semul, etc. and timber is seasoned within 4–5 days; whereas schedule VIII is used for highly refractory timbers like axlewood, babul, sal, jamun, etc. and the seasoning time is about 24–30 days. Kiln seasoning also sterilizes wood from mould growth, fungus and any insects. While seasoning wood, it is always advisable not to mix species

Table 15.3 Seasoning schedule I for 25 mm thick planks

Moisture content (%)	Dry bulb temperature (°C)	Wet bulb temperature (°C)	Relative humidity (%)
Green	52	44	62
60	55	45	55
40	60	46	44
30	65	48	39
20	68	48	33

Table 15.4 Seasoning schedule VII for 25 mm thick planks

Moisture content (%)	Dry bulb temperature (°C)	Wet bulb temperature (°C)	Relative humidity (%)
Green	40	38	88
60	41	38	82
40	42	38	76
35	45	40	72
30	46	40	68
25	47	40	64
20	50	42	61
18	52	42	54
15	55	42	45

with varying drying characteristics and if mixed, the seasoning schedule recommended for slowest to dry material has to be followed. Equalizing and conditioning treatment at the end of seasoning is essential by increasing the relative humidity inside the chamber to reduce the variation in moisture content between the boards. It is also recommended that stack is cooled down to a temperature which is within 15–20 °C of the ambient temperature before taking out of the kiln chamber. This is particularly important for high-temperature drying. Once seasoned to desired moisture content, the timber can be block stalked without stickers and stored in an appropriate place. The existing kilns systems are equipped with the automated kiln control systems which can be programmed to ensure constant rate of heat transfer and efficient drying process.

15.5.2.1 Solar Seasoning Kiln

Use of solar radiation as a source of heat provides opportunity to reduce the energy cost during seasoning and low environment impact makes it an attractive option for seasoning of timber particularly in areas where solar energy is available most part of the year. However, dependence of solar energy on weather and season, intermittent availability of the energy (only during day time) and slow drying rate are some of the limiting factors. Solar seasoning kilns are particularly useful for small-scale operations and as a pre-dryer for conventional kilns. Different designs of solar seasoning kiln have been developed and nearly 35 designs spread in the different parts of the world have been reviewed by Plumtre (1979). Solar seasoning kilns are mainly categorized into two types, i.e. greenhouse-based kiln and external collector based kilns. Among the two, greenhouse-type kilns are very popular as they are easy to design, fabricate and install. Mostly, metal surfaces are used as the solar heat absorbers which are generally corrugated to increase the surface area and painted black to increase the heat absorption. Glass or plastics are used as the glazing material and the entire structure can be build with metal or wooden frame. The schematic representation of a classical greenhouse-type solar kiln and fabricated solar kiln is shown in Figs. 15.15 and 15.16. The quality of seasoned timber in solar

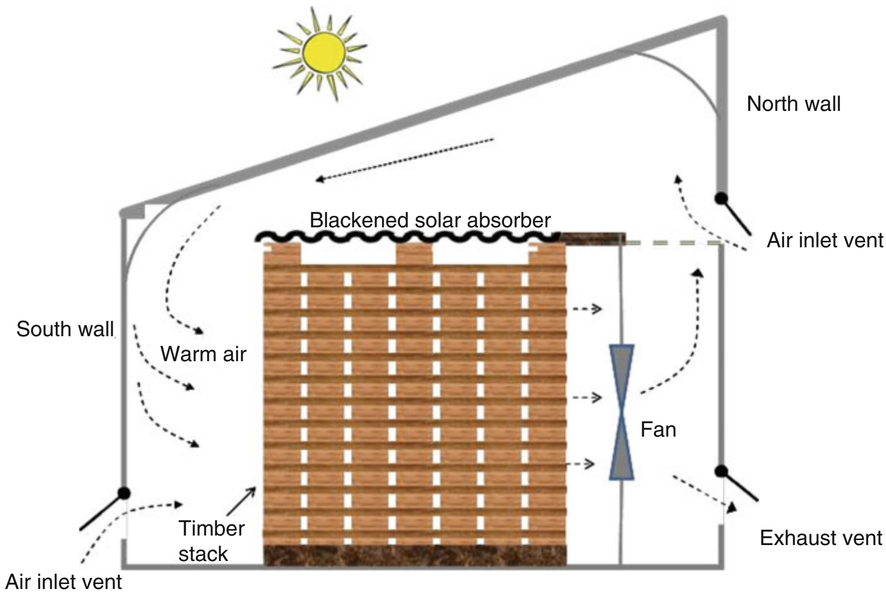

Fig. 15.15 Schematic diagram of a greenhouse-type solar seasoning kiln

Fig. 15.16 A solar seasoning kiln with metal framework

kilns is comparable to the conventional steam-heated kilns though the time requirements are higher.

15.5.3 Dehumidification-Based Seasoning Kilns

Dehumidification-based drying has been explored to season wood and the technology has been found to be energy efficient and tends to produce quality dried wood with minimal defects. The dehumidification seasoning kilns are well suited for slow to dry refractory or moderately refractory timber species (Walker, 2006). Dehumidification-based kilns are classified into two categories namely heat pump-based drying and desiccant-based drying. The heat pump-based dehumidification kilns are operationally similar to refrigeration system where moisture in condensed and drained off from the chamber whereas desiccant-based kilns use a desiccant chemical to absorb the moisture from wood. Both the systems have their own advantages and limitations. Heat pump dehumidification dryers tend to have limitations in maintaining low relative humidity resulting in low moisture extraction rate. Poor design, over-sizing of equipment and poor operational management are few of the major concerns in such systems. While, desiccant-based system requires additional heat energy to charge the desiccant chemical in order to maintain the moisture absorption efficiency of desiccant. Desiccant-based dehumidification is more suitable where low relative humidity is required. The system is also relatively simple to operate and requires low maintenance. The container-type dehumidification kiln with desiccant system at the back of the chamber is shown in Fig. 15.17.

The energy efficiency of such kiln depends on its capacity utilization. The cost of drying is directly proportional to the energy consumption. If the kiln is not used to its full capacity, the energy cost makes such drying uneconomical.

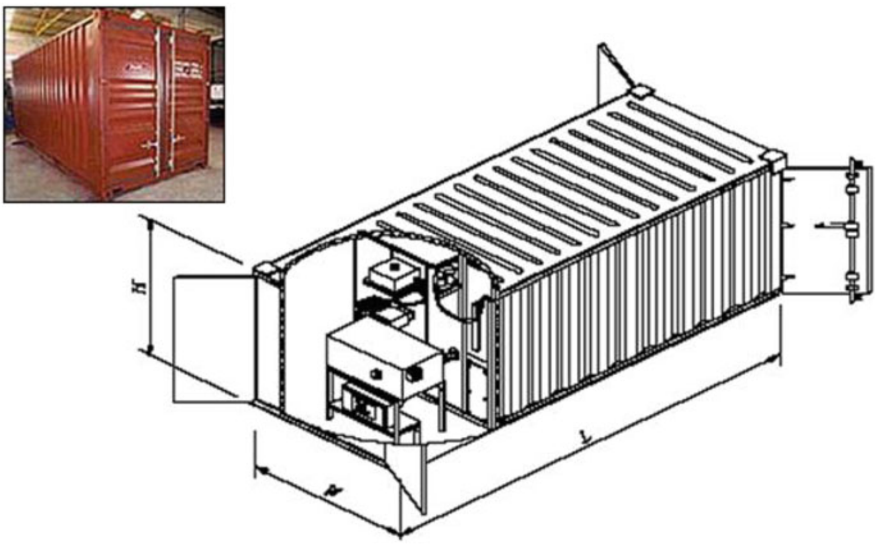

Fig. 15.17 Desiccant-based dehumidification wood seasoning kiln

15.5.4 Vacuum Drying

Vacuum drying is one of the modern developments in wood drying. The level of vacuum generated varies with the specific systems but is generally in the range of 50–200 milli bars (mbar). Since water boils at a lower temperature under vacuum, this allows wood to be dried at a lower temperature which is beneficial as wood is stronger at lower temperature and can withstand greater internal stresses without defects occurring. Also operating in vacuum (with very little oxygen present) and lower temperature, chances of staining or colour change are minimal. Heat transfer in vacuum drying is a challenge and any one of the four modes namely discontinuous vacuum, hot platen, radio frequency or superheated steam is used. However, high investment is the major prohibiting factors the large scale commercial application of the technology. For certain high end and specialized products this technology has great potential and is being used.

15.5.5 Radio-Frequency/Microwave Drying

Dielectric heating (DH) uses electromagnetic waves such as radio-frequency (RF) waves or microwaves (MW) to create heat. The electromagnetic waves interact with moisture in wood and cause the water molecule to vibrate at high frequency resulting in temperature rise and subsequently evaporation of water. Because of the volumetric nature of the heating, it avoids case hardening and other surface damage, which is a major concern in conventional kiln drying of timbers. RF-based drying has been found to be effective particularly for thicker sections of hardwood species and has already gained commercial acceptance in many countries. These techniques are suitable for highly specialized application. Different designs have been adopted in developing the suitable RF dryers suiting to their specific requirements and RF dryers with varying frequency range from 4 to 40 MHz and power rating from 10 to 300 KW have been developed. Microwave dryers have been reported to be appropriate for timbers with low initial moisture content and are prone to develop drying degrades in conventional kilns. RF/MW wood drying system offers rapid and degrade free drying but still has a niche market.

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Chemical Preservatives in Wood Protection 16

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_16

Abstract

Wood is an essential renewable resource which has been utilized in most of the sectors like housing, construction, furniture making, etc. Due to the immense damage caused by the wood degrading agents, there is a surge in demand to protect wood and its products. Wood preservation is an impeccable step to elude the degrading agents. It prolongs the service life of wood and its products. Numerous treatment methodologies have been inculcated for applying the preservatives in wood. As a result, the treated wood improves resistance against the agents of degradation. The preservatives used should be economical and less hazardous to living beings and environment. The main objective of this chapter is to convey to researchers about the recent developments on chemical preservative formulations which have an immense efficiency in enhancing the service life of wood and its products than the ones used earlier.

Keywords

Wood preservation · Chemical preservatives · Wood degrading agents · Service life

16.1 Introduction

Wood plays a vital role in the world economy, due to its abundance in nature and versatility. Wood is extensively used in sectors like construction, furniture making, housing and so on. It will remain as a leading building material until and unless there is an adequate amount of supply at a reasonable cost. Because of its organic nature, wood is susceptible to degradation. There is an increase in demand for preserving wood and its products from biodegradation. Wood preservation implies the safety of wood against any factor which creates irreversible damage and eventually destroys wood. However, wood preservation in an applied sense refers to the enhancement of wood's natural durability by treating it with chemicals that are lethal to insects, fungi and other decaying agents. The prime objective of the preservative treatment of wood is to intensify the service life of wood, thus increasing the ultimate cost of the product and evading the need for frequent replacements. Use of toxic metal complexes as wood preservatives has brought interest in employing natural and eco-friendly preservatives. The existing advancement and employment of novel technologies has been restricted due to unpredictability in terms of the outcome amongst the laboratory and the field routines of natural products substitutes, and legal glitches derived from the absence of globally defined quality standards. Extractives from plants, biological control agents, and combination of chemical and natural procedures are evolving as fractional solutions to regulate wood deteriorating creatures such as fungi and termites (Groenou et al., 1952). Systematic approach has to be made in order to protect wood, starting with moisture content because the deteriorators require water source to deteriorate the wood. Finishes, comprising water repellents, can aid to safeguard wood in insignificant deterioration environments, as above-ground conditions (Loferski, 1999). There are numerous advancements made with respect to the assessment of organic and inorganic biocides for the improvement of viable method to be applied for preservatives. Imperative methodologies for protecting the wood have been employed and also negotiable amount of impact on environment by the preservative formulation is acknowledged. It is anticipated that at some stage, the totally organic systems will be mandatory for wood products in residential uses (Laredo, 1996).

The process of penetrating or incorporating the preservatives into the wood at a depth using traditional methodologies which in turn will provide effective, long-term resistance against the fungi, insects and marine borers is said to be termed as wood preservation. Wood preservation was initially introduced as an industrial process and it is constantly being in use where there is decay is evident and unavoidable (George et al., 1953). For example, decay caused by fungi is completely dependent on the presence of moisture, hence there should be a consideration made on inventing a protocol to maintain the wood from fungal attack, irrespective of wood species. Preservative treatment method should be designed in such a way that there shouldn't be any probabilities of replacing the wood and the protocols must be accurate, justified and of less cost, thus conserving our forest. Wood importing countries will desire to decrease wood import as to lessen currency while the wood exporting countries will implement preservation in order to reduce home demand for replacement wood, thus leaving the extreme volume available for export (Swiderski, 1967). By prolonging the service life of timber, wood preservation diminishes the harvest of valuable forestry resources, eases functioning costs in industries such as utility and railroads, and guarantees harmless conditions where timbers are utilized as support structures. Moreover, to industrial and commercial application, a substantial portion of the treated wood volume is used for residential construction to guard homeowner's funds and offer outdoor living spaces that are a preferred part of living. The practice of utilizing preservative chemicals and treated wood has been and still is occasionally criticized on the basis of health or environmental concerns. Unawareness on the part of the treating industry, poor work practices and lax environmental regulation, all share part of the blame for that negative perception. Innovation in the first half of the twentieth century led to the development of more effective wood protecting chemicals and processing techniques that turned a speciality industry into a commodity business. As can happen in all commodity businesses, research and development was not continuous when profit margins began to collapse and the door was opened for competitive products such as plastics, concrete and steel (Bowyer et al., 2007).

16.2 Wood Degrading Agents

Wood products can be attacked by a variety of biodeteriogens such as fungi, insects and bacteria, depending on where they are used. Fortunately, wood can be protected from biodegradation in a number of ways. The ideal choice depends on the local environment and the organisms present.

16.2.1 Decay

It is the highest destructive form of fungal attack on wood. It is prominently found in three forms, namely brown, white and soft rots. The terminology relates to the physical appearance of the wood after it has been extensively attacked. Brown and white rots result from the growth of highly specialized higher fungi (Basidiomycotina). The hyphae of Basisdiomycetes are able to ramify through the three-dimensional structure of wood creating large bore holes in the cell walls. These fungi utilize extracellular enzymes to degrade the wood cell walls to derive their nourishment. Under optimal conditions the process quickly weakens infected areas. Soft rot is caused by another group of higher fungi (Ascomycotina and Deuteromycotina) which produce fine bore holes without the extensive enlargement seen with the Basidiomycetes (Clausen & Yang, 2007).

Brown rots are usually allied with softwoods. The fungi attack mainly the cell walls carbohydrates (cellulose and hemicelluloses) and change the structure of lignin only slightly. As a consequence, the decayed wood develops a brown colour that will eventually exhibit extensive cracking as it dries. The fungi can wet wood by transferring water over considerable distances along macroscopic root-like structures formed by aggregations of hyphae. White rot affects both softwoods and hardwoods. Cellulose, hemicelluloses and lignin are degraded. Progressive erosion by hyphae in the cell lumen as well as bore holes weakens the cell walls. Wood affected by white rot may darken in the early stages of decay but as the decay advances bleaching may occur. It does not split into fragments but, because the breakdown of the lignin weakens inter-fibre bonding, the wood becomes stringy in texture. Soft rot is a form of decay caused by a quite different group of fungi which are closely related to moulds. They usually attack wood in wet conditions than those favoured by brown and white rot fungi. Soft rot fungi characteristically attack the surface of the wood, gradually eroding inward at the rate of a few millimetres per year (Andersen & Elborne, 1999).

16.2.2 Insects and Termites

Wood destroying insects are of major significance in most regions of the world, although the number of species involved is relatively small. They damage wood by chewing it with their mandibles, although in many cases they derive no direct nourishment from it. From a wood durability perspective, insect attack is less predictable than decay because some insects can bore into sound dry wood, and because insect populations are not uniformly distributed. However, most insects are similar to fungi in attacking only moist wood. In the natural environment most wood decomposes as a result of both insect and microbial activity. Most insect pests of wood are either termites or beetles. Other insects such as wood wasps, moths, carpenter bees, etc. are significant locally (Creffield, 1996).

All termites feed on cellulosic materials. The most important are the subterranean termites that are found throughout the world within 40° to 45° of the equators. The number of species and total termite biomass increases nearer the equator, and they are generally regarded as a more serious threat in tropical and subtropical regions. Like all Isoptera, subterranean termites are social insects that live in colonies that are established in the soil. In their quest for food, subterranean termites may enter buildings and other above-ground structures through enclosed galleries which they construct to protect themselves from desiccation and which connect to the soil and ultimately to the colony. Traditionally wooden structures have been protected by treating the soil under and around the building with an insecticide, subsequent soil treatments are necessary to maintain protection. Physical barriers such as metal caps between building and foundation supports have some limited value in that they force the colony to construct an enclosed gallery across both faces of the cap and thereby warn the homeowner of their presence. Soil barriers such as graded gravel and steel mesh show some promise, as do toxic bait systems. The bait systems use slow-acting insecticides, allowing foraging termites to return to the nest to feed the colony. Building with preservative-treated wood provides another layer of protection if other protection mechanisms fail. The best control is achieved by using preservative-treated wood (Su & Scheffrahn, 1993).

16.3 Necessity of Wood Preservatives

There are certain species of wood which are durable naturally. Resistance against fungi and insects can be exhibited by the heartwood of trees to certain extent. This natural durability can be attributed to amalgamate lethal extractives existing in the wood and low innate penetrability. As a result of this natural durability such woods can be used outdoors and in some cases in ground contact or submersed in water. Wood from naturally durable species is sometimes observed as being environmentally desirable to chemically treated wood, and many of these species have an eye-catching appearance. In addition, some species such as black locust, greenheart has exceptional strength assets. As might be predictable such a blend of desirable attributes has directed to increasing attention in use of durable species from the tropical countries for construction in European countries. Nevertheless, numerous aspects limit the use of naturally durable species. In developed countries the capacity of mounting stock of naturally durable species is comparatively low related to the demand for durable wood products. In view of the limited supply of natural durable wood species, it is valuable to supply less durable wood treated with preservatives. Preservative treatment of wood therefore is significant to protect the wood resources. Wood preservatives are chemical constituents that when appropriately applied to wood, makes it resistant to fungi, insect and woodborer (Bowyer et al., 2007). There are two universal classes of wood preservatives: oils, such as creosote and petroleum solutions of pentachlorophenol; and waterborne salts that are applied as water solutions. The efficiency of the preservatives diverges momentously and can depend not only upon its composition, but also upon the quantity injected into the wood, the depth of penetration, and the conditions to which the treated material is exposed.

The choice of wood preservatives depends upon the character of the wood to be treated, the anticipated service life and the properties of the chemical or formulation. Wood preservation formulations must

- Be toxic to fungi, termites, borers and marine organisms.
- Be free from objectionable properties in use and handling.
- Be chemically stable.
- Be safe to handle.
- Not have corrosive properties.
- Not be expensive.
- The permanency of the wood preservative in the treated wood during various uses such as resistance to:
- Leaching by water.
- Rapid evaporation due to heat.
- Chemical conversion affected by oxidation, reduction and polymerization.
- Chemical or enzymatic action causing a dropping of toxicity level.
- The inflammability of treated wood should not intensify by the preservative.
- Ease of transportation over long distances in wood.

16.4 Types of Wood Preservatives

There are four main types of preservatives, viz., oil type, organic solvent type, non-fixed water-soluble type and fixed water-soluble type (Table 16.1).

16.4.1 Oil Type Preservatives

There are various oil type preservatives like creosote and coal tar creosote. The tar produces a brownish-black oily liquid obtained after the process of distillation or carbonization of bituminous coal. It can also be said as the distillate fractions of coal tar which boils at a temperature between 200 and 400 °C. It is an amalgamation of

Table 16.1 Preservative formulations over the years

Chemical complexes		Metallic complexes	
Chemical	Year	Chemical	Year
Creofixol	1919	Mercuric chloride	1705
Creosote oil + coal tar + petroleum	1920	Aczol	1907
Copper sulphate	1938	Boliden salt	1932
		Chromate zinc chloride	1934
		Zinc sulphate	1945
		Fluorine	Nineteenth century

complex organic compounds. The comparative amounts of it barely rely on the composition of the original coal tar and the process by which it was carbonized. Its advantages are high toxicity to wood destroying microbes, relative insolubility in water and low volatility, which impart to it a great degree of permanence under the most varied use conditions, ease of application, ease with which its depth of penetration can be evaluated, general obtainability and relative cost and long record of satisfactory use. Oil type preservatives comprise of vigorous chemicals, an insecticide or a fungicide, dissolved in an organic solvent, such as a petroleum distillate. Of the millions of organic chemicals, only less than ten can be used as active ingredients in the formulations. Application of these chemicals provides lifelong protection due to their natural insolubility in water. After evaporation of the organic solvent the active chemicals persist in the wood (Jun & Wenjin, 2009).

16.4.1.1 Creosote

Initially, the oil produced from the wood was termed as creosote. It has been recorded that coal tar creosote was the traditional wood preservative used enormously for more than fifteen decades. The oily liquid produced during the carbonization of bituminous coal is said to be creosote. This has a complex chemical composition which gets formed when it is boiled at an extremely high temperature of about 200 to 400 °C. It possesses numerous compounds such as hydrocarbons, tar acids and bases. It has an immense capability of preserving wood and its products and is hydrophobic in nature. As a result, resistant to leaching, noncorrosive to metals, and has a high electrical resistance; it protects timber against splitting and weathering (Gabriele, 2004). Creosote is usually applied by an empty-cell process and occasionally by hot-and-cold open tank process. These are actually very harmful to plants because of its strong odour and volatility. Hence creosoted timber isn't preferred to use in food containers. At certain times, other chemical complexes are bombarded with it in order to fortify by increasing its performance. The addition of 2% pentachlorophenol eradicates the decomposing of creosoted posts in the ground by *Lentinuslepideus*. Copper comprising preservatives are added in contradiction with the marine borer, *Limnoriatripunctata*. Insignificant quantities of arsenic trioxide are added to develop the preservative properties against termite attack. Creosote loading is 400 kg/m^3 in full-cell process and 140 kg/m^3 in empty-cell process (Jacoby & Freeman, 2008).

16.4.1.2 Lindane and Dieldrin

In the early nineteenth century, Lindane was discovered and was in use till 1940's as an effective insecticide which was not accumulating in the environment. It was used as a spray or dipping treatment of hardwood logs against *Lyctus* beetles in joinery treatments by immersion or double vacuum processes, and in situ remedial treatments against insect attack in buildings. Dieldrin was introduced in the year 1948 and is also being used as insecticide which is persistent in the environment. These are stable chemically, insoluble in water and is extremely toxic to insects. Dieldrin is applied in joinery treatments for protection against termites and also used mainly as water-based dispersion for soil pretreatments against termites. It is used as 0.8% solution in petroleum solvent (Morrell & Levien, 2000).

16.4.1.3 Copper 8-Quinolinolate

Copper 8-quinolinolate known as Copper-8 is a relatively new preservative. It is manufactured by condensation of copper 8-quinolinolate and nickel 2-ethyl hexoate. Copper-8 is yellow-brown solid and made soluble in organic solvents by nickel 2-ethyl hexoate to give a green solution. It is toxic to wood pests except termites, but relatively harmless to animals and plants. This preservative is applied in wood material used for food containers, refrigerators, seed boxes and greenhouse. Treatment solution should contain 0.045% Cu (Morrell & Levien, 2000).

16.4.1.4 Copper Naphthenate

The preservative used first in 1920s as 'Cuprinol' gives dark-green waxy solution in organic solvents and waxy solution in organic solvents and waxy wood surface prevents over-painting. It is toxic to wood pests except termites and non-corrosive to iron or steel. Copper naphthenate is mainly used as paint-on preservative for boat maintenance. Treatment solutions contain 1 to 2% Cu (Gjovik et al., 1981).

16.4.1.5 Bis (Tri-N-Butil Tin) Oxide

It is known as tributyl tin oxide, TnBTO, or TBTO, excellent fungicide, more effective than PCP, insoluble in water, soluble in many organic solvents. TBTO has lower toxicity to humans than PCP. This preservative is mainly used as fungicide in joinery treatments and as a general preservative for boat maintenance. TBTO is applied as 0.5 to 1.0% solutions (Brooks, 2000).

16.4.2 Organic Solvent Type

Organic solvent-based preservatives are different from the creosote. These are chemically active and are enormously efficient as fungicides and insecticides. Before applying the preservatives onto any surface of the wood, it should be dissolved in organic solvents (Dobbs & Grant, 1978). About two dozen of complexes were found as preservatives. It was especially used for the joinery timbers as water repellent. In addition to this wax and resins can also be used as water repellents. This shows a significantly higher degree of penetrability. It can also be applied under low vacuum or dipping. The most common organic solvent type preservatives are pentachlorophenol (PCP), benzene hexa-chloride (BHC), dichloride-diphenyl-trichloroethane (DDT), synthetic pyrethroids, metallic soaps, precipitated soaps and fused soaps.

16.4.2.1 Pentachlorophenol

Pentachlorophenol known as Penta or PCP is the utmost vital and extensively used fungicide of organic solvent preservatives. Commercial product manufactured by direct chlorination of phenol comprises about 85% PCP. It is extremely toxic to fungi, insoluble in water and resists leaching, non-volatile and non-corrosive to metals. Five percent solution of PCP in heavy oils is used in the treatments (Zarus, 2004). It has very low solubility in water and low volatility and is a very stable chemical, therefore it is the most promising and widely used preservative of oil borne chemical type (Matsunaga et al., 2009). It has been found ineffective against marine borers and never used for the protection of wood in salt water.

16.4.2.2 Synthetic Pyrethroids

The discovery of synthetic pyrethroids was done by the Rothamsted Experimental Station and was found it as an acceptable alternative for the chlorinated hydrocarbons. These are persistent and highly stable at the site of application, yet can be biodegraded and do not accumulate in the vertebrate body. They are having diverse acute mammalian toxicity; those with high mammalian toxicity were decamethrin. This indeed has remarkable insecticidal effectiveness which is usable at working concentrations and also considered as a safety standpoint. It is clear that synthetic pyrethroids are of great interest as potential wood preservative insecticides (Elliot et al., 1973).

16.4.3 Non-fixed Water-Soluble Type

Waterborne preservatives will let the surface of the wood relatively clean, paintable and devoid of objectionable odour. Among the water-soluble non-fixed wood preservatives are borax, boric acid, sodium pentachlorophenate, copper sulphate, mercuric chloride, and sodium fluoride and zinc sulphate. Although they are highly effective against fungi and insects, boron preservatives are not fixed; hence wood treated with boron salts cannot be used in contact with the ground or in wet conditions. These preservatives may further be categorized as.

16.4.3.1 Leaching Type

These are the salts (organic and inorganic) which are soluble in water (Mantanis et al., 2014). It is only used for the application on timber than on any others. They easily get leached when it is constantly exposed to rain water. Few preservatives which come under this category are:

- *Zinc chloride*: It is fairly lethal to fungal microorganisms and insects. But it is not an effective chemical complex to eradicate termites. It is hygroscopic in nature and also has fire-retardant properties.
- *Boric acid and Borax*: These are extremely toxic to almost all kinds of organisms which are encountered with timber. It has a very good penetrating property making it a very good preservative for wood and its products.
- *Sodium pentachlorophenate*: The water-soluble sodium salt of pentachlorophenol is enormously effective against the sap stain.

16.4.4 Fixed Water-Soluble Type

The fixed water-soluble type intended mainly for external use contains salts that service to fix the preservative chemicals in the wood and render them non-leachable. The most prolonged and effective protection has been achieved by the use of carefully balanced mixtures of copper, chromium and arsenic salts. These are the mixtures of various water-soluble salts with the addition of a fixative salt, usually sodium or potassium dichromate. Once the timber is treated it should be allowed to dry for 3 to 6 weeks of time for a complete fixation. These are used in impregnation of mine props, domestic buildings, food containers and cooling towers. It is preferred for structural elements which are not to be painted and do not have any odour. Concentration of the solutions is about 5%. Few preservatives which come under this category are copper chrome arsenic (CCA), acid cupric chrome composition (ACC), chromated zinc chloride (CZC) and copper chrome boron (CCB).

16.4.4.1 Ammoniacal Copper Arsenate (ACA)

It is known under the trade name of chemonite with the composition of copper hydroxide (Cu $[OH]_2$), arsenic trioxide (As_2O_3) and ammonia (NH_3). In the USA, it is a very well-known wood preservative and is also used to treat refractory softwoods. A slightly modified composition using ammonium hydroxide and arsenic trioxide was developed to treat timber by the Dip diffusion method. The preservative has given good indications of its use in the rural sector and treatment of wooden panels. Service records on chemonite-treated wood show that the preservative provides good protection against fungal decay and termites.

16.4.4.2 Acid Copper Chromate (ACC)

This product known as Celcure consisted of copper sulphate ($CuSO_4.5H_2O$), sodium dichromate ($Na_2Cr_2O_7$) and chromic acetate ($[Cr_2H_3O_3]\ H_2O$). Wood products which are well impregnated with the Celcure have potential anti-termite activity. It shows a commendable resistance against marine borers too.

16.4.4.3 Copper Chrome Arsenic (CCA)

It was initially developed by Kamesam (1933) as a preservative which comprises hexavalent chromium, copper and inorganic arsenic or [$CuSO_4.5H_2O$ (3%) + $Na_2Cr_2O_7/K_2Cr_2O_7$ (4%) + $As_2O_5.2H_2O$ (1%)]. During 1940s, in CCA, copper is the primary fungicide, arsenic is a secondary fungicide and insecticide and chromium is a fixative. CCA is a preservative that was extremely common for many decades as it is having high solubility in water and also it was used to pressure treat lumbers. In the 1970s, it was widely used for residential wood such as picnic tables, decks, fencing, landscaping timbers, etc. Environmental impacts on the use arsenic are of concern as this chemical may leach from the wood into surroundings and soil resulting in toxicity to bio-organisms. Excessive use of arsenic-based preservative is posing serious problems to the environment. Kenneth (2000) reviewed the environmental impacts of arsenic. Long (1997) reviewed the arsenic leaching from pressure-treated wood. Environmental Protection Agency (EPA) and US Consumer Products Safety Commission (USCPSC) assessed the toxicity of arsenic. In 2003, the EPA phased out CCA as it had the potential to cause irreversible damage to human beings.

16.4.4.4 Copper Chrome Boric Composition (CCB)

This was also developed by Kamesam in 1943. It has a chemical composition of copper sulphate ($CuSO_4.5H_2O$), boric acid (H_3BO_3), potassium di-chromate ($K_2Cr_2O_7$) in the ratio [$CuSO_4.5H_2O$ (3%) + $Na_2Cr_2O_7/K_2Cr_2O_7$ (4%) + ($H_3BO_3$1.5%)] by weight. It came into existence as a substitute for CCA as the arsenic was too costly and environmental impacts of arsenic and its high toxicity compared to boron. But CCB, due to its leachable nature, it is only effective when being applied at comparatively higher doses.

16.4.4.5 Chromated Zinc Chloride (CZC)

The preservative is composed of sodium dichromate ($Na_2Cr_2O_7$) and zinc chloride ($ZnCl_2$) in the ratio (81.5:18.5).

16.4.4.6 Fluoro-Chrome-Arsenate-Phenol (FCAP)

These Wolman-type preservatives are mixtures of sodium fluoride and chromate, sodium arsenate and 2,4-dinitrophenol. 2,4-dinitrophenol has recently been replaced by sodium pentachlorophenate to eliminate the yellowing of treated timber. FCAP-type preservatives have been marketed under a wide number of formulations and trade names. They are Triolith, Minolith, Fluoxyth, Flunax, Tanalith U, Triolith U, Basilit UA, Osmolit U, Osmolith UA, Wolmanith UA, Trioxan U and Trioxan UA.

16.5 Wood Coatings

16.5.1 Antiweathering Chemicals

When wood is exposed to the weather unprotected, its appearance soon deteriorates. Continuous wetting and drying causes cracking and splitting, ultraviolet light degrades and breaks down wood in the surface to give products which can be washed away by the rain. Fungi and moulds also growing in the cracks and splits cause the timber to appear dirty.

16.5.2 Paints and Varnishes

Paints and varnishes give the most effective means of maintaining the appearance of wood, provide that they completely cover the wood and they are not damaged in any way. The transparent film of varnish protects the wood from getting wet and screens the surface from damaging by ultraviolet light. Unfortunately, while these coatings give good protection against rainfall, they are unable to prevent changes in moisture content resulting from seasonal fluctuations in atmospheric relative humidity. As a result, the painted wood will shrink or swell with changes in relative humidity, causing the surface coating to crack and split. Water penetrates into the wood and then staining fungi and moulds begin to colonize the surface. In a study conducted in England only 6% of over 200 varnishes tested presented uninterrupted defence for more than 1 year. Maintenance is generally essential with expensive cleaning and varnishing (Williams, 1999).

16.5.3 Water Repellents and Stabilisers

These are used to surface coat the pores of structural material to prevent the absorption of water. This will retard the ingress of water when wood is exposed above the ground. These preservatives reduce the dimensional changes in the wood as a result of moisture changes when the wood is exposed to rainwater for short periods of time. Various substances like waxes, especially paraffin waxes are the well-known water repellents used in wood preservative formulations. The aliphatic and aromatic hydrocarbon resins are inexpensive and efficient but solidify only by loss of solvent, re-dissolve by coating solvents. Natural drying oils, such as linseed oil, can also be used. Generally, a mixture of waxes, hydrocarbon resins and alkyd resins are used in order to prevent these problems. The organo-silicon compounds are the best-known water repellents but they possess many of the disadvantages of heavy organic oils and waxes. The silicones with a high degree of functionality to fix to the wood components are suitable to apply the wood giving good resistance to wetting failure (Leach & Zhang, 2004). Organo-aluminium compounds can incorporate unsaturated chains, and water repellent they can provide excellent adhesive bonding between the wood elements and alkyd systems (De Vetter et al., 2010). Commercial Manalox products are polyoxoaluminium systems. Formaldehyde treatment of wood in the presence of an acid catalyst will crosslink hydroxyl groups on adjacent chains, reducing the dimensions of wood and also the movement (Lloyd et al., 1990). Acetylation, the treatment of wood with acetic anhydride in the presence of a strong acid catalyst considerably reduces the hygroscopicity of wood and increases the resistance to fungi. These chemical treatments are successful on condition that wood is completely impregnated. Impregnation of wood with a high retention of chemicals is called bulking. Some resin systems were used in systems was used in this way as in impregnation. Polyethylene glycol waxes, such as PEG, Carbowax and MoDo, are also used in bulking. These systems are applied particularly for the stabilization of archaeological specimens and also floor blocks. Of the water-repellent formulations, the Madison formula is the best known. The formula consists of paraffin wax, pigments and boiled linseed oil binder with pentachlorophenol and zinc stearate to give water repellency, colour retention and resistance to staining by fungi and moulds. Weather resistance can be improved by using a binder as in Madison formula. In the Royal process developed for the treatment of external joinery a waterborne treatment is followed by a deep treatment with a drying oil (Mantanis, 2017).

16.6 Development of Wood Preservatives

Efforts were being put to keep away the wooden pillars from the soil and vegetation by placing them on the stone blocks. Eventually, uses of essential oils were being practised in order to protect the wood against the biological deteriorators. M. Paulet in his book entitled "conservation des Bios" enumerates 173 processes or methods that were tried, most of which proved unsuccessful. During the first quadrate of the nineteenth century, the wood samples were injected with the chemical preservatives. The need for developing preservation stemmed out of acute scarcity of wood for building ships by the British Navy (Boulton, 1885).

- **Mercuric chloride** was used by Homberg in 1705 and by De Boissiew in 1967. The use is commonly called 'kyanizing' (Boulton, 1885).
- **Copper sulphate** recommended by De Boissiew and Bordenava in 1967 and best known as 'margaryzing' (Boulton, 1885).
- **Chloride of zinc** recommended in 1815 by Thomas Wade and by Boucherie in 1837 and referred as 'burnettizing' (Boulton, 1885).
- Oily liquid preservatives used earlier were Creosote oil, carboleneum and shale oil, respectively. These wood preservatives were suggested by Hutin and Boutigny in 1848 (Boulton, 1885).

Chemical companies have moved towards the development of safer, less toxic biocides. The process of preservative development is long, taking 5 to 7 years for standardization in many countries and often requiring several years beyond that time for the development of substantial commercial use. Despite the high costs associated with these developments, a variety of biocides have recently been developed. Many are variations on existing chemicals employed in agriculture, but several have been developed specifically for wood protection. In addition, a number of older, more expensive compounds have received renewed interest (Freeman et al., 2003).

16.7 Organic and Inorganic Compounds as Wood Preservatives

Boron as borax, boric acid or disodium octaborate tetrahydrate are used as fire retardants in wood. Copper as copper carbonate, copper hydroxide, copper oxychloride, copper sulphate, cuprous oxide and copper hydroxycarbonate.

Chromium as chromium trioxide or sodium dichromate is used as admixtures in water-soluble preservatives salts. Arsenic as arsenate is used in CCA (inorganic compounds). Chlorinated phenols, chlorinated cresols and xylonols, chlorinated napthalenes, nitrated phenols and cresols, chlorinated benzenes, di-chlorodiphenyltrichloroethane (DDT) and organic mercury compound (organic compounds).

16.8 Recent Trends in the Development of Wood Preservatives

Older preservatives still account for a high percentage of the total volume of usage (Baechler, 1963). Wood, upgraded with ethanolamine, has increased fungicidal resistance (Humar et al., 2007). Eucalyptus grandis sapwood treated with chromated copper arsenate (CCA), used engine oil and neem extract provided better protection against termites. Borates are good wood preservatives for the protection of wood from decay fungi and a wide variety of insects. The only drawback was they can also be readily leached from wood under certain conditions (Freeman et al., 2003). Pre-acid treatments (sulphuric acid and phosphoric acid) with pressure was more effective for increasing of retention of both CCA and ACQ than non-pressure methods of application (Yildiz et al., 2010).

The traditional preservatives included di-decyldimethyl ammonium chloride (DDAC) and copper (II) sulphate pentahydrate ($CuSO_4.5H_2O$). The new-generation preservatives included Ammonicalcopperquat (Celcure AC 500) and micronized copper quat (MCQ). Observations on characterized changes to the surface of the all weathered samples in terms of colour change and surface roughness indicated that the treatment with new generation preservatives provided less colour change than traditional preservatives (Ozgenc et al., 2012). Vacuum treatment of pine wood with zinc oxide, zinc borate and copper oxide nanoparticles showed only nano-zinc borate was effective while the other nano-metal preparations did not inhibit mould fungi (Mantanis et al., 2014). It is essential to protect wood from degrading factors like decay, insects and fire; as well as to educate the consumer regarding new wood-treating chemistries and new products (Kaur et al., 2016).

Tripathi (2013) developed an ecofriendly wood preservative ZiBOC ($ZnCl_2$: $Na_2B_4O_7.10H_2O$:$CuSO_4.5H_2O$) which is comparable with CCA in exterior condition. Tripathi et al. (2018) studied the durability of the three timbers used in cooling towers viz., *Pinus roxburghii*, *P. radiata* and *Pseudo tsugamenziesii* as well as assessed the efficacy of three preservatives viz., ZiBOC, CCB and CCA at 2, 4 and 6% concentrations. The wood samples were reviewed and found that all three species of wood were naturally non-durable and 4% of preservative concentration was found to be its threshold level. ZiBOC exhibited maximum retention when compared to the conventional preservatives (CCA, CCB) and also the durability increased significantly.

16.9 New Generation Wood Preservatives

There are few biocides/wood preservatives which are found out to be effective and progressive against the wood degrading agents, namely:

16.9.1 Borates

These are basically considered as unfixed water-based preservatives. They include formulations prepared from sodium tetraborate, sodium pentaborate and boric acid, but the most common form is disodium octaborate tetrahydrate (DOT) (Freeman et al., 2009). Borates are used for pressure treatment of framing lumber used in areas of high termite hazard, such as Hawaii, and as surface treatments for a wide range of wood products, such as log cabins and the interiors of wood structures. They are also applied as supplemental internal treatments via rods or pastes. At higher retentions, borates are used as fire-retardant treatments for wood. Boron has some important advantages, including low mammalian toxicity, activity against both fungi and insects, and low cost. Another advantage of boron is its ability to move and diffuse with water into wood that normally resists traditional pressure treatment. Wood treated with borates has no colour or odour, is non-corrosive, and can be finished. While boron has many potential applications in framing, it is not suitable for applications where the wood is exposed to frequent wetting unless the boron can somehow be protected from liquid water. In some countries, such as New Zealand, boron can be used in applications where occasional wetting occurs and there is interest in the use of borates in slightly more exposed applications with coating requirements. There is also interest in dual treatments, in which borate treatment is followed by pressure treatment with a water-repellent oil-type preservative. Various combinations of silica and boron have been developed that appear to somewhat retard boron depletion, but the degree of permanence and applicability of the treated wood to outdoor exposures has not been well defined (Anon, 2005).

16.9.1.1 Complex Metal-Based System

Copper Naphthenate

It is an organometallic compound that is a dark-green liquid and imparts this colour to the wood. The treated wood changes its colour to light brown upon weathering. The wood may vary from light brown to chocolate-brown if heat is used in the treating process. Copper naphthenate is effective against wood-destroying fungi and insects. It has been used commercially since the 1940s for many wood products. It is a reaction product of copper salts and naphthenic acids that are usually obtained as byproducts in petroleum refining. Copper naphthenate is not a restricted-use pesticide but should be handled as an industrial pesticide (Hunt & Garratt, 1967).

Zinc Napthenate

It is used extensively as a component in over-the-counter wood preservative products. It can be formulated as either a solvent-borne or water-based preservative. Unlike copper naphthenate, zinc napthenate imparts little colour to the wood and thus is more compatible with transparent finishes. When zinc naphthenate is formulated in light solvent, the treated wood may also be paintable. But, wood treated with zinc naphthenate may have a noticeable odour, limiting its indoor use. Zinc is not as effective a fungicide as copper, and zinc naphthenate is not typically used as a stand-alone preservative for exposed structural members. Zinc naphthenate has some preservative efficacy, and it may be sufficient to protect wood used aboveground and partially protected from the weather. In Mississippi, zinc naphthenate pressure treatments have been shown to extend the life of exposed stakes, and brush treatments of a water-based zinc naphthenate significantly improved the performance of pine fully exposed to the weather. Zinc naphthenate, however, was less effective in protecting hardwoods. The addition of a water-repellent component to the treating solution appears to increase the efficacy of zinc naphthenate treatments (Lloyd & Fogel, 2005).

