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# Silviculture, Growth and Yield of Sandalwood

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**Abstract**

Sandalwood (*Santalum album* L.) tree flourishes well from the sea level up to above 1800 m altitude in different types of soils and climate. Sandalwood is a valuable forest tree, however, its disappearance from the natural habitat is at an alarming rate. Attempts have been taken to cultivate the species in farmlands to increase its production. The productive establishing of Sandalwood plantations and the increase of heartwood and oil extraction from these trees is very critical. The growth of Sandalwood is better in presence of a host plant, though it can grow without a host. Tree growth is the outcome of numerous and enormously complex processes, and it could be in terms of tree height, diameter at breast height, basal area or volume. In many instances, the growth takes place in a certain pattern, and it takes a considerable period to obtain information on growth behavior and to estimate expected yield based on the growth. Yield is proportional to heartwood girth which is dependent on site quality, type of soil, etc., and essential oil's yield and quality vary depending on the area of cultivation and age of the plant. In this chapter, details of geo-climatic factors, climatic conditions, geology, topography and soil, where this tree species is habitually distributed are discussed, comprising natural regeneration, phenological details, and vegetative methods of propagation. Further, aspects of seed dormancy, seed germination, and host-sandalwood parasitism are also detailed. Silvicultural practices like inter-cultural operations and tree improvement are highlighted.

**Keywords**

Dormancy · Germination · *Santalum* · Silviculture · Heartwood · Hemi-parasite · Collar girth · DBH

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## 7.1 Introduction

Silviculture is the practice of monitoring the establishment, growth, health, and quality of land covered with trees or forest to meet diverse prerequisites and values of landholders and the public on a sustainable basis (Adams et al. 1994). Silviculture deals with the growth, health, and quality of forests so that forests could be regenerated and managed for the desirable products. It is a set of approaches that are applied for attaining a definite forest managing objectives and to accomplish the application of objectives via manipulating composition and structure of a forest. In some cases in wood production plantations, the aim of silviculture is to increase the growth and quality of prospective crop trees. The term is derived from the Latin silvi (forest) + culture (as in growing) and the silvicultural concept should express the basic principles to local foresters or managers.

Sandalwood is the aromatic heartwood of the genus, *Santalum,* and belongs to family Santalaceae, which includes 30 genera and about 400 species, and many of them are completely or partially parasitic (John 1947). The word Sandal has been derived from Chandana (Sanskrit), Chandan (Persian), Savtador (Greek), and Santal (French). There are references of Sandalwood in Indian mythology, folklore, and ancient scripts. Brandis (1903) suggested that though sandal is a root parasite, it may derive part of its nutrition from the soil as well. Barber (1905) noted that haustoria formation occurred only on the certain roots of Sandalwood and not on all of them. This plant forms a non-obligate relationship with a number of host plants (Nagaveni and Vijayalakshmi 2004). Wood is used in the treatment of major diseases like fever, piles, hemorrhagic conditions, diabetes, dropsy, mental disorders, management of poisons, and skin disorders. Sandalwood products uses are being widely reported in many literatures. Sandalwood fumigation is indicated in warding off evils and organisms, which contaminate the wounds and hasten the wound healing and keep surgical wards aseptic. There are at least three kinds of Sandalwood, namely White Sandal (*Santalum album*) also called "Sweta Chandana," Red Sandal (*Pterocarpus santalinus*), also called "Rakta Chandana" and interior Sandal, called Ku-chandana (*Adenanthera pavonina*). These plants belong to different species and families and have different properties according to their synonyms. Sandalwood is moderate sized evergreen large shrubs or small tree (*S. spicatum*) to tall tree of 12–15 ft minimum height (*S. album* in India and *S. paniculatum* in Hawaii) and the girth of 1.0–2.4 m (Sen Sarma 1982). Ecologically, Sandalwood adapts well in varied agro-climatic and soil conditions, except in waterlogged and very cold areas. It is believed that Sandalwood is an exotic in India, having been taken there from East-Indonesia by traders of the fragrant wood, and holding a pre-eminent position in the Indonesian island (Malay Archipelago), Timor (Ajaubaki, Siso, Buat, Niki –Niki, Kokoi, and Netpala districts) and to a small extent in Alor, Roti, Sumba, and Flores Islands.

Sandalwood plant is a root parasite in its early stage. It ensures its survivality when host plants are available in its surrounding root zone. It has also been found that host is no more required for its growth and development after 3–4 years (Das et al. 2018). A study was carried out by Jain et al. (1988) on the influence of soil properties and their relationship to Sandalwood's growth in three places. They observed that lime status, water holding capacity, pore space, volume expansion on wetting, exchangeable calcium and magnesium and available potash exert positive influence on the increment in girth and height of trees. Das et al. (2018) found that the higher the organic carbon and macro-nutrients (N, P and K) content of the soil, the better is the growth (both height and girth) and survival of the Sandalwood seedlings.

The silviculture of Sandalwood is very much important to understand growth behavior of the species. The present chapter describes silvicultural features, host-parasite relationship, growth and yield of Sandalwood. Information on growth pattern and expected yield could be of immense importance in selecting appropriate management practices for the desired output.