Bis (Tri-N-Butyltin) Oxide (TBTO)

Bis (tri-n-butyltin) oxide, commonly called TBTO, is a colourless to slightly yellow compound which is soluble in organic solvents but insoluble in water. This preservative has lower mammalian toxicity, causes less skin irritation, and has better paintability than pentachlorophenol, but it is not effective against decay when used in ground contact. Therefore, TBTO is recommended only for aboveground use, such as millwork. It has been used as a marine antifoulant, but this use has been almost eliminated because of the environmental impact of tin on shellfish (Shiozawa, 1991).

16.9.2 Quaternary Ammonium Compounds

16.9.2.1 Didecyldimethylammonium Chloride (DDAC)

It is a compound that is effective against wood decay fungi and insects. It is soluble in both organic solvents and water and is stable in wood as a result of chemical fixation reactions. It is currently being used as a component of ammoniacal copper quat (ACQ) for aboveground and ground contact (Kartal et al., 2005).

16.9.3 3-Iodo-2-Propynyl Butyl Carbamate (IPBC)

It is a preservative that is intended for nonstructural, aboveground use only (Ex: Mill work). It is not used for pressure-treating applications such as decks. The IPBC preservative is included as the primary fungicide in several water-repellent-preservative formulations under the trade name Polyphase and marketed by retail stores. However, it is not an effective insecticide. Waterborne and solvent-borne formulations are available. IPBC is also being used in 14:9 combination with didecyldimethylammonium chloride in a sapstain–mould formulation. IPBC contains 97% 3-iodo-2-propynyl butyl carbamate, with a minimum of 43.4% iodine (Kartal et al., 2005).

16.9.4 Polymeric Xylenol Tetrasulphide (PXTS)

It has been listed by the American Wood-Preservers Association as an oil-borne treatment. It has low toxicity to mammals and the available data shows good efficacy. Thus, this could be used as a replacement for creosote or other oil-type preservatives.

16.9.5 Azoles

16.9.5.1 Cyproconazole

It is a water-based fungicide used to protect above-ground wood. Cyproconazole does not protect wood from insects. Although cyproconazole is used as a fungicide on some crops, many of the wood preservative formulations are not intended for use on wood that comes in contact with food. Some cyproconazole wood preservatives also contain the antimicrobial didecyldimethylammonium chloride (DDAC). Cyproconazole has been approved by EPA for surface application or pressure treatment of wood for above-ground uses, including siding, plywood, millwork, shingles, lumber and other uses (Nicholas & Schultz, 1994).

16.9.5.2 Propiconazole

It is an organic triazole biocide that is effective against wood decay fungi but not against insects. It is soluble in some organic solvents, but it has low solubility in water and is stable and leach resistant in wood. It is currently being used commercially for aboveground and sapstain control application in Europe and Canada.

16.9.5.3 Tebuconazole (TEB)

It is an organic triazole biocide that is effective against wood decay fungi, but its efficacy against insects has not yet been evaluated. It is soluble in organic solvents but not in water, and it is stable and leach resistant in wood. Currently, TEB has no commercial application.

16.9.6 Agrochemicals

16.9.6.1 Chlorothalonil (CTL)/[Tetrachloroisophthalonitrile]

It is an organic biocide that is used to a limited extent for mould control. It is effective against wood decay fungi and wood-destroying insects. The CTL has limited solubility in organic solvents and very low solubility in water, but it exhibits good stability and leach resistance in wood. This preservative is being evaluated for both aboveground and ground contact applications.

16.9.6.2 2-(Thiocyanomethylthio) Benzothiozole (TCMTB)

It has been used for many years as an anti-sapstain formulation and millwork preservative. It has been formulated in both solvent-based and water-based forms; the solvent-based formulation is more prevalent for the treatment of millwork.

16.9.6.3 Isothiazolones

These are a class of organic compounds often used for mould control. They are sometimes added to wood preservatives for this purpose and are also used as additives to paints and coatings. One of these compounds, 4,5-dichloro-2-*N*-octyl-4-isothiazolin-3-one (DCOI), has been evaluated fairly extensively and is currently used as a marine anti-fouling agent in paint films. As with other oil-soluble preservatives, the properties of wood treated with DCOI are somewhat dependent on the type of solvent used. The treatment may impart a light brown colour to the wood. DCOI has a noticeable odour and the treated wood may have some odour, depending on the concentration of the treating solution. In some applications, skin sensitization can be a concern (Nicholas & Schultz, 1994).

16.9.7 Uncomplexed Copper Systems

16.9.7.1 Alkaline Copper Quaternary (ACQ)

It is one of a number of recent water-based preservatives developed to address environmental concerns about the use of arsenic and chromium in treated wood. Several formulations of ACQ have been developed and marketed but all share a similar composition. The active fungicide and insecticide components in all ACQ formulations are copper and the quaternary ammonium compounds ('quats'). Copper provides the primary fungicide and insecticide activity in ACQ formulations, while the quaternary ammonium compounds ('quats') provide additional protection against copper tolerant fungi and insects. Alkaline formulating agents, particularly ammonia, have the ability to swell wood cell walls and so improve the penetration of chemicals into wood.

16.10 Environmental Impacts of Wood Preservatives

Preservatives meant to use for outdoors have certain techniques in order to retain the active ingredients in the wood to curtail the leaching activity. But, some amount of active component present in the wood preservatives usually leaches out from the wood. The intensity of leaching of wood barely depends on factors like fixative conditions, preservative retention, exposure, size and shape of the wood. Active constituents present in wood preservatives are lethal to numerous living organisms considerably at a higher concentration. But, laboratory studies indicate that the levels of preservatives leached from treated wood generally are too low to create a biological hazard. Almost all kinds of wood treated with preservative release some quantities of active constituents to the environment. These constituents can be found in soil or sediment samples too (Lebow, 2010).

United State Environmental Protection Agencies (USEPA) were using preservatives like lumber creosote, inorganic arsenical and pentachlorophenol for the treatment. It was realized that the pentachlorophenol and inorganic arsenicals were hazardous to human beings and was even restricted not to use as preservatives but as pesticides at a limited range. The wood treated with CCA should not be burnt, as the smoke was extremely lethal to human being. The nymphs of *Potamanthusluteus* collected from the badly contaminated site of Kymijoki River, Southern Finland in 1997 had generally darkened gills, probably specifying impacts of pollution (Dobbs & Grant, 1978). Significantly lower lymphocytes, white blood cell count and serum globulin were recorded in the wood treatment plant—neighbours who were in consistent exposure with pentachlorophenol and dioxin (Heikkila et al., 1987). An extensive evaluation on CCA-related cancer risk was conducted by the Environmental Risk Management Authority of New Zealand (ERMANZ) in 2003. The studies comprised of five major studies which were updated as the human cancer potency factor developed by the National Academy of Sciences Natural Research Council in 2001. It was reported that the CCA treated wood containing inorganic ions were indirectly increasing the leaching activity. The pH of the water can also affect the leaching of the preservatives. Leaching of CCA significantly increases when the pH of the leaching water is dropped to below 3, and the wood itself also initiates to degrade. Wood preservatives can be harmful to humans if not properly handled. The exposure routes by which they can enter the human body are inhalation (vapour, dust, aerosol, etc.), ingestion (solid and liquid), ocular exposure and through the skin (vapour, liquid and solid). A number of studies have examined the effects of wood preservatives on settlement patterns, growth and biomass development of human of environments. The majority of leaching from wood when treated with waterborne preservatives, the rate and overall amount of leaching from a given product is also affected by preservative penetration and retention and by the surface area of the product (Marer & Grimes, 1992). Randerath et al. (1996) warned that about 250 wood preserving sites are present only in the United States, wherein it requires immediate remediation. These sites consist of WPW (Wood preserving waste) chemicals which are lethal to living beings. They are carcinogenic, mutagenic, neurotoxic, immunotoxic, hematoxic and hepatotoxic. It also causes skin and mucous membrane irritation. The waste discharges and the emissions from these sites produce an immense amount of naphthalene, benzene and PAHs. Due to these emissions, neighbourhood environment would be polluted. The affected individuals possess symptoms like nausea, eye and throat irritation.

Utilizing chemical preservatives do show toxicity against a wide spectrum of microorganisms, but it affects human health as well. Even the most benign chemicals present in surplus may pose health hazards on prolonged contact. Nevertheless, the preservatives recommended for a particular use are carefully assessed for their possible hazards to the environment as well as workers exposed to the same. In the upcoming days, care needs to be taken with respect to the disposal of preservatives. The general phobia that CCA formulations containing arsenic are dangerous and those containing chromium are carcinogenic has no scientific or practical data to support the same. The new formulations containing the so-called environmentally safe molecules are not hazard-free. Pentachlorophenol and its sodium salt were used to protect wood against sap stain, was found to contain some dioxins and their use has been restricted in many countries. One of the substitutes recommended was TCMTB (2-(thiocyanomethylthio) benzothiazole), which is a much expensive chemical. If one goes through the MSDS (Material Safety Data Sheet) of this chemical, it is reported that contact with eyes can produce permanent blindness. Chlorpyriphos is another chemical introduced a few years back for termite control in soil poisoning and recommended as an insecticidal component in light organic solvent type preservatives which was also found to be affecting the nervous system of children (Taylor & Cooper, 2003).

Application of preservatives like copper chrome arsenic (CCA), copper chrome boric acid (CCB), ammoniacal copper zinc arsenate (ACZA), ammonical copper quaternary (ACQ) and ammoniacal copper citrate (ACC) had impacted the settlement of barnacles, oysters and bryozoans (Tarakanadha et al., 2002). Wood treating plants released naphthalene in large amounts in the atmosphere. It has been found that the plant produced around 2.2 mg/m^3 of the total 3.7 mg/m^3 of airborne creosote vapour in the work area. The chemical waste disposed from the wood preservatives causes an irreversible damage to the DNA. There are around 12 chemical constituents present in the vapour phase of creosote like naphthalene, methyl naphthalene, indene, methyl styrene, toluene, xylene, phenol, benzothiophene, di-phenyl, acetanapthalene, creosols and xylenols, respectively. Long-term low-level exposure of these chemicals will cause neurological symptoms and abnormalities to the exposed subjects at the genetic level. The use of natural materials such as traditional tar, wood oils, tannins and plant extracts for wood preservation can solve this problem to a considerable extent (Lebow, 2010).

16.11 Strategies

(a) Use less preservative; comply with regulations and guidelines at all stages of the life cycle for certain preservatives.
(b) Reduce use of arsenic, chromium, creosote and pentachlorophenol containing preservatives and probably in the longer term, copper-containing preservatives. In parallel with this, the trend is for introduction of a much broader suite of alternatives, with main focus on organic preservatives.
(c) Popularization of eco-friendly wood preservatives.
(d) Recover inorganic preservatives from treated wood by collecting and treating ashes and condensate from co-generation or incineration facilities (Italy and Finland).
(e) Require manufacturers to take full life responsibility for their products (Cooper, 1999).

16.12 Wood Preservative Treatment Methods

It is necessary for wood to be treated with the appropriate preservatives for the protection against the bio-deteriorating organisms. Wood like rubber wood is highly susceptible to almost all kinds of fungi, insects, and termites and so on. Untreated logs are very prone to attacks by the fungi and borers. The action of these kinds of bio-deterioraters makes the wood less attractive and in turn makes it of less or no use. The wood therefore needs to be treated with the preservatives which are cost-effective and less harmful to the environment (Kumar & Dev, 1993).

The application of wood preservatives can be categorized into two types:

(a) Non-pressure treatment.
(b) Pressure treatment.

16.12.1 Non-pressure Treatment Method

Non-pressure processes are carried out without the use of artificial pressure under the atmospheric pressure. There are around six methods under non-pressure treatment namely

16.12.1.1 Brush Coating

The simplest method of applying a preservative is brushing and is normally used for preserving small individual items as shown in Fig. 16.1. Brushing is a convenient

Fig. 16.1 Brush coating of samples

way of applying a wood preservative to small individual items and it is desirable to apply preservative to timber already in situ in a building (Findlay, 1985).

16.12.1.2 Spraying

Spraying is a convenient method of applying preservatives to any large areas (Findlay, 1985). Spraying offers more liberal and effective covering of the timber than brushing. The possibility of the preservative penetrating into wood is more in spraying compared to brush coating. Brush application is perfectly satisfactory when it is necessary to apply a superficial coating of a high viscosity fluid, such as a paint or varnish but even then, the loading on the wood surface is only about 25% of that which can be achieved by a simple spray application (Richardson, 1978).

16.12.1.3 Dipping

This method consists of immersing wood in a preservative solution for 2–3 days as shown in Fig. 16.2. It allows better penetration into wood compared to brush coating and spraying. There is little protection against termites and it is not recommended for wood used in contact with the ground.

16.12.1.4 Hot and Cold Open Tank Method

In this process timber is immersed in a bath or preservative which is heated for few hours and allowed to cool while the timber is still submerged in the liquid. During the heating period the air in the cells expands and much of it is expelled as bubbles. During the heating period the air in the cells contracts creating a vacuum and the preservative is drawn into wood. Therefore, the absorption takes place during the cooling period.

Fig. 16.2 Dipping of samples

16.12.1.5 Sap Displacement Method

Sap displacement method can only be applied to green round timbers and bamboo. It uses the hydrostatic pressure due to gravity to force the wood preservative from the butt end of the round timber. It is made to flow along the length of the wooden pole along the flow of sap stream as shown in Fig. 16.3a, b. The poles to be treated are made to stand inclined or vertical in solutions of water-soluble wood preservatives for 2 to 4 days and thereafter inverted for the same period of time (Tewari et al., 1967). This is an excellent and very simple onsite treatment standardized at Institute of Wood Science and Technology, Bangalore. Rural people, who cannot afford to follow any one of the above treatments, can employ the simple sap displacement technique for treating green bamboos/poles. This is done by keeping the butt end of freshly felled bamboos with in a tub containing the preservative solution (6 to 8%) to a depth of 30 to 40 cm after 24 to 48 h the bamboos/poles are reversed with the top end submerged in the solution. They can be removed after 24 to 48 h of reversal.

After the treatment, bamboos/poles must be stored in a rack under the roof to avoid direct sunlight and rain for at least 2 weeks. The bamboo/poles must be stored in shades. The rack must support bamboo in horizontal not in vertical position. If bamboo dries in vertical position the preservative solution may leak out. During these periods of slow drying process, the preservative will diffuse from sap to the surrounding tissue of the bamboo with preservatives like CCA and CCB get fixed. Green bamboos cut fresh in the farm can be treated by sap displacement within 24 to 48 h, from the time of felling. If there is delay between felling and treatment the latter can be taken up by keeping felled green bamboos soaked in fresh water tank, stream, channel or trough for a period ranging from 1 to 2 days. Bamboo treated in green

Fig. 16.3 Sap displacement treatment method (**a**) Eucalyptus poles treated by sap displacement; (**b**) Bamboo poles treated by sap displacement

condition was found effective against the attack of fungi and wood-boring insects. These insects cause severe damage in untreated bamboo which eat the nutritious materials inside the bamboo and weaken the bamboo structures.

16.12.1.6 Diffusion Treatment

Diffusion treatment with boron compounds is one of the simplest, cheapest and effective ways of protecting wood from biodegradation (Dhamodaran & Gnanaharan, 1996). Preservative treatment of wood by diffusion involves the movement of molecules by random motion from regions of high concentration to regions of lower concentration. This is a typically slower method of treatment. This involves some uptake of preservative by bulk flow and thereafter preservative is further distributed by diffusion.

16.12.2 Pressure Treatment

Pressure treatment processes are carried out by applying a positive external pressure to force the liquid into the pores of the wood (Findlay, 1985). The wood is placed into an airtight cylinder and immersed in a preservative as shown in Fig. 16.4. By increasing the pressure drives the chemical into the wood. There are several types of high-pressure processes namely.

16.12.2.1 Bethel or Full Cell Process

This is the normal process used when treating with water-born solutions. The main steps in the full cell process are:

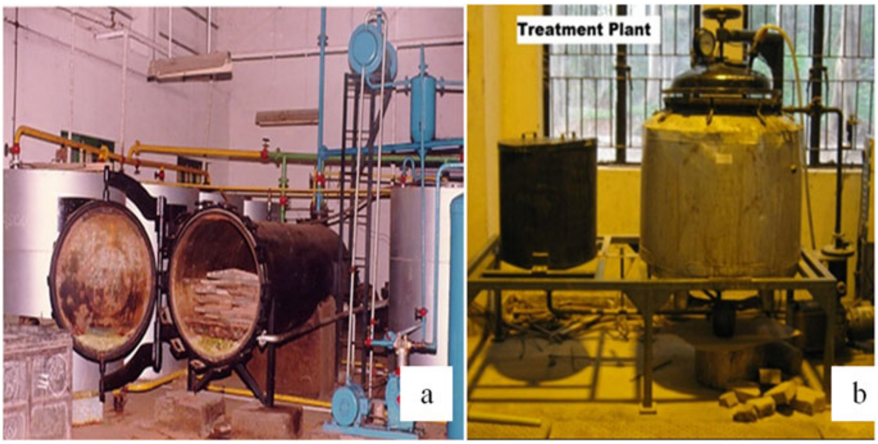

Fig. 16.4 Pressure treatment method: (**a**) pressure treatment cylinder (large scale); (**b**) pressure treatment cylinder (small scale)

(a) The charge of wood sealed in the treating cylinder, and a preliminary vacuum is applied for 30 min or more to remove the air from the cylinder and as much as possible from the wood.
(b) The preservative, previously heated to somewhat above the desired treating temperature, is admitted to the cylinder without admission of air.
(c) After the cylinder is filled pressure is applied until the required preservative is obtained.
(d) When the pressure period is completed the preservative is withdrawn from the cylinder (Wallinger et al., 1974).

16.12.2.2 Empty Cell Process

There are two main types of empty cell processes which are called ruepning and lowery processes. In both processes there is no initial vacuum applied, the preservative is forced into the wood under pressure and subsequently a vacuum is applied to remove the excess of the preservative. This process is normally used with tar oil preservatives. The main steps in the ruepning process are (1) preliminary air pressure applied (2.0–5.0 kg/cm^2), (2) fill cylinder/hold air pressure, (3) build up pressure, (4) maximum pressure held, (5) release pressure, (6) empty cylinder of preservative, (7) final vacuum period and (8) release vacuum.

Pressure treatment of wood is performed in steel pressure cylinders or vessels which range in size from 1.5 m to 3 m in diameter and up to 20 m in length, and are capable of withstanding pressures up to 14 bars. The cylinders are normally mounted on saddle blocks, and equipped with instruments which measure and record processing temperatures/vacuums and pressures. Vacuum pumps and pressure pumps capable of applying vacuum of more than 600 mmHg and pressure of up to 14 bars, respectively are part of the necessary equipment. In addition, preservative storage and mixing tanks are also required, and are normally in the form of steel cylindrical tanks. In Malaysia, the commonly used pressure process for impregnating wood with preservatives against fungal decay and insect attack is the vacuum-pressure process (also known as the Bethell process). The oscillating pressure method (OPM) is also being used. The OPM which rely on the quick changes of vacuum and pressure phases is generally fully automatic in operation, whereas the vacuum-pressure process is mostly semi-automatic. There is a trend now for preference of the automated process for increase in efficiency and efficacy of treatment. The main steps in the lowery process include: (1) fill cylinder with preservative at atmospheric pressure, (2) build up pressure, (3) maximum pressure held, (4) release pressure, (5) empty cylinder of preservative, (6) final vacuum preservative and (7) release vacuum.

16.12.2.3 Boucherie Process

Dr. Boucherie of France developed this process in 1838 for treating green timber or bamboo. This is the most commonly used sap displacement technique where we can treat bamboo quickly in large number. A suitable container is taken for keeping the water-soluble treating solution. The container is provided at the bottom with side tubes fitted with stopcocks and rubber tubes to which green bamboos (along with

Fig. 16.5 Regular and modified Boucherie treatment process

branches) are attached as shown in Fig. 16.5. In order to secure leak-proof contact between the rubber tubes and the bamboos a suitable metallic clamps or other devices are provided. The tank is also fitted with a screw cap which has a suitable valve attached to it. The tank is then filled with treating solution to about two-thirds of its volume and after tightening the cap; air is pumped in through the valve to a pressure of 1.0 to 1.4 kg/sq.cm. It is easily measured by pressure gauge. At this pressure range, the treating liquid forces the sap out of the walls and the preservative displaces the sap, which is then forced out at the narrow end. The treatment is stopped when the colour of the preservative in the drip is nearly the same as that of the solution in the reservoir. After a few preliminary experiments, the concentration of the treating solution and the period of treatment are fixed to obtain requisite absorption of the preservatives and the poles/bamboo is taken off when the treatment is complete (Grover, 1957). The whole treatment will complete within 4 to 8 h.

16.13 Conclusion

The great variety of wood-destroying insects and fungi in the environment constitutes a much greater danger for wood. High temperature and high atmospheric humidity, together with the extraordinarily large number of nondurable wood species are vulnerable to degradation. A considerable amount of this value could be saved through expanding the preservative treatment of wood. Wood preservation makes it possible to reserve precious durable species. Employing chemical complexes as wood preservatives could reduce the impact caused by the bio-deteriorators. Nevertheless, the preservatives obtained from the naturally available plants and its products are more efficient, eco-friendly and need to be produced in large quantities. The major issue for the future is to develop more understanding on the chemistry and different treatment mechanism of wood, in order to help researchers reach a balance between the treatment effectiveness, the global environmental health impacts and the economic costs of the process. By utilizing the wood preservatives very cautiously and also by considering the environmental impacts, the harm caused to the beings living around can be reduced.

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Potential of Botanicals for Wood Protection 17

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https://doi.org/10.1007/978-981-16-8797-6_17

Abstract

The current concern in the field of wood protection is to replace the use of toxic chemicals with natural means of wood protection. Initiatives have been undertaken by the researchers globally to replace toxic chemical methods of wood protection with natural plant derivatives such as essential oils, tannins, and extracts. Derivatives from a range of plant taxa and from various plant parts, such as heartwood, bark, leaves, seeds, and fruits, have been examined for their wood protection properties, and the information is reviewed in this chapter. Combination of natural extracts with cooper and boron salt mixture as wood protectants has been encouraged. However, only few products obtained from plants such as linseed oil, pyrethrum, neem, rotenone, and copperized neem oil are in use. This chapter summarizes a range of promising potential plant extracts and exudates and plant-based products for wood protection, highlighting the gaps in the studies. The advantages and prospects of emerging environmentally friendly wood protection technologies, such as nano, gene, plasma, and wood modification with nanotechnologies, are discussed in this chapter.

Keywords

Bioactive compounds · Bio-oils · Essential oils · Extractives · Nanotechnology · Wood modification

17.1 Introduction

Wood is a sustainable and renewable primary product that continues to be used to produce timber and secondary products. However, wood being a lignocellulosic material composed of lignin, cellulose, hemicelluloses, and small amounts of pectin is susceptible to biodegradation by different biodegraders such as fungi, insects, and termites, which break down plant cell wall polymers by cellulases and hemicellulases (Eaton & Hale, 1993). Therefore, wood is required to be protected with environmentally friendly and biodegradable substances that can ensure longer service life and safe disposal of wood products. Treated wood is a low-cost and effective structural material for construction that can contribute to a sustainable future of the society (FAO, 2016).

Since decades, synthetic oil-based, e.g., creosote and water-based, wood preservatives such as chromated copper arsenate (CCA), chromated copper borate (CCB), alkaline borates, copper azoles, and naphthenates have gained global acceptance due to their efficacy (Asamoah et al., 2011). The retentions of CCA greater than 6.8 kg m^{-3} have been evaluated to increase the service life of the timber over 50 years (Jankowaky et al., 2012). However, the revaluation of chromated arsenical products as wood protectants by the Environment Protection Agency (EPA) of the USA has phased out their uses around residential areas because of adverse effects on human health and environment (Groenier & Lebow, 2006). The hazardous impact of these chemicals has propelled researchers to explore natural, efficient, and cost-effective approaches of wood protection. However, certain limitations including variability between laboratory and field performance of natural products, variability in their efficacy related to environmental conditions, and global disagreements on setting standards defining the quality of their performance have been forbidding the effective implementation of the technologies for wood protection (Singh & Singh, 2012).

Plants are the source of extracts, resins, and oils possessing numerous bioactive compounds with biocidal activity (Kaur et al., 2010). The popularity to use the plant-derived products as wood protectants is due to their biodegrading and biocidal properties. Apart from plant derivatives, there are other environmentally friendly materials like wollastonite with wood protection efficacy against fungi. The current global concern is to develop technologies to effectively deploy the natural compounds, formulations, and products from plants for wood protection. However, factors that are hindering successful use of plant derivatives as wood protectants are restricted knowledge on the action of target natural compounds to control wood deteriorating organisms, impregnation, and retention of natural biocides in wood tissues and their susceptibility to biodegradation (Singh & Singh, 2012).

Several published reviews (Singh & Singh, 2012; Schultz & Nicholas, 2000, 2002, 2007) and patents (USPTO 2013) have proved that a considerable development has been undertaken on the sustainable eco-friendly wood protectants. However, the quest to search sustainable, effective, and eco-friendly wood protection technologies is still in progress. Combination of extracts with additives, metal chelators, co-impregnants such as condensation polymerization of chitosan–melamine co-polymers and water repellants, e.g., wax-based formulations, waterborne, oil-borne silica-based formulations, and resin acids, are some of the emerging approaches of wood protection (Singh & Singh, 2012; Torr et al., 2006). Water repellents provide multiple advantages to wood products, including reducing the decay potential and leaching of biocides from treated wood and enhancing the dimensional stability in exterior exposure (Schultz et al., 2007). Co-impregnation is an effective way to retain biocides in treated wood cell walls forming polymer cross-linkage and discard moisture out of treated timber. Additives increase the efficacy of organic biocides by scavenging the free radicals produced during wood degradation by white and brown rots. Metal chelators, e.g., combination of EDTA (ethylenediaminetetraacetate) with 2-HPNO (2-hydroxypyridine-*N*-oxide) and industrial by-products, e.g., tall oil resin complexes with metal, possess synergistic effects (Schultz & Nicholas, 2008; Mabicka et al., 2005). Eco-friendly wood protection methods are shown in Fig. 17.1.

This chapter summarizes a brief overview for utilization of various plant extracts, exudates, essential, bio-oils, and plant-based products as wood preservatives. The future perspectives for eco-friendly methods of wood protection are discussed, and the gaps existing in the technologies are highlighted.

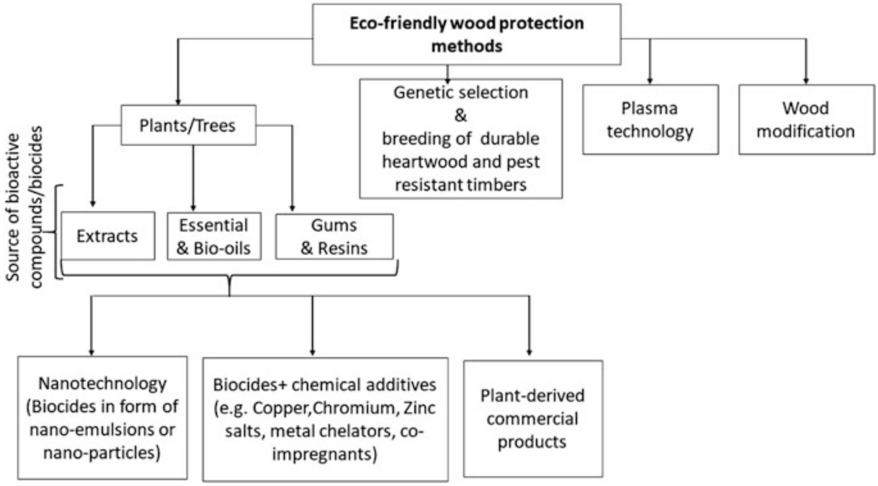

Fig. 17.1 Potential eco-friendly wood protection methods

17.2 Plant Extracts

The plant parts (tubers, roots, stems, leaves) are source of bioactive components often referred as extracts or phytochemicals ("phyto-" from Greek—phyto meaning "plant"), which are responsible for protecting the plant against microbial infections or infestations by pests (Doughari et al., 2009). The plant parts are dried either at low temperature (50–60 °C) or preferably in shade to bring down the initial large moisture content to enable its prolonged storage life. The dried parts are pulverized by mechanical grinders, and the oil is removed by solvent extraction. The constituents in dried parts are extracted with a single solvent or a combination of solvents. As plant contains numerous compounds of different molecule classes, no single solvent system can extract all compounds. Lipophilic extractives can be extracted with nonpolar solvents like hexane, dichloromethane, or diethyl ether and the hydrophilic fraction with water and polar organic solvents such as acetone, ethanol, or methanol (Benouadah et al., 2018). Figure 17.2 demonstrates different sources of botanicals from plants with fungicidal and insecticidal properties.

Extraction has been carried by hot water or stem distillation, Soxhlet extraction using organic solvents, or supercritical fluid (SFE) extraction using carbon dioxide at temperatures 40–100 °C (Sjöström & Raimo, 1999). SFE is an alternative to conventional Soxhlet extraction due to effective solute diffusion and mass transfer (Sjöström & Raimo, 1999). A recently more commonly used technique for extraction is automated accelerated solvent extraction (ASE). The advantage of this method is the combination of elevated temperature and pressure coupled with automation and the ability to use various solvents for extraction (Sjöström & Raimo, 1999).

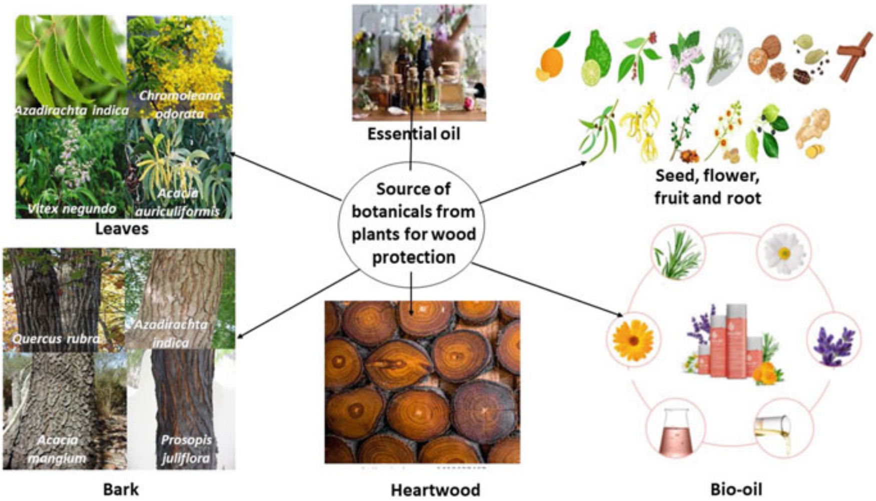

Fig. 17.2 Botanicals from different parts of plants for wood protection

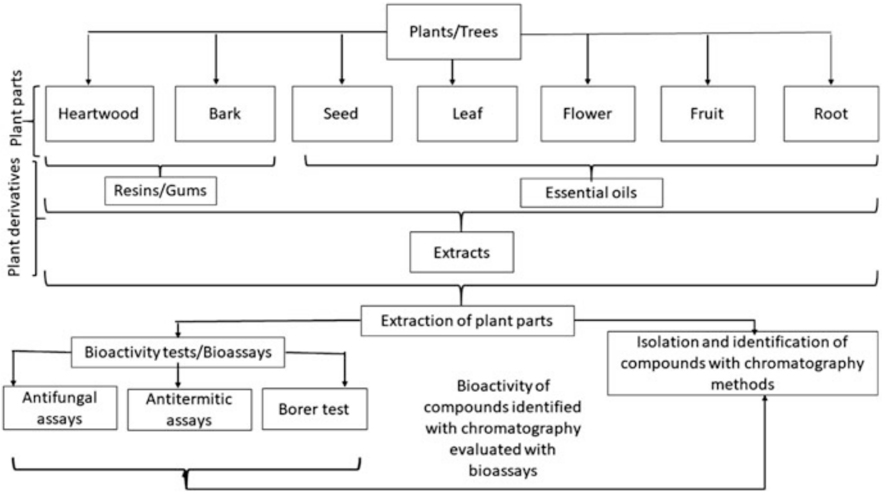

Fig. 17.3 Developmental steps of botanical fungicides and insecticides

The development of analytical chromatographic methods like thin-layer chromatography (TLC), high-performance liquid chromatography (HPLC), high-speed counter-current chromatography (HSCCC), and gas chromatography (GC) coupled with mass spectroscopy (MS) provides numerous options for the qualitative and quantitative estimation of chemical compounds in wood (Benouadah et al., 2018; Davies et al., 2014) and various parts of the plant. Developmental steps toward botanicals for wood preservation are shown in Fig. 17.3.

17.2.1 Heartwood Natural Durability and Bioactivity of Extracts

The key feature of heartwood that provides natural durability is the accumulation of secondary metabolites known as extractives (Taylor et al., 2002). Heartwood extractives are composed of hundreds of secondary metabolites including polyphenols such as tannins, the esters of gallic and ellagic acids or cinnamic acid derivatives, terpenes, flavonoids, phenylpropanoids, amines, and alkaloids that impart durability and biotic resistance to heartwood (Hillis, 1987).

Heartwood formation is a genetically and metabolically controlled programmed cell death process, which leads to the formation of heartwood extractives (Magel et al., 2001). In the transition zone, an increase in metabolic activity of parenchyma cells occurs followed by a series of cumulative events (rapid synthesis of secondary metabolites called extractives, blockages of conducting elements by formation of tyloses, and structural changes in pits) preceding the death of the parenchyma cells (Spicer, 2005). The extractives formed by the living parenchyma cells in the transition zone are released and deposited in the neighboring cells, imparting durability and color in some species (e.g., *Tectona grandis*, *Larix decidua*, *L. kaempferi*, and *Juglans* species). Natural durability of several tropical heartwood species, e.g., *Bagassa guianensis*, *Manilkara huberi*, *Sextonia rubra*, *Vouacapoua americana*, *Andira surinamensis*, *Handroanthus serratifolius*, and *Qualea rosea,* was studied by Rodrigues et al. (2012). The wood extracts from *H. serratifolius* were the most effective against wood degraders.

The quantity and composition of these extractives vary between species, between individual trees of a species and within a tree (Hillis, 1987; Taylor et al., 2002). The natural durability of timber does not necessarily correspond to the amount of extractives, i.e., extractive concentrations, but also depends on the composition of extractives (Taylor et al., 2002). Therefore, heartwood durability research in a breeding program needs to consider the most potent extracts and their chemical composition for the next-generation durability improvement. The genetic selection and propagation of pest-resistant and durable timbers are discussed in the future perspectives of wood protection.

Heartwood extracts can serve as wood protectants alone or in combination with copper and zinc salts (Sen et al., 2009). The heartwood extractives of white cypress pine (*Callitris columellaris*) are well known for their termiticidal activity (French et al., 1979). The two compounds, cedrol and a-cadinol isolated from the extracts of *Taiwania cryptomerioides,* were studied for antitermiticidal and antifungal activity (Chang et al., 2001, 2003). Heartwood sawdust of twelve *Juniperus* species exhibited termiticidal activities (Adams et al., 1988). *J. procera* contains cedrol and cedrane that showed termiticidal activity (Kinyanjui et al., 2000). Heartwood extractives of *Prosopis juliflora* were effective in controlling the growth of various wood-inhabiting fungi and termites (Sirmah et al., 2009a). Chemical analysis of *P. juliflora* heartwood extracts revealed the presence of (−)-mesquitol, a rare flavonoid that imparts durability to the heartwood (Sirmah et al., 2009b). The heartwood of cedar contains some compounds such as thujaplicins and thujic acid, which inhibit the fungal growth (Yang, 2009). The heartwood of *Caesalpinia* *echinata* was reported to be naturally resistant to termite attacks (Roszaini et al., 2006; Silva et al., 2007). The flavonoids in the Prunus wood extracts were tested to be effective against *Coptotermes formosanus* Shiraki (Ohmura et al., 2000). The termite (*Zootermopsis nevadensis*) growth was suppressed in *the wood extracts from Azadirachta indica* than *Pinus densiflora*. The investigation suggested that *A. indica* wood extracts might lead to the development of termite control agents from natural sources (Ohmura et al., 2006). Ellagitannins present in the white oak heartwood extracts imparted resistance against *Poria monticola* (Hart & Hillis, 1972).

Numerous antifungal and antibacterial assays have been reported to test the bioactivity of heartwood extracts. Broth dilution method was successfully used to identify a naphthoquinone derivative from *Tectona grandis* heartwood extracts with fungicidal activity against *T. versicolor* (Niamké et al., 2012) and used to investigate the fungicidal activity of C*innamomum camphora* heartwood extracts against *G. trabeum* and *T. versicolor*. Van Lierde (2013) determined the bioactivity of *E. bosistoana* heartwood extracts against *Trametes versicolor* and *Gloeophyllum trabeum*. The disk diffusion method has been applied to assess antimicrobial activities in crude extracts of *E. globulus* stump wood (Luís et al., 2014). Antifungal activity in the heartwood extracts from the *Cinnamomum porrectum*, *Mangifera indica,* and *Endospermum malaccense* was assessed with a bioassay (Kawamura et al., 2011). Methanol extracts from heartwood, sapwood, and inner and outer bark of port Orford cedar were evaluated for antioxidant activity (Gao et al., 2007). Reports on the bioactivity of wood extracts against wood-decaying fungi and termites are summarized in Table 17.1.

17.2.2 Bark Extracts

Bark extracts are rich source of antioxidants and antimicrobial agents, such as waxes, resins, tannins, suberin, lignin, lignans, phenolic acids, and nonstructural carbohydrates. These extraneous components are further classified into polar constituents (tannins, glycosides, polyphenols), which are more abundant in bark as compared to nonpolar components (fats, waxes, steroids, etc.). Various factors such as age of the tree, environmental condition, and sampling height contribute to the chemical composition of bark (Langenheim, 2003; Romero, 2012). Bark extractives from various European *Pinus* species have been recently investigated as wood adhesives (Tisler et al., 1983). These extractives have been used in protection of fishing nets. Alkaline bark extracts from the maritime pine contain waxes, resins, and phenolics that possess adhesive properties (Fradinho et al., 2002). The stem bark of *Ophelia africana* is rich in flavonoid with which exhibits antimicrobial, anti-inflammatory, anti-allergic, analgesic, gyrostatic, and antioxidant properties (Akinpelu et al., 2009). Bark extracts of *Carya ovata*, *Quercus rubra,* and *Pinus strobes* were reported for their fungicidal activity (Harun & Labosky, 1985). Three stilbenes in the *Pinus banksiana* and *P. resinosa* bark extracts possess antifungal activity against *Trametes versicolor*, *Phanerochaete chrysosporium*, *Neolentinus lepideus*, *Gloeophyllum trabeum,* and *Postia placenta* (Celimene

Table 17.1 Summary of reports that investigated the bioactivity of wood extracts against fungi and termites

Species	Extract type	Fungi/Termite	Reference
Dipteryx odorata	Heartwood extracts	*Postia placenta*	Wanschura et al. (2016)
Acacia mangium, A. auriculiformis	Heartwood extracts	*Phellinus noxius, P. badius*	Mihara et al. (2005)
Michelia formosana	Heartwood extracts	*Lenzites betulina, T. versicolor, Laetiporus sulphureus, G. trabeum, Fomitopsis pinicola*	Wu et al. (2012)
Calocedrus macrolepis	Heartwood extracts	*L. betulina, T. versicolor, Schizophyllum commune, L. sulphureus, G. trabeum, F. pinicola*	Yen et al. (2008)
Juniperus virginiana	Heartwood extracts	*T. versicolor, G. trabeum*	Mun and Prewitt (2011)
Sequoia sempervirens	Heartwood extracts	*T. versicolor, G. trabeum*	Davies et al. (2014)
Tectona grandis	Heartwood extracts	*T. versicolor, F. palustris, Rhizopus oryzae, Cladosporium cladosporioides, Chaetomium globosum*	Lukmandaru (2017)
Aquilaria crassna	Heartwood extracts	*Fusarium solani*	Novriyanti et al. (2010)
Taiwania cryptomerioides	Heartwood extracts	*P. noxius*	Chen et al. (2017)
Eucalyptus bosistoana	Heartwood extracts	*T. versicolor, Coniophora cerebella*	Mishra et al. (2019)
Juniperus virginiana	Wood extracts	*Reticulitermes flavipes, P. placenta, G. trabeum*	Eller et al. (2010)
Chamaecyparis obtusa	Branch heartwood extracts	*T. versicolor, Fomitopsis palustris, Trichoderma virens, Rhizopus oryzae*	Morikawa et al. (2012)
Thuja plicata, Chamaecyparis nootkatensis	Heartwood extracts	*Coptotermes formosanus* (Shiraki), *P. placenta*	Taylor et al. (2006)
Madhuca utilis and *Neobalanocarpus heimii*	Heartwood extracts	*Coptotermes gestroi Wasmann* (Blattodea: Rhinotermitidae)	Kadir et al. (2014)
Taxodium distichum	Heartwood extracts	*Coptotermes formosanus* (Shiraki)	Scheffrahn et al. (1988)
Chamaecyparis thyoides	Heartwood extracts	*Reticulitermes flavipes*	Arango et al. (2006)
Catalpa bignonioides	Heartwood extracts	*R. flavipes*	McDaniel (1992)
Lonchocarpus castilloi	Heartwood extracts	*Cryptotermes brevis*	Reyes-Chilpa et al. (1995)
Camellia japonica	Heartwood extracts	*C. formosanus*	Arihara et al. (2004)

et al., 1999). *Pinus pinaster* and *Abies nordmanniana* bark extracts exhibited antifungal activity against *Trametes versicolor* and *Coniophora puteana* (Özgenç et al., 2017).

Bark extracts from *Psorospermum febrifugum* and *Milicia excelsa* were reported for antifungal activity (Nagawa et al., 2015). Methanolic bark extracts of *Cleistanthus collinus* and *Prosopis juliflora* were effective against white rot and brown rot fungi (Jain et al., 2011). The efficacy of *Acacia nilotica* and *A. auriculiformis* bark methanol extracts and copperized extracts has termiticidal and fungicidal activities (Venmalar & Mishra, 2014). Copperized *A. nilotica* and *A. auriculiformis* extracts were more effective compared to methanol extracts. The *Khaya ivorensis* bark extract has significant termiticidal activity on *Triplochiton scleroxylon* and *Vitex doniana* woods (Adedeji et al., 2018). Antioxidant properties of mangrove plant (*Rhizophora apiculata*) impart termiticidal activity (Khalil et al., 2009). The bark extract of *Delonix regia* showed antioxidant activity and inhibited the growth of fungal mycelial growth (Salem et al., 2014). Bark extracts from *Acacia mollissima* and *Schinopsis lorentzii* showed termiticidal activity against *Reticulitermes grassei* (Tascioglu et al., 2012). The bioactivity of *Madhuca utilis* and *Neobalanocarpus heimii* bark extracts was reported against *Coptotermes gestroi* (Kadir et al., 2014). Wood particleboards impregnated with *Pinus brutia* bark extracts showed improved performance in decay resistance (Nemli et al., 2006). Phenolic glucosides extracted from the bark of *Populus ussuriensis* possess antioxidant properties (Si et al., 2011).