## 7.2 Distribution

Sandalwood is spread across the Hawaiian Archipelago in the North (30° N) to New Zealand in the South (40° S). Also, it is distributed through Indonesia in the West to Juan Fernandez Islands in the East. It is assumed that Sandalwood was introduced to India from the Timor, Indonesia (Shetty 1977), though some are of the opinion that it is indigenous to Peninsular India. In the Republic of India, Sandalwood is largely distributed in the Deccan Plateau and the total extent of its distribution is about 9600 km$^2$ of which 90% (8200 km$^2$) are in the southern states, mainly Karnataka and Tamil Nadu (Srinivasan et al. 1992). In Karnataka, it covered about 5245 km$^2$ which account for more than 50% area of the country. It is distributed in the southern part of the state as well as in the northern part of the state. In Tamil Nadu, it is distributed over an area of 3045 km$^2$, mainly in North Arcot (Javadis and Yelagiri Hills), Salem, Periyar, Coimbatore, and Vellore districts. The dense population exists in Chitteries, Javadis, parts of Shevaroys and Tenmalai hills. Also, Sandalwood is found to be distributed in Andhra Pradesh, Maharashtra, Madhya Pradesh, Orissa, Gujarat, Rajasthan, Uttar Pradesh, and Manipur. In Andhra Pradesh (175 km$^2$), it is mainly distributed in Chittoor, Kadapa, and Kurnool districts. In Madhya Pradesh (33 km$^2$), it is found scattered in Forest Divisions of Sehora, Sagar, and Seoni, and in Kerala (15 km$^2$) in Wynad, Marayoor, and Tenmalai. In Maharashtra (18 km$^2$), they are spread in small pockets only. In Orissa (25 km$^2$), it is found in Jeypore, Kalahandi, and Paralakhemundi Forest Division. In Uttar Pradesh, Sandalwood trees occur naturally in small patches in forests, and attempts have been made for its artificial regeneration, i.e., implanting Sandalwood seedlings or seeds after harvesting timber. Only a few thousand trees are located in Kangra valley near Jwaladevi of Himachal Pradesh. Occurrence of Sandalwood has also been reported in Manipur and Gujarat states (ICFRE 1992). The state of West Bengal is cited in the map of occurrence and distribution of *Santalum album* L. in India (Srinivasan et al. 1992). In West Bengal, Sandalwood was introduced in 1960s in the forest complexes, and now it is naturally coming up in parts of Bankura (Hirbundh) and Medinipur (Arabari) districts from the bird droppings in forest and adjoining non-forest areas.

The distribution of Sandalwood is also found outside India, mainly in Sri Lanka and South East Asia (Timor, Indonesia, Malaysia, Cambodia, Vietnam, Myanmar, Thailand, and China), the Pacific (Papua New Guinea, Fiji, New Caledonia, and Hawaii), and to some extent northwest of Western Australia (Kanunurra). This important species is categorized as "vulnerable" by International Union for Conservation of Nature and Natural Resources (IUCN), due to the over exploitation. The tree flourishes well from sea the level up to 1800 m altitude in different types of soils and climate.

## 7.3 Geology, Rocks, and Soils

Red ferruginous loam is the best suited soil for Sandalwood tree growth. The underlying rock often is metamorphic, and is predominantly gneiss and frequently found on the rocky grounds and on stony or gravelly soils (Troup 1921). Sandalwood is able of grow in varied soil types, especially sandy, clayey, lateritic, loamy, and black cotton soil avoiding waterlogged conditions. The Working Plan for the Sandalwood forests of the Khanapur, Nagargali, and Gujnal Ranges of Belagavi Division in Karnataka described laterite as the most common underlying rock in the higher hills with schist and trap rock on the northwest and an out crop of crystalline limestone on the south-west, respectively. In Malwa plateau of Gulbarga, Bidar in Karnataka and Bhir and Aurangabad in Maharashtra, the principal geological formation is Deccan Trap, consisting of basalt and dolerite capped up in places by laterite (Khan 1957). The soil in the Sandalwood tract is black cotton except in the districts of Bidar and parts of Gulbarga and Bhir, where Deccan Trap being of metamorphic origin contains ferruginous loams commonly called lateritic soils (Khan 1957). The Working Plan of Sarsi-Siddapur Sandalwood growing areas of Karnataka reported the geologic formation as archaic with characteristic features of laterisation. In Coimbatore Central Division of Tamil Nadu, Sandalwood is found in almost every type of soil. It is found in stony red soil along the higher reaches of Moyar valley, on alluvial soil along Hallurhalla, on rich loams in Hulical, Kallar, Jacanare Reserve Forest and shallow gravelly soil on the Melur and Pillurslopes (Jayaraman 1973). Also, it has been reported that Sandalwood occurs on sandy soil of Quilon in Kerala. In a study on soil properties and their relation to Sandalwood growth it was observed that lime status, water holding capacity, pore space, volume expansion on wetting, exchangeable calcium and magnesium, available potash exerts positive influence on the increment of girth and height. Sandalwood requires good drainage and does not withstand waterlogged ground. It is assumed that the heartwood with superior aroma is extracted from the tree growing in dried regions, mostly on red or stony ground. In addition, the yield of essential oil will be relatively higher than those trees grown in fertile regions (Gunther 1952).

## 7.4 Morphology and Phenology

Sandalwood is an evergreen tree, and being a complete or partial root parasite at the early age, generally grows in the dry deciduous forests of the Deccan Plateau and attains a height of 12 of 15 m and a girth of 1.0–2.4 m with slender drooping along with erect branching (Fig. 7.1a). In the early stage, it grows well under partial shade, but in middle and late stages, it cannot tolerate heavy overhead shade. Its tap root is moderately long and delicate. Lateral roots are fibrous, delicate, and distributed down the main root. Stem is initially green and tender, gradually turns brownish and hard. Bark is reddish brown or dark brown in color, smooth in young trees and becomes rough with deep vertical cracks as the tree matures. Leaves are opposite and decussate, and sometime show whorled arrangement. The shape of leaf varies and six morphological forms have been extensively recognized. They are ovate, lanceolate, elliptic, linear, big, and small (Kulkarni and Srimathi 1982). Color of

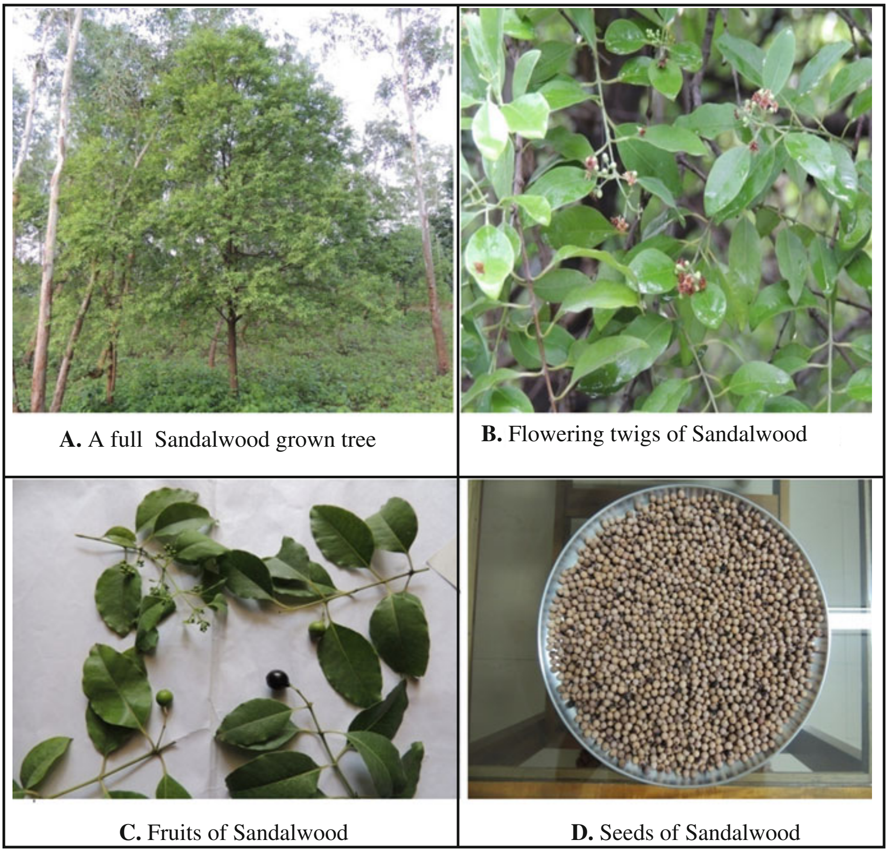


**Fig. 7.1** Sandalwood morphology (Photos by: Sudhir Chandra Das). (**a**) A full grown Sandalwood tree. (**b**) Flowering twigs of Sandalwood. (**C**) Fruits of Sandalwood. (**d**) Seeds of Sandalwood

leaves varies from greenish yellow to deep green. Leaf is dorso-ventral, palisade and spongy parenchyma is clearly distinguishable, epidermis is single-layered on both the surfaces and is covered with thick waxy cuticle. Flowers are unscented straw yellow colored at initiation but turns to deep purplish brown on maturation (Fig. 7.1b). They occur in axillary or terminal cymose panicles. The floral organs develop in acropetal succession. Flowers are tetra to pentamerous and hermaphrodite. Flowering sets in at early stage, after 4–5 years of age. Generally, tree flowers two times in 1 year, (1) between March and May; and (2) between September and November. It takes about 30–35 days from initiation of bud to the opening of flower, and the period necessary from the initial stage to ripening of fruit is about 85–95 days. After the sunrise, anthesis is observed, and continues up to midday. Pollen remains viable at room temperature up to 7 days. The stigma remains receptive for 20–48 h. It is a cross-pollinated species.

The fruit is a succulent drupe, purplish black when fully mature and single seeded (Fig. 7.1c). The shape of the fruit varies from globose, ovate to elongate. The color of the fruit changes from green to purplish black at maturity. Fresh purple colored fruits are preferably collected from the trees or those fallen on the ground. The fruits are collected during April–May and November–December. Seeds are obtained by removing the fleshy portion of the fruit (Fig. 7.1d) and are covered by testa. Seeds show polymorphic characters, varying in size and shape. The seeds of both the season are similar in quality. Seeds of all members of Santalaceae possess santalic acid which is a characteristic feature of the family. Sandalwood seeds which exhibit polymorphic form maintain its identity in respect of germination, occurrence, and other characters. Seed weight is 6000 seeds/kg. The seed viability can be maintained for longer period when stored at low temperature (5 °C) in air tight container.