17.2.3 Leaf Extracts

Plant leaves are one of the major sources of flavonoids. Studies revealed that leaf extracts of neem impart termiticidal effect on the wood of *Khaya senegalensis* (Sotannde et al., 2011). Alcoholic extracts of neem (*Azadirachta indicia*) leaves exhibit antifungal activities against *Polyporus versicolor* and *Poria monticola* (Kabir et al., 2008). Leaf extracts of water pepper (*Polygonum hydropiper*) and *Acacia mollissima* were reported as alternative wood preservatives for indoor applications (Tascioglu et al., 2012). Leaves of some poisonous plants like *Sternbergia candida* and *Nerium oleande*r possess antifungal activity (Goktas et al., 2007). The influence of leaf extract from *Chromolaena odorata* has been evaluated on the durability of *Antiaris toxicaria* (Boasiako & Damohan, 2010). The methanol extract of teak (*Tectona grandis*) possesses antifungal activity and acts as an effective wood preservative against *Arthrinium phaeospermum*, the causal agent of wood decay in *Albania falcataria* (Astiti & Suprapta, 2012). Cinnamaldehyde and eugenol are the major constituents present in the leaves of cinnamon and clove, which exhibit resistance against white rot fungus, *Lenzites betulina,* and brown-rot fungus, *Laetiporus sulphureus* (Cheng et al., 2008). Leaf extracts of Ghanaian pawpaw impart durability to *Alstonia* wood (*Alstonia boonei*) (Asamoah et al., 2011). Antifungal and antimicrobial activities of methanolic extracts of leaves of *Eucalyptus torquata* and *E. sideroxylon* were assessed by a modified disk diffusion assay (Ashour, 2008). *Gliricidia sepium* methanol extracts and copperized extracts were reported to have termiticidal and fungicidal activities (Venmalar & Mishra, 2014). A broth dilution assay was used to test antifungal activity of *Eucalyptus maculata* leaf extracts (Takahashi et al., 2004). The structural saponin derivatives, 6α-O-[β-D-xylopyranosyl-(1→3)-β-D-quinovopyranosyl]-(25,S)-5α-spirostan-3β-ol, were isolated from the leaves of *Solanum hispidum* that inhibited the growth of *Trichophyton mentagrophytes* and *Trichophyton rubrum* (González et al., 2004).

The hexane leaf extracts of *Rhazya stricta* Decne, *Lantana camara* L., *Ruta chalepensis* L., and *Heliotropium bacciferum* Forssk. were evaluated to be promising against the subterranean termite *Psammotermes hybostoma* (Alshehry et al., 2014). Repellent, antifeedant, and toxic activities of *Lantana camara* leaf extract were reported against *Reticulitermes flavipes* termite (Yuan & Hu, 2012). The leaf extract of *Flourensia cernua* showed termiticidal activity (Tellez et al., 2001). The leaves of six plants, *Acorus calamus*, *L. camara*, *Parthenium hausteneum*, *Pongamia glabra*, *Jatropha curcas*, and *Tagetes erecta* were reported to be toxic against *Odontotermes obesus* (Sharma et al., 1999). Extracts from *Polygonum hydropiper* and *P. Parviflorus* showed hundred percent mortality against the termites, *Odontotermes assamensis* and *O. obesus* (Rahman et al., 2005).

17.2.4 Flower, Fruit, Seed, and Root Extracts

Extractives from flowers, fruits, seeds, and roots are rich source of essential oils, terpenes, flavonoids, and phenolic compounds. The antitermiticidal and antifungal properties of plant seeds and fruit peels have been globally accepted by the researchers. Antifungal and antimicrobial activities of methanolic extracts from the flowers of *E. torquata* and *E. sideroxylon* were assessed by a modified disk diffusion assay (Ashour, 2008). The hydroalcoholic extracts of *Lippia adoensis* and *Olinia rochetiana*, aqueous extracts from onion (*Allium cepa*), garlic (*Allium sativum*), fruit and root extracts of *Zanthoxylum americanum* and *Echinops ellenbeckii*, and crude methanol extracts from the aerial parts of *Pterocaulon alopecuroides* inhibit the growth of dermatophytes like *Candida albicans* (Abad et al., 2007). The root of *Cichorium intybus* having a bitter taste inhibits fungal growth (Mares et al., 2005). The ethanol extract of grape (*Citrus paradises*) imparts antifungal activity against yeasts (Cvetnić & Vladimir, 2004). Seed extract of *Withania somnifera* (Indian ginseng), *Croton tiglium (Jamalgota),* and *Hygrophila auriculata* (Talimkhana) caused changes in tunneling behavior, number of bacterial colonies in hindgut, and activities of enzymes in midgut of *O. obesus* (Ahmed et al., 2007). Seed extracts of *Maesa lanceolata*, *Chenopodium ambrosioides,* and *Vernonia hymenolepis* were effective against *Macrotermes* (Addisu et al., 2014). The antifungal activity of *Lantana camara* against *T. versicolor* and *Oligoporus placenta* was reported (Tripathi et al., 2009). Antimicrobial and antifungal activity has been reported in the root extracts of *Rubia tinctorum* (Ozen et al., 2014). The mixture of *Zingiber officinale* with *Allium sativum* extract was found to be the most toxic against *Macrotermes bellicosus* under laboratory and field conditions (Cynthia et al., 2016). The quinines extracted from the roots *of Diospyros sylvatica* using chloroform exhibited high toxicity against *Odontotermes obesus* (Ganapaty et al., 2004). The extracts from the root, stem, and bark of *Jatropha curcas* exhibited potential termiticidal effects (Verma et al., 2013). The antifeedant activity of *Xylopia aethiopica* hexane extract from fruits and aqueous methanol extract from its seeds was evaluated against *Reticulitermes speratus*. The hexane extracts from *X. aethiopica* contained six ent-kaurane diterpenes of which ent-kaur-16-en-19-oic acid showed strong antifeedant activity against *R. speratus* (Lajide et al., 1995).

CAY-1, a novel saponin derivative of *Capsicum frutescens,* the plant known as cayenne pepper, exhibits antifungal activity (Renault et al., 2003). Four triterpenoid saponins isolated from the berries of *Hedera helix* possess strong molluscicidal activity against *Biomphalaria glabrata* (Hostettmann, 1980). Four sesquiterpenes, daucane esters derived from the roots of wild carrot (*Daucus carota*), have been studied to impart natural resistance against *Aspergillus niger* and *Fusarium oxysporum* (Ahmed et al., 2005).

Various sesquiterpene lactones derived from the root exudates of *Solanum abutiloides* have been evaluated to inhibit the growth of *Fusarium oxysporum* (Yokose et al., 2004). Medicinal plants from Asteraceae family are rich source of sesquiterpenes such as diterpenoids and triterpenoids. Sesquiterpenes lactones isolated from *Ajan fruticulosa* and *Xanthium macrocarpum* were proved to be effective against *Candida albicans, Candida glabrata,* and *Aspergillus fumigates* (Meng et al., 2001; Lavault et al., 2005). Phenol protocatechuic acid deposited in dead outer scales of onions imparts resistance against onion smudge (Scheffer & Cowling, 1966).

The antifungal peptide, named vulgarinin, showed antifungal activity toward fungal species such as *Fusarium oxysporum, Mycosphaerella arachidicola, Physalospora piricola,* and *Botrytis cinerea* (Wong & Ng, 2005). The small cysteine-rich peptides, named defensins isolated from *Trigonella foenumgraecum,* exhibited antifungal activity against the fungi, *Rhizoctonia solani* and *Phaeoisariopsis personata* (Olli & Kirti, 2006). The chitins, an antifungal protein, were purified from the bulbs of the plant *Urginea indica* (Shenoy et al., 2006). AFP-J, constituent of *Solanum tuberosum,* inhibits yeast fungal strains, including *Candida albicans*, *Trichosporon beigelii,* and *Saccharomyces cerevisiae* (Park et al., 2005).

17.3 Essential Oils

Repellency and toxicity of essential oils from vetiver grass, cassia leaf, clove bud, cedarwood, *Eucalyptus globules*, *Eucalyptus citriodora*, lemongrass, and Geranium were reported against *Formosan* subterranean termites (Zhu et al., 2001a). Vetiver oil has long-lasting activity and hence has been proven the most effective. A component of vetiver grass oil, nootkatone (a sesquiterpene ketone), as a strong repellent and toxicant to Formosan subterranean termite, was reported (Zhu et al., 2001b). Vetiver oil and nootkatone act as an effective barrier to Formosan subterranean termites and red imported fire ants at concentrations ranging from 5 to 100 mg of sand (Maistrello et al., 2001a; Zhu et al., 2001a, b; Henderson et al., 2005a, b). They act as arrestants, repellents, and feeding deterrents. Nootkatone negatively affects termites for 12 months and is more long-lasting than vetiver oil (Maistrello et al., 2003). Nootkatone acts as a feeding deterrent that results in almost a complete loss of *Pseudotrichonympha grassii* wood, and mulch treatments to reduce the spread of *Formosan* subterranean termites (Mao et al., 2006). A study provided preliminary evidence that vetiver grass root mulch treatment decreases the tunneling activity and wood consumption of *Formosan* subterranean termites and increases their mortality (Nix et al., 2006). Essential oils of aerial parts of Maca (*Lepidium meyenii*) act as a feeding deterrent to termites. Minor components, 3-methoxyphenylacetonitrile and benzyl thiocyanate, showed good activity against Formosan subterranean termites (Tellez et al., 2002). The essential oil of catnip, *Nepeta cataria* (Lamiaceae), acts as a barrier to subterranean termites*, R. flavipes* (Kollar) and *R. virginicus* (Banks) (Peterson & Wilson, 2003). *Calocedrus formosana* leaf essential oil and its main constituent, T-muurolol, caused 100% mortality of *Chordodes formosanus* at the dosage of 5 mg (Cheng et al., 2004). The antitermitic activity of eleven essential oils from three species of coniferous tree has been reported against *C. Formosanus* (Cheng et al., 2007). One-hundred-percent mortality was recorded with dosages of 10 mg of heartwood and sapwood essential oils of *Calocedrus macrolepis* var. *formosana* and *Cryptomeria japonica* and the leaf essential oil of *Chaemocyparis obtusa* var. *formosana*. Among all, heartwood of *C. macrolepis* var. *formosana* exhibited the strongest termiticidal property. Leaf essential oil from two *Melaleuca* species (gelam and cajupati) was tested for their termiticidal activity. Gelam oils were rich in compounds with a high boiling point and separated into the elemene-rich type and g-terpinene and terpinolene type. Cajupati oils were characterized into three chemotypes according to their 1, 8 cineole content high, low, or none. Gelam oils were found to be more effective than cajupati oils (Sakasegawa et al., 2003). Out of the 29 plant species screened for termiticidal activities, 19 of them showed good termiticidal activity in which clove bud oil and garlic oil showed potent antitermiticidal activity (Park & Shin, 2005). Effective control of molds on rubberwood was achieved using anise oil, lime oil and tangerine oil, cinnamon oil, and clove oil (Matan & Matan, 2007, 2008). Essential oils from lemongrass, rosemary, tea tree, and thyme are effective against mold on wood (Yang & Clausen, 2007). A comparative study involving a range of essential oil compound-based formulations, which included cinnamaldehyde, cinnamic acid, cassia oil, and wood tar oil, revealed that cinnamaldehyde, cassia oil, and wood tar oil are effective against brown rot fungus *Tyromyces palustris* and white rot fungus *Trametes versicolor* and cinnamic acid is effective only against *T. versicolor* (Kartal et al., 2006). The wood treated with all compounds showed resistance against the subterranean termite, *Coptotermes formosanus*. The leaf essential oil of *Coleus amboinicus*, *Calotropis* extract, and root extract of *Diospyros sylvatica* showed 100% mortality against *O. obesus* (Singh et al., 2002; Ganapaty et al., 2004). Eremophilone oil from an Australian native tree *Eremophila mitchelli* Benth is known to have termiticidal activity (Scown et al., 2009). Orange oil extract was reported to be effectively used for controlling termites (Raina et al., 2007). Lavender oil contains linalool, which inhibits the growth of *Candida albicans* (Abad et al., 2007). The essential oil of Catnip, *Nepeta cataria,* acts as a barrier to subterranean termites *Reticulitermes flavipes* (Kollar) and *R. virginicus* (Banks), the most important flagellate species for cellulose digestion in the *Formosan* subterranean termite (Maistrello et al., 2001b). Vetiver oil and nootkatone can be used as novel pesticides that can be incorporated into potting media for substrate (Peterson & Wilson, 2003). Further, similar investigation showed that the presence of two monoterpenes (Z, E-and E, Z-nepetalactone) in Catnip oil from *Nepeta cataria* acted as an inhibitor for termite *Coptotermes formosans* (Chauhan & Raina, 2006). The efficacy of pure and copper incorporated seed oils of cashew (*Anacardium occidentale*) and neem (*Azadirachta indica*) was reported against termites and fungi as wood preservatives (Venmalar & Nagaveni, 2005).

17.4 Bio-Oils and Wood Vinegars

Water repellence and dimensional stability of wood treated with natural oils have been studied (Borgin, 1961; Paajanen et al., 1999; Van Eckeveld et al., 2001a, b). Natural oils appear to be capable of preventing water uptake by wood, and their chemical and physical composition is promising (Sailer and Rapp 2001). These oils are categorized as drying, semi-drying, and nondrying oils depending on their film-forming ability on the treated material (e.g., wood). Drying and semi-drying oils have been used for wood preservatives and paint formulation binders. Nondrying oils are used as plasticizers in nitrogen cellulose-based coatings (Teaca et al., 2019). Unsaturated dry oils can oxidize when exposed to atmospheric oxygen, which results in a more protective layer on the wood surface (Porter et al., 1981; Porter & Wujek, 1984).

Vegetable oils have been used as efficient wood protectants due to their antifungicidal, antitermiticidal, and efficient water-repellent properties (Teaca et al., 2019). Linseed and tall oils are widely used wood protectants. Other vegetable oils including soybean oil, hemp oil, pomegranate seed oil, and orange oil derived from orange peel have been evaluated as promising wood protectants (Ozgenc et al., 2013). Tall oil is obtained from the kraft pulping of coniferous species and constitutes resin acids, fatty acids, and fatty alcohols. The presence of some bioactive compounds like the constituents of heartwood extracts imparts decay resistance to tall oil (Van Eckeveld, 2001). Combination of tall oil with linseed oil enhances wood preservation. Incorporation of linseed oil with boric acid reduces leachability and improves efficacy against termites (Lyon et al., 2007a). The ammonium borate oleate (ABO) as a wood preservative has been positively tested against white and brown rot fungi and termites (Lyon et al., 2007b, 2009).

Whole bio-oils and their lignin-rich fractions were studied as potential environmentally benign wood preservatives to replace metal-based CCA and copper systems that have raised environmental concerns (Mohan et al., 2008). The pyrolytic bio-oil produced from the palm fruit shells was effective against dry wood termites

(*Cryptotermes* spp.) and particularly against the blue stain fungi, *Ceratocystis* species (Sunarta et al., 2011).

The tar oil from the pyrolysis of Macadamia nut shells was used to protect wood against various wood-decaying fungi and termites in laboratory conditions even after leaching process of treated specimens (Kartal et al., 2011). The impregnation of sapwood of white pine and American beech with a copper chloride solution or a mixture of copper chloride and sodium borate followed by a PF resin containing various amounts of pyrolytic oil increased the resistance of the treated samples to fungal degradation (Mourant et al., 2007). The efficacy of cashew nutshell liquid-based products (CNSLs) was evaluated against termites and fungi for protecting the wood (Remadevi et al., 2002). Incorporation of sodium chloride with CNSL resulted in the protection of *Terminalia ivorensis* against basidiomycetes fungi (Adetogun, 2011). Fungicidal and termiticidal properties of filtrates from biomass slurry fuel production using sugi (*Cryptomeria japonica*) and acacia (*Acacia mangium*) wood were evaluated under laboratory conditions (Kartal et al., 2004). Wood vinegars produced by the dry distillation of wood under high temperatures are reported to possess termiticidal activity (Yatagai et al., 2002). Wood used in housing or wood constructions treated with wood vinegar and tar extracted from wood vinegars produced from coconut shells and coir may prevent penetration of termite workers (Wititsiri, 2011). The efficacy of tall oil derivatives was tested against biological degradation in comparison with preservatives currently in use (Jermer et al., 1993). The effectiveness of the wood–vinegar–liquor in controlling wood-destroying fungi and termites was examined by Inoue et al. (2000). Bio-oil pyrolyzed from giant cane was evaluated as a wood preservative by Temiz et al. (2013). The termiticidal activity of coconut shell oil was found to be on par with commercial wood preservatives (Shiny & Remadevi, 2014).

17.5 Plant Exudates

17.5.1 Resins

Most of the Southeast Asian Dipterocarpaceae timbers are resin exudation trees (Schulte & Schone, 1996). Resins of the dipterocarp species contain a variety of terpenoids, which are soluble in hydrocarbons (e.g., turpentine) and alcohols (Diaz et al., 1966; Bisset et al., 1971). The most common plant resins include amber, oleoresin, Canada balsam, Boswellia resin, and balm of Gilead and frankincense (Teaca et al., 2019). Some resin wood coatings formulations are shellac from the insects such as *Laccifer lacca, Coccus lacca, Kerria lacca*, and colophony from rosin oil obtained from coniferous and pine species, dammar from Dipterocarpaceae species, Venice turpentine from *Larix decidua*, benzoin from Styrax, mastic from *Pistacia*, and sandarac from *Tetraclinis cypress* (Teaca et al., 2019).

The sesquiterpenoid, α-gurjunene isolated from the crude resin of *Dipterocarpus kerrii,* was evaluated for its termiticidal activity against *Zootermopsis angusticollis* (Richardson et al., 1989). The uncharacterized sesquiterpenes isolated from *D. kerrii* resin have been evaluated to be effective against *Neotermes delbergiae* (Richardson et al., 1991). The compounds, alloaromadendrene, humulene, and caryophyllene, isolated from Dipterocarpaceae species are most effective against Southeast Asian termites *Neotermes* species (Messer et al., 1990).

The bark of various pine species including radiata pine and ponderosa pine is the source of waxes and resins. Waxes and resins from these species have been used as bonding agents in the manufacture of wood products (Anderson et al., 1961; Hall et al., 1960). The wood specimens treated with the natural waxes derived from the bark of Aleppo pine were studied by Passialis and Voulgaridis (1999). The antimicrobial activity of guayule (*Parthenium argentatum*) resin was investigated by Bultman et al. (1991). Impregnated wood with the resin from wood and stem of guayule provides protection against wood-destroying organisms, including decay fungi, termites, and marine borers (Nakayama et al., 2001).

17.5.2 Waxes

Waxes are widely used as coating material in wood industry being easy to apply as an additive in different formulations (Liu et al., 2011). Waxes are a mixture of long-chain lipophilic compounds soluble in solvents and dispersible in water, yield low viscosity liquid on melting, which makes them suitable to be used as components of wood protective coatings and adhesives, and enhance moisture resistance and dimensional stability and preventing leachability of biocides from wood (Bulian & Graystone, 2009; Broda, 2020).

Propolis (bee wax) is natural resinous glue synthesized by honeybees and from products harvested from tree buds and other plant exudations mixed with their saliva, bee enzymes, beeswax, and pollen (Broda, 2020). Propolis has been widely used as wood protectant due to its chemical composition (polyphenols, terpenoids, steroids, amino acids, aromatic compounds, volatile oils), and mechanical, antifungal, and antibacterial properties (Broda, 2020). Propolis-based varnish has been used by the Italians to polish musical instruments for enhancing their acoustic properties or used it as a mixture with other ingredients as a coloring or finishing coat (Broda, 2020). Propolis has also been tried in a mixture with silanes for better wood finishing. Budija et al. (2020) evaluated that an ethanol extract of propolis from Eastern Slovenia effectively protected Norway spruce wood against brown-rot fungi *Antrodia vaillantii* and *G. trabeum*, and a white rot fungus *T. versicolor*. The Scot pine and paulownia wood treated with 7% methanol extract of Turkish propolis were more resistant to *Neolentinus lepideus* and *T. versicolor* (Broda, 2020; Akçay et al., 2020). Ethanol extracts of propolis greater than 12% concentration have been tested to impart decay resistance to the Scot pinewood against *Coniophora puteana* (Wozniak et al., 2020). Propolis from Argentina was evaluated for antifungal activity against wood-degrading phytopathogenic molds such as *Aspergillus niger*, *Trichoderma* species, *Penicillium notatum,* and *Fusarium* species (Quiroga et al., 2006).

17.6 Combination of Metals and Plant Biocides

A combination of certain metals (chelators for fungal enzymes) with extractives (e.g., condensed tannins, gallic acid derivatives) has been tested to enhance antifungal activity (González-Laredo et al., 2015). Therefore, it is important to find the right combination of metal chelators and biocides that promotes the required synergistic action. Another approach is to increase the efficacy of organic biocides with the addition of antioxidants that synergically can scavenge the free radicals action of wood degrading microorganisms (Morris & Stirling, 2012). Incorporation of *Cleistanthus collinus* and *Prosopis juliflora* bark extracts with copper sulfate and potassium dichromate was evaluated to be effective against wood-rotting fungi (Jain et al., 2011). Combination of *Azadirachta indica* bark extracts with chlorpyrifos proved to possess antitermiticidal effect on the wood of *Khaya senegalensis* (Sotannde et al., 2011). Leaves, bark, and seed extracts of *A. indica* in combination with copper sulfate and boric acid act as biocide against fungi and as an insect repellent (Islam et al., 2009). Studies revealed that the potential of enzymatic-hydrolyzed okra formulations with $CuCl_2$ and $Na_2B_4O_7.10H_2O$ resists *Postia placenta* and *Gloeophyllum trabeum* (Ahn et al., 2010). Bark extracts from *A. auriculiformis*, *A. nilotica,* and *G. sepium* leaf extract incorporated with copper (Cu^{2+}) have been evaluated for their antifungal and antitermiticidal activities (Venmalar & Mishra, 2014). The addition of heartwood extracts from the Juglans species with acid copper chromate and boric acid has been tested on beech sapwood for white rot resistance (Feraydoni & Hosseinihashemi, 2012). The use of rosin as a copper-based fixing agent has been proved to be an effective wood preservative. Rosin is a translucent product obtained from the solvent extraction of softwoods that has a suitable hydrophobic character and affinity for the wood structure. This feature prevents leaching of the copper and maintains a low moisture absorbing tendency in the treated wood (Hien et al., 2012).

17.7 Tannin Complexes

Tannins are widely found in root, bark, stem, and outer layers of plant tissue. They are low molecular weight phenolic compounds that are soluble in water and alcohol. They form complexes with proteins, carbohydrates, gelatin, and alkaloids. Tannins have been widely used as adhesives and wood preservatives (Mitchell & Sleeter, 1980; Laks et al., 1988; Lotz & Hollaway, 1988). However, the major problem with tannins and tannin-derived compounds is their difficulties to fix in treated wood.

Tannins can coordinate with heavy metal ions by forming stable complexes. Additives such as ferric chloride and metallic salts can retain the tannin complexes in treated wood (Mitchell & Sleeter, 1980; Laks et al., 1988). Hexamine can bound tannin compounds in wood cell walls. Impregnated wood with such formulations has been evaluated to possess fire and water-resistant properties (Tondi et al., 2012). Tannin formulations comprising of sulfide derivatives of catechins and cupric complexes have been evaluated as an effective biocide against wood degraders

(Laks, 1991). Halogenated tannin extracts and chemically modified tannins inhibited biodegradation of wood (Lotz, 1993; Yamaguchi & Yoshino, 2005). Tannins extracted from the fibrous mesocarp of coconut mixed with copper showed fungal inhibition due to the enhanced retention values and the phenolic nature of solutions (Lomelí-Ramírez et al., 2012). Combination of tannin bark extracts from sugar maple (*Acer saccharum*) with citric acid when applied on *Leucaena leucocephala* wood showed high anti-mold effectiveness (Salem et al., 2019). The efficacy of valonia, chestnut, tara, and sulfated oak tannins evaluated against brown rot (*C. puteana* and *P. placenta)* and white rot fungi (*T. versicolor* and *P. ostreatus*) showed that the scot pinewood impregnated with the tannins efficiently suppressed the attack by brown fungi while they were not effective against white rot. The best antifungal activity was observed for valonia and chestnut tannins due to the higher ellagitannin content (Tomak & Gonultas, 2018).

Boron compounds are inexpensive and environmentally accepted wood preservative. However, their use is restricted to indoor applications or in combination with other biocides as they are easily leachable from treated wood (Thevenon et al., 2009). Boron leaching has been markedly reduced in wood preservatives by cross-linking and hardening of condensed tannins with hexamine. Boron can be covalently fixed to the tannin–hexamine network (Tondi et al., 2012). The treated wood with this system has shown a significantly enhanced durability before and after leaching (Thevenon et al., 2010).

17.8 Plant-Based Products

Synergistic combinations of selected compounds derived from natural sources are recognized as the most promising approach for obtaining successful control of wood degrading organisms. A synergistic biocide for interior application called durazol has been developed based on several components that are well known to the wood preservation industry. The combination of actives in durazol acts synergistically to protect wood from several fungi and termites at lower concentrations (Clausen & Green, 2009). The field evaluation of neem-based formulations (Neem Guard, Nimbicidine, MultiNeem, Vanguard, Nemactin, Rakshak) in the plots of mango plants against *O. Obesus* was proved to be effective with Nimbicidine and Nemactin up to two months, and Rakshak, MultiNeem, Neem guard, and Vanguard were effective up to one month (Singh et al., 2002). TERMILONE is the registered trademark for Eremophilone oil extractive from an Australian native tree *Eremophila mitchelli* Benth (Scown et al., 2009). A combination of three chemicals (cashew nutshell liquid, sulfated wattle tannin, and copper chloride) has been used to develop an environmentally friendly termite preservative (Mwalongo et al., 1999). A commercial product, "Blockaid," has been developed in Australia and uses a range of plant extracts to create a paint on nontoxic termite barrier for buildings. Termites are strongly repelled by some toxic materials to the extent that they become disoriented and eventually die from starvation rather than consume cross-treated samples (Xie et al., 1995; Peterson & Wilson, 2003).

Rotenone is a colorless, crystalline isoflavone broad-spectrum pesticide and insecticide derived from seeds, stems, and roots of several tropical and subtropical plant species such as *Tephrosia virginiana*, *Pachyrhizus erosus*, *Deguelia utilis*, *Lonchocarpus urucu*, *Derris elliptica*, *Derris involuta*, *Mundulea sericea*, *Piscidia piscipula, Millettia,* and *Tephrosia* species (Ahmad et al., 2018; Nellis, 1994; Barton & Meth-Cohn, 1999). It is effective against a range of insect pests like potato beetles, cucumber beetles, flea beetles, cabbage worms, raspberry, asparagus beetles, and various other arthropods by interfering with nicotinamide adenine dinucleotide (NAD) (a coenzyme found in all living cells) during the formation of ATP (adenosine triphosphate) (Ahmad et al., 2018).

Nicotine is another important insecticide isolated from the leaves of *Nicotiana tabacum*, *N. rustica*, *Duboisia hopwoodii,* and *Asclepias syriaca* (Ahmad et al., 2018). Pyrethrin derived from pulverized dried flowers of *Chrysanthemum cinerariifolium* acts on the nervous systems of insects. The sabadilla is an alkaloid compound derived from the plant *Schoenocaulon officinale*. The dried S. *officinale* seed extracts contain cevadine and veratridine alkaloids, which have insecticidal properties (Hayes, 1982). Sabadilla acts like pyrethrins and affects the voltage-dependent sodium channels at axons in the nervous systems insect pests of crops, mammals, and human beings (Bloomquist, 1996). Ryanodine is another natural insecticide isolated from the stem wood of *Ryania speciosa* (Roskov et al., 2014).

17.9 Potential Eco-Friendly Wood Protection Technologies for the Future

17.9.1 Genetic Propagation of Durable and Pest-Resistant Alternative Heartwood Timbers

The global decline in the tropical heartwood timbers (e.g., teak, mahogany, and rosewood) due to illegal smuggling and urge for eco-friendly wood protection methods has raised the demand for genetic selection and propagation of alternative durable and pest-resistant timbers (e.g., *Eucalyptus* species). The extracts from different parts of genetically propagated trees can act as a potential wood protectant. The heartwood obtained from these trees can be used as potential building and secondary wood materials.

One of such initiative to propagate genetically pest-resistant and class 1 ground durable heartwood trees has been undertaken by the New Zealand Dryland Forests Initiative (NZDFI), which aims to establish a sustainable natural durable timber industry in New Zealand. The natural durability of heartwood is highly variable within a species and lower at the center of a tree. Therefore, it is critical to ascertain that trees meet international standards for durability to ensure a viable industry based on plantation-grown naturally durable *Eucalyptus*. A strategy to ensure that wood from future plantings meets industry requirement is to select superior genotypes in a breeding program. Several *Eucalyptus* species have been planted by NZDFI, but the primary focus is on *E. bosistoana* as it is a class 1 durable timber.

Variability in composition and content of extractives exists not only between species but also between and within trees of a single species. Variability in the extractive content within individual trees is related to age of the tree's cambium, i.e., the distance from the pith. The extractive content increases from the inner to the outer heartwood (Hillis, 1987). Therefore, growing heartwood trees in short-rotation plantations as envisaged by NZDFI will result in larger amounts of young heartwood, making it even more critical to ensure that it meets the technical specification of in-ground durability. This is possible as variation also exists between trees of a species and trees with good durability at a young age have been reported (Bush et al., 2011). It was shown that the variation in extractive content is partly under genetic control (Li et al., 2018), and therefore, NZDFI's strategy is to select the *E. bosistoana* trees with most potent extracts. Therefore, heartwood durability research in a breeding program needs to consider the most potent extracts and their chemical composition for the next-generation durability improvement (Mishra, 2019; Mishra et al., 2019).

17.9.2 Nanotechnology

Nanotechnology is one of the emerging and promising wood preservation fields that can be applied to wood by three methods, impregnation of wood with suspension of metallic nanoparticles, encapsulation of biocides with nanocarriers, and wood modification (Evans et al., 2008). Advantages of nanoparticles include characteristic size (smaller than the diameter of pores in the wood cells), capacity to treat a large effective surface area, high dispersion stability, and long-term protection to wood against biodegradation (González-Laredo et al., 2015; Teng et al., 2018). The disadvantage of leaching in conventional wood preservatives, which affects the efficacy of the wood treatment and the potential impacts on human health and the environment, can be overcome by nano-encapsulation technology (Borges et al., 2018).

Wood pieces are impregnated with nanosized metallic wood preservatives, such as silver, copper, and zinc oxide through a vacuum pressure treatment in a closed cylinder. The treatment helps in deeper penetration and higher homogeneous uptake of the particles into the wood, compared to the uptake rates when using conventional formulations, and subsequently protects the wood from certain targeted fungi or insects (Teng et al., 2018; Taghiyari et al., 2014). The other approach involved encapsulation of hydrophobic biocide with nanocarriers, which enables better water dispensability and protects wood from degradation (Iavicoli et al., 2017). Studies revealed that various nanomaterials have been used for surface modification of wood such as coating treatment to enhance its hydrophobicity and resistance to weathering (Hubbe et al., 2015).

Nanometals, such as copper, zinc, zinc borate, zinc oxide, titanium dioxide, and silver, have been used as wood preservatives (Civardi et al., 2016; Bak et al., 2012; Mantanis et al., 2014; Taghiyari et al., 2014). Nanosilver, nanocopper, and nanozinc have been evaluated to be efficient oxides on imparting resistance to the Paulownia

(*Paulownia fortunei*) wood against *Coriolus versicolor* (Akhtari & Ganjipour, 2013). The efficacy of nanosilver has been evaluated against white rot (*Trametes versicolor*) and brown rot (*Lenzites acuta*) fungi on several tropical wood species (Moya et al., 2017). The results showed higher efficacy of nanosilver against *T. versicolor* compared to *L. acuta*. Efficacy of wood treated with metallic nanoparticles based on termite bioassays was reported (Clausen et al. 2009; Mantanis et al., 2014). Lower termite mortality has been reported in $ZnSO_4$-treated wood compared to nano-ZnO (Sekine et al., 2009). Efficacy of photo-catalytic activity of nanoTiO_2 imparted decay resistance to *Pinus Sylvestris*, *Abies alba*, *Juglans regia*, *Castanea sativa*, *Prunus avium*, *Quercus petrea*, *Fagus sylvatica,* and *Fraxinus excelsior* against *Hypocrea lixii* (white rot) and *Mucor circinelloides* (brown rot) (De Flipo et al., 2013; Borges et al., 2018). Efficacy of metal (copper oxide) nanoparticles using leaf extracts of Neem (*Azadirachta indica*), Pongamia (*Pongamia pinnata*), and Lantana (*Lantana camara*) and extract of orange peel (*Citrus reticulata*) were evaluated against termites (*Odontotermes horni* (Wasmann), *O. obesus* (Rambur), O. *redemanni* (Wasmann), *Microtermes obesi* (Holmgren)) and fungi (*T. hirsutus* and *O. placenta*) (Shiny et al., 2019). The results suggested that the formulation of copper oxide nanoparticles was found to be effective as a wood protectant against fungi and termites.

Polymeric nanocarriers are another nano-based wood preservation method, which has received far less attention from researchers in wood preservation as compared to nanometal preservatives. The active ingredient can be encapsulated into polymeric nanocarriers through several techniques such as nanoprecipitation (Gu et al., 2015; Martínez et al., 2017), emulsion–diffusion (Lee et al., 2013), double emulsification (Nabi-Meibodi et al., 2013), emulsion–coacervation (Chirio et al., 2011), and layer-by-layer method (Chai et al., 2017).

17.9.3 Wood Modification

Conventional wood modification involved modifying the cell wall polymers of wood by different methods, such as thermal, chemical, surface, and impregnation. The modification methods usually produce nontoxic materials and enhance the service life of treated wood. However, these methods have several disadvantages, which propelled researchers to explore next-generation nano-based wood preservation technology. Conventional wood-modifying treatments can impart decay resistance against fungi and improve mechanical properties of the wood, but do not provide sufficient long-term protection against wood-damaging insects (Teng et al., 2018).

Employing nanotechnology in wood modification by chemical and physical coating treatments has been tested to improve the performance and service life of wood. However, this is an emerging next-generation wood protection technology, which needs further exploration. The physical approach involved application of presynthesized nanomaterials directly or added into existing wood coating. Wood surface is coated with the nanomaterials by spraying coating, brushing, or dipping

(Rassam et al., 2012; Havrlik & Ryparova, 2015). The chemical method and the applied nanomaterials can be in situ synthesized on wood surface by chemical reactions such as hydrothermal method and sol-gel deposition methods (Teng et al., 2018; Wang & Piao, 2011; Liu et al., 2015). The chemical approach offers an advantage by addressing distribution and interaction issues compared to physical approach (Teng et al., 2018; Mishra et al., 2017).

The nanomaterials can act as water repellents (control the rate of water sorption) and dimensional stabilizers (control swelling from moisture sorption). The beechwood (*Fagus orientalis*) treated with nano-ZnO particles provided substantial water resistance and dimensional stability to the treated wood (Soltani et al., 2013). Nanomaterials have the property to modify the wood surface to super-hydrophobic with a water contact angle higher than 150°. The advantages of superhydrophobic wood surface involved water droplets cannot adhere to surface but easily roll-off, can take away pollutants, and thus exhibit self-cleaning effects. Super-hydrophobicity on wood surface has been evaluated with the nanoparticles such as silica–polymer nanocomposites (Chang et al., 2015), tungsten trioxide (Sun & Song, 2018), and titanium dioxide nanoparticles (Pánek et al., 2017). Nano-based coatings with titanium dioxide nanoparticles (Zuccheri et al., 2013), polymers (Ong et al., 2006), and zinc oxide nanoparticles (Nosáľ & Reinprecht, 2017) can provide decay resistance and improve scratch and abrasion resistance (Kanokwijitsilp et al., 2013), and fire retardancy (Soltani et al., 2016) of wood.

17.9.3.1 Wood Modification with Plasma Technology

The surface modification of wood with plasma technology is a cost-effective, eco-friendly, and high-performance wood protection method, which aims to alter the surface characteristics of the wood on applying the principle of electrical gas discharge or plasma. Plasma is a partially or fully ionized gas in which neutral atoms are split into electrons, ions and free radicals, often referred to as a fourth state of matter (Tino et al., 2014). Plasmas from various sources such as by chemical or enzymatic grafting of functional molecules, coating by application of sol–gel methods, including deposition of nanoparticles, surface impregnation, and with various mechanical operations can be used to treat wood surfaces (Petric, 2013). The wood properties targeted to improve with this technique include surface activation for better gluing and adhesion of surface coatings, wettability and resistance to weathering, resistance to pests, fire retardancy, and mechanical properties, such as hardness and abrasion resistance (Petric, 2013). The Durawood Technology introduced by the European wood processing industry facilitates a cost-efficient, durable, and eco-friendly plasma-based wood protection against wood-degrading fungi (Tino et al., 2014).

Combination of nanoparticles with plasma technologies, sol–gel technique (Xie et al., 2001), and thermal and nonthermal processes (Sokołowska et al., 2009) have been applied to modify wood surfaces. Sun et al. (2012) reported hydrothermal fabrication of wood surface with TiO_2 sub-microspheres. Bamboo surfaces were functionalized with nano-structured ZnO, resulting in the generation of ZnO seeds on the bamboo surface followed by a solution treatment to promote the crystal growth (Yu et al., 2012). Similarly, ZnO nanostructures were formed also on surfaces of solid Chinese fir wood (Yu et al., 2010) and on rubberwood (Salla et al., 2012). Resistance of wood surfaces to fungal decay has been improved by plasma treatment. The treatment of Norway spruce veneers with the combination of hydrolyzable tannins and laccase imparted resistance to veneers against *Staphylococcus aureus* (Widsten et al., 2010).

17.10 Discussion and Conclusion

The global restrictions on the traditionally relied first-generation wood preservatives, e.g., creosote, oil-borne pentachlorophenol (Penta), and the water-borne arsenicals, principally chromated copper arsenate (CCA), paved the way to develop eco-friendly, sustainable, cost-effective, and efficient wood protection methods. The industrial utilization of biocides depends on several factors such as wood species, length of service lifetime, cost of treatment, decay risk, disposal, discrepancies between laboratory and field trials, variations in efficacy of organic biocides in nutrient medium and on biocide impregnated wood, target-specific activity of bioactive compounds, and inconsistencies among legislation and registration of new compounds (Singh & Singh, 2012; Tascioglu et al., 2012). However, the limitations have not been forbidden for developing wood protection technologies using natural compounds as biocides. Efficacy of wood preservatives can be enhanced by refinements with formulations and treatment methods to achieve better penetration of biocides into wood cell walls.

Botanicals from plants exhibit a broad spectrum of antifungal, termiticidal, and antimicrobial activities. They are renewable, readily available, cost-effective, non-toxic, and eco-friendly. However, limitations include high heterogeneity depending on the source from which they are derived, lack of appropriate retention inside the impregnated wood tissue, easy leachability, and target specificity (Broda, 2020). These limitations have been surmountable by combining organic biocides such as tannins, chitosan, and plant oils with environmentally friendly additives, organic compounds such as heterocycles and carbamates, antioxidants, metal-sequestering agents, and biocontrol agents (BCAs).

Genetic engineering approaches can be employed for economic production of durable and pest-resistant trees, which can facilitate production of specific active compounds in large quantities. Bioactivity of botanicals can be enhanced by gene technology. Genetic selection and propagation of durable heartwood tees through shorter breeding cycle can be another approach to improve the composition of heartwood extracts. Extracts obtained from these trees can act as second- and third-generation biocides for wood protection. Biotechnological approaches can be used to evaluate the potential of industrial biowastes as wood protectants. The old creosote-treated woods can be recycled through pyrolysis to produce tar oils to treat wood products (González-Laredo et al., 2015). Bioconversion processes have the potential to be integrated with biomass treatments, energy production, and for the recovery of useful biochemicals. Genome mining is another least explored area in natural product chemistry (Van Lanen & Shen, 2006). Discovering the new compounds from natural sources is a long and tedious process, which involved extraction, isolation, and identification of compounds coupled with bioassays. The process of identifying natural products to specific targets can be accelerated by searching a genome for DNA sequences that encode enzymes associated with the biosynthesis of products. Rapid and cost-effective genome sequencing technology coupled with computational modeling can help in search of target specificity of bioactive compounds. These compounds can be used as effective biocides for wood protection.

Nanotechnology, chemical modification of wood with nanoparticles, and plasma technology are promising next-generation wood protection methods. Surface modification of wood by plasma treatments, enzymatic grafting of functional molecules to surfaces, and deposition of nanoparticles by sol–gel techniques appear to be highly attractive areas of wood protection technologies in future. Nanoparticles coupled with plasma wood modification can enhance the performance of wood preservatives, prolonging the wood product service life. Numbers of published reports have questioned the health hazards associated with nanoparticles (Lee et al., 2010). Several advantages of nanoformulations, such as difficulties to determine the hazardous effect of nanoformulations, less toxicity of nano-based formulation compared to conventional wood preservatives, and homogenous incorporation of biocides as nanoparticles in wood, which prevents leaching and random degradation of biocides, have urged to consider nanotechnology as a promising tool toward next-generation wood protection. However, to understand potential impact of nanotechnology, further investigations are needed to identify opportunities and potential risks.

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18 Preservation of Engineered Wood Composites (Solid Wood Plywood, Blockboards/Flush Doors) Made from Plantation Timbers

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_18

Abstract

In the present scenario of diminishing harvests of trees from forests for environmental protection and maintenance of ecological balance, wood of conventional tree species having high natural durability is no longer available for various industrial and structural applications. The main cause for repeated demand of timber for the same structure is due to its deterioration, by borers, fungi, and termites. To protect wood from decay and insect attack consisted of brushing and rubbing preservatives onto the surface of the treated wood, in India, the wood preservation practices have been introduced nearly a century back and have been accelerated during the last 50 years. As the result of work done in various parts of the world under severe deteriorating conditions and also in India, it has been found generally that well-preserved wood gives a life of 3 to 5 times that of an untreated timber on land and sometimes 8–10 times under cover. Various treatment methods may be used depending on the timber species and the end-use applications. Most of the preserving processes may be grouped into either pressure processes or nonpressure processes. The efficiency of preservative treatment depends upon the proper choice of preservative chemicals, which give varying degree of protection either individually or in combination of two or more chemicals against fungi, borer, termite, and other wood-destroying organisms. Chemicals used in the solution—when the finished plywood, blockboard, or flush door or their core stock, are treated by dip diffusion or pressure impregnation process, and the preservative chemicals are used in a solution may be classified as (1) oil type, (2) organic solvent type, and (3) water-soluble type—leachable and nonleachable. A number of chlorinated hydrocarbon and organochloro phosphorus and synthetic pyrethroids like lindane EC, chlorpyrifos EC, bifenthrin EC are used as glue line poisoning chemicals. Several remedial measures are also available for treating products made from wood and wood-based panels like plywood, blockboard, and particleboards when signs of decay are visible under service conditions.