## 7.5 Seeds and Seed Dormancy

The matured purplish black fruits are collected during March/April and November/December. Fruits are de-pulped by rubbing, dried in shade, treated with fungicide, and stored in air tight container. Freshly collected seeds are dormant for a period of 2 months and remain viable up to 9 months. The failure of apparently ripe seeds to germinate in a suitable environment may be due to single factor or a combination of factors. The main causes of seed dormancy are (1) impermeable seed coat, (2) mechanically resistant seed coats, (3) rudimentary embryos, (4) physiologically immature embryos, and (5) morphologically mature but physiologically dormant embryos. The dormancy in Sandalwood seeds is due to the hard (impermeable) seed coat and presence of phenolic compounds in the seed coat, which hinders germination of the seeds. Physical pretreatments of seeds by soaking in water, alternate wetting and drying, or hot and cold water treatment will not be able to break the dormancy. However, chemical pretreatments of seeds by soaking in 0.05% gibberellic acid overnight can break dormancy and sowing of treated seeds ensures uniform germination up to 60% in 60 days (Nagaveni and Srimathi 1980). It was also reported that chemical treatment of seeds in hydrogen peroxide (1%), indole acetic acid (100 ppm), hydrochloric acid (0.5%), or gibberellic acid (500 ppm) can effectively break the dormancy of seeds and enhance germination. A scarified seed with concentrated sulfuric acid also induces early germination breaking seed dormancy (Nagaveni and Srimathi 1981).

## 7.6 Seed Germination and Seedlings Raising

Germination is epigeal, radical emerging out by breaking the false seed coat after 20–30 days. The hypocotyl elongates by very pronounced arching, the loop appearing above ground while cotyledons remain underground. Germinations of seeds are very low (15–20%) when the seeds are sown in mother bed (sand beds) after hot and cold water treatment, or alternate wetting and drying due to its hard seed coat and dormancy. Sandalwood seeds have been found to germinate fast when the seed coat is completely removed or seeds are soaked in 0.05% gibberellic acid for 12–16 h (Nagaveni and Srimathi 1981). The duration of germination is much prolonged after the dormancy period in Sandalwood seeds and starts in 25–30 days and reaches hardly 60–70% in 90 days with 0.05% (500 ppm) $GA_3$ soaking (Table 7.1) for 16–24 h (Das and Tah 2013), but rate of germination is faster from 30 to 60 days and most of the germination takes place within 60 days (Fig. 7.2). Germination of seeds will continue up to 90 days but rate of germination is very slow. Gunaga et al. (2014) found that overnight soaking of seeds in $GA_3$ solution @300 ppm (68%) and 500 ppm (63%) resulted in better germination over the control (38%) and observed that germination of bird dispersed seeds achieved highest seed germination within short time as compared to de-pulped seeds. The treated seeds are sown in the sand beds (germination beds) @400–500 g/m$^2$. Traditionally the seedlings at 2–3 leaf stage are transferred to poly-bags of 500 cc capacity or hycopots of 300 cc capacities with a potting mixture of sand, soil, and farm-yard manure FYM in 2:1:1 ratio with *Cajanus cajan* or *Mimosa pudica* as a pot (primary) host. Host plants are to be pruned periodically at monthly intervals to encourage the growth of Sandalwood seedlings. The germination media in beds or in trays must be treated with fungicide (0.25% Dithane M45) periodically as prophylactic measure. The physical and genetic quality of seedlings greatly influences survival, growth,

**Table 7.1** Treatment of Sandalwood seeds with different concentration of $GA_3$

| Sample size—300 seeds/treatment | | | | |
|---|---|---|---|---|
| $GA_3$ | No. of seeds germinated 90 days after sowing | | Germination % | |
| Conc. | 16 h soaking | 24 h soaking | 16 h soaking | 24 h soaking |
| 100 ppm | 101 | 154 | 33.67 | 51.33 |
| 300 ppm | 125 | 165 | 41.67 | 55.00 |
| 500 ppm | 162 | 201 | 54.00 | 67.00 |
| 1000 ppm | 171 | 209 | 57.00 | 69.67 |
| 0.0 ppm | 25 | 30 | 8.33 | 10.00 |

Source: Das SC, Tah J (2013) Effect of GA3 on seed germination of sandal (Santalum album L.). Int J Curr Sci 8: 79–84.

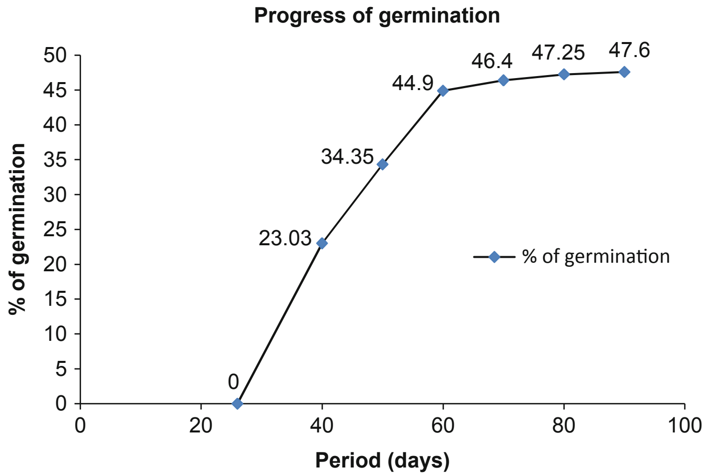


**Fig. 7.2** Progress of germination over time (Das 2014)

and productivity. "Quality of seedlings" integrates genetic, morphological, and physiological characters which ultimately determine the seedling performance. Seedlings are sensitive to both drought and sunlight but needs lateral shade. Plantable seedlings of 30–40 cm height with dark brown stem can be produced within 6–8 months.

## 7.7 Vegetative Propagation

Batabyal et al. (2014) suggested that the use of 15 cm long stem cuttings obtained from 3- to 4-year-old Sandalwood trees are better for propagation. Noteworthy to mention that treating stem cuttings with indole-3-acetic acid (IAA) (1.5 mg/L) and gibberellin ($GA_3$) (1.5 mg/L) results in an increased number of leaves per branch, though rooting frequency amongst the treatments were not reported. Moreover, increase in the number of branches per cutting was observed with the application of 1.5 mg/L indole-butyric acid (IBA) and kinetin, each. Batabyal (2015) has studied different methods of vegetative propagation. Vegetative propagation of Sandalwood is done through (1) air layering, (2) root suckers, and (3) stem cuttings. Air layering is not promising but root suckers showed greater success. In air layering, branches of 1.5–2 cm diameter are chosen during June–July, when there are frequent showers. 1 cm ring of bark is removed and the exposed branch is treated with Seradex B and covered with moss. The wound is kept moist, within 35–50 days callus formation occurs and roots emerged in 15–20% cases. When the roots develop to about 8 cm, the branchlets are separated from the tree and planted with a host in a pit or pot. For root suckers, a trench of 30 cm wide and 30 cm deep is dug around a mature Sandalwood tree at a distance of 1.5–2 m from base. The cut ends of the radiating root put forth shoots profusely in about 40 days. The shoots having roots are cut off from mother shoots at 10–15 cm distance and cuttings are treated with Indole-butyric acid (IBA) (100 ppm) and planted with host in pots. In about 3–4 months root system gets established. Cleft grafting method adopted for clonal multiplication using 12 month old root-stock gave 60% success. Winter is the best time for cleft grafting. Success rate of this technique largely depends on age of root-stock, period of grafting, diameter of scion and genotype. Vegetative propagation using root cuttings is also useful. Secondary roots of 5 cm long obtained during April and treated with Seradex and planted horizontally in nursery bed and watered regularly resulted in sprouting in 30–40 days. The cuttings with shoot and roots are transplanted to pots along with hosts. The success rate was found to be up to 60% in this method. There is no report of successful vegetative propagation through stem cuttings till date.

Tissue Culture technique is also used to multiply Sandalwood plants, but it is not popularized due to its initial stage of parasitism. Yeast extract was found to initiate and stimulate the proliferation of Sandalwood endosperm. However, for a satisfactory proliferation an auxin (2,4-D) and a cytokinin (Kinetin) in conjunction with yeast extract are required (Rangaswamy and Rao 1963). Studies in culturing of lateral buds, root tips and haustoria of Sandalwood were also carried out. Induction of embryonic proliferation in Sandalwood was studied and it was found that similarity existed in the morphogenetic potentialities of the embryo of Sandalwood and other angiospermic parasites. Somatic embryogenesis in seedling callus of Sandalwood has been observed by Bapat and Rao (1979). Lakshmi Sita et al. (1982) induced Sandalwood somatic embryogenesis from shoot callus cultures derived from 20 to 25 year old trees. Rathore et al. (2007) described micropropagation methods through axillary shoot proliferation and is having high potential for rapid and mass production of clonal planting material of Sandalwood from plus trees. Scientists conducted field trial of micropropagated plants of Sandalwood and found that the survival is 70% by the end of 6 months. Mamatha and Rathore (2014) studied the effect of sucrose, agar-agar concentration, and pH of the media on somatic embryo induction, maturation, and germination from the explants of the mature trees and found that during maturation, size of the somatic embryos increased with increase in the concentration of sucrose in the medium favoring adventitious shoot induction and embryo creaking.

## 7.8 Natural and Artificial Regeneration

In natural regeneration, germination of Sandalwood seeds is found profuse from the bird droppings in the forest floor as well as in the village yards and bunds of the agricultural fields. In Tamil Nadu bush sowing is practiced in which about five seeds are sown in a bush. Germination takes place in about a month's time. These young seedlings will be benefitting from the moisture available during the entire Northeast monsoon rains. By the time the moisture in the upper layer of soil reduces considerably during January–February, the stem of the seedlings would turn to brown from green, thus enhancing its endurance. These robust seedlings would withstand successfully the moisture stress of the first summer they encounter. It would take

5–6 years for the Sandalwood saplings to emerge strikingly 3–4 m over and above the bushes. Rai and Kulkarni (1986) have reported that dibbling of seeds in bushes and sowing of seeds on the mounds in the trench-mound method were the most commonly followed in the past, success rate was normally around 30–40%. Natural regeneration is generally good but population density is poor due to biotic and abiotic interferences. It is capable of regenerating profusely in the absence of fire and grazing. Most of the populations are devoid of large girth class mostly due to smuggling. Hanumantha et al. (2014) conducted studies pertaining to phenology and natural regeneration of Sandalwood (*Santalum album* L.) under different plantations like Bamboo, Eucalyptus, Acacia, medicinal plants garden, and natural forest where several birds are involved in dispersal of seeds and their result showed that the overall regeneration was highest in medicinal plants garden followed by natural forest and bamboo plantation.