Keywords

Wood preservation · Panel products · Durability · Timbers · Preservative chemicals · Oil type · Synthetic pyrethroids

18.1 Introduction to Wood Preservation

Wood is a versatile raw material and has been used by man from time immemorial. Excavations carried out by the archeologists at Harappa and Mohenjo-Daro of Indus valley civilization and other sites of ancient India have thrown a floodlight on various kinds of timber used by the people. Probably, the first attempts made to protect wood from decay and insect attack consisted of brushing and rubbing preservatives onto the surface of the treated wood. Thus, forest products became a part of human civilization with economic development of the country and the rate of anticipated industrial growth literacy and urbanization the demand for the wood has also increased. India has a rich source of more than 1600 timbers species having commercial value and wood of conventional tree species having high natural durability is no longer available for various industrial and structural applications. At present, in India, due to scarcity and hike in prices of conventionally preferred timber species like teak, sal, rosewood, and mahogany, dependence on fast-growing, nonconventional plantation timber is increasing. Currently, the market is flooded with a number of fast-growing species with low natural durability, which are used for various purposes like manufacture of plywood, blockboards, matchboxes, packing cases, handicrafts, furniture, and building materials. Several of these timbers do not possess a high degree of natural durability. Increased use of sapwood without proper treatment, especially in the production of household furniture, doors, windows, wardrobes, etc., is compounding the insect problem. Most woods are rich source of food for a host of fungi and insects. However, being biological, it is susceptible to attack by a number of decay-causing and wood-destroying organisms.

For various reasons, particularly due to encouragement of rural population for agriculture purposes into the forests hydroelectric scheme, soil erosion, heavy grazing, etc., the productive forest area has seriously come down. In view of the above alarming situation, the forest departments are raising man-made forest of local and exotic species. With the increase in use of plantation timbers like poplar, rubber, silver oak, and other farm-grown timbers, service life of wood composites like plywood, blockboard, and flush door has been found to be lower compared to similar produces made from traditional forest tree species. This is due to the fact that timber from many fast-growing tree species is susceptible to attack by borers, termites, and fungi. Moreover, because of construction design and associated compactness once such attack is noticed remedial measures are extremely difficult if not impossible. Therefore, the question is how to solve the above situation, because timber will ever remain as the most important material for structural use by man. The main cause for repeated demand of timber for the same structure is due to its deterioration, by borers, fungi, and termites. The deterioration is limited in naturally durable timber species like teak, sal, deodar, and bijasal. However, the outer sapwood of all the timbers is liable to deterioration on examination. It has been found that the naturally durable woods have toxic chemicals, which give them resistance to deterioration. Some woods are also said to contain large amounts of silica, which also give high resistance to deterioration. These have given clue to investigate the properties of various chemical substances, which are toxic to the deteriorating against and evolving suitable compositions and concentration that should be injected into the timber to give it high resistance. This is the birth of wood preservation in the world.

In India, the wood preservation practices have been introduced nearly a century back and have been accelerated during the last 50 years. Sir Ralph Pearson introduced wood preservation on modern and scientific lines in India in the year 1908. In view of his valuable pioneer research work at FRI, he is entitled as a father of wood preservation. Dr. Kamesam wood preservation scientist worked in FRI Dehra Dun and developed a promising wood preservative chemical ASCU. He worked in Germany with Dr. Falk and developed a composition containing arsenic and chromium called Falk-Kamesam (CCA). After returning to India in 1936, he further developed his earlier composition and introduced copper, which is truly toxic to the deteriorating biological agents. During world war when it became difficult, to obtain arsenic pentoxide, he introduced boron, which is also toxic to the deteriorating agents, and this composition is called as copper chrome boric (CCB). As the result of work done in various parts of the world under severe deteriorating conditions and also in India, it has been found generally that well-preserved wood gives a life of 3 to 5 times that of an untreated timber on land and sometimes 8–10 times under cover.

Major Development in Wood Preservation

- 1830—BETHELL PROCESS—SAP DISPLACEMENT CREOSOTE, COPPER SULFATE.
- 1850–1900 COPPER—CHROME ARSENIC, COPPER CHROME
- 1950—INORGANIC BORATES—ORGANOTIN COMPOUNDS
- 1960—LIGHT ORGANIC SOLVENT PRESERVATIVES
- 1980—ALKYL AMMONIUM COMPOUNDS
- 1990—CHROME OR ARSENIC-FREE PRESERAVATIVES
- 1995—VAPOUR-PHASE TREATMENTS ORGANO BORON METHYL BORATE, ETHYL BORATE, BUTYL BORATE, PROPYL BORATE.
- 2010—ORGANIC-BASED SYNTHETIC PYRETHYRIODS.

In the present scenario of diminishing harvests of trees from forests for environmental protection and maintenance of ecological balance, wood of conventional tree species having high natural durability is no longer available for various industrial and structural applications. The nation has necessarily to depend upon rapid growth trees, as the sustainable source of wood in future. Some such species that have already made a place for them are rubberwood, poplar, eucalyptus, and silver oak.

However, incidences of attack by the wood-destroying organisms can be prevented by incorporating suitable treatments in the process of manufacturing various panel materials including plywood, blockboards, and flush doors. IPIRTI has done extensive research on these aspects and also for the treatment of plywood/ blockboard/flush door, which can be easily adopted by the industry for manufacturing quality products. Many factories have already adopted some of these techniques.

18.2 Prophylactic Protections

Most woods are rich source of food for a host of fungi and insects. Staining fungi cause discoloration, but the wood-destroying fungi reduce the strength of wood. A variety of insects that bore through bark, sapwood, and even heartwood cause deterioration in the quality of logs. Apart from deterioration caused by the above biological agencies, wood also deteriorates during drying. Cut ends of the logs split severely during drying. Losses resulting from physical and biological deterioration of logs may be as high as 20% of log volume. Therefore, prophylactic treatment of green timber is of utmost importance. In the manufacture of wood-based panels, green timber may be in either log or veneer form. Protective measures of these two types are briefly described below.

18.3 Protective Measures for Logs

Insecticidal Sprays: Insecticidal sprays may be either water- or oil-borne. Water-borne sprays such as 1% gamma BHC emulsion in water or solution of 1.5% borax plus 0.5% sodium pentachlorophenate in water are more suitable for treatment during dry seasons. Oil-borne sprays such as 1% gamma BHC in fuel oil should be used in rainy season. Resin or wax that prevents the insecticide from washing out may be added to this composition to enhance their effect.

End Coatings: An ideal coating material for protecting the cut ends of the logs should have good adhesion and leach resistance and be capable of sealing the end against escape of moisture and entry of fungal and insect infestation. Thick bituminous paint, which is dispersed in the bitumen cut back, and rosin in coal tar are some of the recommended compositions. Logs brought to the mill yard should be kept submerged in log ponds or under water sprays to prevent deterioration during storage.

18.4 Protection of Veneer During Transit and Storage

Veneers are one of the most important raw materials in plywood industries. Veneers peeled from plantation timbers, which are nondurable, are degraded by insects during transit and storage, thus causing serious economic loss. Generally, veneers produced are dried to 8–10% mc and stored for plywood production in ideal conditions. But the present trend is that veneer units are situated far away from plywood factories and freshly peeled veneers are transported to the main factory without drying them. During this period, they are degraded by mold fungi causing staining and discoloration. If the dried veneers are stored for more than one-month borers also attack if timber is nondurable. Simple treatment methods using environmentally friendly preservatives can prevent such eventualities, which consists of the following:

- Dipping peeled veneers in 3% solution of 0.5:1:1.5 sodium pentachlorophenate boric acid borax followed by diffusion storage or 3–4% CCA, CCB, or ACC in water.
- Pressure impregnation of 1:1.5 (borax: boric acid) or 3–4% CCA, CCB, or ACC. The use of CCA, CCB, and ACC in veneer treatment imparts greenish color to veneers.

(**Note:** Some of the preservatives are known to interfere in gluing and bonding; therefore, modification of adhesive formulation may be required to achieve proper bonding while making plywood using treated veneers.)

18.4.1 Preservation of Sawn Wood

All sawn wood in solid form from nondurable timbers and sapwood of even durable timbers requires preservative treatment to enhance the service life. It has been estimated that preservation/treatment enhances durability by 3–6 times, saves money not only from the replacement cost, but also helps in maintaining wood resources. IS: 401–2001 code of practice for preservation of timber gives details regarding, choice of treatment, preservatives, treatment methods, and retention of preservative for various end uses. Durability and treatability of Indian timbers are also appended at the end.

Some of the treatment methods and preservatives are as follows:

18.4.2 Brushing/Spraying

Water-soluble or oil-soluble preservatives can be brushed or sprayed on solid timber or finished components of furniture, joinery, etc., in house construction and for packing cases. The treatments will give a preservative coating all around the timber and depth of penetration will not be through and through. For large-scale applications, the above method may not be suitable. Preservatives chemicals are as follows:

Boric acid: borax (1:1.5).
Sodium pentachlorophenate 2% water-soluble.
CCA, CCB, ACC—3–4%.
Zinc naphthenate 8%, copper naphthenate 6%,
Trichlorophenol 4%, lindane 20EC 1%, bifenthrin 0.025%.
Chlorpyrifos 1%, lindane 1%.

After application of water-soluble preservatives, the wood has to be dried to required moisture content; therefore, oil-soluble preservatives are more suitable for brushing/spraying as there is no requirement of drying the wood after treatment.

18.4.3 Diffusion Treatments

This method is ideally suited for large-scale applications. Rough sawn timber is dipped in water/solution of boric acid: borax; sodium pentachlorophenate (1:1.5:1) or CCA, CCB, and ACC 3–4% for certain period, and the timber is stacked closely under slow-drying conditions for certain time, before drying it to required moisture content. Depending on the thickness, dipping time and stacking time are to be altered (Fig. 18.1a, b). Through-and-through penetration of preservative is obtained in some of the easily treatable nondurable timbers like *Hevea brasiliensis* (rubberwood), *Populus* spp. (poplar), *Mangifera indica* (mango), and *Bombax ceiba (semal).*

18.4.4 Vacuum Cum Pressure Impregnation

Vacuum cum pressure impregnation, which is also known as pressure process, of timber is carried out to get maximum penetration with adequate retention hence more service life. Vacuum cum pressure impregnation requires elaborate treatment plants. Both water-soluble preservatives and oil-soluble preservatives can be used in this system. For vacuum cum pressure impregnation, timber has to be dried to 12% m.c.

Water-soluble preservatives: boric acid; borax (1:1.5); CCA, CCB, ACC.

Oil-soluble preservatives: zinc naphthenate, copper naphthenates, trichlorophenol, lindane 20 EC, chloropyrifos 20EC/50EC, bifenthrin 2.5 EC.

18.5 Preservation of Wood Composites

18.5.1 Treatment of Core Stock of Flush Doors/Blockboards

With the increase in use of timbers of plantation origin and timbers from farmlands for core stock of flush doors/blockboard, menace of powder post (Borer) attack has reached epidemic proportions. Because of the construction design and associated compactness, once borer attack is noticed remedial measures to arrest/stop the borer infestation are practically impossible, without damaging the boards. IPIRTI was

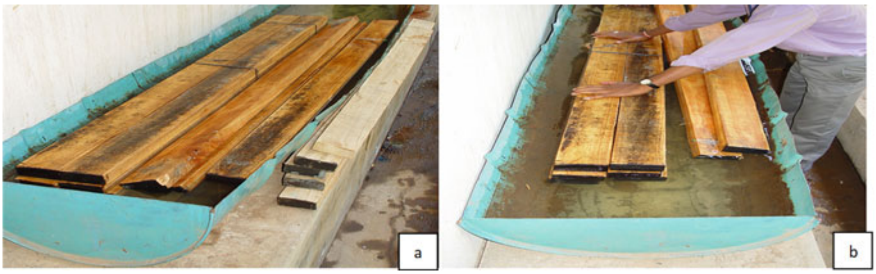

Fig. 18.1 Diffusion treatments of core stock (**a**) and (**b**)

done extensive research related to the treatment of core stock for effective protection of flush door/blockboards that can be easily practiced by the industries. Some of the recommendations are shortlisted:

- Dip diffusion treatment of planks using 1:1.5 (borax: boric acid) mixture.
- Pressure impregnation using 1:1.5 (borax: boric acid); 3–4% solution CCA, CCB, or ACC.
- Painting or spraying of core stock battens with light organic solvent-based preservatives like copper naphthenate, zinc naphthenate, or trichlorophenol.

(**Note:** Some of the preservatives may interfere in bonding; therefore, adhesive formulations may have to be modified.)

18.5.2 Glue Line Treatments

Some preservative chemicals can be incorporated into the adhesive formulation for enhancing durability of plywood made from woods susceptible to borer attack. This is a simple process in which the preservative chemical along with the adhesive penetrates into the veneer layers during the process of manufacture of plywood (Fig. 18.2). Chemicals that are included in Indian standard specification IS 12120–1992 are as follows: boric acid 1% (for urea/melamine resin), lindane −410 g ai/m^3, and chlorpyrifos 205 g ai/m^3 (for urea/melamine/phenolic resin). Recently, IPIRTI has evaluated a synthetic pyrethroid bifenthrin at 5 g ai/m^3, which was found to be effective.

Similar procedure of incorporation of preservative chemicals in the adhesive, while manufacture of particleboards can be adopted to protect particleboards from fungal/termite attack. Suggested preservative chemicals are sodium trichlorophenate 2%, sodium pentachlorophenate 1%, trichlorophenol 2%, and borax.

Fig. 18.2 Glue line treatment of veneer

18.5.3 Prophylactic Protection

Most woods are rich source of food for a host of fungi and insects. Staining fungi cause discoloration, but the wood-destroying fungi reduce the strength of wood. A variety of insects that bore through bark, sapwood, and even heartwood cause deterioration in the quality of logs. Apart from deterioration caused by the above biological agencies, wood also deteriorates during drying. Cut ends of the logs split severely during drying. Losses resulting from physical and biological deterioration of logs may be as high as 20% of log volume. Therefore, prophylactic treatment of green timber is of utmost importance. In the manufacture of wood-based panels green timber may be either in log or veneer form. Protective measures of these two types are briefly described below.

18.5.4 Protective Measures for Logs

Insecticidal Sprays: Insecticidal sprays may be either water- or oil-borne. Water-borne sprays such as 1% gamma BHC emulsion in water or solution of 1.5% borax plus 0.5% sodium pentachlorophenate in water are more suitable for treatment during dry seasons. Oil-borne sprays such as 1% gamma BHC in fuel oil should be used in rainy season. Resin or wax, which prevents the insecticide from washing out, may be added to this composition to enhance their effect.

End Coatings: An ideal coating material for protecting the cut ends of the logs should have good adhesion and leach resistance and capable of sealing the end against escape of moisture and entry of fungal and insect infestation. Thick bituminous paint, which is dispersed in the bitumen cut back, and rosin in coal tar are some of the recommended compositions.

Log Ponding: Logs brought to the mill yard should be kept submerged in log ponds or under water **sprays** to prevent deterioration during storage as shown in Fig. 18.3.

18.6 Wood Preserving Processes

The objective of wood preservation is to introduce the preservative into the wood so that a deep continuous layer of treated wood contains sufficient preservative to prevent decay and insect attack. Various treatment methods may be used depending on the timber species and the end use. Most of the preserving processes may be grouped into either pressure processes (Fig. 18.4) or nonpressure processes. Nonpressure processes are carried out without the use of artificial pressure, while pressure processes are in which the wood is placed in a treating cylinder and impregnated with preservative by applying pressure or vacuum and pressure.

There is also a third group of miscellaneous processes in which the wood is treated in one way or another with slight to moderate pressure but not in a closed cylinder. Pressure processes the most successful method of preservative treatment of wood is the use of pressure impregnation of the wood. This is done in specially

Fig. 18.3 Logs stored in log pond

Fig. 18.4 Vacuum pressure treatment plant

constructed plants where the timber is treated under pressure in a closed steel cylinder.

Depending on the actual process to be used, the timber may be subjected to a preliminary vacuum. After the preliminary treatment, if used, the cylinder is filled with the preservative solution at a specified temperature and then pressure is applied to it. The amount of pressure applied and the duration of the pressure period depend on the species, penetration required, and the usual pressure applied is between 800 and 1400 kPa high-pressure processes. There are several types of high-pressure processes some using only pressure and others using vacuum and pressure.

18.6.1 The Full Cell Process

In the full cell process, the aim of the treatment is to retain as much as possible of the preservative by making the cells full of preservative solution. This is the normal process used when treating with water-borne solutions. Where high retentions of creosote are required in very hazardous environments, as is the case in marine piles, full cell is often employed. In the case of creosote, it has to be heated to temperatures about 65 to 100 °C during the pressure period to lower the viscosity, to enable the liquid to penetrate. The main steps in the full cell process are (a) preliminary vacuum period, (b) fill cylinder with preservative, (c) build up pressure, (d) maximum pressure held, (e) release pressure, (f) empty cylinder of preservative, (g) final vacuum period, and (h) release vacuum The amount of pressure and vacuum applied and also their period of application vary with the species, the retention required, etc.

18.6.2 Rueping Treatment/Empty Cell Process

When the fill cylinder with preservative and release pressure at atmospheric pressure empty cylinder of preservative build up pressure of final vacuum period maximum pressure held release vacuum.

There are two main types of empty cell processes, which are called Rueping and Lowry processes. In both processes, there is no initial vacuum applied, the preservative is forced into the wood under pressure, and subsequently, a vacuum is applied to remove the excess of the preservative. Empty cell processes are applicable when it is required as deep penetration as possible with a limited final retention. This process is normally used with tar oil preservatives. The main steps in the Rueping process are (a) preliminary air pressure applied, (b) fill cylinder/hold air pressure, (c) build-up pressure, (d) maximum pressure held, (e) release pressure, (f) empty cylinder of preservative, (g) final vacuum period, and (h) release vacuum.

18.6.3 Oscillating Pressure Process

This is a variation of full cell process for the treatment of timber of high moisture content with water-borne preservatives. As the name applies, this process utilizes repeated applications of high and low pressure. The high pressure is over 1000 kPa, and the low pressure generally is in the vacuum range. The timber to be treated should be steam conditioned at temperatures around 125 °C. After removing from the steam cylinder, it is allowed to cool for some time after which the timber is subjected to a brief pressure in a pressure cylinder. This is followed by cycles of vacuum and pressure, which are of predetermined intensity and duration, depending on the size and species of material to be treated. The plant required is more complex than that used for other pressure processes, and high standards of operational and technical control are necessary.

18.6.4 Low-Pressure Processes

There are few processes where low external pressures are used to treat the wood, most important being the double-vacuum process. Double-vacuum process uses about one-tenth of the pressures involved in full cell process and is widely employed in developed countries mainly for treating timber joinery components with organic solvents. The main steps of this process are as follows: Preliminary air pressure applied to release pressure filled air in the cylinder hold air pressure of empty cylinder of preservative build up pressure final vacuum period maximum pressure held release vacuum.

18.6.4.1 Lowry Treatment/Empty Cell Process

And the main steps in the Lowry process are (a) fill cylinder with preservative at atmospheric pressure, (b) build up pressure, (c) maximum pressure held, (d) release pressure, (e) empty cylinder of preservative, (f) final vacuum period, and (g) release vacuum.

(a) Application of an initial vacuum.
(b) Flooding with preservative.
(c) Application of pressure.
(d) Release of pressure.
(e) Application of final vacuum.

The above steps are very similar to the steps employed in the full cell process except the pressure applied is much less.

18.6.5 Solvent Recovery Process

These processes use an organic solvent preservative with a solvent where the solvent could be recovered after carrying the preservative into the wood. The treating solution is usually butane or isobutene together with isopropyl or polyethylene glycol containing 2% to 4% PCP. The timber treated in this way is dry at the end of the process and could be used immediately. However, the solvents are expensive and involve high operational costs and extreme care is required in handling highly flammable solvents.

18.7 Nonpressure Processes

There are a number of nonpressure processes of treating wood, which is quite varied in their procedure. Some of the important methods are listed below.

18.7.1 Brush Treatment or Brushing

The simplest method of applying a preservative is brushing and is normally used for preserving small individual items, and also, when it is required to apply to a timber already installed in a building, brushing may be the only way possible. Brush treatment is used to ends of any timbers, which have been cut to size after they have already been pressure impregnated. In order to have an appreciable effect, the preservative should be flooded on the surface by brushing to get the maximum amount absorbed. An important factor is the timber to be treated should be dry. Tar oils, if they are too viscose, should be heated before applying. Brushing can be repeated at regular intervals depending on the environment to which it is exposed. Care should be taken to brush any exposed grain with sufficient preservative.

18.7.2 Spraying

The spraying offers a more liberal and effective covering of the timber than brushing. The possibility of the preservative penetrating into holes, cracks, splits, etc., is more in spraying. This method is often employed when it is required to apply the preservative to large areas and also to roof members with woodworm, which enables the preservative to reach the timber, which is inaccessible to brushing.

18.7.3 Immersion or Dipping

Immersion or dipping involves immersing the timber/plywood in the preservative for a short time, and the same treatment is known as steeping or soaking and immersion may extend to several hours or days (Fig. 18.5). Immersion gives a better chance of the preservative reaching the holes, cracks, and splits. The degree of penetration depends on the duration of immersion, the timber species, and also on the type of preservative. Absorption is rapid during the first few hours only, and it takes a long time to get an appreciable penetration. Steeping is important where other methods of treatment are not available. In any case, it is more expensive than brushing as it requires large tanks and more preservative.

18.7.4 Hot and Cold Method

This process is sometimes known as open tank process or thermal process. Next to the pressure treatment, this offers a very satisfactory method of impregnation. In this process, seasoned timber is immersed in a bath or preservative, which is heated for few hours and allowed to cool, while the timber is still submerged in the liquid. Sometimes, the cooling is done by transferring quickly the timber from the hot bath to a cool bath of the preservative. During the heating period, the air in the cells expands and much of it is expelled as bubbles. During the cooling period, the remaining air in the cells contracts creating a vacuum and the preservative is drawn into the wood.

Therefore, practically whole of the absorption takes place during the cooling period. The temperature of the hot bath is normally between 80° and 95° C in the case when creosote is used as the preservative. The duration of submerging in the hot bath depends on the size of the timber and the species of timber. If the absorption of the preservative is too much, the duration of the cooling period can be reduced or the

Fig. 18.5 Veneer dipping

timber can be reheated in the preservative and removed, while it is still hot. It is also sometimes possible to increase the penetration by increasing the duration of heating. This process is effective for treating permeable timbers or timbers, which are moderately resistant to impregnation and normally used to treat fence posts and other farm timbers.

18.7.5 Sap Displacement Method

Sap displacement method can only be applied to round timbers in green condition and uses the hydrostatic pressure due to gravity to force the preservative from the butt end of the round timber. This method is commonly known as the Boucherie process, which originally used copper sulfate as the preservative. However, it is possible to use other water-soluble salts such as CCA salts. In this method, a cap is fitted to the butt end of a freshly sawn pole or round timber and then one end of a flexible tube is connected to the cap and the other end to a tank containing the preservative at a place as high as possible. The caps mentioned above are sometimes modified from old tubes of vehicle tyres.

There are modifications to this process such as the application of a vacuum from the top end. A major problem is the difficulty in having air-tight caps at the ends. This method gives a greater concentration of the preservative at the butt end, and this is welcome, especially in the case of poles going into the ground, which are most vulnerable to decay. With sap displacement, it may be assumed that logs of almost any species can have preservative solution forced through them if they have been freshly felled and are still full of sap. However, by inspecting a log, it is possible to find whether it is generally suitable for sap displacement treatment. The two most important criteria are the sapwood thickness and wood structure (in hardwoods).

1. Sapwood thickness unless the heartwood is sufficiently durable to last the required length of time without treatment, complete reliance is placed on the

treated sapwood shell. The treated sapwood layer should be strong enough to perform the task of the post or the pole if and when the center decays. A rule of thumb for minimal strength loss is that the sapwood thickness should not be less than one third of the radius of the log.

2. Wood structure (in hardwoods): In hardwoods, flow will only be through the vessels, and preservative movement from these to the fibers must be by diffusion. As preservatives of CCA type will diffuse only a very short distance, it follows that vessels must be fairly uniformly distributed and close together. This immediately rules out fast-grown ring-porous species, and a quick examination of a cleanly cut surface with a hand lens will soon identify such species.

18.7.6 Diffusion Processes

Diffusion processes can only be applied to very green timber and normally carried out at sawmills soon after the logs have been converted to sawn timber. The treatment has to be carried out at least within 7 days and in some cases within 2–3 days. The preservatives used in the diffusion treatment are highly soluble in water, and most commonly used salts are mixtures of borax and boric acid or polyborates and also borofluoride/chrome/arsenic (BFCA).

The process involves dipping freshly sawn timber in a concentrated treating solution, which is heated up to a temperature of 30 to 65 °C. The concentration of the treating solution depends upon the thickness of the timber. The timber just after immersion is closed piled (block stacked) and completely covered with a tarpaulin or polythene sheet so that drying is prevented as much as possible. The time for the diffusion of the preservative into the wood to take place is between 4 weeks for 25-mm-thick material and 15 weeks for 75-mm-thick material. The duration varies with different species when the penetration is complete; the timber is removed and restacked for normal seasoning. The main advantage of this method is that some timbers that are very resistant to impregnation can be treated this way. Furthermore, the cost of capital investment and the cost of the preservatives are not so high. There are two main disadvantages, firstly being the non-fixing nature of these preservatives and secondly the treatment can be applied only to freshly sawn timber. However, using the double diffusion process, it is possible to fix the preservative in the timber. One method is to immerse the freshly sawn timber in a solution of copper sulfate for several days and then transfer the timbers to a solution of sodium dichromate and sodium arsenate. These two chemicals react together within the wood, forming a product, which is insoluble. Although it gives a good fixation of the preservative, the control over the treatment is hardly possible.

18.8 Preservative Treatment of Plywood

Wood is an organic material, which is subject to break down due to chemical and biological agencies. Its natural resistance to various destructive agencies varies greatly with species. The natural durability of plywood assemblies is in general closely related to the natural durability of the species from which the plywood is being made. In plywood assemblies, certain choices and arrangement of species can sometimes be used to provide special resistance to particular destructive agencies. Factors inherent in plywood manufacture often ensure sterile conditions in respect of fungus and insect attack, which may have been present in the raw material. Cross-lamination and glue lines too may also provide some resistance to borer and fungi.

The efficiency of preservative treatment depends upon the proper choice of preservative chemicals, which give varying degree of protection either individually or in combination of two or more chemicals against fungi, borer, termite, and other wood-destroying organisms. In general, plywood can be given preservative treatment by the same method that is used for solid wood. The type of preservative is required for plywood so that it shall be economical and effective. As a guiding principle, where maximum protection is required the plywood should be maximum penetrated by the preservative so that no untreated portions are left exposed when the sheet is cut or drilled. Preservation of panel material like plywood can be carried out mainly in three different stages of manufacture.

18.8.1 Treatment of Raw Material

Treatment of Raw Material, i.e., veneers and core stock of flush door/blockboard before panels, is manufactured:

1. Treatment of plywood.
2. Glue line treatment.

18.8.1.1 Treatment of Raw Materials: Veneers and Blocks of Core Stock

Veneers of all susceptible species and sapwood of all species irrespective of their durability class have to be given a treatment either by dipping or by spraying with chemicals. The chemicals used for treating veneers should have the following characteristics.

Toxicity to wood-destroying agencies like borers/fungi including molds should not cause difficulty in further operations like gluing, painting, and finishing, should not vaporize or during drying hot pressing, should be nontoxic to man and animals, and should be economical and easily available in market. Following chemicals can be used for treating veneers:

3% boric acid: borax mixture (1:1).
1.5% Borax +0.5% NaPcp or NaTcp.
2% phenol 1% HCHO.

For blockboard treatment, 3% boric acid: borax (1:1) solutions can be employed using dip diffusion techniques or by giving pressure treatments.

18.8.2 Treatment of Plywood

Pressure impregnation—partial penetrability of the veneer and glue line and penetration from the end grains of veneers make it possible to impregnate plywood by pressure or pressure cum vacuum treatment after manufacture of plywood. The plywood should be BWP or BWR type of stand pressure impregnation. The degree of penetration depends upon the permeability of veneers or timbers used in plywood making. The use of full cell process is recommended for pressure impregnation of plywood.

Full cell process is used when maximum absorption of the preservative is desired, that is filling up the cells and saturating cell walls with the preservative. In case of thin planks and plywood, spacers or grills should be used to separate the pieces. The door is tightly closed, and then, a vacuum of at least 56 cm of mercury is created and maintained for half an hour. The object of this operation is to remove as much air as possible from the cells. At the end of the vacuum period, the preservative is introduced into the cylinder with the vacuum pump working. Vacuum pump is stopped and the cylinder is subjected to an antiseptic pressure of 3.5 to 12.5 kg/ cm^2, depending on the species, size refractory nature of the material, etc. The pressure is held until the desired absorption is obtained, after which the preservative is withdrawn from the cylinder and finally a vacuum of 38 to 56 cm of mercury for about 15 min is once again applied to free the material from the dripping preservative. Specified retention of toxic chemicals during treatment may be obtained by a proper selection of the concentration in the treatment solution and the duration of pressure and vacuum periods. This method is recommended to treat refractory material or material needed high preservative retention (refer IS: 401-2001).

18.8.3 Soaking Plywood in Preservative Solution

Soaking treatment can be carried out by dipping plywood in solutions of preservative for sufficiently long periods until the desired absorption is obtained. The method may be modified to a hot and cold treatment. Hot and cold dipping may be done in either of the two ways mentioned below:

By dipping the plywood in a hot solution of the preservative at a temperature of 60–80 °C, maintaining at this temperature for a suitable period and allowing it to cool until the required absorption is obtained. Alternatively, the plywood may be removed from the hot solution and dipped into another vessel of cold solution of the same preservative.

plywood sheets as they come out from the hot press and dipped into the cold preservative solution till desired level of obsorption is obtained.

18.8.4 Vapor-Phase Treatment

A new method for treating panel products is developed especially plywood/ blockboard, whereas adhesive is used in urea- or melamine-based. In this method, treatment is done in a vapor phase. Moisture is totally eliminated as urea resin cannot tolerate water. Combination of boric acid plus methyl alcohol is used in this system, wherein the preservative, which is having high vapor hydrolysis on the surface of timber and boric acid, is deposited.

There is no water present in the system, and preservative in a vapor state penetration is very rapid and structure of wood will not interfere. This process is suitable for all types of panel products and solid wood. Since boric acid is leachable, this treatment is recommended for interior applications only. The use of a single chemical or a composition of two or more chemicals for prophylactic treatment of timber products depends on the type of the material to be treated or the process applied for treatment.

Chemicals used in the solution—when the finished plywood, blockboard, or flush door or their core stock—are treated by dip diffusion or pressure impregnation process, and the preservative chemicals are used in a solution. Such chemicals may be classified as follows:

(1) Oil type, (2) organic solvent type, and (3) water-soluble type—leachable and non-leachable.

18.8.4.1 Oil Type

Coal tar creosote is a fraction of coal tar distillate with a boiling point range above 200 °C is suitable for treating timber and timber products for exterior use. It may be used as such 50% mixture with petroleum fuel oil, which ensures stability to creosote against evaporation and leaching from the treated material used under marine conditions. Recommended absorption varies widely depending on the type of material and their uses.

**Creosote is highly toxic and gives good protection against termites and is non-corrosive. However, this treatment is not recommended for plywood as this will give black color to the plywood.

18.8.4.2 Organic Solvent Type

Preservative chemicals under this category are used in suitable organic solvent and may be used separately or in combination. The choice of the solvent depends on the solubility of the preservative and the use to which the treated material is put.

Preservative chemicals like copper and zinc naphthenates copper and zinc abietates and some chlorinated hydrocarbons or organophosphorus compounds like lindane, chlorpyrifos, and synthetic pyrethroids are used.

Plywood that is put to less severe environmental conditions is treated with organic solvent-type preservative. Effective dosage varies from 0.5 to 0.8 kg of chemicals per cubic meter of plywood.

18.8.4.3 Water-Soluble Type

(a) Water-soluble (leachable-type)—the chemicals in this category include both organic and inorganic compounds soluble in water. However, these preservatives are subjected to leaching that is the amount of the preservative in the treated material gets gradually depleted owing to the dissolving effect of water. However, plywood treated with leachable-type preservatives can be painted, varnished, or waxed. Water-soluble chemicals are used in low concentration of 1–2% solution. These are generally odorless and involve little fire hazard, e.g., boric acid and borax.

(b) Water-soluble (fixed-type)—these preservatives consist of various salts having broad-spectrum efficacy against a variety of organisms. The chemicals contain toxic elements such as copper, zinc, arsenic, and boron along with fixative salts usually sodium or potassium dichromate.
The role of chromium is to fix the toxic elements in the timber, so that the toxic salts become difficult to leach by the action of water. It is, however, necessary that the treated material be allowed to dry for 2–3 weeks to complete the fixation process.
Plywood or board treated with fixed type preservative chemicals is suitable for exterior use. The chemicals used in these are CCA, ACC, CCB, ACA, and BCCA.

These preservative are widely used worldwide in plywood industries. Some of the Bureau of Indian Standard recommended compositions, which are normally used in plywood industries are given below:

(a) Copper–chrome–arsenic (CCA)	
Copper sulfate $CuSO_4$ $5H_2O$	37.5 g
Na_2 Cr_2O_7 $2H_2O/K_2Cr_2O_7$	50.0 g
Arsenic pentoxide AS_2O_5 $2H_2O$	12.5 g
(b)Acid copper chrome (ACC)	
Chromic acetate $(C_2H_3O_2)_3$ H_2O or Boric acid H_3BO_3	5 g
Copper sulfate $CuSO_4$ $5H_2O$	50 g
Sodium/potassium dichromate	45 g
(c) Copper chrome boron composition	
Copper sulfate	35 g
Sodium/potassium dichromate	47 g
Boric acid	18 g

18.8.4.4 Preservative Chemicals for Glue Line Treatment of Plywood

Glue line application of preservative chemicals is the simplest method of treating plywood to render its resistant against insect attack. This treatment is carried out by adding suitable chemical in the glue mix together with hardener, filler, etc. The process is very simple, and no special equipments are required and it follows the conventional process of plywood manufacture. A number of chlorinated hydrocarbon and organochloro phosphorus and synthetic pyrethroids like lindane EC, chlorpyrifos EC, Bifenthrin EC are used as glue line poisoning chemicals.

18.9 Remedial Treatment of Wood and Wood-Based Panels

Several remedial measures are also available for treating products made from wood and wood-based panels like plywood, blockboard, and particleboards when signs of decay are visible under service conditions. However, neither the conventional treatment methods nor preservatives are suitable for remedial treatments. Some of the treatment measures are as follows:

- Fumigating the products using agricultural fumigants like aluminum phosphide, or ethylene dibromide and carbon tetrachloride mixture (1:1) or DDVP, when insect attack (borer/termite) is noticed. Fumigation kills the existing infestation only, and therefore, this is a temporary treatment. Reinfestations can occur at later stage. Therefore, fumigation may be followed up by permanent treatment.
- Permanent treatment:
  For remedial treatment, water-soluble preservatives are seldom used. Instead, light organic solvent-based preservatives like zinc naphthenates 8%, copper naphthenate 6%, chlorpyrifos 1%, lindane 1%, bifenthrin 0.05%, and trichlorophenol 4% may be applied by brush. Two applications with a gap of 15 days are recommended against borer/termite damage. The treatment methods/ schedules/chemicals are given in Table 18.1 and flow chart (Fig. 18.6).

Table 18.1 List of preservatives recommended for treatment of plywood protection during service life

• Coal tar creosote and fuel oil (50:50) by weight. In high termite-infested areas, it is preferable to add 1% dieldrin (exterior applications)
• Boric acid: borax (1:1.5)
• 3% of boric acid: borax: sodium pentachlorophenate (1:1.5:0.5)
• Zinc naphthenate 8%, copper naphthenate 6%
• Trichlorophenol 4%, lindane 20EC 1%, bifenthrin 0.025%
• Chlorpyrifos 1%, fipronil 0.1%
• **Light organic solvent preservative (LOSP)**: Zinc naphthenate and copper naphthenate can be treated by dipping or by brushing in mineral turpentine or paint thinner
• **Preservative that may be used include the following:**
– Formaldehyde 0.5%
– Phenol + copper sulfate (1:1) 1%
– Sodium pentachlorophenate +boron compounds (0.5 + 1.5) %
– Borax 2%

Fig. 18.6 Flow chart preservative treatment for plywood/block board/flush door and remedial treatment for observed insect attack

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Wood Modification for Wood Protection

19

B. N. Giridhar and K. K. Pandey

Contents

Abstract

Wood-based materials are used in variety of applications. It is a good engineering and structural material because of good mechanical strength, low thermal expansion, and esthetic appeal. However, being biological material, it is susceptible to environmental degradation. It is necessary to treat wood to provide specific properties depending on the intended application. A usual problem associated with wood during its outdoor application is degradation resulting from solar UV radiation. The degradation starts immediately after the wood is exposed to sunlight. All the constituent polymers of wood possess reactive -OH groups, which are hydrophilic in nature that results in its dimensional instability and makes it susceptible to microbial attack termed biodegradation. Wood changes dimension with changing moisture content because the hydroxyl groups present in cell wall polymers attract moisture through hydrogen bonding resulting in cell wall swelling. The process is reversible, and wood shrinks during drying process

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_19

as it loses moisture. Wood undergoes biodegradation because organisms recognize the polysaccharide wood polymers (cellulose and hemicelluloses) and have very specific enzyme systems which can degrade these polymers resulting in strength loss. Traditional wood preservatives such as chromated copper arsenate (CCA) are under threat because of environmental concerns about leaching of copper, chromium, and particularly arsenic into the environment. Accordingly, there is a need to develop alternative more environmental friendly treatments to prevent such degradation. One of the viable methods is to chemically modify the wood to increase its hydrophobicity, thereby arresting biological attack. Wood modification is one of the effective methods to enhance durability of fast-growing timbers usually having low durability. With increased dimensional stability and resistance to microorganisms, modified wood can be an excellent choice for outdoor applications.

This chapter describes the overview of wood modification technologies particularly the processes of thermal and chemical modification. Modified wood can be useful for many specific end uses including fencing, decking, wall paneling, etc. Modification of wood is one of the most effective methods to obtain dimensionally stable wooden product.

Keywords

Acetylation · Chemical modification · Dimensional stability · Thermal modification · Weathering of wood · Wood protection

19.1 Introduction

Wood is a naturally available material that has long been recognized for its versatile nature and broad range of indoor and outdoor applications. The huge diversity in the properties among timber species makes different species useful for a specific use. Rapid increase in demand of high quality of timber for construction and other uses has increased pressure on primary timber species. One of the solutions for this problem is to increase the use of short rotational fast-growing plantation timbers. However, these fast-growing timbers are susceptible to environmental and microbial degradation and require preservative treatment to increase their service life when used outdoors. Particularly the sapwood of these species has a low durability. Therefore, the development of technologies for improving the properties (e.g., dimensional stability and durability) of these wood species is necessary. This problem is solved by using traditional biocides preservatives. There has been growing environmental and legislative pressure on the use of certain biocide-based wood preservatives. Therefore, there is a need to develop alternative more environmentally friendly treatments to prevent such degradation. One means of achieving this is the modification of wood polymers.

Chemically, wood is a polymeric composite made up of cellulose, hemicelluloses, and lignin. Physical and chemical properties exhibited by the

Fig. 19.1 Weathering of wood and coating failure due to weathering

wood are related to these three cell polymers constituents of wood. All of these wood polymers have accessible hydroxyl groups that make it susceptible to environmental degradation. It attracts moisture through hydrogen bonding, making it dimensionally unstable, which in turn promotes biological degradation. A combination of physical, chemical, and biological factors causes degradation of wood through a complex process termed as weathering (Feist & Hon, 1984; Hon, 2001; Evans et al., 2005; Evans, 2013; Williams, 2005). The environmental factors which contribute to weathering degradation process include solar UV radiation, moisture, heat, atmospheric pollution and biological agents. Wood and wood-based products used for structural purposes, for outdoor uses, siding, windows, decks, roofs and fencing are affected by weathering. Weathering affects physical, chemical and mechanical properties of wood. The degradation is manifested by physical changes (discoloration, surface fading, roughening and cracking), microstructure damage and mechanical destruction. Colonization of mold on the surface also discolors the wood. Weathering affects coating adhesion and results in premature coating failure (Fig. 19.1).

The weathering process is primarily initiated by solar UV radiations; presence of other factors expedites and promotes the degradation process. The solar UV radiation (wavelength range 290–410 nm) has sufficient energy to break many of the chemical bonds and degrade wood polymers lignin and carbohydrates. The chromophoric groups present in the cell wall polymers mostly absorb in the UV region and involve in photoreactions. Wood extractives mainly absorb light in the visible region and undergo photobleaching. Water-soluble chemicals from the wood surface also leach out due to rain.

Color change is the most common effect of UV degradation of wood (Fig. 19.2). The process is very rapid. Light-colored woods darken in color and become yellow or brown due to the accumulation of photo-degraded fragments in the wood surfaces. Photodegradation of wood polymers results in color changes. Dark-colored woods that are rich in phenolic extractives may fade initially before becoming yellow or brown. Wood-exposed outdoors turn gray as photo-degraded lignin fragments are

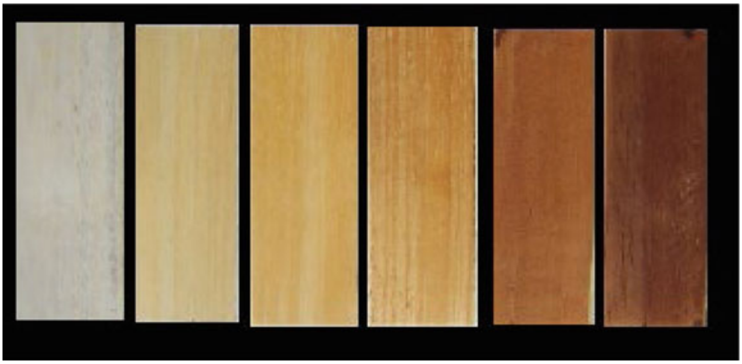


Fig. 19.2 Color changes in wood surfaces of rubberwood due to xenon source exposure; irradiation period increases from left to right. Sample in the extreme left is control (unexposed wood)

leached from the wood (Feist & Hon, 1984). The presence of fungal spores, hyphae, etc. further alters wood appearance.

The origin of light-induced discoloring (photoyellowing) of wood is reasonably well known (Feist & Hon, 1984; Hon, 2001; Williams, 2005; Evans et al., 2005; Evans, 2013). Photochemical reaction in lignin initiated by UV light absorption oxidizes lignin phenols into quinones in presence of atmospheric oxygen. Phenolic radicals are generated by absorption of UV light by phenolic hydroxyl groups in lignin leading to formation of carbonyl-based chromophoric (quinonoid) structures as a result of demethylation or cleavage of the side chain (Hon, 2001). The degradation is also manifested by formation of microscale cracks on the wood surfaces. Microscopic changes in anatomical structure of wood precede macroscopic damage. The destruction occurs in lignin-rich middle lamella that binds adjacent fibers. The light-degraded fragments of lignin leach away by rain and top surface layer of wood becomes carbohydrate-rich, which further promotes biodegradation.

Chemical characterization (lignin degradation) of weathered wood is carried out using surface-sensitive spectroscopic techniques (e.g., Fourier transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy). Lignin degradation within few hours of UV light exposure is evidenced from FTIR spectra of degraded wood surfaces (Hon & Chang, 1984; Tolvaj & Faix, 1995; Müller et al., 2003; Colom et al., 2003; Pandey, 2005; Pandey & Vuorinen, 2008). Significant lignin degradation is also observed within few days exposure to natural weathering (Evans et al., 1996; Pandey & Pitman, 2002).

Water plays an important role in the weathering of wood. Dimensional change caused by the wetting and drying of wood through moisture absorption by wood generates surface stresses that cause checking and warping of timber. The presence of moisture further enhances photodegradation process. Swelling of wood due to moisture absorption opens upon inaccessible region of the cell wall and facilitates light penetration. Presence of moisture also promotes the decay of wood due to biological agents. Though atmospheric temperature has no direct consequence on the wood, it accelerates the photochemical reactions involved in the weathering of wood. The thermal degradation of wood polymers generally occurs at higher temperature (generally >150 °C).

19.2 Protection of Wood Against Weathering

The most common method of protecting wood from weathering is through the use of coatings such as paints, varnishes, stains, or water repellents. The following are alternative methods to protect wood against weathering.

- Wood coating- paints and varnishes.
- Application of inorganic wood preservatives.
- Chemical modification of wood polymers.
- Impregnation of lumen with monomers and its subsequent polymerization.
- Thermal modification of wood.

19.2.1 Treatment with Inorganic Chemicals and Wood Preservatives

Treatment of wood surfaces with aqueous inorganic chemicals improves the weathering durability of wood and also increases the service life of natural finishes used outdoors. Aqueous solution of chromium trioxide is effective at protecting wood surfaces from weathering. Many other compounds like trivalent chromium compounds, iron (III) chloride or nitrate, manganese (III) acetate, potassium permanganate nonoxidative titanates and zirconates have been tested (Evans et al., 2005). Several other chemical combinations (e.g., acid copper chromate, acid cobalt chromate, acid zinc chromate, lead chromate, ammonium chromate, sodium dichromate, acid copper-chrome-arsenate, ammoniacal copper-chrome-arsenate, ammoniacal copper chromate, ammoniacal cupric oxide and copper, chromium, and iron molybdate) have also been tested. Some of these treatments have been found effective at protecting wood surfaces from weathering. Inorganic compounds used as components of wood preservatives such as chromated copper arsenate (CCA), can also provide some protection against weathering. Wood preservatives such as copper azole, copper monoethanolamine have been tested and found to increase the hydrophobicity of wood also reduced the susceptibility of the wood to photodegradation to some extent (Evans et al., 2005). However, treatment of wood with most of these compounds changes the color of wood and some of these chemicals have environmental and health issues.

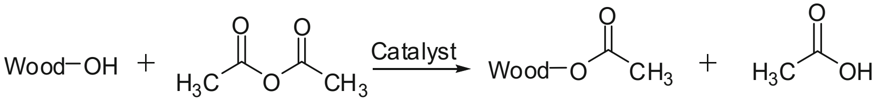
19.2.2 Wood Modification

The processes of wood modification aim altering the molecular structure of the cell wall components and are effective in improving the dimensional stability and durability of wood. Modified wood is a new material that does not present any environmental hazard at the end of the product life cycle (Hill, 2006). The three well-known methods of wood modification which have been exploited commercially are thermal, chemical, and impregnation modification.

19.2.2.1 Chemical Modification of Wood

Chemical modification involves substituting hydrophilic OH groups of wood constituents by hydrophobic groups through either esterification with chemicals such as acid anhydrides, acid chlorides, isocyanates, or etherification with alkylene oxides. Among the several processes studied, acetylation of wood is the most stable and industrially accepted process. Chemical modification of cell wall polymers is an effective method to induce dimensional stability, UV resistance and biological resistance in wood (Rowell, 1983, 2006, 2013; Takahashi, 1996; Plakette et al., 1996).

In acetylation process, acetic anhydride reacts with the hydroxyl groups of wood polymers (lignin, cellulose and hemicellulose). The reaction replaces hydroxyl groups with acetyl groups (Rowell, 1983, 2006; Hill, 2006).



Acetylation of with acetic anhydride

The acetylation results in increased weight percent gain (WPG), which can be estimated using Eq. (19.1),

$$\mathrm{WPG} = [(W_{\mathrm{m}} - W_{\mathrm{o}})/W_{\mathrm{o}}]100 \tag{19.1}$$

where, W_o and W_m are oven-dried weight of unmodified and chemically modified wood samples, respectively. Value of WPG is indicative of degree of modification. FTIR spectra of modified wood show the structural changes in wood cell wall after modification (Fig. 19.3). The esterification of wood by acetic anhydride is characterized from increase in the carbonyl stretching absorption at around 1739 cm^{-1}, which is indicative of acetyl groups. The reduction in the intensity of O-H band indicates substitution of hydroxyl groups through esterification. Modification is also indicated by an increase in peak at 1365 cm^{-1} (C-H deformation of cellulose and hemicellulose) and a prominent C-O stretching peak at 1216 cm^{-1}.

The moisture adsorption behavior of modified wood is evaluated by calculating equilibrium moisture content (EMC) of unmodified and modified wood at different relative humidity conditions. The equilibrium moisture content (EMC) of chemically modified wood is lower than unmodified wood (Fig. 19.4). This indicates that modified wood is more hydrophobic than unmodified wood.

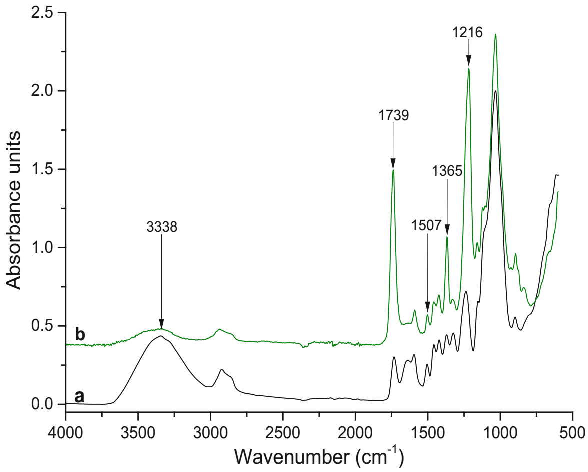


Fig. 19.3 FTIR spectra of (**a**) unmodified and (**b**) chemically modified *M. dubia* wood

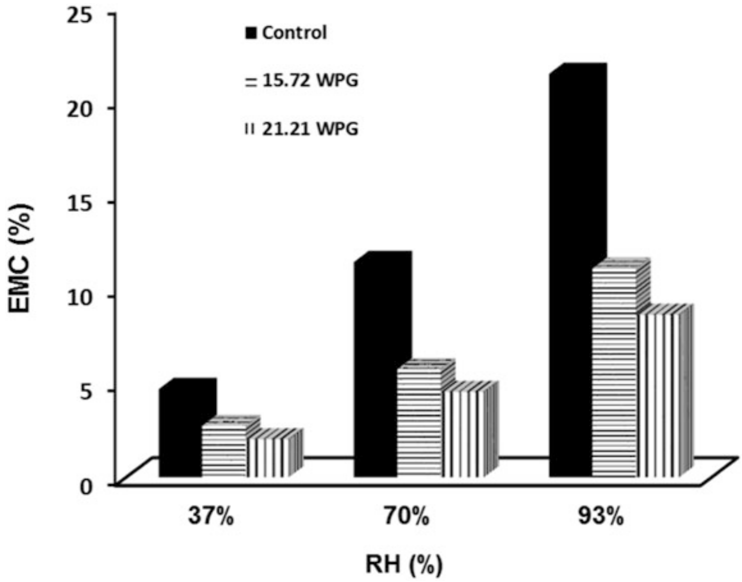


Fig. 19.4 Equilibrium moisture content (EMC) of unmodified and chemically modified *Meliadubia* wood exposed to different humidity levels

Dimensional stability of modified wood can be estimated by evaluating Antiswelling Efficiency (ASE). ASE can be calculated by measuring volumetric swelling coefficients for unmodified (S_u) and modified (S_m) wood. The values of volumetric swelling coefficients were calculated using Eq. (19.2) (Rowell & Ellis, 1978),

Table 19.1 Antiswelling efficiency of chemically modified *M. dubia*

S. no.	Weight percent gain (WPG)	% Antiswelling efficiency (ASE)
1.	15.72	57.38
2.	21.21	71.49

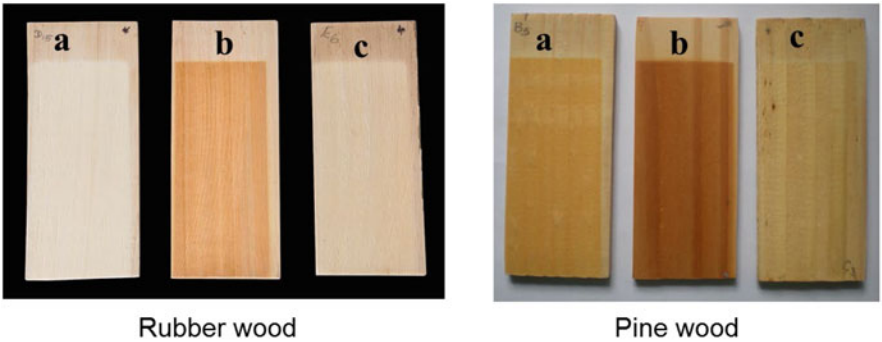


Fig. 19.5 Effect of UV irradiation on chemically modified wood. (**a**) acetylated wood, (**b**) untreated control, and (**c**) benzoylated wood

$$S(\%) = (V_2 - V_1)/V_1 \times 100 \tag{19.2}$$

where V_2 is the volume of saturated sample and V_1 is the volume of the oven-dried sample. Antiswelling efficiency (ASE) can be calculated using Eq. (19.3),

$$\text{ASE}\,(\%) = (S_\text{u} - S_\text{m})/S_\text{u} \times 100 \tag{19.3}$$

Modified wood exhibits high antiswelling efficiency (ASE) indicating dimensional stability (resistance to swelling and shrinkage) (Table 19.1). The hydrophobic nature and ASE of modified wood increase with increase in the extent of modification.

Modified wood is more durable and has good resistance against decay fungi. The acetylation of rubberwood with isopropenyl acetate has been found to be very effective in inhibiting decay due to brown-rot and white-rot fungi (Giridhar & Pandey, 2016).

Chemically modified wood has superior UV resistance; therefore natural appearance of wood is retained for longer duration under outdoor use. The color of untreated specimens deepens/darkened upon UV light irradiation, whereas no significant darkening was noticed in modified wood (Fig. 19.5). The darkening of wood observed in unmodified wood is significantly reduced in acetylated wood (Plakette et al., 1996; Chang & Chang, 2001; Chang et al., 2002; Pandey & Chandrashekar, 2006; Evans, 2009). This shows the effectiveness of chemical modification in restricting photodiscoloration. The chemical modification of wood substrate is also effective in inducing resistance to natural weathering (Pandey & Pitman, 2002). The color darkening due to weathering can be avoided/restricted by chemical

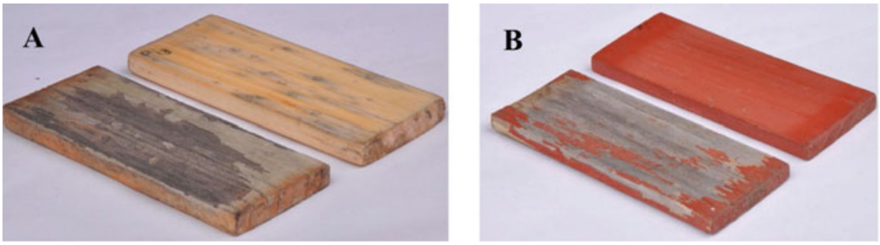


Fig. 19.6 Performance of PU coating on unmodified (left sample) and acetylated pine wood (right sample) after 1 year of natural weathering. (**a**) Transparent coating; (**b**) opaque coating on pine

modification of wood. Benzoylation of wood with benzoyl chloride has been found to induce good photostability (Evans et al., 2002; Pandey & Chandrashekar, 2006).

Chemically modified wood improves coatings adhesion and enhances performance of paints and varnishes significantly (Pandey & Srinivas, 2015; Vollmer & Evans, 2013). The chemical modification of wood is very effective in restricting degradation of paints. Chemical modification of wood substrate prior to coating enhances service life of coating considerably (Fig. 19.6).

Chemically modified wood has good decay resistance against fungi and termites (Rowell, 2006, 2013; Bongers et al., 2015; Kumar, 1994). Chemically modified wood has no significant adverse impact in the strength properties of wood. It is nontoxic and can be safely reused and recycled. Chemically modified wood is ideal for exterior applications such as doors, shutters, window frames, garden furniture, decking, high durability particleboards, fiberboard, etc.

19.2.2.2 Thermal Modification of Wood

Thermal modification of wood is an environmental friendly method of improving weathering properties. In thermal modification, wood is heated between 150 and 250 °C under controlled conditions (in the absence of oxygen) (Viitanen 1994; Esteves & Pereira, 2009). It can be done under a steam blanket (hygrothermal modification), under nitrogen, or in a vacuum. Thermal modification is carried out either in very limited supply of oxygen or in the presence of inert gases, steam, oil or under vacuum that permanently changes the physical, chemical, and mechanical properties of wood (Candelier et al., 2016; Dubey et al., 2010, 2011, 2012; Hill, 2006; Militz, 2002; Sandberg et al., 2017; Srinivas & Pandey, 2012; Tuong & Li, 2010). Thermal modification generally imparts moisture resistance, decay resistance, and improves dimensional stability of wood (Boonstra & Tjeerdsma, 2006; Kamdem et al., 2002; Bekhta & Niemz, 2003; Sailer et al., 2000).

Thermal modification changes the esthetic properties and wood attains a uniform dark color due to formation of colored degradation products (Fig. 19.7). Heat treatment results in color darkening and uniform coloration of wood. Color darkening increases with time and temperature. Heat-treated wood became more uniform in color throughout the surface (Militz, 2002; Esteves et al., 2008a, b). The color changes in heat-treated wood can be analyzed by measuring CIELab color

Fig. 19.7 Effect of thermal modification on color changes of *Meliadubia*. Severity of treatment increases from left to right, extreme left sample is untreated (control) wood

parameters (L^*, a^*, b^*, and ΔE^*) using a spectrocolorimeter. The color became darker and uniform throughout the wood with heat treatment. CIE lightness color coordinate (L^*) decreased with treatment severity and weight loss percentage. Overall color changes (ΔE^*) depend upon temperature and exposure durations (Srinivas & Pandey, 2012; Esteves et al., 2008b; Peña & Hale, 2009).

Heat treatment modifies the chemical components of the wood, resulting in weight loss. It is an important feature of thermal modification and also an indication of quality for thermally modified wood. The weight loss due to heat treatment can be determined using Eq. (19.4),

$$\%\text{Weight loss} = [(W_o - W_t)/W_o] \times 100 \qquad (19.4)$$

where, W_o and W_t are oven-dried weight of unmodified (control) and heat-treated wood samples, respectively. Weight loss of the samples depends on the temperature as well as time of treatment (Fig. 19.8). Weight loss increases with severity of treatment (i.e., temperature and time of treatment).

Heat treatment modified chemical components of wood, resulting in weight loss and color changes. Extent of changes depends upon process parameters (temperature and heat treatment time). Thermochemical degradation of cell wall polymers results in generation of structures which are responsible for color darkening of treated wood. Typical FTIR spectra of unmodified and thermally modified samples are shown in Fig. 19.9. Heat treatment results in degradation of hemicelluloses and formation of acetic acid (Esteves & Pereira, 2009; Tjeerdsma & Militz, 2005). Degradation of carbohydrates is indicated by the changes in the intensity of bands at 1727, 1368, 1226, 898, and 835 cm^{-1}. The increase in intensity of absorption of band at 1104 and 1159 cm^{-1}, assigned to the cellulose C-O-C stretch, indicates the increase in crystallinity of cellulose. The intensity of bands at 1604 cm^{-1}, assigned to aromatic C=C stretching in lignin, increase due to thermal treatment.

Heat-treated wood attained hydrophobic nature as compared to unmodified wood (Fig. 19.10). The EMC values decreased with the treatment severity. This indicates

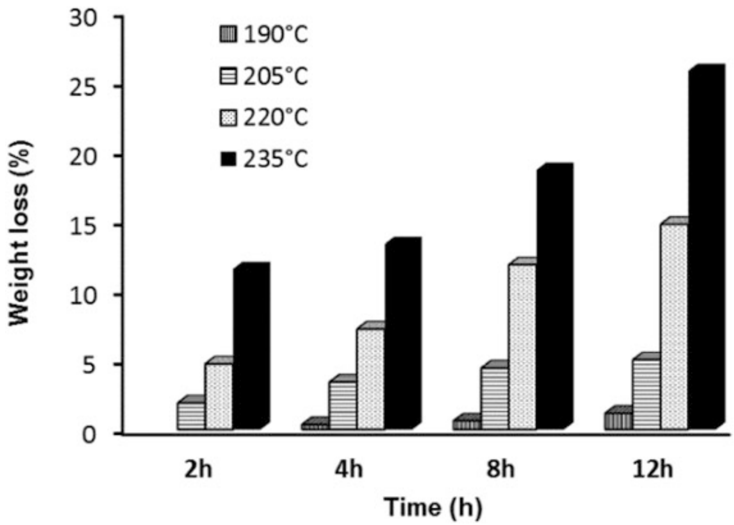
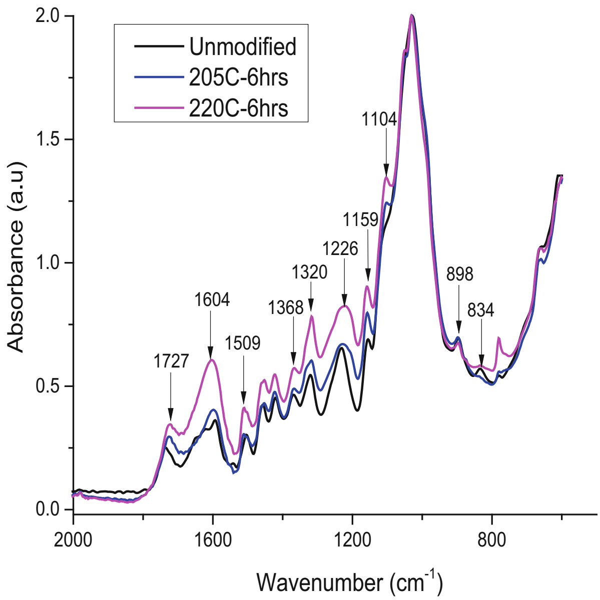


Fig. 19.8 Effect of heat treatment on weight loss of *M. dubia* wood

Fig. 19.9 FTIR spectra of thermally modified *M. dubia* wood



that hydrophobicity increased with increasing temperature and time of heat treatment.

Heat treatment of wood results in the reduction of volumetric swelling coefficient. ASE increases with heat treatment severity (Table 19.2). This shows that thermally modified wood is less hygroscopic and dimensionally stable in compared to

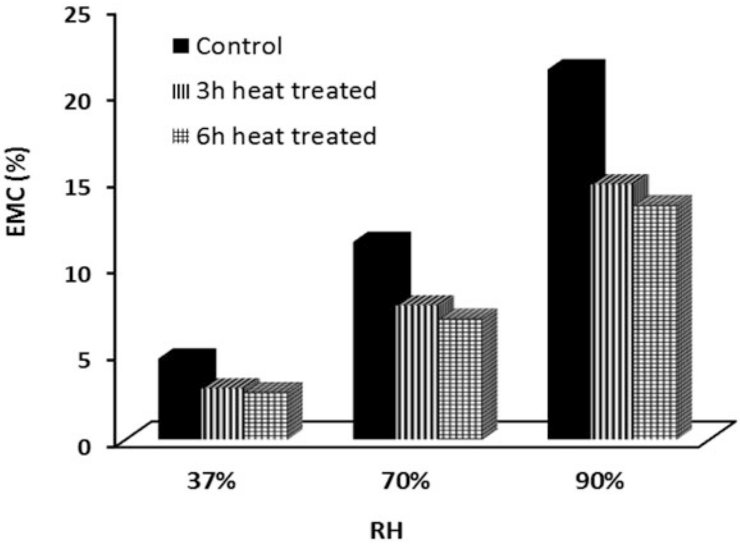


Fig. 19.10 EMC of thermally modified Melia wood

Table 19.2 Antiswelling efficiency (ASE) of thermally modified *M. dubia*

S. no.	Heat treatment duration (h)	Weight loss (%)	% Antiswelling efficiency (ASE)
1.	3 h	5.73	50.69
2.	6 h	10.62	56.72

unmodified wood. Increase in dimensional stability of wood is mainly due to degradation of wood structure mainly in hemicellulose and an increase in condensed lignin internal unit bonds (Tuong & Li, 2010; Esteves et al., 2008b). Decreased hygroscopic nature of wood and improved dimension stability of wood result in improved resistance against decay fungi, although it is associated with loss in some of the mechanical properties, depending upon the severity of treatment (Esteves & Pereira, 2009; Srinivasa & Pandey, 2012). The changes in the cell wall components from hygroscopic to hydrophobic by making –OH groups less accessible make the thermally modified wood more dimensionally stable (Boonstra & Tjeerdsma, 2006; Viitanen et al., 1994). However, mechanical properties are adversely affected due to various chemical transformations during thermal modification (Bak & Nemeth, 2012; Kocaefe et al., 2008). The changes in properties due to thermal modification depend on many factors including the type of wood, type of medium for heat transfer, and severity of treatment (temperature and time of treatment) (Esteves & Pereira, 2009; Lee et al., 2018).

Thermally modified wood has been recommended for both indoor and outdoor applications. However, behavior of thermally modified wood against UV light exposure is still not clearly established. Some of the researchers found thermally modified wood weathering resistant (Ayadi et al., 2003; Nuopponen et al., 2004;

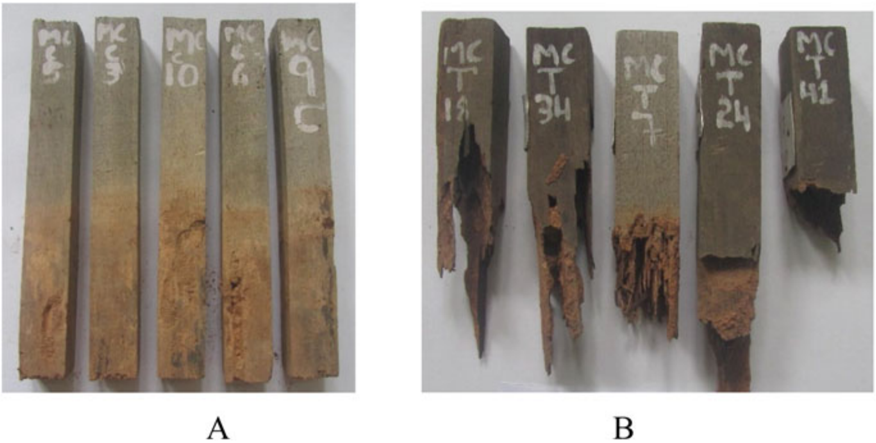


Fig. 19.11 Condition of (**a**) untreated, (**b**) vacuum heat-treated *M. dubia* wood after 6-months exposure to termite test yard

Temiz et al., 2006; Dubey et al., 2010; Tomak et al., 2014; Altgen & Militz, 2016). On the other hand, there are contrary reports indicating thermally treated wood vulnerable to UV degradation (Yildiz et al., 2011; Srinivas & Pandey, 2012; Huang et al., 2012; Tolvaj et al., 2014; Xing et al., 2015; Nemeth et al., 2016). This indicates that weathering behavior of thermally modified wood might be dependent on the timber species, treatment process and conditions. For example, presence and nature of extractives in wood may influence weathering resistance (Passauer et al., 2015).

Thermal modification of wood induces decay resistance against white-rot and brown-rot fungus. Weight loss in *M. dubia* wood due to exposure to a brown-rot fungus (*Polyporus meliae*) reduced from 63.57 $\pm$ 3.57 in unmodified control wood to 18.75 $\pm$ 2.54 in thermally modified wood. However, thermally modified wood is ineffective in providing termite resistance wood. Thermally modified *M. dubia* wood was found to be more prone to termite decay as compared to untreated wood (Fig. 19.11).

Heat treatment is also an effective method to inhibit the leaching of water-soluble extractives of wood and hence can tackle the problem of staining on wood surfaces due to their leaching (Hu et al., 2012; Pandey et al., 2016). The thermally modified wood has been recommended for interior decoration and outdoor uses. Since there is no chemicals treatment involved, it is also environmentally friendly. Modified wood is suitable for decking, flooring, siding, cladding, garden furniture, window, doors frame and indoor furniture.

19.3 Conclusions

Wood is a renewable material that can be used for several purposes. However, being biological material, it is susceptible to dimensional instability due to adsorption/desorption of moisture, photodegradation due to solar radiation, and biodegradation due to microorganism. As a result of degradation, a huge quantity of unfinished and finished wood is degraded and requires frequent replacement. To ensure long life, wood substrates are usually treated with chemical preservatives and coated with various decorative and protective finishes such as paints, transparent finishes/varnishes, etc. Substrate modification is an effective method of enhancing durability of wood. Chemical modification provides a nontoxic treatment solution for fast-growing timbers usually associated with low durability. Modified wood has outstanding dimensional stability, good decay resistance, improved coatings adhesion and it enhances performance of paints and varnishes significantly. Thermal modification of wood is another ecofriendly method to impart uniform coloration, improve dimensional stability and fungal resistance of wood.

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Advancements in Nanotechnological Applications for Wood Protection

20

Sreeja Nair, Shiny K S, and Sundararaj R

Contents

Abstract

Nanoscience and technological research deals with manipulating physical, chemical, and biological properties of the materials in nanoscale. Due to superior qualities demonstrated by nanomaterials, it finds application in various fields. Recently, nanoscience has gained much attention in the field of wood science and technology. Wood can be treated with nanoparticle in dispersions, or emulsions or nanoparticles can be synthesized on wood surface. Nanocomposites can also be prepared from wood or wood-based substances with at least a particle in nanoscale. Use of nanoparticles instead of their bulk counterparts increases total surface area of absorption thereby improving UV stability of surface wood coatings without affecting the transparency of the coatings. Thermal stability, fire

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_20

retardancy, moisture resistance, and mechanical properties can also be improved using nanoparticles. Inherent properties of the nanoparticles depend on the properties that are enhanced, as TiO_2 provides better UV stability but do not improve thermal properties. SiO_2 improves the fire retardancy of treated wood and wood nanocomposites. ZnO and CuO nanoparticles improve the resistance of treated wood against biodeteriorating agents compared to its bulk counterparts due to its effective penetration. Recently, research has been focused on biosynthesis of nanoparticles and its use in an environmentally friendly manner.

Keywords

Nanotechnology · Wood · UV stability · Moisture resistance · Thermal stability · Biodegradation

20.1 Introduction

Nanotechnology is an emerging field that has tremendous applications in the preparation of new generation materials in various fields of science and technology. Nobel laureate Richard P. Feynman presented the term "nanotechnology" as "There's Plenty of Room at the Bottom" (Feynman, 1960). Ever since, nanotechnology has revolutionized technological advancements in multidisciplinary fields making things compact, lighter, smaller, stronger, and more efficient. Nanotechnology refers to preparing or modifying materials in nanoscale (10–100 nm) to improve their properties (Siegel et al., 1999). Specifically, nanotechnology is defined as the technology, engineering, and science related to understanding and controlling the matter at nanoscale (NNI, 2005). As the bulk material approaches nanoscale, the physical, chemical, and biological properties of these materials change in a desirable manner. By altering the size of particles in nano range controlling their internal and surface chemistry, their assembly, it is possible to prepare materials of various functionalities in a unique way (Siegel et al., 1999). During preparation, nanomaterials break the bonds between the atoms and thus remain with high energy and relatively unstable. Extremely smaller size and incredible increase in the total surface area also contribute to its high reactivity (Darweesh, 2018). This makes it more available to chemical reactions. Increased catalytic properties make nanomaterials attractive in chemical and biological reactions making it more efficient and relatively less laborious (Gatoo et al., 2014). Novel characteristics exhibited by nanomaterials include high porosity, high thermal conductivity, enhanced optical and magnetic properties, colloidal stability, increased strength, and hardness (Khan et al., 2017). These properties make nanomaterials to be studied extensively during recent years for the manufacture of functional materials that can answer many challenges in science and technology.

Materials with at least one dimension in <100 nm roughly are termed as nanomaterials (Gonsalves et al., 2000). Nanomaterials fall into different categories according to their morphology, size, and physicochemical characteristics. Metal, ceramic or polymer as nanoparticles, nanotemplates, nanofibers, and nanowires are some of them that are commonly used for various applications (Khan et al., 2017). These can be 0D spheres and clusters, 1D nanofibers and wires, 2D plates and films, networks, and 3D materials (Gonsalves et al., 2000; Darweesh, 2018). Nanomaterials can also be incorporated into bulk materials to form nanocomposites to enhance various properties. Nanomaterials are extensively studied for the potential applications in optics, electronics, solar cells, fuel cells, and batteries. Unique surface properties and extremely smaller size make nanomaterials an attractive candidate for various biological applications including biotechnology, nanomedicines, and drug delivery systems. Biosensors are employed in pollution control that uses nanoparticles to detect small number of gases, pesticides, and other impurities in water, soil, and air. Key applications of nanomaterials in agricultural field include pesticide and pathogen detection, plant protection, food processing and packaging, etc. Soil reclamation, environmental remediation, and water treatment are also some other highlighted areas of nanotechnology. The chapter briefly discusses about the advancements of nanotechnology in the field of wood science and technology with special reference to property enhancement to prevent deterioration of wood under various conditions.

20.2 Nanomaterials in Wood Protection

Wood is a natural polymer composite made of cellulose (40–50%), hemicellulose (15–35%), and lignin (25–35%). The composition of these varies with species making it suitable for various residential, commercial, and industrial constructional applications delivering desirable qualities to wood. Nevertheless, being a natural polymer makes it susceptible for degradation overtime by various physical, chemical, and biological factors (Rowell, 2005; Evans, 2009). The practice of protecting wood from these environmental factors is rendered by various treatment methods that involve physical, mechanical, chemical, and biological processes (Rowell, 2005; Evans, 2009; Lebow, 2010). Chemical preservatives have provided efficient protection to the exposed wood but have certain pros and cons. Pollution due to the release of chemicals into the surrounding environment on prolonged exposure makes chemical wood protection less desirable. Now, the trend is to shift toward the use of indigenous wood preservatives that are with less negative impacts. The indigenous wood protection can only render short-term protection. Growing awareness about diminishing forest resources, nonavailability of naturally durable wood varieties, and sustainability of natural biomass has called attention to the research on more eco-friendly and efficient wood protection measures for strategic development. Idea of environmental benign wood protection often ends up in some natural resources or in chemicals that are leach-resistant and with low environmental hazard. In this context, the potential of nanotechnology in wood protection becomes apparent and realizable.

Nanotechnology is an emerging field, likely to have vast application in forest, forest products, and wood science and technology sector. Plant protection, forest management and operations, protection of wood and wood-based products are the major areas of focus. Nanotechnology in wood protection not only deals with making new products but also intends to modify the existing products and processes for better performance. Evans et al. (2008) have discussed that nanotechnology can have large industrial applications for wood protection and pointed out that the potential of large-scale use of nanoparticles for wood protection still remains unrecognized by researchers in the field. Many researchers have reviewed application of nanotechnology in wood protection. Borges et al. (2018) have emphasized that wood treatments based on nanoparticles may play an important role in the next generation of wood protection systems. The patents granted regarding the application of various nanoparticles in wood preservation and coating systems were reviewed by Mishra et al. (2018). A recent development on application in nanotechnology on wood-based industry was reviewed in detail by Jasmani et al. (2020).

Wood preservatives of improved performance can be prepared by replacing the bulk metallic counterparts with their nanoforms. Nano-based materials can be applied to wood in different ways. Some of the nanocompounds can be impregnated into the wood pertaining direct entry to interiors through the pores. The reduced size to nano is a key advantage, as the nanoparticles have a lesser size than the wood pores that facilitate an easy penetration into the wood (Freeman & Mclntyre, 2008). Some of the nanocompounds can be synthesized on the wood surface by various physical and chemical methods. Coatings that are applied to the wood using lacquers, paints, or varnishes function as both decorative and protective layers (Lebow, 2010). Nanomaterials can be embedded into these polymer coatings to function as additives, fillers, binders, and pigments. Recent trend is also to prepare nanoemulsions with immiscible liquid components to make one of the components disperse in nanoform. Recently, wood polymer-based nanobiocomposites are extensively studied due to improved optical and thermal characteristics.

Microparticle addition into polymer coatings increases the opacity of the coating, reduces flexibility and gloss. However, reducing the size to nano improves these properties making nanoparticles desirable additives for transparent polymer coatings (Marathe & Kantak, 2008). Nanomaterials used in wood protection provide some advantages, including the capacity to be applied to a large surface area, improved dispersion, and long-term protection (Clausen et al., 2009, 2010a, b). Nanocomponents can also provide a higher penetration and long-term fixation in wood (Ogrodnik et al., 2017). Addition of nanoparticles instead of microparticles improves the transparency of the coatings (Nair et al., 2018). Nanotechnology-based wood surface treatment methods are reviewed in detail by Papadopoulos and Taghiyari (2019).

20.2.1 Nanoparticles for UV Protection

Several approaches have been developed to provide UV protection to the wood exposed exterior including surface treatments with organic and inorganic UV absorbers (UVAs), surface modification, application of transparent, opaque coatings and finishes, etc. (Schaller & Rogez, 2007; Evans et al., 2015). Surface modification of wood using chemical reagents provides protection for a limited period. Weathering largely being a surface phenomenon is confined on the surface layers. Apparently, application of protective coatings is the simplest and cost-effective method for commercial application (Jirous-Rajkovic & Miklecic, 2021). Use of organic and inorganic UVAs either separate or in combination as additives to coatings provides better UV stabilization (Blanchard & Blanchet, 2011; Auclair et al., 2011). Nevertheless, UV absorbers filter out the harmful wavelengths from light spectrum, the stability on wood surface determines its efficiency for prolonged application. Loss of UVAs due to evaporation, migration, leaching, and photochemical reactions from the wood surface affects the stability (Evans et al., 2015). Hindered Amine Light stabilizers (HALs) are used in combination of UVAs and to further improve the performance of clear coatings (Schaller & Rogez, 2007; Forsthuber & Grull, 2010).

Inorganic metal oxides are common additives to UV protective paints and coatings that block UVA radiations (320–400 nm) and partially UVB radiations (290–320 nm). Nanoparticles of copper, zinc, boron, silver, cerium, titanium etc., have been greatly studied as fillers and additives in wood coatings. ZnO and TiO_2 nanoparticles are widely employed in UV protective sunscreens, paints, and coatings (Mitchnick et al., 1999; Smijs & Pavel, 2011; Schneider & Lim, 2018). These pigments in opaque coatings improve photostabilization by absorption or scattering of light. Reduction of the size of these metal oxides into nano increased surface area of light absorption and scattering. As the particle size reduces, the UV screening ability increases. Addition of nanoparticles can also confer increased durability to the coatings by ensuring high reactivity and better adhesion onto the wood surface. Reduction in particle size also increases the transparency and the esthetics by reducing the whiteness when compared to the microparticles (Smijs & Pavel, 2011; Khan et al., 2017).

Several studies reported on the photostabilizing effect of nano metal oxide-treated wood. ZnO nanofilms formed on bamboo by immersing in ZnO nanosol provided better photostability. The time of treatment is critical factor that affects the efficiency of nanoparticle treatment. Prolonged exposure to nanosol increased aggregation of particle on the surface. The uniformity of the coating is lost and reduced its effectiveness (Yu et al., 2010). Impregnation of nano-ZnO prevented photoyellowing of wood. Increased surface area of nanoparticles balances for total contact surface available for scavenging and reducing the free radical formation during lignin degradation (Clausen, 2010; Clausen et al., 2010a; Afrouzi et al., 2013). The size, concentration, and form of the nanoparticle in use affect the efficiency of nanoparticles (Blanchard & Blanchet, 2011; Nair et al., 2018). ZnO and CeO_2 incorporated in waterborne UV curable polyurethane/polyacrylate resin coated onto wood showed decrease in color stability with increased concentration of nanoparticles. Rather than dispersing uniformly higher concentration of nanoparticles led to the agglomerations that reduced the photoprotection efficiency (Blanchard & Blanchet, 2011). Efficiency of nanoparticle dispersions greatly depends on the uniformity of dispersion. Ultrasonication proved to be an effective mechanism for preventing agglomeration. This provides stability to dispersions preventing the settling of nanoparticles (Kamalgharibi et al., 2016; Nair et al., 2018). Nikolic et al. (2015) have recently reviewed the use of nanofillers in wood coatings and emphasized the need for improvement of dispersions for better stability, adherence, and performance of polymer coatings. Akhtari and Nicholas (2015) reported that nano-ZnO and micro-TiO_2 coating on copper amine azole-treated wood significantly reduced surface checking and warp. The inherent properties of the nanoparticles ultimately determine the dispersion characteristics and the performance of coated wood. Nano-TiO_2 and nano-ZnO particles in polymer coatings prevented the photoyellowing of wood (Veronovski et al., 2013; Guo et al., 2017; Shen et al., 2018). Thermally modified wood coated with nano-TiO_2 and nano-ZnO improved surface durability of waterborne polyacrylate clear coatings. However, the adhesion properties varied with the type of nanoparticle in use. Nano-TiO_2 maintained good adhesive coating whereas, nano-ZnO poor adhesion was noted (Miklecic et al., 2017).

Nano-ZnO, -CeO_2, and -TiO_2 dispersions were prepared in propylene glycol resulted in a stable dispersion with uniformly dispersed nanoparticles. *Wrightia tinctoria* specimens coated nano-ZnO, and TiO_2 dispersions enhanced UV stability and prevented yellowing of the wood. However, CeO_2 nanoparticles are found less effective than zinc and titanium nanoparticles (Nair et al., 2018). Higher the concentration of nanoparticles in the dispersion higher photoprotection was observed (Fig. 20.1). However, increase in concentration resulted in increased whiteness (Nair et al., 2018). Similar observations were reported with increase in concentration of TiO_2 in varnish 0–1.5% significantly decreased water absorption and increased weathering performance (Moya et al., 2016). Combining organic and inorganic UV absorbers can provide better photostability. Oak wood (*Quercus robur* L.) with a base coat of acrylic, water, and oil-based transparent coatings in combination with benzotriazoles, HALs, ZnO, and TiO_2 nanoparticles as initial transparent penetrating layer effectively slowed degradation under the influence of UV and VIS radiations (Panek et al., 2019). Silanes are commonly used for surface functionalization and efficient grafting of nanoparticles into polymers. Depending on the functional groups, different levels of effect can be achieved (Spear et al., 2021). Coatings combining silanes, a mixture of methyltrimethoxysilane and hexadecyltrimethoxysilane and TiO_2 nanoparticles showed improved weathering performance and slowed surface color change (Zheng et al., 2015; Srinivas & Pandey, 2017).

20.2.2 Nanoparticles for Moisture Resistance

Wood is a hygroscopic material that absorbs and desorbs water in response to the surrounding temperature and humidity. Hydrophilicity and hygroscopicity of wood are due to the free surface hydroxyl groups (–OH) of cellulose, hemicellulose, or lignin. Highly porous nature of wood also increases the water and moisture absorption (Tu et al., 2018). Water absorption and desorption causes dimensional changes

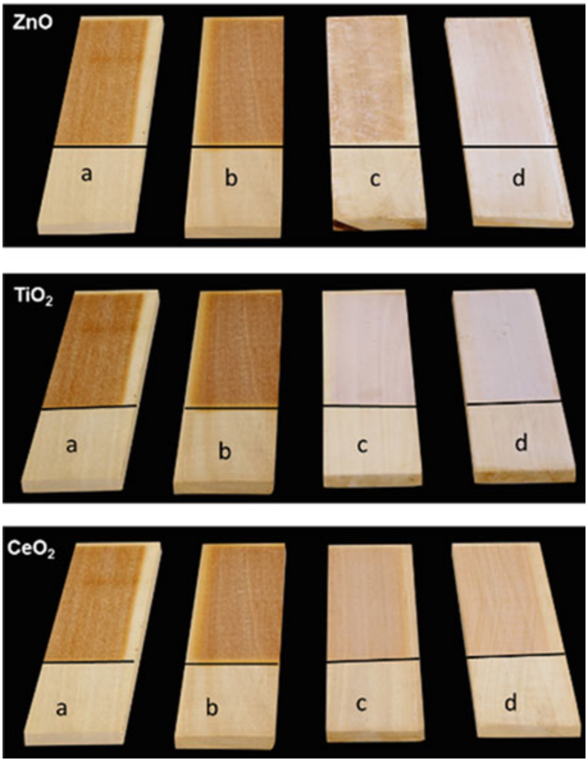

Fig. 20.1 Color changes after 500 h of UV exposure of (*a*) uncoated, (*b*) PG coated, and coated with nano metal oxides dispersed in PG (*c* and *d*). Concentration of nanoparticles is: (c) 1%, and (d) 2.5% (Nair et al., 2018)

in wood and problems in wood seasoning. Dimensional changes due to swelling and shrinking anisotropy on moisture absorption lead to cracking and splitting of wood. This results in deformations that affect the esthetics of wood, workability, and its commercial value. Absorption of moisture also increases rate of weathering and surface erosion of wood. Imparting hydrophobicity to wood essentially involves removing the accessible hydroxyl groups from the wood surface. Hydrophobicity of wood in turn improves the biological durability, corrosion resistance, and self-cleaning properties (Hill, 2006; Wang & Piao, 2011).