In artificial regeneration, the following methods are commonly adopted: (1) dibbling of Sandalwood seeds in bushes, (2) sowing of seeds on mounds in trench—mound technique, (3) planting of polypot or hycopot raised seedlings. Seeds are collected either from identified seed stands or from plus trees, processed and stored in seed processing units for dibbling in forest areas or raising seedlings in nurseries. In nurseries the Sandalwood seedlings are raised in “5 × 8” polypots or 300 cc hycopots, which are maintained for 6–8 months before planting. The polypot or hycopot raised 6–8 months old seedlings in nursery is transplanted to the main field in the pits dug well in advance after getting a good rain at a spacing of 2.5 m × 2.5 m or 3 m × 3 m. Transplanting of seedlings raised in the nursery is one of the commonly used methods for raising plantations. This method is costly; however, high success rate offsets the cost factor. After pit planting, a host plant (Arhar/*Cajanus cajan*, Tulsi/*Ocimum sanctum* or Nayantara /*Catharanthus roseus*) is to be planted at the side of the Sandalwood seedlings. Four different host species, which were the best as reported by different scientists, may be selected as secondary host plants for the main field. These are *Cynodon dactylon, Albizia saman, Casuarina equisetifolia,* and *Pongamia pinnata* (Das 2014). Sandalwood plants established haustorial connections with the secondary hosts in the main field to draw nutrition. Nagaveni and Vijayalakshmi (2014) observed the symbiotic relationship of Sandalwood plants with that of Arbuscular Mycorrhizal (AM) fungi revealed that plants growing in different places showed diverse AM species association and the intensity of colonization were higher in Sandalwood roots than the host.

## 7.9 Host–Sandalwood Parasitism

Sandalwood is a hemi–root parasite, firstly reported by Scott (1871). The importance of this fact was realized, when Barber (1906) reported the details of haustorial formation, growth and development of haustoria. The formation of haustoria is more or less confined to younger roots and they arise from external layers of rootlets, unlike lateral rootlets, which are formed deep in its tissues. The establishments of connection and histological changes that take place during contact have been explained in detail by Barber (1906), Bhatnagar (1965), and others. Brandis (1903) suggested that though Sandalwood is a root parasite, it may derive part of its nutrition from the soil as well. It was also reported that Sandalwood requires a primary host at nursery stage (Annapurna et al. 2006), and secondary long term host in the field. Being a hemi-parasite, the silvicultural requirements are unique, and there is no adequate understanding of the same. Its regeneration and establishment has been problematic because of the poor understanding of host–parasite relationships. Sandal plants in agro-forestry or forestry systems may have to tolerate varying levels of competition and complementary interactions from the component crops or plants. So an understanding of the complementary and competitive influence of the host on sandal is necessary for a successful growing of Sandalwood. When host is introduced in the pots at the early phase there is possibility of competition for soil moisture and nutrient between Sandalwood and host. The plant with a haustorial adaptation on its own roots, parasitize the roots of other tree but without major harm to its hosts. This plant forms a non-obligate relationship with a number of other plants like *Pongamia pinnata* and *Casuarina equisetifolia* (Nagaveni and Vijayalakshmi 2004). Subbarao et al. (1990) worked on nodule haustoria and microbial features of *Cajanus* and *Pongamia* parasitized by Sandalwood. They concluded that the parasitic dependence of Sandalwood saplings on nodulated host plants was apparent with the steady improvement in their nitrogen content. In natural surroundings, the survivability of Sandalwood trees is exclusively reliant on other woody plant species, which serve as host in their surrounding area. However, nodulated nitrogen fixing trees are superior hosts for Sandalwood when compared to non-nodulated trees is a question, and requires more research studies to answer this question.

Sandalwood can parasitize with more than 300 host species, ranging from grasses to leguminous trees in nature. This tree species exhibits varied growth patterns with diverse host species. Lack of understanding of the host–plant relationship causes the failure of sandal seedling production. It has been reported that *Cajanus cajan* is the best host plants for Sandalwood in nursery. Four different host species, which were the best as reported by different scientists, were selected as secondary host plants for the main field. These were *Cynodon dactylon, Albizia saman, Casuarina equisetifolia, Pongamia pinnata*. It depends on its host for phosphorus (P), potassium (K), and magnesium (Mg). Sekar et al. (2000) opined that combined application of *Azospirillum*, Phosphobacteria, and Vesicular Arbuscular Mycorrhizal (VAM) fungi provide better growth in Sandalwood by improving the nutrient uptake under nursery condition. Hayman (1986) highlighted that VAM fungi augment plant mineral nutrition, particularly phosphorus. In addition to their impact on plant nutrition, their communication with plant pathogens, such as bacteria, fungi, and nematodes might reduce the disease severity. Nagaveni and Vijayalakshmi (2007) studied on resistance of Sandalwood to determine the bio-protective effect of arbuscular mycorrhizal fungi in Sandalwood plant infected with wilt causing pathogen *Fusarium oxysporum.* They also studied the differential response in the haustorial formation as growth of Sandalwood plant (*Santalum album*) in respect to different host. Rocha et al. (2014) conducted anatomical studies of haustoria with host *Casuarina* reveals that vascular connections between the host and the Sandalwood tree became so close that the host and the parasitic route became almost a single physiological unit catering to the nutritional requirement of Sandalwood tree. Their study with $^{32}P$ radio tracer technique suggested that the host plants need not be present in the same pit of Sandalwood tree as it can extend its root to distance of 1.5–3 m to form haustoria on neighboring plants.

## 7.10 Inter-Cultural and Tending Operations

Subsidiary silvicultural operations are very important for the proper growth and development of a plant, and the host plants are to be pruned periodically when they overgrow Sandalwood saplings. All Sandalwood trees are to be pruned once in 4 years. Shrubs and plants useful as hosts are retained and other unwanted plants like Lantana should be removed to provide more space for development of Sandalwood trees. Fencing may be erected to protect young regenerating plants against grazing. Full overhead light should be allowed by judicious lopping of overtopping branches of surrounding trees. Thinning may be carried out as and when required to give Sandalwood trees a space of 5–6 m depending on the size of the trees retained. Only best and healthy Sandalwood trees should be retained in thinning for the final harvest and tending is better done from June to November.

## 7.11 Tree Improvement

Tree improvement in Sandalwood was initiated in 1978 with an aim of establishing trees that can produce well-developed thick heartwood and essential oil in a short period of time. Studies so far done are mainly focused on (1) genetics and genetic improvement, (2) variation and conservation of genetic resources, (3) production of improved planting stock, and (4) breeding for resistance to spike disease. Genetics and genetic improvement studies showed that the number of chromosomes in Sandalwood root tip is $2n = 20$. Nevertheless, 40 chromosomes could be observed in the haustorium part cells. Two to five-fold rise in the chromosomes size was also detected, and was accredited to endopolyploidy (Srimathi and Sreenivasaya 1962). The variation in the magnitude of standard error from tree to tree suggests that they are governed by genetic factors. For delimiting different types of Sandalwood it was suggested that results of biometric analysis could be helpful. Variations in leaves, flowering behavior, germination, and 3-phenotypes have also been reported. For genetic conservation, in situ conservation has been undertaken at Janiguda in Orissa and Thindlu in Karnataka. For ex situ three clonal banks at Gottipura, Bangalore Division (Karnataka), Karvetinagar, Chittoor Division (Andhra Pradesh), and Kurumbapatti, Salem Division (Tamil Nadu) with 50, 10, and 31 plus trees and one germplasm bank at Gottipura have been established. A clonal bank over 1 ha was established in Gottipura, Hoskote, Bangalore. The clonal bank consisted of rametes collected from 60 plus trees identified in Karnataka, Tamil Nadu Kerala, and

Andhra Pradesh. For production of improved planting stock (a) selection of plus trees, (b) identification of seed stands, (c) establishment of clonal seed orchards, (d) progeny trials, and (e) tissue culture were carried out. As a continued effort, four seed stands have been identified at Achalpatty (Kerala), Chitteri (Tamil Nadu), Rayalpad (Karnataka), and Juniguda (Orissa). Clonal seed orchards have also been established at Nallal (Karnataka) and Tirupati (Andhra Pradesh) for raising quality plantations and obtaining maximum genetic gain.

The common breeding system of *Santalum* species could be designated as facultatively allogamous (incompletely outbreeding) with dissimilarity amongst individuals and families at the level of self-incompatibility (Ma et al. 2006; Tamla et al. 2011) and with inability for parthenocarpy or apomixis (Ma et al. 2006; Tamla et al. 2011). The favored outcrossing nature of the breeding system, and the capability for self-fertilization is beneficial. Across all *Santalum* species investigated, only low proportions of controlled cross-pollinated flowers productively developed into mature seeds. The proportions ranged differently, i.e., 7.5% in *S. lanceolatum* (Tamla et al. 2011), 1.3% in *S. spicatum* (Rugkhla et al. 1997) and between 9.4 and 14% in *S. album* (Rugkhla et al. 1997; Ma et al. 2006).

Breeding for resistance to spike disease is one of the several control measures suggested. It has been reported that there is no natural resistance to spike disease, it is possible to obtain some resistant strains by selection and screening. The apparent resistance is likely to be due to absence of adequate spike inoculums and other climatic factors. In another tree improvement program, Shankaranarayana et al. (1997) had shown a highly significant and positive correlation between optical density (O.D) and oil content ($r = 0.929$) and concluded that this method should be useful in rapid screening of Sandalwood plants for their oil content and in selection of plus trees among different provenances. In order to increase essential oil content and monetary profits from Sandalwood, Zhang et al. (2010) induced polyploidy in this tree species. Polyploidy is one of the largely applied methods for plant breeding. Polyploid plants usually have bigger cells, and plants are frequently superior with thick shoots, bigger leaves, fruits, and higher nutritional contents, etc. The karyo-morphological features of Sandalwood were reported by Zhang et al. (2010). According to them, a simple chromocenter type was noticed in the interphase nucleus, while chromosomes in the prophase were of the interstitial type. The meristematic cells in few *Santalum* species shoot-tips were found to be mixoploid, i.e., 2n = 2x = 20 and 2n = 4x = 40. Two dissimilar karyotypes were noticed, i.e., one diploid (2n = 2x = 20) and one tetraploid (2n = 4x = 40); their karyotypic formulae were 2n = 20 = 18 m + 2sm and 2n = 40 = 32 m (2SAT) + 8sm, respectively. The chromosomes of both karyotypes presented the occurrence of centromeres mostly in a median position, and a few sub-median centromeres, of 2B type, of a primitive and symmetrical nature.