Surface modification processes viz., acetylation, benzoylation, furfurylation, and treatments with silanes, organosilicons or oils are common approaches for improving hydrophobicity of wood (Bryne & Walinder, 2010; De Vetter et al., 2010; Xiao et al., 2010; Dubey et al., 2012). Several studies have reported the use of inorganic materials alone or in combination to provide moisture resistance to wood surfaces. Wood surfaces are treated with SiO_2 and TiO_2 via a sol–gel method to improve its dimensional stability, antiphoto degradability, corrosion resistance, and hardness (Unger et al., 2012).

Super hydrophobic, self-cleaning surfaces in nature as lotus leaf, have water contact angle of 160° and rolling angle of 2°. Studies have shown that super hydrophobicity can functionally achieved by lowering the surface energy and changing surface roughness in nano range. Such super hydrophobic, mechanically durable wood surfaces can prepare by either modifying nanoparticles using silanes or dispersing it in polymers or preparing nanocomposites. Treatment of wood surfaces with alkyl chain thiols, organic silanes, polydimethylsiloxane-based polymers with incorporated nanoparticles or nanostructured features can reduce the contact area between the surface and the water droplet (Gaur & Khanna, 2015). Silica, TiO_2 nanoparticles surface modified using silanes showed large contact angle of 164° and sliding angle less than 3° (Wang et al., 2013; Lu & Hu, 2016). Surface roughness can be enhanced by introducing nanoparticles such as nano-TiO_2, nano-SiO_2, nano-ZrO_2, nano-ZnO, etc. Aggregation of nanoparticle clusters minimizes contact area and enhances nonwetting behavior (Gaur & Khanna, 2015). Nano metal oxides especially oxides of aluminum, zinc, and silica on the surface of the wood make it super hydrophobic (Chang et al., 2015). Wood surface coated with a Fe^{3+}-doped SiO_2/TiO_2 composite film exhibited strong hydrophobicity and photocatalytic activity. Effective moisture repellency prevents degradation of organic pollutants on the surface providing good self-cleaning function (Xuan et al., 2018).

Dip coating in suspensions of hydrophobic silica (SiO_2) nanoparticles dispersed in polydimethylsiloxane (PDMS) solution provided better dimensional stability (Bak et al., 2018; Gong & He, 2020). PDMS improved the bonding of the silica nanoparticles to the wood structure by partly replacing free sites for adhesion of water molecules. PDMS and SiO_2 together could lower equilibrium moisture content and water uptake compared to the basic nano-SiO_2 treatment. Mechanical abrasion of the surface is a critical factor that reduces the durability of coated wood. Abrasion and wear and tear of coatings exposes the underlying wood surface, accelerating moisture absorption, degradation of wood (Bak et al., 2018). TiO_2 nanoparticles—Perfluoroalkyl methacrylic copolymer (PMC) emulsion on PDMS precoated wood significantly reduced abrasion, retained the rough surface textures, thus sustaining the super hydrophobicity of the surface. Hydrophobicity and photocatalytic activity of TiO_2 nanoparticles in coatings preserved the underlying wood substrate from photodegradation during UV exposure (Tu et al., 2018). Increased water resistance is an outcome of physical and chemical interactions of wood substrates, nanoparticle modifiers, and coatings materials. Methyltrimethoxysilane (MTMS) modification of SiO_2 substantially increased the water resistance of teak wood (Kanokwijitsilp et al., 2013). *Dalbergia sissoo* wood has been modified into a super hydrophobic wood through simple immersion method using TiO_2 nanoparticles and perfluorooctyltriethoxysilane (PFOTS) (Pandit et al., 2019).

20.2.3 Nanoparticles for Improved Mechanical Properties

Nanoparticles as fillers added to the composites and polymer coatings improve the rigidity of the coating, mechanical characteristics, and thermal stability (Zou et al., 2008). Nano-sized inorganic particles uniformly dispersed in the polymer coatings increase interfacial area for interaction, preventing agglomeration ensures good adhesion properties. This in turn increases the stiffness, tensile strength, storage modulus, and flexural modulus of the nanocomposites (Wang et al., 2013). Furthermore, this can lead to improvements in scratch, wear, and abrasion resistance (Kanokwijitsilp et al., 2013). Superior wear resistance is rendered by the higher physical interlocking between the film and the wood surface resulted in due to the presence of inorganic nanoparticles (Kanokwijitsilp et al., 2013). Wood flour-polypropylene nanocomposites with SiO_2 and TiO_2 additives led to an increase in mechanical strength. However, significant decrease in the mechanical strength was observed on addition of more nanofillers. Nano-SiO_2 containing nanocomposites showed more favorable mechanical properties than those containing nano-TiO_2 (Ismaeilimoghadam et al., 2016). Silica/montmorillonite hybrid nanoparticles surface activated with γ-methacryloxypropyltrimethoxysilane (MPTS) in polyethylene-based wood/polymer composites enhanced the tensile strength, impact strength, modulus of rupture, and modulus of elasticity compared to the control samples without nanoparticles (Jiang et al., 2019).

The characteristic of nanofillers determines the properties of nanocomposites prepared from it. MDF prepared from urea-formaldehyde (UF) resin using aluminum oxide nanoparticles as nanofillers improved internal bonding strength and the modulus of rupture of boards significantly. In addition, formaldehyde emissions from MDF decreased with an increase in the concentration of nanofillers (Kumar et al., 2013; Gupta et al., 2018). Carbon nanotubes (CNTs) also improved physical and mechanical properties. Mechanical properties of rice straw/polypropylene composites with nanoclay are generally greater than nanosilica composites (Ashori, 2012).

20.2.4 Nanoparticles for Fire Resistance

Fire proofing of wood is one of the major aspects studied in effective utilization of wood for constructional applications. Most of the approaches involve the use of fire-retardant chemicals that reduce the time of onset of ignition, onset of glow, reducing the spread of flame or by reducing the production of smoke or volatiles (Popescu & Pfriem, 2019; Esmailpour et al., 2020a, b). These chemicals are either applied as surface coatings or impregnated deep into the wood cells applying pressure or directly added to the wood-based composite boards (Seo et al., 2017). Commonly used flame-retardant chemicals include borates, chlorides, oxides, phosphates or sulfates of ammonium and other metal salts, aluminum, silicates, boric acid, and other halogen-containing compounds (Seo et al., 2017). Such wood used in humid conditions undergoes weathering and leaching of fire-resistant salts from treated wood reducing the efficiency and causing environmental hazards. Increasing concerns on health and environmental hazards research are focused on leach-resistant and effective fire-resistant systems (Taghiyari, 2011; Popescu & Pfriem, 2019).

Nanoparticles as additives or fillers to polymer coatings or nanobiocomposites materials create opportunities to modify the fire retardancy. Due to larger surface nanoparticles can provide a larger area to absorb the heat and improve thermal stability (Zou et al., 2008; Habibzade et al., 2016). Fillers like silicates are incombustible materials that fill the lumen of wood on impregnation provide fire resistance. On heating to higher temperature, it can be intumescent forming a protective layer (Bulewicz et al., 1985). Utilizing alkaline silicates in nanoscale, better impregnation loads are achieved and improve fire-retardant performance (Giudice & Pereyra, 2010). Nano silver-impregnated wood specimens increased ignition time. Improvement in the ignition time is via heat-transferring effects (Taghiyari, 2011; Habibzade et al., 2016). However, synergistic effect of nano silver with other fire-retarding materials can provide a better result (Taghiyari, 2011). Pine wood impregnated with nanoZnO synthesized by sol-gel method increased ignition and combustion time. The differential penetration exhibited due to higher anisotropy of wood, these characteristics showed variation on the specimen studied (Favarim & Leite, 2018). Fir wood (*Abies alba*) impregnated with 0, 5, 10, and 15% nano-SiO_2 concentration, the minimum weight loss (%) and maximum fire resistance properties were obtained for 15% nano-SiO_2 (Rangavar et al., 2012). Impregnation of styrene monomer with different concentration of nano-ZnO showed improvement in ignition time. However, the flammability of styrene does not allow considerable improvement in fire-retarding properties (Habibzade et al., 2016).

Ignition and burning of wood are surface processes thereby surface treatment of wood can also prevent ignition and combustion substantially. Wood coating materials nanocomposites with particles in nano size as fillers increase the hardness of the polymer material and enhance thermal properties (Nikolic et al., 2015). Wood surface pretreated with 3-aminopropyltrimethoxysilane (APTMS) and nano-TiO_2 synthesized using the sol-gel method considerably increased thermal stability by increasing the ignition temperature. Flammability was also reduced with longer spread time and took more time to get burnt (Deraman & Chandren, 2019). The minimum concentration of oxygen that supports flaming combustion referred as Limiting oxygen index (LOI), is one of the major indices analyzed for thermal stability. LOI reduced with addition of TiO_2, SiO_2, and nanoclay in styrene acrylonitrile copolymer. Nanoclay and silicate layers formed on the surface increased barrier property to oxygen and heat that delayed the burning capacity of the composite (Devi & Maji, 2013). Increase in the thermal, physical, and mechanical properties depends considerably on the interfacial interactions with the binder and degree of dispersion of the nanoparticles in coatings (Cristea et al., 2011). Nano-wollastonite (NW), mineral containing silicon, calcium, and oxygen impregnated into solid wood and in MDF limited the heat conductivity, reduced combustibility, and penetration of fire (Poshtiri et al., 2014; Esmailpour et al., 2020b) on mixing NW with graphene (5%) in a water-based paint enhanced the thermal properties of beech wood by onset of ignition and glowing and reduced burnt area for thermal properties (Esmailpour et al., 2020a). Recently, bamboo has been extensively exploited for constructional and household applications. Studies have shown that flammability of bamboo can be considerably reduced by utilizing nanoparticle coatings. Ren et al. (2018) showed that ZnO–TiO_2-layered double-nanostructures synthesized on a bamboo substrate improved the thermal stability and flame-retardant property by increasing the LOI from 25.6 to 30.2%. MgAl-layered double hydroxide (MgAl-LDH) coated on bamboo, reduced total heat release and smoke than untreated bamboo (Yao et al., 2019). Nano silicon dioxide (nano-SiO_2) and ammonium polyphosphate (APP) synergistically improved the thermal stability and fire retardancy of WPC. Highest efficiency in heat release onset of ignition and LOI was observed at APP 8%/nano-SiO_2 6% (Pan et al., 2014). Addition of carbon nanotubes and Al_2O_3 nanoparticles in urea formaldehyde resins reduced the curing time and significantly enhanced thermal conductivity (Gupta et al., 2018).

20.2.5 Nanoparticles Against Wood Biodegradation

A lot of reports are available in literature citing application of nanomaterials for protecting wood against biodegradation. Reports by Clausen (2007) deal with implications of nanoscience in wood protection. They have discussed three approaches to wood protection systems using nanomaterials which include direct application of nanometals to wood-based products, wherein wood pieces are impregnated with nano-sized metallic wood preservatives, such as silver, copper, and zinc oxide through a vacuum pressure treatment in a closed cylinder. This results in deeper penetration and uniform uptake of the particles compared to conventional formulations and subsequently protect the wood from certain targeted fungi or insects (Teng et al., 2018; Taghiyari et al., 2020). Clausen et al. (2009, 2010a) explored the feasibility of nano zinc oxide as a wood preservative. Clausen et al. (2011) reported that nano-ZnO treated wood repelled termites and was found to be more toxic to termites than the wood treated with soluble metal oxide formulations. Secondly, slow release of biocides embedded in nano polymer matrices where biocides encapsulated in customized nano polymer networks could provide prolonged protection as surface treatments for engineered composites (Clausen et al., 2010b; Clausen, 2012). Scots pine was impregnated with encapsulated nano silver into polystyrene-soybean copolymer and tested against white-rot fungi (*Trametes versicolor*) and all the components played important roles in the synergistic effect in increasing the decay resistance of Scots pine (Can et al., 2018). Finally, controlled delivery of biocides with nanocarriers where fungicides (tebuconazole, chlorothalonil, and kathon 930) and an insecticide (chlorpyrifos) incorporated into nanoparticles were reported on wood protection with high biological efficacy for all of them (Liu et al., 2001, 2002). Mattos et al. (2017) have reviewed the different biocide delivery systems (BDS) in crop and wood protection. Wibowo et al. (2014) reported that the insecticidal effect of fipronil-encapsulated silica nanocapsules against economically important subterranean termites could be controlled by tuning the shell thickness.

Terzi et al. (2016) evaluated the resistance of Scots pine wood vacuum-treated with nanoparticles of ZnO, B_2O_3, CuO, TiO_2, CeO_2, and SnO_2 against decay, mold fungi, and subterranean termites. Mold growth in wood specimens was significantly inhibited by treatment with nano-ZnO and nano-B_2O_3; however, nano-SnO_2 inhibited *Trichoderma harzianum* growth only. Brown-rot fungus was significantly inhibited by all nanocompounds but only nano-CuO and nano-SnO_2 were effective against white-rot fungus. Nano-CuO and nano-B_2O_3 treatments showed inhibition in termite feeding whereas nano-ZnO and nano-CeO_2 showed moderate resistance to termites. Nair et al. (2017) reported the decay resistance of rubberwood (*Hevea brasiliensis*) impregnated with dispersion of ZnO and CuO nanoparticles in propylene glycol against white-rot (*Trametes hirsuta*) and brown-rot (*Polyporus meliae*). Mantanis et al. (2014) reported the resistance of pine wood vacuum treated with zinc oxide, zinc borate, and copper oxide nanoparticles against mold and decay fungi and the subterranean termites. The mold fungi were negligibly inhibited by nano zinc borate and other preparations had no effect. White-rot fungus, *T. versicolor* was significantly inhibited by the zinc- and copper-based preparations but brown-rot fungus *T. palustris* was not inhibited. The copper-based treatments were much less effective against the subterranean termites, *Coptotermes formosanus*.

Lykidis et al. (2013) investigated the resistance of black pine (*Pinus nigra* L.) wood pressure-treated with nano-sized zinc borate and zinc oxide dispersions against brown-rot (*Coniophora puteana*). The zinc borate-based formulations gave encouraging results. Marzbani et al. (2015) studied the decay resistance of particleboards treated with nano zinc oxide against the white-rot fungus *Trametes versicolor* and the brown-rot species *Coniophora puteana* and reported the maximum decay resistance at a concentration of 15% zinc oxide nanoparticles. Lykidis et al. (2016a) evaluated the biological resistance of Scots pine (*Pinus sylvestris* L.) wood impregnated with nano-sized zinc oxide and zinc borate against brown-rot fungi and found out that nano-sized zinc oxide inhibited the biological degradation of pine wood against *Serpula lacrymans*, while it was ineffective against *Poria placenta*. Pine wood treated with nano-sized zinc borate exhibited higher biological resistance against the fungi *Serpula lacrymans* and *Poria placenta*. Lykidis et al. (2016b) reported the resistance of nano dispersions of zinc oxide and zinc borate impregnated European beech (*Fagus sylvatica* L.) against termites. Nano-ZnO dispersions were found to be more efficient than nano-ZnB. Enhancing the durability of wood against wood-destroying fungi using nano zinc has been reported by Bak et al. (2012). Five commercial products were tested by Green and Arango (2007) in order to explore a broad range of formulation and silver forms, colloidal, ionic, and nanoparticles and concluded that silver is not likely to be a stand-alone treatment for control of termite damage but may make an important additive for paints and preservatives.

Harandi et al. (2016) studied the antifungal properties of TiO_2 and ZnO nanoparticles in polyvinyl butyral (PVB) and reported that 2% nano-TiO_2 and nano-ZnO in 5% PVB provided antifungal effects in darkness. Nanofibrous textiles with biocide addition have been used to protect wooden materials Havrlik and Ryparová (2015). The effect of impregnation with wollastonite nanofibers, a non-toxic mineral material, on the biological durability of poplar wood (*Populus nigra*) against a white-rot fungus (*Trametes versicolor*) was studied by Karimi et al. (2013) and recommended to use nano-wollastonite suspension for improving the biological durability of poplar wood. Moya et al. (2017) studied the efficacy of nano silver on white-rot (*T. versicolor*) and brown-rot (*Lenzite sacuta*) fungi on several tropical wood species. The results showed higher efficacy of nano silver against *T. versicolor* compared to *L. sacuta*. Künniger et al. (2014) reported that effect of nanosilver (nano-Ag) was insufficient for coatings to give protection against mold, blue stain fungi, and algae. Decay resistance was reported by *Hypocrea lixii* (white-rot) and *Mucor circinelloides* (brown-rot) in *Pinus Sylvestris* L., *Abies alba* M., *Junglas regia* L., *Castanea sativa* M., *Prunus avium* L., *Quercus petrea* L., *Fagus sylvatica* L., and *Fraxinus excelsior* L. through photocatalytic activity of nano-TiO_2 (De Filpo et al., 2013).

Akhtari and Ganjipour (2013) investigated and compared the effects of nano silver, nano copper, and nano zinc oxide on the resistance of Paulownia (*Paulownia fortunei*) wood against white-rot fungus (*Coriolus versicolor)* and found out that nano silver, nano copper, and nano zinc oxide significantly increased the decay resistance of Paulownia against *C. versicolor*. Akhtari and Nicholas (2013) reported that micronized copper oxide and zinc oxide are effective in controlling degradation of wood by termites, with copper oxide being slightly more effective than zinc oxide. Kartal et al. (2009) evaluated leachability and efficacy of southern yellow pine wood treated with copper, zinc, or boron nanoparticles against mold fungi, decay fungi, and eastern subterranean termites. All specimens treated with nano zinc or nano zinc plus silver inhibited termite feeding, but the copper treatments were less effective against termites. Nano zinc showed leach resistance, decay by the white-rot fungus and termite mortality, and inhibition of termite feeding.

Matsunaga et al. (2009) examined the distribution of copper in wood treated with a nano-Cu preservative and found out that copper particles are not uniformly distributed in treated wood, but they accumulate in voids which act as the flow paths for liquids in wood. Nosáľ and Reinprecht (2017) reported that application of zinc oxide (ZnO) nanoparticles into surface structure of wood-based composites such as particleboards, fiberboards, etc. improved their antibacterial and antimold properties. Oliva et al. (2015) used nanocomposite (TiO_2-polyethylenetartaramide) for applicative studies, and it has shown a good efficacy against fungal attack by *Trametes versicolor* on wood specimens (*Fagus sylvatica*).

Taghiyari et al. (2014b) reported that nano copper can be recommended for the particleboard manufacturing industry as it improved biological resistance against *T. versicolor* as well as hardness of panels. Taghiyari et al. (2014a) reported the effect of wollastonite nanofibers (NW) on biological resistance against *Antrodia vaillantii* and concluded that NW can be used to improve the biological resistance in wood-composite materials, medium-density fiberboards (MDF) made from wood and chicken-feather fibers (CF) against fungi attack. Taghiyari et al. (2015) studied the effects of aqueous dispersion of silver and zinc oxide nanoparticles on air and liquid permeability of Paulownia wood exposed to *T. versicolor* and concluded that both heat treatment at 150 °C and the impregnation with zinc oxide significantly inhibited growth of the fungus.

Reinprecht and Zuzana (2017) reported the antimold efficiency of nano zinc oxide applied into wood alone or in combination with polyacrylate (5% Paraloid B-72) and essential oils. The antimold efficiency of ZnO nanoparticles was relatively poor; however, it was evidently improved in presence of clove and oregano oils. Nano zinc oxide nanoparticles added into melamine-urea-formaldehyde (MUF) glue of particleboard demonstrated higher biological resistance against the molds *Penicillium brevicompactum*, *Aspergillus niger,* and against the brown-rot fungus *Coniophora puteana* (Reinprecht et al., 2018).

Recently, nano-sized fraction of basic copper (Cu) carbonate ($CuCO_3{\cdot}Cu(OH)_2$) nanoparticles (NPs) were introduced to the market for wood protection as micronized copper (MC) formulations. Civardi et al. (2015) reported that the presence of particular nano effects of MCA against *R. placenta* did not enhance antifungal efficacy, but provide evidence that attributes the main effectiveness of MCA to azoles. There are currently two commercially available nanomicronized copper systems, namely micronized copper quaternary (MCQ), where dimethyl didecylammonium carbonate/bicarbonate is used as a cobiocide, and micronized copper azole (MCA), where tebuconazole or a combination of tebuconazole-propiconazole is used as a cobiocide (Mclntyre & Freeman, 2008; Freeman & Mclntyre, 2008). The effect of surface treatment by copper azole type C (CA-C), alkaline copper quat type C (ACQ-C), and tebuconazole-propiconazole combo (TP) on fungal decay and termite resistance was evaluated by Ma et al. (2013).

Even though metal nanoparticles are found to be effective in protecting wood against biodegradation, commercially available nanoparticles are synthesized using chemical and physical methods which are not cost-effective and environmentally friendly. Synthesis of nanoparticles using plants, fungi, yeast, bacteria, and viruses has been accepted as an alternative approach and is referred to as biological synthesis (Souza et al., 2019; Thakkar et al., 2010).

Use of biologically synthesized nanoparticles is a new approach in wood protection. Preliminary studies by Shiny et al. (2019) evaluated the efficacy of copper oxide nanoparticles synthesized using leaf extracts of Neem (*Azadirachta indica*), Pongamia (*Pongamia pinnata*), Lantana (*Lantana camara*), and extract of orange peel (*Citrus reticulata*) against termites and fungi (*T. hirsutus* and *O. placenta*) and reported (Fig. 20.2) that the formulation of copper oxide nanoparticles is an effective wood protectant against fungi and termites. Shiny and Sundararaj (2021) reported that prophylactic treatment of rubberwood with Lantana leaf extract and CuO nanoparticle formulation imparted effective protection from *Lyctus africanus* beetle attack, compared to Lantana leaf extract and zinc oxide nanoparticle formulation. Shiny et al. (2021) synthesized copper oxide nanoparticles using leaf extracts of *Lantana camara* and *Nerium oleander*. The formulation of copper oxide nanoparticle and Lantana leaf extract prevented decay by white-rot and brown-rot fungi significantly. However, copper oxide nanoparticle and Nerium leaf extract formulation inhibited the growth of brown-rot fungi only.

20.3 Conclusion

Wood science and technological research in recent years has been focused on the use of nanomaterials to improve various physical, chemical, and biological properties of wood and wood-based products. Biodegradation of wood and the action of various environmental factors in combination limits its use largely. These limitations can be

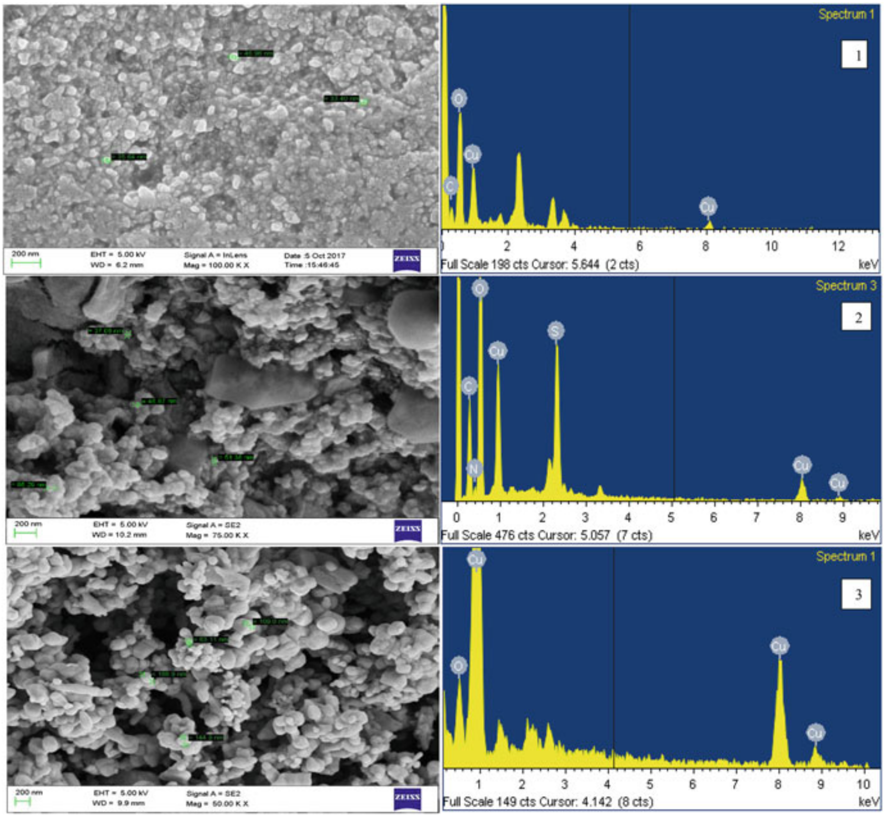

Fig. 20.2 SEM and EDAX profile of biologically synthesized CuO nanoparticles using (1) *Lantana camara* leaf extract (CuO-Np-BS-L. c) (Shiny et al., 2019), (2) *Nerium oleander* leaf extract (CuO-Np-BS-N. o), and (3) Commercial CuO nanopowder (CuO-Np) (Shiny et al., 2021)

reduced by using nanomaterials, nanoparticles, nano metal oxides, etc. Zinc, titanium, and cerium oxide nanoparticles are proved to enhance the UV stability of wood coatings. Nano-TiO_2, nano-SiO_2, nano-ZrO_2, and nano-ZnO improves the surface roughness, enhances the moisture resistance and hydrophobicity. Nano-TiO_2 and nano-SiO_2 as additives to nanocomposites improve the mechanical properties and abrasion resistance. Nano-SiO_2 is reported to enhance thermal properties and fire retardancy of wood and wood nanocomposites. Nano-ZnO, nano-CuO, and nano-CeO_2 enhance the biological resistance of treated wood by inhibiting wood decay fungi, wood bores, and termites. Recently, the research has been focused on reducing the use of toxic chemicals for the synthesis of nanoparticles and thereby reducing the hazards related to its suitability for various applications.

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Biodegradation: A Vital Component in Life Cycle Assessment of Wood

21

Swati Mishra, P. Swetha, and R. Sundararaj

Contents

Abstract

Climate change is an emergency crisis worldwide, especially in developing countries like India and needs immediate address. India has taken a step toward forest-based industries to reduce carbon emission and its environmental footprint because of its ability to regenerate and carbon locking capacity. However, green

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R. Sundararaj (ed.), *Science of Wood Degradation and its Protection*,
https://doi.org/10.1007/978-981-16-8797-6_21

investments are not always sustainable and thereby it is important to assess the life cycle of a product or process to interpret sustainability. Life Cycle Assessment (LCA) is one of the strongest tools for life cycle analysis but the quality of its result depends on the quality of the framework. The standard LCA framework incorporates production, extraction, transportation, manufacturing-related units, economic and social aspects, recyclability, and disposal but one of the major missing study components is biodegradation. Wood is susceptible to biodegradation under certain conditions and emits carbon and methane which are important to study to understand the complete life cycle of wood and take corrective measures by the results.

Keywords

Biodegradation · Life cycle assessment design · Wood-based industries · Climate Impacts · Carbon Emission

21.1 Introduction

Wood is a sensory-rich cosmopolitan material that has been an integral part of human lives from ancient times to modern societies. Owing to its utility, durability, functionality, and structural integrity, the material has penetrated numerous sectors such as fuel, construction, furniture, sports, tools, weapons or crafts (Mishra & Sundararaj, 2021). Aside from the mechanical properties, the esthetics and sensation of the mere grain make it one of the most versatile materials that fit into any setting and blend tastefully extending from indoors to outdoors. Wood offers varied color, structure, texture, and aroma and can be designed and colored as desired to achieve desired finesse (Bipat, 2021). Wood is a varied household to industrial material that can fit from indoors to outdoors as an elegant or rustic item (Mishra & Sundararaj, 2021).Wooden structures are stronger and durable as compared to most materials and can be repaired or maintained easily and although costly, old wood can be restored as well. Also, its ability to regenerate and store carbon after harvesting makes it one of the most preferred materials. About 50% of the dry weight of wood accounts for carbon (Karsenty et al., 2003). Some of the major benefits of wood are thermal insulation, acoustic insulation, adaptability, durability, fire resistance, and structural stability in addition to health benefits owing to its subjective comfort (Garay et al., 2021). It is also used extensively in industries cause of ease of manufacturing and it also strengthens rural development through technological intervention. Sustainable trade in timber and timber products from well-managed forests promotes protection, production, and growth of the forest biome. Also, the energy utilized in harvest, transport, manufacturing, and recycling in wood is minimal compared with other materials (Adhikari & Ozarska, 2018). Wood, over the ages, has evolved from a simple and readily available material to a modern engineering material. It is one of the key elements in nature that has had a distinctive relationship with humans over time (D'Costa, 2015). The increased demand and scarcity of timber have caused an imbalance in national trade and have often spurred conflict over control of the shared resources. Citing India as an example, the imbalance in the demand and the supply has remained wide. India is one of the major wood users in the Asia–Pacific region with 4500 varieties of wood-yielding species (Nuthan et al., 2009), including some of the best known and most highly prized tropical hardwoods species, including Teak (*Tectona grandis*), Sal (*Shorearobusta*), Rosewood (*Dalbergia latifolia*), and more, yet it remains a net importer of wood and wood-based panel products (Shrivastava, 2017). The changing climate, increased demand, and scarcity of the resource demand a new perspective to assess the sustainability of this natural material. Therefore, life cycle analysis of a product, process or organization becomes necessary to calculate the environmental footprint of a product or a service.

Life Cycle Assessment (LCA) is a systematized set of procedures for compilation and examination of input and output data of materials, energy, processes, and associated environmental directly or indirectly attributable to the functioning of a product or service system through its entire life cycle (ISO 14040). The accuracy of the LCA tool is largely based on the system design and inclusion of all the possible components and correct questions. In wood-related life cycle studies, one of the most importantly ignored factors that have resulted in the decline of the wood in the home grounds has been biodegradation. Biodegradation is not necessarily limited to the biotic or abiotic degradation of wood but also that of the soil and the forests (Godell et al., 2020). It is imperative to understand that if wood can naturally lock and store carbon, its biodegradation is responsible for the carbon emissions and thereby increasing the environmental footprint. Thus, biodegradation has to become a key component of the system design in the life cycle assessment of wood.

21.2 Major Wood-Based Industries

Wood is one of the earliest recognized and widely used materials that have met a varying array of human requirements. It has established its importance in human lives serving as a primary material at the dawn of civilization and evolving itself as a primary material in human civilization and has continuously evolved itself. Even plywood and veneer can be traced back to 3000 BC. Then, the purpose of plywood and veneer was limited to decoration and were traded internationally as high-value decorative items in Egypt, Greece, and Rome (Frances, 2017). Veneered art is recent in origin as compared to decorative items made from hardwood or softwood (Edwards, 2008). Plywood production and development of wood-based composite materials have increased substantially in most parts of the world during the past few decades. It has revolutionized the wood sector and provided new opportunities for ingenious and versatile products from other wood sources. Wet process fiberboard was developed in the nineteenth century and it was commonly used for insulation, sheathing, and panelling and particleboard evolved in the efforts to use shavings, sawdust or leftover small wood particles (Owens & Lund, 2009). Recently plywood is being replaced by modern composites using flakes of wood strands for many structural applications. Composites are extensively used in larger volumes and varied production sectors, for instance, medium-density fiberboard for core stock in furniture, mineral- bonded products using wood wool and cement to make panels (Pandey & Rangaraju, 2008). Products moulded from wood particles and composites are greatly extending the wood resource and enhancing its utility and supporting the economy. Despite the expansion and popularization of engineered wood, solid wood is still a popular and affluent choice and the sector continues to thrive. Some of the major wood-based industries have been listed.

21.2.1 Paper and Pulp Industry

The pulp and paper industry is one of the most fragmented and important cellulose fiber- based industries in India employing over a million people directly or indirectly. The major issue in this industry that has not allowed the market to hit its potential is the shortage of good quality fibrous raw material. There is a huge gap between the fiber demand of existing pulp mills and supply from forest resources (Sharda et al., 2000). For the paper industry to grow sustainably on a wider scale, the availability of cellulosic raw material is paramount which presents a tremendous scope for farm forestry to increase production and bridge the gap between demand and availability of resources. Only a few paper mills can keep up with international quality standards while most of them use poorer quality of cellulose fiber or it gets degraded over time from lack of proper storage and suitable condition (Sayed et al., 2020). *Dendrocalamus strictus* is the widely used species followed by *Bambusa bambos* and *Melocanna baccifera* (Dhamodaran et al., 2003) and this makes up to 83% of all bamboos used for pulping. Major pulpwood species are bamboo, *Casuarina* spp., *Eucalyptus* spp., *Leucaena* spp., *Acacia spp., Populus* spp. (Raj & Lal, 2013).

21.2.2 Match Industries

The matchwood industry is one of the oldest wood-based industries. In India, 75% of the total match industries are based in Tamil Nadu. There is nearly 6000 matchwood industries in the state with mechanized to semimechanized production and also as cottage industries (Raj & Lal, 2013). The per capita consumption of matches in India has been steadily growing. The industry saw growth from 1970 to 1987 but currently, it is staggering. This is a consequence of increasing demand against declining wood resources. Even the veneer quality wood for matchboxes accounting for 44% is short in supply. About 40–45% of woodwaste in the match industry is mostly debarked and untreated wood (Saigal & Bose, 2003). Major species used in this industry are *Ailanthus excelsa, Albizia falcataria, Alianthus triphysa, Albizia lebbeck, Anthocephalus cadamba, Erythrina indica, Populus* spp. (Raj & Lal, 2013).

21.2.3 Timber and Sawn Wood Industries

Timber has been one of the oldest building materials for centuries (Fig. 21.1a, b). Temples and monuments built from wood are in excellent condition to date which is a standing testament to the durability and strength of the timber. Although the use of timber for the constructional purpose has declined with the advent of steel and concrete, yet, many wood-based products such as veneers, plywood, sawn wood, and particleboard have developed hugely for furniture (Fig. 21.2a, b) making, interior decoration, and other formwork (Green & Karsh, 2012).

Since independence, the sawmill capacity in India has expanded but without any technological intervention. Around 80% of the sawn wood comes from various hardwood species and the other 20% from coniferous species. The industry is unable to modernize because of the struggle for raw material and the consumer demand concentrated on a small group of well-introduced species, mainly Teak and Sal, and they are unable to meet the overall requirements (Ramage et al., 2017). Another cause for it is the unorganized market for sawn timber. The Indian timber markets

Fig. 21.1 (**a**) Wood structure in housing; (**b**) Wooden interiors

Fig. 21.2 (**a**, **b**) Wooden furniture

showcase that Teak (*Tectona grandis*), Sal (*Shorea robusta*), Laurel (*Termina liaalota*), Mango (*Mangifera* spp.), Ben teak (*Lagerstroemia lanceolata*), Deodar (*Cedrus deodara*), Kail (*Pinus wallichiana*), and Chir (*Pinus roxburghii*) are commonly used in sawn wood industries (Raj & Lal, 2013).

The industry would be more developed if it were not for the shrinking availability and high price of the raw material. The end-use sectors using sawn wood are housing and construction, packaging, furniture, automobiles, handicrafts, and miscellaneous industries. The effluent and solid wastes from wood treated with fungicides contaminate the nearby waterways and contaminate the soil on site. When disposed of in landfills, the anaerobic decomposition leads to toxic effects (Browne, 1972). Major species used in sawn wood sector *are Tectona grandis, Azadirachta indica, Pterocarpus* spp.*, Mangifera indica, Artocarpus* spp.*, Dalbergia* spp.*, Dipterocarpus* spp.*, and Eugenia* spp. (Raj & Lal, 2013).

21.2.4 Plywood and Related Industries

The growth of urbanization and industrialization has raised the living standards and there is an increasing growth in interior design sector and plywood has been growing faster than ever to meet these demands. These industries depend heavily on various species which attract large-scale promotion from government or privatized schemes. After cement and steel, the plywood and panel industries contribute immensely to the housing sector. Plantation wood such as Poplar and Eucalyptus is grown as part of the agro-forestry scheme to overcome the shortage of raw materials. Major species used in this sector are *Populus* spp., *Melia dubia, Paulownia* spp., *Eucalyptus* spp., and *Ailanthus* spp. (Raj & Lal, 2013).

Particleboard is a substitute developed for constructional wood from low-grade waste woods or ligneous agricultural residues. They are predominantly used for wall panelling and interior decor in domestic spaces and industries. Major raw materials used are wood waste, pine needles, casuarina needles, and ligneous agricultural residues (Raj & Lal, 2013). Fiberboard is made of sheet materials manufactured from refined or partially refined wood or vegetable fibers.

21.2.5 Dendro Biomass Power Generation Industries

Biomass is an important fuel source in the energy sector, it is produced through chemical storage or solar energy in plants and other organic matter as a result of photosynthesis. Among all the biomass, the role of dendro biomass is very significant due to their higher calorific value and increased fuel efficiency. Hence, a large number of dendro biomass based power plants have been established across the country to generate electricity (Thirumurugan et al., 2018). Major energy crops are *Prosopis* spp., *Acacia* spp., *Albizia* spp., *Dalbergia sissoo, Leucaena leucocephala, Casuarina equisetifolia, Eucalyptus* spp., *Gliricidia* spp., *Ceasalpinea* spp., *Chuckrassia* spp., and other hardwoods (Thirumurugan et al., 2018; Raj & Lal, 2013).

21.3 Wood Degradation: An Important Issue in the Wood-Based Industries

Wood, like any other material, has its limitations. It is hygroscopic in nature and absorbs moisture from the atmosphere which causes it to shrink and swell. Thereby, proper storage conditions should be necessitated for the protection of logs. The wood-based industries have to store the harvested raw material during the rainy season so they can sustain the raw materials for the lean period and keep the processes ongoing. Postharvest management factors such as handling, storage, and utilization of industrial wood demand a scientific intervention to reduce loss of wood (Xavier et al., 2019). Wood is an organic material and biological deterioration occurs in it from the attack of fungi, termites, beetles, ants, etc. Nonbiological deterioration can be from sunlight, wind, water, chemicals, and fire. The biological agents take a heavy toll on stored industrial raw materials and it needs proper addressing (Ajuong & Pinion, 2010). Wood-based industries suffer major losses due to the loss of the wood through decomposition and deterioration. Hence, seasoning and preservative industries must grow in huge volume to avoid postharvest losses. The storage centers should also be as per the standards to avoid any damage to the harvested wood.

21.3.1 Types of Wood Biodegradation

21.3.1.1 Deterioration Without Decomposition

Wood degradation is not always caused by the fungi attack but is sometimes also caused by poor drying practices and wet conditions of the fresh cut wood. Mildew, fungi, sap-stain fungi, algae, bacteria, and moulds develop over the surface of such woods (Fig. 21.3) or penetrate the ray cells of sapwood. The wood storage cells are used as food by these organisms but do not decay or affect the strength of wood seriously; rather some discoloration or stains would be observed (Kirk & Cowling, 1984). They end up in lower grade timber because of its appearance. However, they end up in a lower grade for some grading lumber and are not preferred by consumers because of their appearance. Blue stain, also called sap stain (Fig. 21.4) occurs mostly in the sapwood of both hardwood and softwood; it develops during various stages of manufacture, storage or shipping or even in the finished product if optimum conditions are available.

Although heartwood is immune to blue stain fungus, its price drastically reduces due to its appearance (Shupe et al., 2008). Surface moulds with colored spored such as *Aspergillus* spp. and *Penicillium* spp., algae and fungi with dark-colored hyphae discolor the wood interior by penetrating deep into the sapwood. The wood can also be disintegrated mechanically by species of insects, birds or even mammals. Apart from this, certain chemical changes in wood cell walls caused by enzymatic and

Fig. 21.3 Wood decay seen in building structures

Fig. 21.4 Blue stain in pine wood

nonenzymatic oxidation of certain organic compounds in sapwood also result in staining in both softwoods and hardwoods.

21.3.1.2 Deterioration with Decomposition

The water-insoluble polymers present in wood such as cellulose, hemicelluloses, and lignin undergo biological, hydrolytic or oxidative degradation if they come in physical contact with the enzymes and metabolites produced by wood-destroying fungi, insects, and marine borers. Insects and marine borers disrupt the lignin barrier by grinding the wood very finely. Some fungi secrete nonenzymatic cellulose-depolymerizing agents that are small enough to penetrate the lignin sheath (Kirk & Cowling, 1984).

21.3.1.3 Mechano-Biochemical Decomposition

The biochemical decomposition varies across species and also depends on the lignin content in the wood. Termites and most other wood-digesting insects rely on polysaccharolytic microbes in their guts whereas beetles and marine borers use their own cellulase and gut microbes in decomposing the wood particles. The structural polymers are not digested by ambrosia beetles, lyctus beetles, carpenter ants, and carpenter bees (Verevkin et al., 2019).

21.3.1.4 Biochemical Decomposition

Wood-decay fungi are grouped into three categories: brown-rot, white-rot, and soft-rot that attack the three main chemical components of wood: cellulose, hemicellulose, and lignin. When wood-degrading fungi metabolize wood, there is a rapid decrease in strength and the extent of strength loss varies depending on the type of fungi involved, wood species, and lumber dimensions (Verevkin et al., 2019).

21.4 The Carbon Cycle of Wood

Forest-based industries play an important and complex role in the global carbon cycle. Forest resources are renewable and due to its ability to sequester and store a massive amount of carbon, it contributes to significant carbon pools during their use and even after being discarded. When the trees die and decay or it is burnt, the carbon is released back into the atmosphere. The carbon absorbed by sustainably managed mature forest is the same amount as it is given off by decaying dead trees, animals, and microbes that live off that tree during its entire life cycle (Zeng, 2008). It is similar in sustainably managed woodland or energy crops. On account of carbon balance, wood is never faster than added by new growth. Therefore, the carbon released from wood fuel is never more than carbon being absorbed by a new tree. It is carbon neutral. Therefore, there is an increased effort across the globe in expanding the forested land to increase carbon storage. Recycling is an important part of the carbon cycle because it extends the duration of carbon storage in products. It has been estimated that the amount of carbon stored in forest products is increasing per year on a global basis (Brown, 1998).

21.4.1 Emissions Associated with the End of the Life Cycle (Anaerobic Biodegradation)

The forest-based products, at the end of their lives, are recycled, used as fuel or sent to landfills. Emissions associated with the end-of-life cycle include manufacturing and transport and burning of the product for energy production. During the combustion of used wood products, there is emission of carbon, methane, and nitrous oxide but the carbon emission from wood is relatively smaller (Miner, 2010). Calculating estimating carbon storage in forest products and assuming that they are burnt instead of being recycled or sent to the landfills, about three million tons of carbon dioxide are released per year. Under anaerobic conditions, effluent and solid wastes can degrade to a mixture of carbon dioxide and methane. Emission estimates due to anaerobic conditions are highly uncertain due to the lack of information on global waste management practices and incomplete scientific understanding of the factors that influence methane generation (Miner, 2010).

Considering the methane emissions from effluent and fibrous wood wastes in landfills, it can be assumed that 25% of the waste is biomass carbon (Heath et al., 1996) and only about 50% of the biomass carbon can degrade under anaerobic conditions to gas containing equal amounts (by volume) of methane and carbon dioxide; none of the landfills are equipped to capture methane, so there is only about 10% oxidation in the upper layers of the landfills via natural processes (the IPCC default assumption); under these scenarios, ultimate emissions from wood product wastes placed in landfills in 2007 are expected to be approximately two million tons of carbon dioxide equivalent (NCASI, 2013).

21.4.2 Emission from Wood Decay (Aerobic and Anaerobic)

The forest of the world is calculated to have absorbed as much as 30% of the total anthropogenic carbon dioxide emissions in the past few decades. Thus, reforestation, forest management, and increased use of wood and its production are promoted to combat climate change. The climate in the anthropocene is impacting most life on earth (Miner, 2010; Janusz et al., 2017). Disruption in this process is caused by pathogens that attack living trees; reduce tree growth; and cause premature tree mortality. These effects in turn reduce the carbon sequestration capacity of forests and accelerate the cycling of sequestered carbon. On a global scale, around 85 billion tons of carbon are recycled back into the atmosphere through lingo-cellulose decay by the microbes. Aerobic white-rot fungi are the only organism that efficiently mineralizes all cell wall components of the wood to carbon dioxide and water and thereby plays an important role in carbon and nitrogen cycling (Janusz et al., 2017). Methane is another potent greenhouse gas that is produced from the decomposition of wood under anaerobic conditions. Methane formation in tree stems under anaerobic conditions may be associated with bacterial wetwood on poorly drained soils. Anaerobic or microaerobic conditions occur even in the heartwood of trees growing on well-drained soils to an extent that mineralization of heartwood by associated decay fungi is hampered. It is proposed that wood decay fungi themselves can produce small amounts of methane without involving methanogenic archaea (Bodelier, 2011).

21.4.3 Role of Wood-Decaying Fungi in the Carbon Cycle of Forest Ecosystems and the Main Ecological Factors

Climate warming is majorly due to an increase in the atmospheric concentration of greenhouse gases such as carbon dioxide, methane, and nitric oxide. Basidiomycota (wood- or xylotrophic basidiomycetes) fungi play a leading role in converting organic carbon to carbon dioxide by decomposition of wood and oxidation. It is responsible for solid-state fermentation of the lignocellulosic wood complex. The role of xylotrophic basidiomycetes in the biosphere is currently undervalued and many aspects of the ecology of these organisms are low or not known at all. The data about the intensity of decomposition of timber are insufficient. The C–CO_2 exchange from the forest to the atmosphere is based on the reduction of atmospheric CO_2 into organic carbon deposited in the wood. This plays an important role in climate regulation (Baumgartner, 1969; Cannell & Milne, 1995). Wood is the main carbon reservoir in forests but it gets emitted to the atmosphere on decomposition by wood-decaying fungi. The decomposition of deadwood is mainly performed by basidial fungi under normal conditions; it is the only known group of microorganisms that are capable of the biological conversion of all wood compounds. Some climate changes can modify the fungal complexes and lead to an imbalance between photosynthetic storage and the emission of greenhouse gases. The studies on the influence of humidity and temperature against conversion activities of fungi make bits of help identify the stimulus of different types of fungi and their role in climate change. The conversion activity of wood-decaying fungi is directly related to humidity, ambient temperature, degree of decomposition of the wood substrate, and physiological characteristics of fungi. The carbon dioxide emissions increase linearly with an increase in moisture content, reaching its peak at 55% (NCASI, 2013). The carbon emission rate from deadwood trees depends on species identity and fungal decomposer community. Moreover, they are controlled by environmental conditions that affect the activity of fungal decomposers.

21.4.4 Wood-Based Industry-Greenhouse Gas Emissions in Perspective

Paper, paperboard, wood, and wood panels are made into a variety of products and are difficult to calculate all the emissions associated with the manufacturing step of these products. However, the basic life cycle studies can be adopted and redesigned as per the necessity to study the emissions related to the manufacturing processes. For instance, the process of converting rolls of the uncoated free sheet into reams of office paper involves only cutting and packaging, with a small amount of printing required on the packaging. Tissue and paper towel converting operations consist mainly of cutting, folding, and placing in printed packages (Pandey & Rangaraju, 2008). Converting sawn wood into pellets results in almost no emissions of greenhouse gases, but other products involve much more final processing (Miner, 2010).

21.5 Life Cycle Assessment of Wood

Wood has been an integral part of Indian culture since historical times and is again revolutionizing the market; it is one of the largest consumers of wood in Southeast Asia and supports major industrial sectors such as plywood, furniture, paper and pulp, construction, sports goods, handicrafts, match sticks, and pencil industries. The Indian timber industry is advancing with a growing knowledge base and synergistic contribution from the flagship schemes of the government. This growth in alignment with sustainable forest management is credible but an increased dependence on any particular material creates a dearth and an imbalance in the ecosystem. Therefore, it is necessary to conduct a life cycle assessment (Fig. 21.5) for natural materials like wood and wood-based industries to intricately understand the impact caused by every processing unit of these industries and measure its sustainability (Mishra, 2020). LCA is one of the tools that analyze the entire life cycle of the product in terms of sustainability. It evaluates the environmental impact of a product and also the processes associated with it. The four types of LCA are Cradle-Grave analysis, Gate-Gate analysis, Gate-Grave analysis, and Gate-Cradle analysis and the four main components of LCA structure are Goal Definition and Scoping, Inventory Analysis, Impact Assessment, and Improvement Assessment. LCA is an approach to accurately assess the environmental burdens not merely on technical and economic considerations but also incorporates the biological and social aspects to it, to understand the chain of direct and indirect impacts on the environment (Klöpffer, 2014). The goal of LCA is to compare the entire spectrum of environmental effects

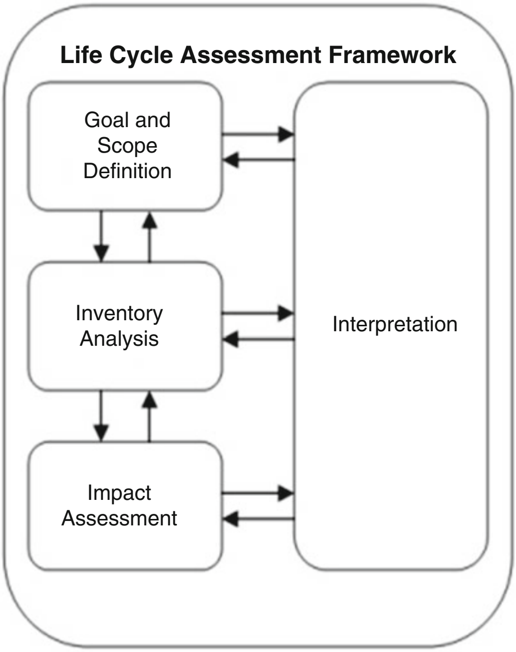

Fig. 21.5 ISO 14000 frame work for life cycle assessment

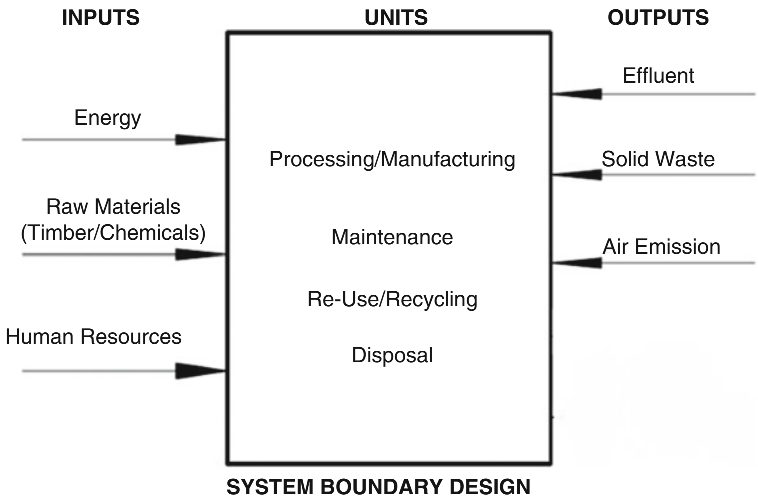

Fig. 21.6 System boundary design of LCA of wood process

of products and services through its entire life cycle considering the input and outflow during its production and recyclability, landfill disposal or burning at the end of its life cycle.

Furniture has gained attention for its sustainability and environmental index in wake of net-zero energy building. It is responsible for 10% of the building's impact on global warming and nonrenewable energy demand which makes it an important part of a building's design (Hoxha & Jusselme, 2017). Similarly, plywood and sawmill industries and wooden handicrafts are rising in demand and occupying a larger niche. Fewer studies on the LCA of these wood-based industries have been conducted through eco-sensitive life cycle inventory analysis which does not deliver the scenario of impact on humans completely or the fluctuating variation of impact over time through consumer demand or cultural factor (Klöpffer, 2008). Another important factor that is not included in the previous LCA studies of wood-based industries is biodegradation that is not included in the design of the LCA. The result of the LCA study completely depends on the selection of system boundary (Fig. 21.6) and life cycle inventories. Here, we have divided the entire system into three subsystems, i.e., process, maintenance, outflows (comprises of emissions and waste management).

The system boundary has three main units while assessing the Life Cycle Assessment (LCA) of Wood Industries: Process, Maintenance and Outflows. Process includes manufacturing/production processes of wood-based industries and inflows such as energy per unit time, material fed and extracted per unit time, processing temperature and other production operations (Klöpffer, 2008). The assessment of the production data gives primary carbon and energy footprint values and environmental impact related to the production of the wooden component. The study highlights the neglection of biological factor in the wood industries. The biodegradation of wood

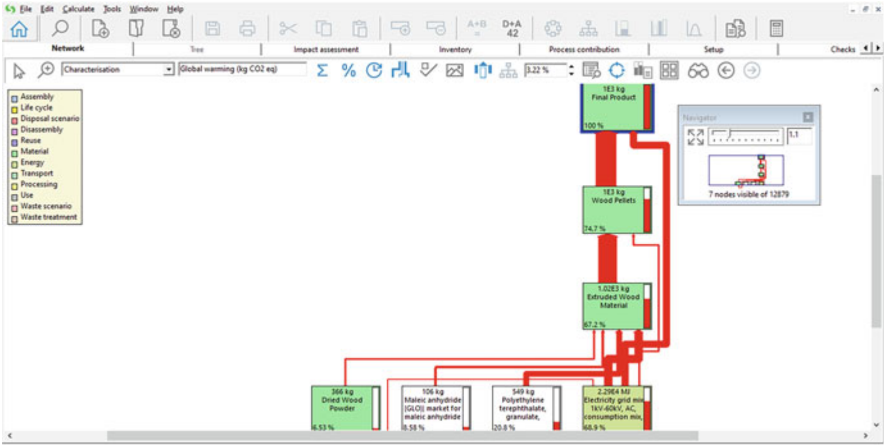

Fig. 21.7 Features of LCA in SimaPro (Simapro Manual)

material has to be included to calculate the loss of material and carbon emission. Henceforth, the questionnaire should include the amount of biodegradation in a certain period (over 1 month is preferred).

Maintenance includes general services, repair, and servicing of machines but the questionnaire for this needs to be designed carefully (Klöpffer, 2005). Manpower is one of the most important input resources in maintenance and it is difficult to quantify human resources, thus the questionnaire has to be qualitative and inclining toward social and labor rights.

Outflows subsystem consists of waste generated and waste management practices such as disposal, reuse, recycling or transferring it to waste centers. But this will not include logistics as we are considering a gate-gate analysis study (Klassen & Greis, 1993). The assessment of the data of outflows tells about the management practices that focus on reducing the carbon and energy footprint of the industries as a whole. However, this standard design of LCA does not specify if it should be an iterative study. The variables such as consumer demand, cultural factors, and seasonal changes, changes in industrial policies or performance are not considered in the standard design. The data collected from these varied components are interpreted through LCA software such as SimaPro (Fig. 21.7), GaBI, OpenLCA, and more. SimaPro has emerged as one of the best tools for LCA study.

21.5.1 Carbon Estimation from the Life Cycle Assessment of Wood

Over the past few decades, there is a growing awareness amongst consumers about the impacts of products and processes on the environment. Manufacturers are faced with strict environmental regulations while struggling to meet consumers' demands and stay competitive in the marketplace. Also, there is pressure from the public and government to reduce forestry operations and shift to alternative materials which have a higher impact than wood (Raj & Lal, 2013). Life cycle assessment (LCA) is one of the approaches to accurately assess the environmental burdens associated with the manufacturing of a product from resource extraction to end-of-life. LCA methodology helps to quantify and provide information about environmental qualities (Fava et al., 1991, 2009). LCA is comprised of four main stages: (1) goal and scope, (2) life cycle inventory, (3) impact assessment, and (4) interpretation. It is a process to evaluate the environmental burdens associated with a product or a service (Fava et al., 1991, 2009). Carbon is released from harvested materials at all stages of processing, product use, and final disposal. The net flux of carbon from the forest-based sector is calculated as the difference between the annual harvesting of carbon and the release of carbon (Fig. 21.8) from the processing, burning, and decomposition of forest products. This life cycle analysis helps in understanding the carbon emission source at varying stages (Miner, 2010). In India, there is a lack of study about the flow of carbon from the period timber is cut to its end-of-life.

The forest products are classified into four lifespans based on the fraction of time the product can retain carbon in it: very short, short, medium, and long. Some carbons in the wood product remain intact for years and decay at a slower rate while carbon in the paper is released promptly (Gundimeda, 2001). The carbon lost annually can be determined through carbon retention curve assigned to each forestry product. It presents the remaining carbon in the pool after its use, as the forest product ages. The proportion of carbon remaining in the product with the increase in its age can be calculated using the equation suggested by Row and Phelps (1990)

$$\mathrm{FCU} = d - a/(1 + b \times e - ct)$$

where, FCU is the fraction [0 . . . 1] of carbon remaining in use in different products; a, b, d (dimensionless), and c (year^{-1}) are parameters; and t is time (in years).

At the end of the life of a product, the carbon that is left can be recycled into raw material, burnt as energy or sent to the landfills to decompose slowly. Both decomposition and burning release carbon immediately into the atmosphere whereas recycling returns carbon to the previous age class of forest product. In landfills, carbon release occurs through gradual decomposition. The rate of decomposition depends on the products disposed in the landfills (Gundimeda, 2001).

The carbon transferred to open dumps (landfills) decays and is released into the atmosphere. In the case of modern sanitary landfills, solid waste is strongly compacted, covered or capped within a layer of soil in a dry, anaerobic, and acidic environment and so little or no decay takes place (Rathje, 1989). However, in India, carbon is discarded in open dumps, which has a higher decomposition rate than the modern landfills. Due to anaerobic decay in landfills, the decay rate chosen is such that carbon in landfills decomposes in 100 years. Karjalainen et al. (2002) estimated that the decay rate in landfills is 0.5%/annum. Kurz et al. (1992) used low decomposition rates between 1 and 2% per year for about 80% of the material stored in them, while the remaining material in landfills decomposes even more slowly forming long-term storage of carbon.

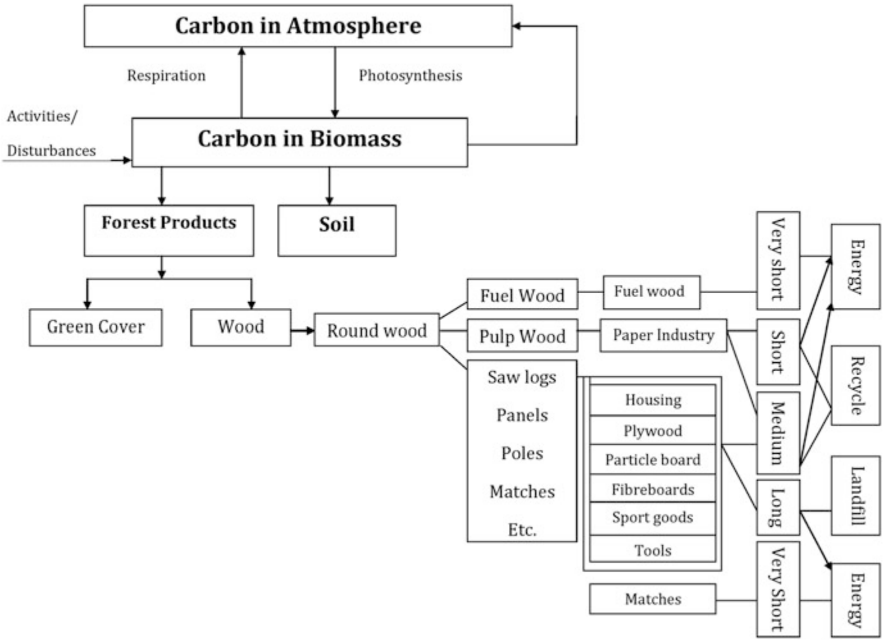

Fig. 21.8 Flow of carbon in different products (Gundimeda, 2001)

To examine the effect of decay rate in landfills on the carbon stored, two decay rates (low and high) are used. In the "low decay rate" scenario, the assumption is that products are disposed of in sanitary landfills, where the carbon decays in 200 years (at the rate of 0.5%/annum) and in the "high decay rate" scenario, the products are disposed of in open landfills, where carbon is released in 100 years (at the rate of 10%/annum) (Gundimeda, 2001).

21.6 Conclusion

Wood-based industries pose minimal environmental footprint and have reduced carbon emission as opposed to other alternate materials, but as discussed above wood can become a source of carbon emission and economic losses if it is not provided proper treatment or stored in humid or rooms with poor indoor quality. The study of life cycle over the decades has been evolving and now incorporates socio-economic factors along with long-term emissions and recyclability but still has not developed to study the emission from biodegradation. Biodegradation has to be studied over some time to get accurate results and has to be integrated with the economic aspect as well. Climate change and impacts on biodiversity are the raging issues today and we must follow a holistic approach to achieve sustainability on a larger scale. Therefore, it is essential to focus minutely on all the units of the life

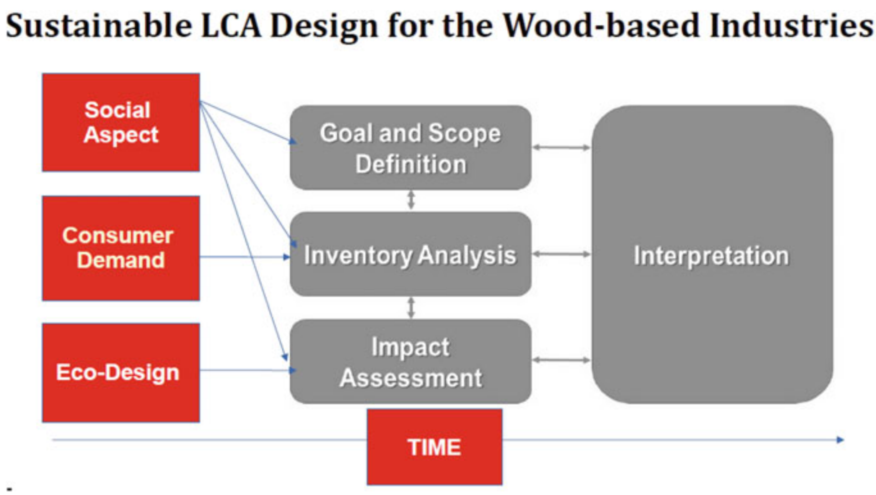

Fig. 21.9 Ecodesign incorporation for study of biodegradation

cycle of wood-based industries and the factors associated with it. This study finds a suitable LCA design that focuses on a wider spectrum of environment and sustainable development incorporating biodegradation. This design would help in understanding the inter-relations between the units and how they affect each other and also minimize the climate and biodiversity impact. The unit of ecodesign (Fig. 21.9) has to be introduced in LCA design which studies biodegradation and even other biological factors on wood that might go unnoticed or its minimal damages are ignored. These minimal damages over time might lead to big issues.

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Invasion of Wood Degraders Through Wood Import and Need to Strengthen the Plant Quarantine Measures in India

22

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Abstract

Wood-based industry plays a vital role in strengthening Indian economic sector. The wood, plywood, and allied products industries are key sectors having immense potential for gaining through trade. Major imported wood species are meranti, teak, and pine. India imports small quantities of temperate hardwoods such as ash, maple, cherry, oak, walnut, and beech for commercial, home interiors, and furniture. Various wood degraders such as fungi, bacteria, and insects may be introduced along with the imported material and may pose a serious threat. In this review, guidelines of importation, approved treatments associated with wood packaging material, schedule of treatment, phytosanitary certificate, and role of customs in release of wooden packaging materials are described in brief. Various potential wood degraders which need thorough monitoring are listed as a cautionary measure to avoid invasion. Role of The Directorate of Plant Protection, Quarantine, and Storage (DPPQ&S) at Faridabad under the Ministry of Agriculture (Department of Agriculture and Co-operation) plays responsible role for implementation of plant quarantine regulations.

Keywords

Wood degraders · Invasive · Plant quarantine · Wood import · Treatment · Pest

22.1 Introduction

Wood-based industry plays a vital role in strengthening Indian economic sector. The wood, plywood, and allied products industries are key sectors having immense potential for gaining through trade (Shrivastava & Saxena, 2017). China ranks first in the world in the list of wood exporters (USD 13544087 thousand in 2016) followed by Canada, USA, Germany, and Russian federation. China (USD 19627360 thousand in 2016) is also the country which imports highest wood followed by USA, Japan, Germany, and United Kingdom (*FAOSTAT-Forestry database*). The total trade value of the Indian wood industry in fiscal year 2020 amounted to over 47 billion rupees. In the fiscal year 2020, wood value at 39.64 billion Indian rupees was imported to India (*FAOSTAT-Forestry database*). Top countries that India exported woods include United States, United Arab Emirates, Nepal, United Kingdom, and Sri Lanka. Top partner countries and regions from which India imports wood include United States, Malaysia, China, and Myanmar (https://wits.worldbank.org/) (Table 22.1). In recent years, there is immense increase in export and import of wood, the industry faces set of challenges; therefore, import policy of wood and wood products in India has been liberalized with a view to support local needs and to facilitate conservation of existing forest resources (Vanam, 2019). Now one of the possible ways of invasion of pests is through the import of wood (Figs. 22.1a–d, 22.2, and 22.3a, b).

At present in India, forest and tree cover has increased to 24.4% equivalent to 3097 (sq. miles). Though there is various conservation and management measures incorporated, forest areas comprise of various flora and fauna and protection of each wood harvested from forest is difficult (Kumari et al., 2019). There are various species of fungi, bacteria, and insects survive on wood for food which in turns lead to various damages to the wood. Since it is a natural resource, it has to be protected and used efficiently. In forest, cultivable land and in wood structures, there is always problem of wood decay, degradation, and stains.

Wood degradation is caused by three primary sources, i.e., fungi or bacteria, insects or weathering (Knight & Heikkenen, 1980). These primary sources are affected by four factors, i.e., moisture, oxygen, temperature, and food. Lignin-degrading bacteria are Actinomycetes, α-Proteobacteria, and γ-Proteobacteria (Bugg et al., 2011; Huang et al., 2013). Other than fungi and bacteria, insects also play an important role in wood degradation. Three important insects causing wood damage are termites, beetles, and carpenter ants.

As the trade increases, the chances of alien species invasion also aggravate. The transport of biological materials and products is a major pathway for the introduction of alien species, particularly diseases and insects. Forest pests can move between countries via a number of pathways including importation of logs, chips, solid wood packaging, and propagative materials (Leal et al., 2010). This can cause large-scale infestations/infections resulting in destruction of our native ecosystems, where natural immunity does not exist. In November 2003, the Government of India (Ministry of Agriculture, Department of Agriculture and Co-operation) notified the Plant Quarantine (Regulation of Import to India Order) (referred to as PQ Order, 2003). The Directorate of Plant Protection, Quarantine, and Storage (DPPQ & S) at Faridabad under the Ministry of Agriculture (Department of Agriculture and Co-operation) is responsible for implementation of plant quarantine regulations.

Recently, successful elimination of termite entry to India is reported. Interception of two non-native species of Coptotermes: *Coptotermes testaceus* (Linnaeus) and *Coptotermes sjostedti* Holmgren are reported (Nagaraju et al., 2020). Pathway of

Table 22.1 List of tree species for wood permitted to be imported with additional declarations and special conditions

Tree species	Country of origin	Tree species	Country of origin
Abies spp.(Firwood)	Europe (except Portugal)	*Fagus sylvatica* (European Beech)	Europe
Alnus spp.(Alder)	USA and Europe	*Imperata cylindrica*	Indonesia
Bambusa bambos	Indonesia	*Juglans* spp. (Walnut)	USA, Europe, North America except USA
Betula spp. (Birch)	Europe, North America	*Khaya senegalensis* (African mahogany)	Australia
Betula platyphylla (Brich wood dowels)	China	*Khayaivorensis* (Khaya)	Africa
Buxus sempervirens (Boxwood)	Turkey, Spain, France, Germany	*Liquidambar styraciflua*	Australia, USA
Chamaecyparis nootkatensis	Canada	*Liriodendron tulipifera*	Australia, USA
Dipteryxodorata(Cumaru)	Brazil	*Ochroma pyramidale* (Balsa)	Germany
Ermophila mitchelli Eucalyptus calophylla (Corymbiacalophylla)	Australia	*Picea abies* (Spruce)	North America, China, Africa, Europe, Malaysia
Eucalyptus camaldulensis	Thailand	*Picea engelmannii, P. glauca, P. mariana, P. rubens*	Canada
Eucalyptus globulus	Sri Lanka, Cameroon	*Picea sitchensis*	Canada, Ivory Coast
Eucalyptus grandis/ Eucalyptus spp.	Uruguay, South America, South Africa, Australia, New Zealand, Fiji, Papua New Guinea, South Africa, Cameroon	*Pinus taeda*	Australia, USA
Piratinera guianenesis (Snakewood)	Central South America	*Salix spp.* (Willows)	Europe
Populus nigra	Belgium, Germany	*Shorealaevis*	Indonesia

(continued)

Table 22.1 (continued)

Tree species	Country of origin	Tree species	Country of origin
Prunus spp. (Cherry)	USA North America, Europe	*Tabebuia impetiginosa* (Ipe)	Brazil
Pseudotsugamenziesii (Douglas fir)	China, North America, New Zealand, Australia, Fiji, Papua New Guinea, South Africa	*Thuja plicata*	Canada
Quassia amara (Quassia)	Mexico, Brazil	*Tilia americana* (Bass wood)	USA
		Tectona grandis (Teak)	Ecuador

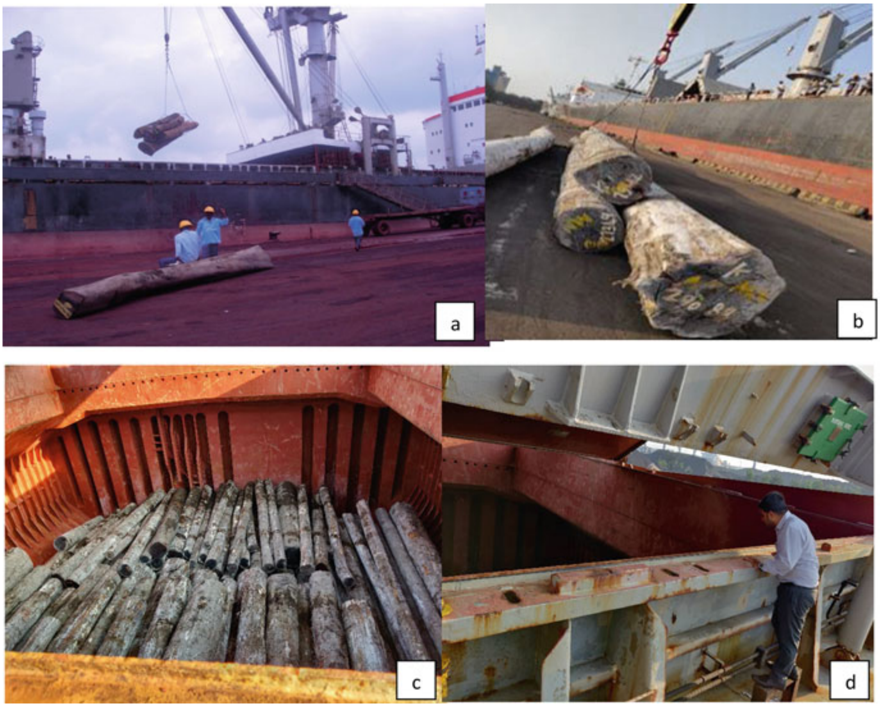

Fig. 22.1 (**a–d**) Wood import through seaports, a possible way of bioinvasion

Coptotermes gestroi straight from the neotropics to the Indian mainland and its interception was also reported (Venkatesan et al., 2021) (Fig. 22.4). A wood infesting *Apatemonachus* (Coleoptera: Bostrychidae) in Big-leaf Mahogany (*Swietenia macrophylla* King) (Fig. 22.5) plantations in India (Durai et al., 2017) is one such report which affirms the importance of strict quarantine measures.

Fig. 22.2 Imported sawn wood samples in the container which bear less risk compared to with bark wooden logs

India is well aware of the problems of bioinvasion and its obligations toward SPS agreement and is gearing itself up to meet the challenges. Currently India is importing several wood species from many countries. Below are few of the examples of invasion of pest and diseases around the world. The Asian long-horned beetle, pine shoot beetle, Asian gypsy moth (*Lymantria dispar*), chestnut blight (*Cryphonectria parasitica*), and Dutch elm disease (*Ceratocystis ulmi*) are some of

Fig. 22.3 Imported round wooden logs without bark (**a**) and with bark (**b**) also examination of the same by Plant Quarantine official inside the port before the discharge

Fig. 22.4 Corrugated box in which dead termites were found in the imported material from USA

the classic examples of wood pest and diseases invasion. As volume of forest products trade increases so do the chances of alien species invasion that can cause large-scale infestations and destruction of forest ecosystems, where natural immunity does not exist. In this review, guidelines of importation, approved treatments associated with wood packaging material, schedule of treatment, phytosanitary certificate, and role of customs in release of wooden packaging materials are described in brief.

22.2 Wood-Degrading Fungi

Depending upon their capacity of degradation they are divided into three groups (1) brown-rot fungi, (2) white-rot fungi, and (3) soft-rot fungi (Liers et al., 2011).

22.2.1 White-Rot Fungi

Ninety percent of wood-rotting fungi are white-rot type belonging to Basidiomycota. These groups of fungi survive on various substrates trees, conifers, crops, forest

Fig. 22.5 *Apate monachus* (Coleoptera: Bostrychidae) infested big-leaf mahogany plantation

litters, and soils (Rytioja et al., 2014). White-rot fungi are able to degrade all three cell wall polymers of trees by secreting enzymes. Under ambient moisture condition, white mycelia growth can be seen on the surface. White-rot fungi tend to attack hard wood compared to soft wood. The members of Polyporales and Agaricales, i.e., *Ganoderma* spp., *Phlebia radiata*, *Lentinula edodes* or *Pleurotus* spp., mostly represent white-rot fungi. Enzymes involved in lignin degradation in white-rot fungi are oxidative type, i.e., laccase, lignin peroxidase, manganese peroxidase, versatile peroxidase, and the dye-decolorizing peroxidises (Figs. 22.6a–d, 22.7, and 22.8).

22.2.2 Brown-Rot Fungi

Brown-rot fungi more often attack softwoods and are usually found in coniferous ecosystems (Gilbertson, 1980; Sigoillot et al., 2012). Brown-rotted wood will develop a reddish brown color and have a charred appearance. They mainly include basidiomycota (*Fomitopsi spalustris*, *Gloeophyllum trabeum*, *Lezites trabea*, *Poria cocoos*, *Postia placenta,* and *Serpula lacrymans* and some species of the genera *Daedalea, Piptoporus, Pycnoporellus*, *Neolentinus,* and *Paxillus* (Martinez et al., 2005); and to lesser extent Ascomycota (*Aspergillus niger*, *Fusarium oxysporum,* and *Fusarium merismoides*). Brown-rot fungi have been reported to produce several

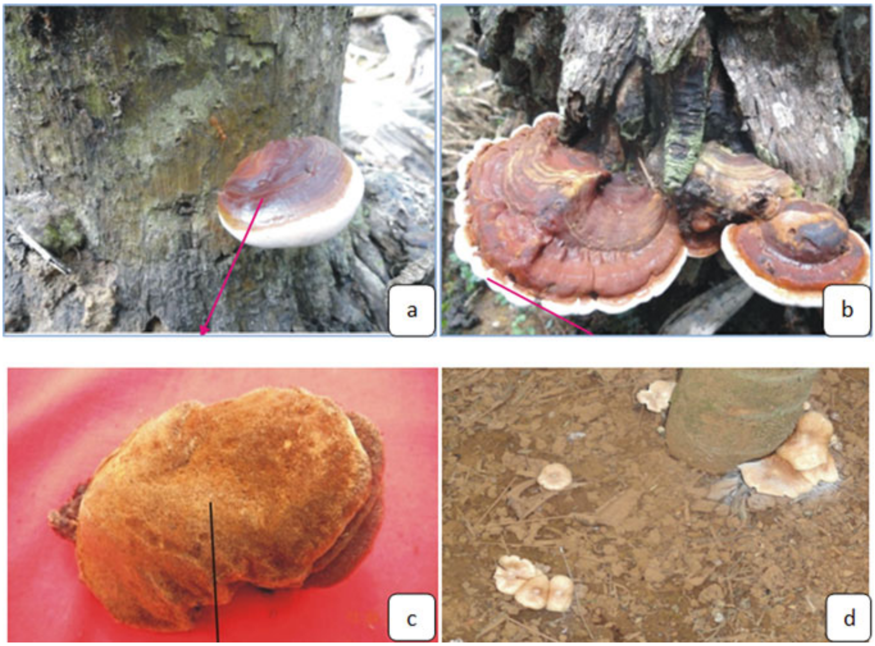

Fig. 22.6 (**a**, **b**) *Ganoderma* sp.; (**c**) *Heterobasidium*; and (**d**) *Armillaria* sp. on forest trees. (Source: Original pictures by Dr. Raju J).

Fig. 22.7 Mycelial growth on the imported wooden logs leads to discoloration of wood

endo β-1, 4-glucanases and β-glucosidases, but typically are described as lacking cellobiohydrolase (CBH) and other exoglucanases.

Fig. 22.8 Mycelial growth on the imported wooden logs leads to decaying of wood and reduces the market value as well as demand

22.2.3 Soft-Rot Fungi

Representatives from Ascomycota mostly cause soft-rot decay. The ability to degrade lignin by these fungi is limited (Cragg et al., 2015). However, members of the Xylariales order (from the *Daldinia*, *Hypoxylon*, and *Xylaria*genera) currently grouped with soft-rot fungi. Soft-rot fungi are often found in more extreme and wetter conditions that are less suitable for traditional white- and brown-rot fungi. Their damage tends to be confined to the external few mm of wood that is exposed to the environment, possibly because oxygen levels are too low in interior wood below ground to support more aggressive Basidiomycota fungal species.

22.3 Wood-Degrading Bacteria

Bacterial wood degradation is basically called as tunneling or erosion. Tunneling bacteria can also degrade a range of lignocellulosic substrates with high lignin content. Tunneling bacteria (TB) seem to require the presence of oxygen for their activity, erosion bacteria (EB) can tolerate conditions with extremely low levels of oxygen (Singh et al., 1990). Wood-degrading bacteria enter wood tissues generally via rays. Cell walls of ray parenchyma in many wood species are not lignified, and thus can be more easily degraded compared to lignin-containing cell walls.

22.3.1 Tunneling Bacteria

Bacteria belonging to this group have been aptly named tunneling bacteria, because they produce tunnels as they degrade the cell wall (Nilsson & Singh, 2014).

TB primarily degrade cell walls by way of tunneling, and thus are surrounded by the substrate. The tunneling strategy also enables TB to explore all available cell wall areas in situations involving cohabitation and cell wall attack by other wood-degrading microorganisms, such as EB and soft-rot fungi, aided by their ability to change shape and move in all directions within the cell wall. This adaptation enables TB to efficiently utilize their nutrition without entering in direct competition with cohabiting microorganisms.

22.3.2 Erosion Bacteria

EB are present in terrestrial and aquatic environments and can colonize and degrade wood exposed in oxygenated environments as well as under conditions with extremely low levels of oxygen (Björdal, 2000; Kim & Singh, 2000). EB can degrade lignocellulosic substrates under complete anoxic conditions. EB degraded cell walls in a way that produced channels (troughs) in the faces of cell walls being eroded a feature considered very characteristic of EB attack.

22.4 Wood-Degrading Insects

Three important insects which damage wood are termites, beetles, and carpenter ants. Some insects attack trees or wood that is partially moist as a result of contact with the ground or becomes wet from faulty construction, improper maintenance or previous insect activity.

22.4.1 Termites

Termites have been a major treat to wood both in forest as well as in structures due to its cellulose-degrading capability. Loss due to termite attack not only confines itself into the internal household materials but also extends its magnitude to the storage of commercial wood/wooden items, crops and farmhouses, sometimes the entire housing, and/or structure made up of wooden resources. Subterranean termites nest in the soil and can attack structures by building tubes that connect their nest to wood in structures. In standing tree, they penetrate through the root, building their chambers within the trunk, destroying the heartwood, and making the trees hollow, thus causing loss of productivity.

22.4.2 Carpenter Ants

Carpenter ants are scientifically known as *Camponotus* spp. (Hymenoptera: Formicidae). Carpenter ants tunnel into the wood of stumps, logs, dead standing trees, the dead interior of living trees, and wooden portions of buildings. The most obvious sign of a carpenter ant colony is the large amount of sawdust-like borings piled on the ground beneath entrance holes. The galleries are also distinctive with their vertical, honeycomb appearance, and smooth walls that are free of boring dust.

22.4.3 Beetles Causing Wood Degradation

Sal heartwood borer (*Hoplocerambyx spinicornis* Newn.) is a beetle of the order-Coleoptera, family-Cerambycidae. The heartwood borer was first noticed as a pest on sal in 1899. These beetles primarily attack sapwood but will also destroy heartwood. They digest the cellulose component of the cell wall at moisture content of 15% and above. Lyctid beetles' damage can be identified as large pores in wood such as oak, hickory, and ash which are most susceptible, but species such as yellow poplar, sweet gum, and cherry can also be infested.

22.5 Invasion of Wood Pest and Diseases

Rapidly growing global trade has a great potential to increase bioinvasion by opening unintentional but major dispersal opportunities. Invasion by non-native species now ranks second to habitat loss as the major threat to biodiversity (Wilcove et al., 1998). Bioinvasion occurs through movement of organisms from its original ecosystems to new area through trade (Tables 22.2 and 22.3). The sparse data available suggest that the pace of invasions is accelerating parallel with the growth of global trade (CAST, 2000). The classical example of exotic insect invasion on introduced tree species in India is that of *Heteropsylla cubana* (Homoptera: Psylidae) a subabul, *Leucaena leucocephala*. The insect was first reported from Chengalpattu (Tamil Nadu) in South India during February 1998 and later it invaded the entire Leucaena plantation in the country by October 1990 (Singh, 1988; Singh & Bhandari, 1989; Misra & Singh, 1990).

The chestnut blight fungus, *Endothia parasitica* [Murr] A. and A., Dutch elm disease (*Ceratocystis ulmi* [Buism.] C. Moreau), the European strain of the gypsy moth, *Lymantria dispar* L., and leafy spurge *Euphorbia esul*L., are few of the more commonly known introduced forest and range pests in the United States. Not only did they change the forests, but they resulted in serious economic loss over a large portion of the country (U.S. Congress, Office of Technology Assessment, 1993). Other introduced pathogens affecting forest or ornamental trees include *Phytophthora cinnamomi* (ink disease of chestnut) and probably other *Phytophthora* species, *Ceratocystis fimbriata* sp. *Platani* (canker stain), *Mycosphaerella pini* (redb and needle blight on pine), *Mycosphaerella dearnessii* (brown-spot needle blight of pines), and *Erwinia amylovora* (fire blight on *Crataegus* sp. and *Sorbus* sp. in forests). Recently, *Trichoderma koningiopsis* was reported in India from imported wooden logs from Ghana and Panama (Raju et al., 2021) (Fig. 22.9).

Pests and diseases on their own are not capable of traveling long distances but these have been known to cross geographical boundaries along with infested, infected or contaminated plant materials carried by man from one country to another. Some of the notable insect pests, which got introduced into India, have caused considerable damage to Indian agriculture. There are many records of insects, nematodes, fungi, and bacteria from the imported agricultural products, whereas only few reports are available on the pests/pathogens intercepted on imported wood

Table 22.2 List of wood species and countries from where import is prohibited along with justifications

S. No.	Tree species	Categories of plant material	Prohibited from the countries	Justification for prohibition
1.	Chestnut (*Castanea* spp.)	Seeds/ Fruits/ Grafts, and other planting material	North America (USA and Canada)	Chestnut blight or canker (*Cryphonectria (Endothia) parasitica*)—American strain
2.	Elm (*Ulmus* spp.)	Plants/ planting material	North America (USA and Canada) and Europe and Russia	Dutch elm disease (*Ceratocystis ulmi*)—American and European strains, Elm mottle virus, Elm bark beetles (Scolytidae), Elm phloem necrosis (Phytoplasmas), and White-banded elm leaf hopper (*Scaphoidousluteolus*)—vector of Elm phloem necrosis
3.	Oak (*Quercus* spp.)	Seeds/Root grafts	United States of America	Due to incidence of destructive Oak wilt (*Ceratocystis fagacearum*) and Oak bark beetles (*Pseudopityophthorus* spp.)
4.	Pine (*Pinus* spp.) and other coniferous species	Seeds/ Saplings Wood with bark	North America (Canada, USA, and Mexico) North America (Canada and USA), Asia (China, Hong Kong, Japan, Korea, Republic of Taiwan)	Due to incidence of destructive pests such as Pine rusts [Stalactiform rust (*Cronartium coleosporioides*), Comandra blister rust (*C. blistercomandrae*), sweet fern blister rust (*C. comptoniae*), Southern fusiform rust (*C. fusiforme*), Western gall rust (*Endocronartium harknessii*), Brown spot needle blight (*Mycosphaerella dearnesii*, syn. Scirrhiaacicola), Seedling die-back pitch canker (*Fusarium moniliforme*f. sp. *subglutinans*), and Needle cast (*Lophodermium* spp.)

(continued)

Table 22.2 (continued)

S. No.	Tree species	Categories of plant material	Prohibited from the countries	Justification for prohibition
				Due to destructive Pine wood nematode (*Bursaphelenchus xylophilus*)

in India. Thakur (2002) and Bhandari (2004) listed 15 insect species from wood imported at Bhavnagar (Gujarat), Tuticorin (Tamil Nadu), and Vishakhapatnam (Andhra Pradesh) harbors. Most of these insects are woodborers and all of them, except *Silvanus* spp. are common in India. These species include bark beetles, woodborers, powder post beetles, longhorn beetle larvae, curculinoid, snout beetle, scavengers, and predator beetles. Muthaiyan (1990) reported 47 species of insects through the ports of Chennai, Tuticorin, and Visakhapatnam on logs imported from Canada, Chile, Indonesia, Malaysia, Myanmar (Burma), Papua New Guinea, Singapore, Solomon Islands, Timor islands, and Vietnam. Of these *Neuroctenus serrulatus* is not known to occur in India and five species are known to be of major economic importance. There are many more exotic species, but the exact route of their entry into India is not understood. This may be because of lack of observation and study on imported wood and wood products in India. A large consignment of wood logs imported might have more chances of containing different types of living organisms on or inside the wood. While other consignments will be either in the form of edible or processed one, the wood logs are imported directly cut from the forest and often without treatment. Though many people tested imported agricultural products for fungi, bacteria, and virus, no reports are available on entry of fungi through wood and wood products. Regional Plant Quarantine Station (RPQS), Chennai listed out 25 fungi and bacteria in the year 2000–2001 from plants/plant material. Systematic studies on insect pests and pathogens imported to India through wood and wood products have not been carried out. Ahmed et al. (2006) reported the interception of Red-haired bark beetle, *Hylurgus ligniperda* on *Pinus radiata* logs imported from Costa Rica. Remadevi et al. (2012) reported interception of 55 species of insects under 17 families and also scorpions and spiders and fungi representing 13 genera in wooden logs imported in 2002–2003 from many countries through the ports of Mumbai Port trust, Mumbai; Kandla Port Trust, Gujarat; Tuticorin Port Trust, Tamil Nadu; New Mangalore Port Trust, Karnataka; Port Blair, Andaman and Nicobar Islands, and Kolkata Port Trust, Kolkata (Tables 22.4 and 22.5). Recently, *Cordylomera spinicornis* was intercepted in Tali wood imported from African countries (Raju et al., 2019) (Fig. 22.10).

As a result of international trade, many bark- and wood-infesting insects are inadvertently transported in wood packing materials (WPM) such as crating, dunnage, and pallets (AQIS, 2005). The invasive insect *Leptocybe invasa,* which is becoming serious on eucalyptus, is presumed to have arrived from Australian eucalyptus plantations and nurseries in several localities in Tamil Nadu,

Table 22.3 List of Tree species restricted import permissible only with the recommendation of authorized institutions with additional declarations and special conditions

Tree species	Categories of plant material	Additional declarations required to be incorporated into PSC
1. Chestnut (*Castanea* spp.)	1. Seeds/fruits/grafts and other planting material	Freedom from: Chestnut blight or canker (*Cryphonectria (Endothia) parasitica*)—American strain
2. Elm (*Ulmus* spp.)	1. Seeds/plants	Freedom from: (a) Dutch elm disease (Ceratocystis ulmi)—American and European strains (b) Elm mottle virus, (c) Elm bark beetles (Scolytidae), (d) White-banded elm leaf hopper (*Scaphoidousluteolus*)—Vector of Elm phloem necrosis, and (e) Seed Bruchid (*Bruchidius* spp.)
3. Oak (*Quercus* spp.)	1. Seeds/plants	Freedom from: (a) Oak wilt (*Ceratocystis fagacearum*), (b) Oak bark beetles (*Pseudopityophthorus* spp.), and (c) Seed Bruchids (*Bruchidius* spp.)
4. Pine (*Pinus* spp.) and other coniferous species	1. Seeds/plants	1. Freedom from: (a) Pine rusts (Stalactiform blister rust (*Cronartium coleosporioides*), Comandra blister rust (*C. comandrae*), sweet fern blister rust (*C. comptoniae*), Southern fusiform rust (*C. fusiforme*)), (b) Western gall rust (*Endocronartium harknessii*), (c) Brown spot needle blight (*Mycosphaerella dearnesii*, syn. Scirrhiaacicola), (d) Seedling die-back and pitch canker (*Fusarium moniliforme*f. sp. *subglutinans*), (e) Needle cast (*Lophodermium* spp.), (f) Pine wood nematode (*Bursaphelenchus xylophilus*), (g) Seed chalcid (*Eurytomas ciromatis*), and (h) Seed Bruchids (*Bruchidius* spp.)
5. Poplar (Populus spp.)	1. Stem cuttings/ plants	Freedom from: (a) Hypoxylon canker (*Hypoxylon mammatum*), (b) Poplar rust (*Melampsora medusae*), (c) Septoria canker of poplar (*Mycosphaerella populorum,* syn. *Septoria musiva*), (d) Gummosis (Euitypaarmeniacae), and (e) Poplar mosaic virus
6. Walnut (Juglans spp.)	1. Seeds (nuts)/plants	Freedom from: (a) Bacterial blight (*Xanthomonas juglandis*), (b) Bark canker (*Erwinia nigrifluens*), (c) Gummosis (Euitypaarmeniacae), and (d) Codling moth (Carpocapsapomonella)

Responsibility of authorized Institutions Subject to the recommendation, supervision, monitoring, and testing by Director, Forest Research Institute, Dehradun or any other research institute under Indian Council of Forestry Research and Education

Fig. 22.9 Fungal growth on timber logs covering entire part of the wood inside the container

Pondicherry, Karnataka, and Andhra Pradesh. This tiny wasp induced galls on shoot terminals and on petioles and midribs in saplings and trees of eucalyptus. The likely source of introduction of this pest insect to India could be through exchange of vegetative materials of eucalyptus (Jacob et al., 2007).

22.6 Pest Risk Assessment Methodologies Developed in Different Countries

Risk analysis of potential invaders is a way to prevent or suppress the number of potential invasive species. Successful colonization is governed by several factors independent of or dependent on the invading species. The most prominent factors governing successful establishment are the ecological opportunities on arrival, competitiveness of the invader, suitable climate, available host species, and species abilities or life history traits, e.g., wide tolerance of hosts, asexuality, and tolerance of population gaps enhance the possibility for establishment, the number of invading individuals (NRC, 1983, 1996).

Risk assessment of accidental species invasions has been improved greatly thanks to the analytic framework initiated by Whiteaker and Doren (1989) and developed by Orr et al. (1993). The model is a pathway-centered analysis, focused on a particular important commodity that also serves as a dispersal pathway for exotic species. The protocol involves listing all the known exotic species that could become associated with the commodity in the habitat of origin. Each species is then ranked, in terms of the probability of establishment and the probability of harmful economic or environmental effects. From these two qualitative measures, a single estimate of unmitigated invasion risk is calculated for each species.

Biogeographical similarity between donor and recipient areas has been thought to be one of the most crucial issues affecting invasions of insects (Niemelä & Mattson, 1996; Vermeij, 1996). The finding that distribution of insect species is ultimately determined and altered by climate has been used to determine the potential distribution ranges of potential invaders by Geographical Information System (GIS) (Williams & Liebhold, 2002; Crozier & Dwyer, 2006).

There is also an increasing number of GIS-based habitat models for estimating the risk of potential invaders (Kalkhan & Stohlgren, 2000; Thuiller et al., 2005), which

Table 22.4 List of insects intercepted from imported wood in India

Sl. No.	Scientific name of the insect	Family	Species of imported timber	Status of insect in India
1.	*Cephagogus* sp.	Brenthidae	*I. palembanica*	Not reported
2.	*Anthia* sp.	Carabidae	*Shorea* sp.	Reported
3.	*Mochtherustetraspilotus*	Carabidae	*I. palembanica*	Reported
4.	*Rhaphumapraeusta* Lameere	Cerambycidae	*I. palembanica*	Reported
5.	*Bothrideres* sp. Indet	Colydiidae	*Shorea* sp.	Reported
6.	*Trachypolis hispida* Weber	Colydiidae	*Shorea* sp.	Reported
7.	*Xanthiasiccana* Pasc	Colydiidae	*I. palembanica*	Not known
8.	*Zygopus* sp. Indet	Curculionidae	*I. palembanica*	Not known
9.	*Rhizopertha dominica*	Bostrichidae	*I. palembanica*	Reported
10.	*Minthea rugicollis*	Lyctidae	*N. diderrichii*	Reported
11.	*Carpophilus* sp. *Indet*	Nitidulidae	*I. palembanica*	Reported
12.	*Carpophilus flavipes* Murray	Nitidulidae	*I. palembanica*	Reported
13.	*Crossotarsus squamatus*	Platypodidae	*I. palembanica*	Reported
14.	*Platypus rectangulus Sampson*	Platypodidae	*I. palembanica*	No information
15.	*Platypus parallelus*	Platypodidae	*I. palembanica*	Cicumtropical in distribution
16.	*Platypus solidus*	Platypodidae	*Shorea* sp.	Reported
17.	*Platypus* sp.	Platypodidae	*I. palembanica*	Reported
18.	*Xylothrips flavipes*	Scolytidae	*Shorea* sp.	Reported
19.	*Xyleborus similis*	Scolytidae	*Shorea* sp.	Reported
20.	*Xyleborus* sp. *Indet*	Scolytidae	*N. diderrichii*	Reported
21.	*Xyleborus* sp.	Scolytidae	*I. palembanica*	Reported
22.	*Silvanus* sp. *Indet*	Silvanidae	*Shorea* sp.	Reported
23.	*Ceropria indutawied*	Tenebrionidae	*I. palembanica*	Reported
24.	*Hyperops* sp.	Tenebrionidae	*I. palembanica*	Reported
25.	*Gonocephalum* sp.	Tenebrionidae	*I. palembanica*	Reported
26.	*Acanthomyrm exluciolae*	Formicidae	*T. grandis*	Not reported
27.	*Anoplolepis gracilipes (Smith)*	Formicidae	*Shorea* sp.	Reported
28.	*Cardiocondyla dealate*	Formicidae	*T. grandis*	Reported
29.	*Diacamma cyaniventre*	Formicidae	*Shorea* sp.	Reported
30.	*Myrmicaria brunniaa*	Formicidae	*T. grandis*	Reported
31.	*Solenopsis geminate*	Formicidae	*T. grandis*	Reported
32.	*Tetramorium bicarinatum*	Formicidae	*I. palembanica*	Reported

Source: Remadevi et al. (2012)

Table 22.5 List of fungi on different imported timber species

Sl. No.	Fungal group/family/species	Species of imported timber
1.	*Alternaria* sp.	*T. grandis*
2.	*Aspergillus* sp.-1	*N. diderrichii*
3.	*Aspergillus* sp.-2 and 3	*I. palembanica*
4.	*Cirrenalia* sp.	*N. diderrichii*
5.	*Cladosporium* sp., *Fusarium* sp., Eurotiaceae, *Trichocladium* sp.	*I. palembanica*
6.	*Hydronectriatethys* Kohlm. & E. Kohlm.	*Erythrophleum* sp.
7.	*Penicillium* sp., Coelomycete-2, Coelomycete-1	*Shorea* sp.
8.	Ascomycete-1	*T. grandis*
9.	Ascomycete-2	*I. palembanica*
10.	Deuteromycete-2	*Erythrophleum* sp.
11.	Deuteromycete-3	*N. diderrichii*
12.	Deuteromycete-4	*I. palembanica*
13.	Hypomycete-1	*Erythrophleum* sp.
14.	Hypomycete-2	*N. diderrichii*
15.	Hypomycete-3	*I. palembanica*

Source: Remadevi et al. (2012)

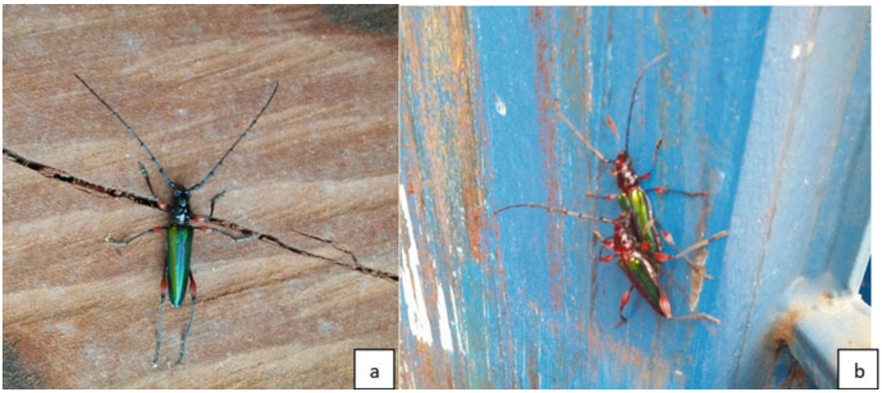

Fig. 22.10 Live pest *Cordylomera spinicornis* was intercepted in Tali wooden logs imported from African countries. (Source: Original pictures by Dr. Raju J).

are moreover aimed at evaluating the potential of exotic plants to invade a certain habitat. Host availability estimation is crucial when herbivorous insects are considered, and therefore palatability tests are conducted or estimates are made of suitable hosts for the most invasive pests (MacFarlane & Meyer, 2005).

The risk of establishment is most severe where the main host species for the potential invader occurs naturally or is widely cultivated. Climatic comparisons and simulations of climatically or biogeographically suitable areas for targeted high-risk species have become increasingly important in targeting preventive or eradicative efforts where they are most needed (Vanhanen, 2008). Generally, a good match between physical factors of the donor habitat and the new habitat of the immigrant species will increase the probability of establishment (Kiritani & Yamamura, 2003).

Adaptation to the prevalent climate plays a crucial role in establishing a population in a new continent after arrival. Prevailing climate defines the seasonal phenology to which the introduced species must adapt (Vermeij, 1996; Niemelä & Mattson, 1996). Seasonal climate patterns, particularly moisture and temperature, can be also crucial, especially for introduced forest pathogens.

Biotic factors: The rate of primary production, the amount of unused resources, anthropogenic disturbance of the habitat, and low species richness have been thought to be the basic principles that make some biotas more prone to invasions (Sher & Hyatt, 1999; Davis et al., 2000; Byers, 2002). Alone, the presence of available hosts in a new region is not enough. Suitable hosts must be adequately abundant for invading insects to find them (Futuyma, 1991).

Dispersal: The dispersal of an indigenous species is not only a demographic and spatial stage, but also an integration phase and an evolution process between the native biota and the invader. In extreme cases, an invader may cause the extinction of a native species (Vermeij, 1996; Clavero & García-Berthou, 2005).

The PRA follows a format and terminology laid out by the International Plant Protection Convention of the Food and Agriculture Organization of the United Nations. A PRA provides an assessment of the plant pest risk based on scientific literature, scientific data, and analysis of potential pathways of introduction. It also rates the risk in a number of categories.

It should be noted that a PRA is a "living document," and information on the ecological, economic, and scientific significance may be added as it becomes available. To gain through knowledge of a pest in a new environment takes years of intensive research, in which time an invasive forest insect such as BSLB may cause extensive long-term damage to the ecosystem and the economy that relies upon it.

22.7 Laws or Conventions on Bioinvasive Species

22.7.1 International Level

The WTO agreement 1995 on application of sanitary and phytosanitary measures has a considerable impact on trade of agriproducts. As a result, International Standards on Phytosanitary Measures (ISPMs) are brought out by the committee of experts on phytosanitary measures constituted under the International Plant Protection Convention (IPPC) under aegis of FAO, Rome (FAO, 2001). This is circulated among the members of the committee for adaptation and comments.

The IPPC is an international treaty to secure action to prevent the spread and introduction of pests of plants and plant products, and to promote appropriate measures for their control. It is governed by the Commission on Phytosanitary Measures (CPM) which adopt International Standards for Phytosanitary Measures (ISPMs). The CPM has confirmed the IPPC as the preferred forum for national IPPC reporting and the exchange of more general information among the phytosanitary community. The IPPC Secretariat coordinates the activities of the convention and is provided by the FAO. The International Plant Protection Convention is a legally binding agreement among the contracting governments and until now 127 countries have deposited their instruments and many countries have accepted the amendments made in the revised text of the convention. The main objectives of IPPC are concerned with prevention of global spread of pests in international trade. WTO-SPS Agreement provides basic rules for formulating and adopting appropriate measures to protect human, animal, and plant life (WTO, 1995).

International Standards for Phytosanitary Measures (ISPM) are adopted by contracting parties to the IPPC, and by FAO Members that are not contracting parties, through the Interim Commission on Phytosanitary Measures. ISPMs are the standards, guidelines, and recommendations recognized as the basis for phytosanitary measures applied by Members of the World Trade Organization under the Agreement on the Application of Sanitary and Phytosanitary Measures. Noncontracting parties to the IPPC are also encouraged to observe these standards.

The introduction of measures to treat packaging wood to kill pests and pathogens of quarantine concern is reducing the risks from this dangerous pathway. International Standards for Phytosanitary Measures (ISPM) Number 15, through the auspices of IPPC, is now in place for many countries globally and will, over time, be introduced for all wood packaging in international trade. Current measures to kill pests include heat treatment (HT) to reach a core temperature in the wood of 56 °C for 30 min or fumigation with methyl bromide to a set schedule. There is no doubt that these measures kill the great majority of pests that might be associated with the packaging wood (IPPC, 2002).

In recognition that wood packaging material (WPM) is an important pathway for the movement of pests, the world community approved new international standards for WPM in 2002 (FAO, 2002). These standards are often referred to as ISPM-15 (ISPM = International Standards for Phytosanitary Measures). The principal objective of ISPM-15 is to reduce the risk of introducing pests associated with WPM. Current ISPM-15 standards for WPM allow for the presence of bark when the wood is either heat-treated or fumigated with methyl bromide according to approved protocols. ISPM-15 also requires that all WPMs used in international trade be marked to indicate the country of origin, the type of treatment used, and the company that conducted the treatment (FAO, 2002). Presently, the only internationally accepted treatment options for WPM under the ISPM-15 are heat treatment or fumigation with methyl bromide.

The "International Forest Quarantine Research Group" or IFQRG (http://www.forestry-quarantine.org) was initiated in 2003. One of the principal objectives of

IFQRG is to conduct research that addresses important questions related to ISPM-15.

22.7.2 National Level

The import policy of wood and wood products in India has been liberalized with a view to support local needs and to facilitate conservation of existing forest resources. To safeguard Indian agricultural, horticultural, and forest plants from exotic pests, Government of India has taken legislative steps and implemented various regulations framed under DIP Act, 1914 (Destructive Insect Pest Act) (Tables 22.6 and 22.7). The import of agricultural commodities including wood and wooden materials is presently regulated through the Plant Quarantine (Regulation of Import into India) Order, 2003, issued under DIP Act, 1914 incorporating the provisions of New Policy on Seed Development, 1988. Further, the significance of Plant Quarantine has increased in view of globalization and liberalization in international trade of plants and plant material in the wake of Sanitary and Phytosanitary (SPS) Agreement under World Trade Organization (WTO, 1995).

India is a signatory to WTO–SPS agreement and International Plant Protection Convention (IPPC). Till recently, the import of wood to the country was regulated by the plants, fruits, and seeds (Regulation of Imports into India) Order 1989, treating wood as a plant material. In November 2003, the rules are updated through plant quarantine (Regulation of import into India) order 2003. As per this order, the list of plants and plant materials including of forest and related seeds are restricted for import to India. This order has stringent clauses and was amended in further orders (February, March, April, and May, 2004). The details of amendments are as follows:

In exercise of the powers conferred by subsection (1) of Section 3 of the Destructive Insects and Pests Act, 1914 (2 of 1914), the Central Government hereby makes the following Order, for the purpose of prohibiting and regulating the import into India of agricultural articles mentioned herein, namely:

ISPM-15, the Standards prescribed for WPM describe about the phytosanitary treatment or measures required to be taken to reduce the risk of introduction and/or spread of quarantine pests associated with WPM (including dunnage), made of coniferous and nonconiferous raw wood. As regards imports, subclause 20A of Clause 3 of the Plant Quarantine (Regulation of Import into India) Order, 2003, require that all WPMs, raw or solid, shall be subject to specified treatment and carrying the ISPM-15 marking on it. As regards goods exported from India, since many countries require that the WPM is to be treated prior to shipment in order to satisfy their Plant Quarantine requirements, the Directorate of Plant Protection Quarantine & Storage have issued instructions to various phytosanitary certificate issuing authorities for strict adherence to the protocols and guidelines issued by that Department for issuance of Phytosanitary certificates. In order to explain the requirements of ISPM-15 on imports and exports of goods packed in raw or solid wood materials, significance of ISPM–15

Table 22.6 List of points of entry for import of plants/plant materials and other articles

	Seaports	Airports	Land frontier stations
1.	Alleppey (Kerala)	Amritsar (Punjab)	Agartala (Tripura)
2.	Bhavnagar (Gujarat)	Bangalore (Karnataka)	Amritsar Rly. Stn. (Punjab)
3.	Kolkata (WestBengal)	Kolkata (West Bengal)	Attari Rly.Stn. (Punjab)
4.	Calicut (Kerala)	Chennai (Tamil Nadu)	Attari Wagha Border
			Check post (Punjab)
5.	Chennai (Tamil Nadu)	Hyderabad (Telangana)	Bongaon (West Bengal)
6.	Cochin (Kerala)	Mumbai (Maharashtra)	Gede Road Rly. Stn. (West Bengal)
7.	Cuddalore (Tamil Nadu)	New Delhi (Delhi)	Jogbani (Bihar)
8.	Goa (Goa)	Patna (Bihar)	Moreh (Manipur)
9.	Gopalpur (Orissa)	Tiruchirapalli (Tamil Nadu)	Panitanki (West Bengal)
10.	Haldia (West Bengal)[a]	Trivandrum (Kerala)	Raxual (Bihar)
11.	Jamnagar (Gujarat)	Varanasi (Uttar Pradesh)	Rupadiha (Uttar Pradesh)
12.	Beypore (Kerala)	Guwahati (Assam)	Sonauli (Uttar Pradesh)
13.	Kakinada (Andhra Pradesh)	Calicut (Kerala)	Banbasa (Uttaranchal)
14.	Kandla (Gujarat)	Coimbatore (Tamil Nadu)	Zokhwathar (Mizoram)
15.	Karwar (Karnataka)	Bagdogra (West Bangal)	Changrabandha (West Bengal)
16.	Krishnapatnam (Andhra Pradesh)	Cochin (Kerala)	Ghozadanga (West Bengal)
17.	Machlipatnam (Andhra Pradesh)	Indore(Madhya Pradesh)	Mehadipur (West Bengal)
18.	Mandvi (Gujarat)	Goa (Goa)	Gauriphanta (Uttar Pradesh)
19.	Mangalore (Karnataka)	Tirupati (Andhra Pradesh)	Vittamod (Bihar)
20.	Mumbai (Maharashtra)	Port Blair (Andaman and Nicobar Islands)	Jaigaon (West Bengal)
21.	Mundra (Gujarat)	Nashik (Maharashtra)	Chamurchi (West Bengal)
22.	Nagapatnam (Tamil Nadu)	Madurai (Tamil Nadu)	Hatisar (Dadgiri) (Assam)
23.	Nova Shiva (Maharashtra)	Bhubaneswar (Odisha)	Darranga (Assam)
24.	Navlakhi (Gujarat)	Kannur (Kerala)	Barhni (Uttar Pradesh)
25.	Okha (Gujarat)		
26.	Paradeep (Orissa)[a]		
27.	Pondicherry		
28.	Porbander (Gujarat)		
29.	Rameshwaram (Tamil Nadu)		

(continued)

Table 22.6 (continued)

	Seaports	Airports	Land frontier stations
30.	Tiruvananthapuram (Kerala)		
31.	Tuticorin (Tamil Nadu)		
32.	Veraval (Gujarat)		
33.	Visakhapatnam (Andhra Pradesh)		
34.	Vizhinjam (Kerala)		
35.	Kollam (Quilon) (Kerala)		
36.	Karaikal (Puducherry)		
37.	Pipavav (Gujarat)		
38.	Hazira (Gujarat)		
39.	Jaigarh (Maharashtra)		
40.	Kattupalli (Tamil Nadu)		
41.	Port Blair (Andaman and Nicobar Islands)		
42.	Dahej Port (Gujarat)		
43.	Dhamra Port (Orissa)		
44.	Kamarajar Port, Chennai (Tamil Nadu)		
45.	Nancowry (Kamorta) (Andaman and Nicobar Island)		
46.	Port Meadow (Andaman and Nicobar Island)		

[a] For import of food grains by Food Corporation of India only (PQ Order 2003, Schedule-I www.plantquarantineindia.org)

Table 22.7 Major ports importing wood and wood products

Sl. No.	Port name	Product
1.	Mangalore, Karnataka	Timber logs and Plywood
2.	Tuticorin, Tamil Nadu	Timber logs and Plywood
3.	Chennai, Tamil Nadu	Timber logs and Plywood
4.	Vishakhapatnam, Andhra Pradesh	Timber logs and Plywood
5.	Cochin, Kerala	Timber logs and Plywood
6.	Kandla, Gujarat	Timber logs and Plywood
7.	Mundra, Gujarat	Timber logs and Plywood

marking on WPM and its identification by various stakeholders who handle import/export consignments at customs stations, it is stated that during monthly trade facilitation meetings held in the Commissionerate, the Plant Quarantine Officers may be required to explain the compliance requirements in terms of the ISPM-15 so that minimum inconvenience is caused to the importers/exporters while ensuring checking of the wood packaging (Figs. 22.11, 22.12, and 22.13).

Fig. 22.11 Inspection of imported wooden logs by Plant Quarantine official and deeply observing for presence of any pests. (Source: Original pictures by Dr. Raju J).

Fig. 22.12 Presence of wood beetle along with its larvae after removing the bark on the suspected part of the imported wooden logs. (Source: Original pictures by Dr. Raju J).

22.8 Approved Treatments Associated with Wood Packaging Material (2018)

The approved treatments may be applied to units of WPM or to pieces of wood that are to be made into WPM. Use of debarked wood irrespective of the type of treatment applied, WPM must be made of debarked wood.

For this standard, any number of visually separate and clearly distinct small pieces of bark may remain if they are:

Fig. 22.13 Tunneling/damage symptoms of insects beneath the bark indicate the presence of pests. (Source: Original pictures by Dr. Raju J).

- Less than 3 cm in width (regardless of the length) or
- Greater than 3 cm in width, with the total surface area of an individual piece of bark less than 50 cm^2

For methyl bromide and sulfuryl fluoride treatments, the removal of bark must be carried out before treatment as the presence of bark on the wood may affect treatment efficacy. For heat treatment, the removal of bark may be carried out before or after treatment. When a dimension limitation is specified for a certain type of heat treatment (e.g., dielectric heating), any bark must be included in the dimension measurement (Anonymous, 2018a).

22.8.1 Heat Treatment

Various energy sources or processes may be suitable to achieve the required treatment parameters. For example, conventional steam heating, kiln-drying, heat-enabled chemical pressure impregnation, and dielectric heating (microwave, radio frequency) may all be considered heat treatments provided they meet the heat treatment parameters specified in this standard.

NPPOs should ensure that treatment providers monitor the treatment temperature at a location likely to be the coldest, which will be the location taking the longest time to reach the target temperature in the wood, to ensure that the target temperature is maintained for the duration of treatment throughout the batch of wood being treated. The point at which a piece of wood is the coldest may vary depending on the energy source or process applied, the moisture content, and the initial temperature distribution in the wood.

When using dielectric heating as a heat source, the coldest part of the wood during treatment is usually the surface. In some situations (e.g., dielectric heating of wood of large dimensions that has been frozen and until the wood has thawed), the core may be the coldest part of the wood.

Fig. 22.14 Model of Forced hot air treatment plant for wooden crates

When using conventional heat chamber technology, the fundamental requirement is to achieve a minimum temperature of 56 °C for a minimum duration of 30 continuous minutes throughout the entire profile of the wood (including its core).

This temperature can be measured by inserting temperature sensors in the core of the wood. Alternatively, when using kiln-drying heat chambers or other heat treatment chambers, treatment schedules may be developed based on a series of test treatments during which the core temperature of the wood at various locations inside the heat chamber has been measured and correlated with chamber air temperature, taking into account the moisture content of the wood and other substantial parameters (such as species and thickness of the wood, air flow rate, and humidity). The test series must demonstrate that a minimum temperature of 56 °C is maintained for a minimum duration of 30 continuous minutes throughout the entire profile of the wood (Figs. 22.14, 22.15, and 22.16).

22.8.2 Heat Treatment Using Dielectric Heating (Treatment Code for the Mark: DH)

Where dielectric heating (microwaves or radio waves) is used, WPM must be heated to achieve a minimum temperature of 60 °C for 1 continuous minute throughout the entire profile of the wood (including its surface). Treatment providers using dielectric heating must verify that their schedules achieve specified treatment parameters (taking into account the moisture content of the wood, its size and density, and the

Fig. 22.15 Forced hot air treatment unit for wooden crates with proper demarcations

Fig. 22.16 Sample of wooden crate which has under gone heat treatment with authentic label and ready to use

frequency of microwaves or radio waves). An authentic label should be provided once the wood is treated (Fig. 22.4).

22.8.3 Methyl Bromide Treatment (Treatment Code for the Mark: MB)

NPPOs are encouraged to promote the use of alternative treatments approved in this standard 4. Use of methyl bromide should take into account the CPM recommendation on the replacement or reduction of the use of methyl bromide as a phytosanitary measure. (IPPC 2002).

Table 22.8 Minimum required CT over 24 h for wood packaging material fumigated with methyl bromide

Temperature (°C)	Minimum required CT (g h/m^3) over 24 h	Minimum final concentration (g/m^3) after 24 h[a]
21.0 or above	650	24
16.0–20.9	800	28
10.0–15.9	900	32

[a] In circumstances when the minimum final concentration is not achieved after 24 h, a deviation in the concentration of ~5% is permitted provided additional treatment time is added to the end of the treatment to achieve the prescribed CT

Wood packaging material containing a piece of wood exceeding 20 cm in cross-section at its smallest dimension must not be treated with methyl bromide.

The fumigation of WPM with methyl bromide must be in accordance with a schedule specified or approved by the NPPO that achieves the minimum concentration–time product 5 (CT) over 24 h at the temperature and final residual concentration specified in Table 22.8. This CT must be achieved throughout the profile of the wood, including its core, although the concentration is measured in the ambient atmosphere. The minimum temperature of the wood and its surrounding atmosphere must not be less than 10 °C and the minimum exposure time must not be less than 24 h. Monitoring of gas concentrations must be carried out at a minimum at 2, 4, and 24 h from the beginning of the treatment. In the case of longer exposure times and weaker concentrations, additional measurement of the gas concentrations should be recorded at the end of fumigation.

If the CT is not achieved over 24 h, corrective action needs to be taken to ensure the CT is reached; for example, the treatment is restarted or the treatment time extended for a maximum of 2 h without adding more methyl bromide to achieve the required CT (see the footnote to Table 22.8).

22.8.4 Sulfuryl Fluoride Treatment (Treatment Code for the Mark: SF)

Wood packaging material containing a piece of wood exceeding 20 cm in cross-section at its smallest dimension must not be treated with sulfuryl fluoride. WPM with moisture content higher than 75% (dry basis) must not be treated with sulfuryl fluoride.

The fumigation of WPM with sulfuryl fluoride must be in accordance with a schedule specified or approved by the NPPO that achieves the minimum CT5 over 24 or 48 h at the target temperature and final residual concentration specified in Table 22.9. This CT must be achieved throughout the profile of the wood, including its core, although the concentration is measured in the ambient atmosphere. Small increases in the treatment time (not more than 2 h) may be permitted to achieve the required CT if the minimum final concentration is not reached. The minimum temperature of the wood must not be lower than 20 °C and the minimum exposure

Table 22.9 Minimum required CT over 24 or 48 h for wood packaging material fumigated with sulfuryl fluoride

Temperature (°C)	Minimum required CT (g h/m^3)	Minimum final concentration (g/m^3)[a]
30 or above for 24 h	1400	41
20 or above for 48 h	3000	29

[a] If the minimum final concentration is not achieved after 24 or 48 h by the end of the treatment, a deviation in the concentration of ~5% is permitted, provided additional treatment time is added at the end of the treatment to achieve the prescribed CT

time must not be less than the time stated for each temperature in Table 22.9. Monitoring of gas concentration must be carried out at a minimum of 2, 4, 24, and, when appropriate, 48 h from the beginning of the treatment. In the case of longer exposure times and weaker concentrations, additional measurements of the gas concentrations should be recorded at the end of fumigation.

If the CT is not achieved within a single 24- or 48-h period (even if the minimum final concentration is achieved), corrective action should be taken. The treatment time may be extended for a maximum of 2 h without adding more sulfuryl fluoride, or it may be restarted.

22.9 The Mark and Its Application

A mark indicating that WPM has been subjected to approve phytosanitary treatment in accordance with this standard 6 comprises the following required components:

- The symbol
- A country code
- A producer/treatment provider code
- A treatment code using the appropriate abbreviation according to Annex 1 (HT, DH, MB or SF)

22.9.1 Symbol

The design of the symbol (which may have been registered under national, regional or international procedures, as either a trademark or a certification/collective/guarantee mark) must resemble closely that shown in the examples illustrated below and must be presented to the left of the other components.

22.9.2 Country Code

The country code must be the International Organization for Standards (ISO) two-letter country code (shown in the examples as “XX”). It must be separated by a hyphen from the producer/treatment provider code.

22.9.3 Producer/Treatment Provider Code

The producer/treatment provider code is a unique code assigned by the NPPO to the producer of the WPM or treatment provider who applies the marks or the entity otherwise responsible to the NPPO for ensuring that appropriately treated wood is used and properly marked (shown in the examples as “000”). The number and order of digits and/or letters are assigned by the NPPO.

22.9.4 Treatment Code

The treatment code is an IPPC abbreviation as provided in Annex 1 for the approved measure used and shown in the examples as “YY” (Table 22.10). The treatment code must appear after the combined country and producer/treatment provider codes. It must appear on a separate line from the country code and producer/treatment provider code, or be separated by a hyphen if presented on the same line as the other codes.

22.9.5 Application of the Mark

The size, font types used, and position of the mark may vary, but its size must be sufficient to be both visible and legible to inspectors without the use of a visual aid. The mark must be rectangular or square in shape and contained within a border line with a vertical line separating the symbol from the code components. To facilitate the use of stenciling, small gaps in the border, the vertical line, and elsewhere among the components of the mark, may be present.

No other information shall be contained within the border of the mark. If additional marks (e.g., trademarks of the producer, logo of the authorizing body) are considered useful to protect the use of the mark on a national level, such information may be provided adjacent to but outside of the border of the mark.

The mark must be:

- Legible
- Durable and not transferable
- Placed in a location that is visible when the wood packaging is in use, preferably on at least two opposite sides of the wood packaging unit

Table 22.10 Treatment code and treatment type

Sl. No.	Treatment code	Treatment type
1.	HT	Heat treatment
2.	DH	Dielectric heating
3.	MB	Methyl bromide
4.	SF	Sulfuryl fluoride

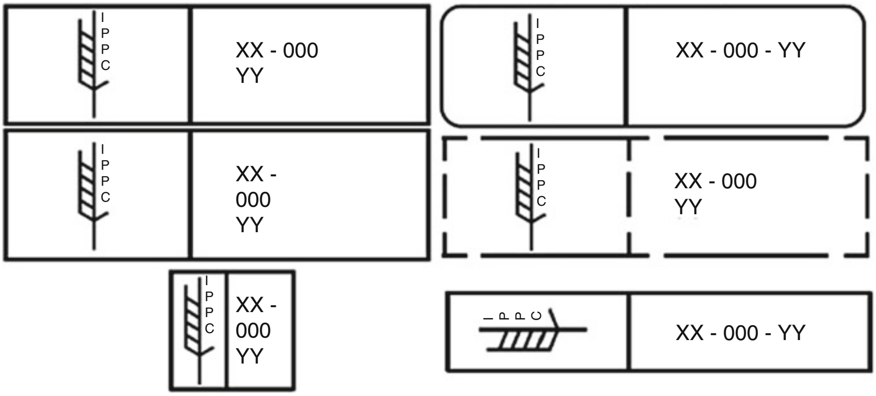

Fig. 22.17 The above pictures illustrate some acceptable variants of the wood packaging material along with the logo

The mark must not be hand drawn.

The use of red or orange should be avoided because these colors are used in the labeling of dangerous goods.

Where various components are integrated into a unit of WPM, the resultant composite unit should be considered as a single unit for marking purposes. On a composite unit of WPM made of both treated wood and processed wood material (where the processed component does not require treatment), it may be appropriate for the mark to appear on the processed wood material components to ensure that the mark is in a visible location and is of a sufficient size. This approach to the application of the mark applies only to composite single units, not to temporary assemblies of WPM.

Special consideration of legible application of the mark to dunnage may be necessary because treated wood for use as dunnage may not be cut to final length until loading of a conveyance takes place. It is important that shippers ensure that all dunnages used to secure or support commodities is treated and displays the mark described in this annex, and that the marks are clear and legible. Small pieces of wood that do not include all the required elements of the mark should not be used for dunnage (Figs. 22.17 and 22.18).

Options for marking dunnage appropriately include:

- Application of the mark to pieces of wood intended for use as dunnage along their entire length at very short intervals (NB: where very small pieces are subsequently cut for use as dunnage, the cuts should be made so that an entire mark is present on the dunnage used).
- Additional application of the mark to treated dunnage in a visible location after cutting, provided that the shipper is authorized in accordance with ISPM-15 Regulation of wood packaging material in international trade.

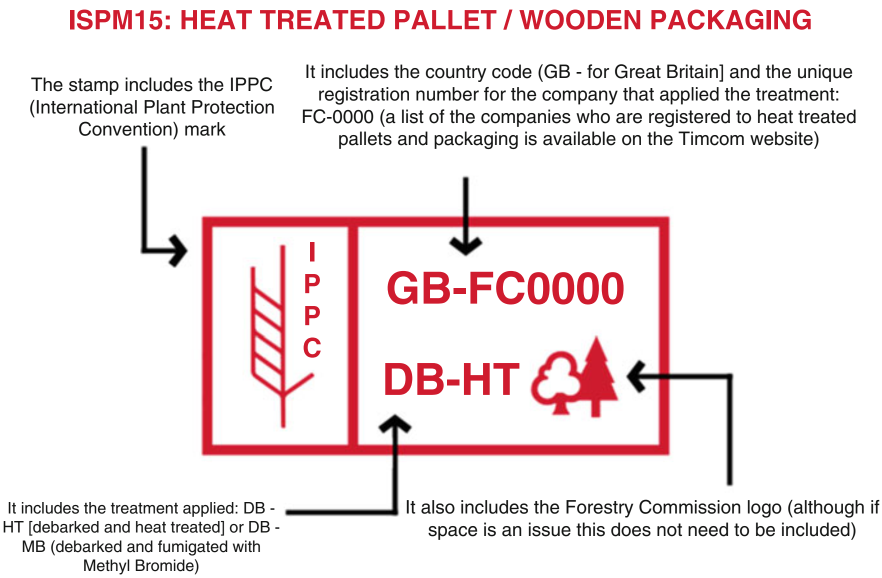

Fig. 22.18 Sample of authentic IPPC logo neatly labeled indicating the individual marks niceties

The examples below illustrate some acceptable variants of the required components of the mark that is used to certify that the WPM that bears such a mark has been subjected to an approved treatment. No variations in the symbol should be accepted. Variations in the layout of the mark should be accepted provided that they meet the requirements set out in this annex.

In order to minimize the risk of introduction or spread of pests, secure disposal methods where required should be carried out with the least possible delay.

Secure disposal of noncompliant WPM is a risk management option that may be used by the NPPO of the importing country when an emergency action is either not available or is not desirable. The methods listed below are recommended for the secure disposal of noncompliant WPM:

1. Incineration, if permitted.
2. Deep burial in sites approved by appropriate authorities (NB: the depth of burial may depend on climatic conditions and the pest intercepted, but is recommended to be at least 2 m. The material should be covered immediately after burial and should remain buried. Note, also, that deep burial is not a suitable disposal option for wood infested with termites or some root pathogens.)
3. Processing (NB: Chipping should be used only if combined with further processing in a manner approved by the NPPO of the importing country for the elimination of pests of concern, e.g., the manufacture of oriented strand board.)
4. Other methods endorsed by the NPPO as effective for the pests of concern.
5. Return to exporting country, if appropriate

22.10 Role of Customs in Release of Wooden Packaging Materials

Release/detention of consignments: A release order is issued to Customs, if a consignment on inspection is found to be free from pests. However, in case it is found infested with live pests, the same is permitted clearance only after fumigation and reinspection. The detention order is issued, if the consignment is imported in contravention of the PQ Regulations, for arranging deportation failing which the same shall be destroyed at the cost of importer under the supervision of the Plant Quarantine Officer, in presence of Customs Officers after giving due notice in advance, i.e., for perishable plant material 24–48 h and 7 days for other plant material. The Customs will ensure that plant/plant materials (primary agricultural products) are granted clearance for home consumption only after necessary permission is granted by the concerned Plant and Quarantine Officer (Anonymous, 2018b).

In terms of Plant Quarantine (Regulation of Import into India) Order, 2003, no article, packed with raw or solid WPM shall be released by the Customs unless the WPM has been appropriately treated and marked as per International Standards for Phytosanitary Measures (ISPM) No. 15 or accompanied by a phytosanitary certificate with the treatment endorsed. The proper officer of Customs shall grant release of such articles packed with untreated WPM only after ensuring that the WPM has been appropriately treated at the point of entry under the supervision of Plant Quarantine Officer. The Customs Officers are required to report the noncompliant cases to the concerned Plant Quarantine Station/authorities for necessary action (Anonymous, 2018b).

22.11 Conclusion

The impact of invasive pests on the environment and agricultural production is tremendous. With the development of agricultural technology as well as biotic and abiotic factors, the crop losses and insect-pest problems are changing continuously. The Plant Quarantine process acts as powerful weapon in eliminating or preventing the entry of invasive pests into the country. A stringent domestic quarantine can prevent the exotic pests. The impact of invasion of insect pests can be minimized with international cooperation through exchange of information on invasive pests and their natural enemies. The interdisciplinary coordinated work among researchers helps in identifying and assessing their ecological problems.

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