## 7.12 Conservation of Sandalwood

In India, eight Sandalwood growing areas have been recognized as prospective sources of Sandalwood on the basis of population density, phenotypic characteristics, latitude, longitude, and eco-climate. The provenances vary in climate and edaphic preference since they are located in different localities of South and Central India. The extraction and disposal of Sandalwood came under the Forest Department in 1864 in Mysore state. In Karnataka (formerly Mysore) the forest working plan for Sandalwood extraction were prepared for Hunsur Taluk in 1910, Heggadadevanakote in 1920, and Narasimharajapura in 1926. Ecologically Sandalwood has adapted various agro-climatic and soil conditions for in situ regeneration with an exception of waterlogged areas and very cold places. It is clear that distribution and abundance of Sandalwood is mostly confined to Deccan Plateau. The demand for Sandalwood and oil is increasing day by day and the gap between demand and supply are widening. Difficulty in the seed germination due to dormancy coupled with the hemi-parasitic nature of Sandalwood plants creates serious problems in their artificial regenerations. Illegal felling of Sandalwood trees for smuggling also poses other threats to its survival. Protection and management of forests are the primary responsibility of State Forest Department and they are performing that by integrating modern technology including wireless network, remote sensing, geographical information system, information technology, and global positioning system and better mobility of the field staff by providing vehicles for patrolling and constructing check posts but people's awareness is a major factor which is needed very much for the conservation of Sandalwood plantations. So people's awareness is very much needed to protect our shrinking wealth of Sandalwood (which is so difficult to regenerate). Now-a-days local communities are encouraged and involved in conservation, protection, and management of forests through joint forest management committees (JFMCs) or village level committees.

## 7.13 Growth and Yield of Sandalwood

There are many internal and external factors which influence growth of any biological system. Tree growth can be analyzed by dividing the process into two components, positive and negative. Biotic potential, photosynthetic activity, soil nutrients, etc. contribute to the positive component while limited resources, harsh environmental conditions, aging, etc. contribute to negative component of growth. In order to study growth pattern and habits, one has to collect data regularly on increase in height and girth with respect to time. Trees are perennials and continue to grow in height and girth to a considerable extent, given the favorable conditions. In many instances, growth takes place in a certain pattern and it takes considerable period to obtain information on growth behavior and to estimate expected yield based on the growth. Tree growth could be in terms of tree height, diameter at breast height (DBH), basal area or volume. Information on growth pattern and expected yield at the early stage of plantation could be of immense importance in selecting appropriate management practices for the desired output.

Sandalwood is considered as a slow growing tree under forest conditions. Kushalappa (1995) reported that Sandalwood responses well to lime application. Application of bio-fertilizers to trees will greatly improve Sandalwood growth (Harley and Smith 1983). Rajagopal Shetty (1977) reported that growth rate of Sandalwood in Javadis is 1 cm girth at breast height per annum (0.33 cm DBH). Similar growth behavior had also been reported by Ranganathan and Wilson (1934). More or less the same growth rate was observed on the trees in plantations also (Srimathi and Kulkarni 1983). The mean annual diameter increment in trees each from Andhra Pradesh (Horsleykonda, Chittoor district) and Tamil Nadu (Sanamavu R. F., Salem North) was found to be around 0.287 and 0.195 cm, respectively (Sarma and Rai 1986). Venkatesan (1980) has reported that though earlier studies had indicated a growth rate of 1.23 cm girth per year, it could vary from 1 to 5 cm per year. The relationship between DBH (X) and yield of scented heartwood (Y) per tree in different DBH classes of sandal at Belgaum-Karnataka is expressed in the form of a power curve, $Y = 0.001476X\ (X^{3.3564})$ (Rai and Sarma 1986). Karnataka Forest Department also computed expected weight of actual Sandalwood (Heartwood) at various girths of sandal trees. Studies indicate that a healthy Sandalwood tree growing under ideal conditions show an increment of 1.0 kg per year with a girth of 1.5 cm (Rai 1990). Growth reported by Lahiri (2010) from Ballavpur in Mohammad Bazar Range of Birbhum Forest Division that Sandalwood trees attained 60 cm bhg (over bark) in 21 years and height is 7.0 m. and heartwood girth at breast height is 26 cm. Somashekar et al. (2014) studied the field performance of tissue culture raised Sandalwood plants as Agro-forestry models and found that tissue culture through axillary proliferation and somatic embryogenesis offers highest clonal propagation efficiency. It was also observed that from 1st to 4th year the plants are growing vigorously attaining height 5.5 m and collar girth 34 cm at the end of 4th year. Nagaveni and Vijayalakshmi (2002) opined that microbial inoculation to the seedlings of *Eucalyptus camaldulensis, Wrightia tinctoria,* and *Bombax ceiba* improved the growth and biomass under nursery conditions which may further result in better performance of seedlings in field planting.

## 7.14 Growth Study

The growth of sandal trees was influenced by the presence of host plant to a great extent both in nursery and in main field. Field experiments were conducted at Bagaldhara and Rangamati of Hirbandh Block under Bankura (South) Forest Division (Das 2014). In his study, the sandalwood seedlings were planted in the field along with host plant both singly as well as in combination. Some seedlings were planted without host in the month of July 2011. Soil work was done periodically and inter-culture operations were done 3 times after planting at 3 weeks interval. Manure (cowdung/vermicompost) @ 500 g/pit was applied at the time of pit filling. Fertilizer (NPK—10:26:26) was applied twice @ 40 g/plant at 3 weeks interval after planting.

**Table 7.2** Growth of Sandalwood seedlings with and without host plants at Bagaldhara and Rangamati 2011 plantation

| Type of host | Growth in 1st year (Bagaldhara) | | | Growth in 1st year (Rangamati) | | |
|---|---|---|---|---|---|---|
| | Av. height (Cm) | Av. girth (Cm) | Survival % | Av. height (Cm) | Av. girth (Cm) | Survival % |
| $T_3$:Arhar + Tulsi | 110.58 | 4.51 | 82% | 60.50 | 2.31 | 76% |
| $T_1$:Arhar (*Cajanus cajan*) | 99.32 | 4.45 | 80% | 61.57 | 2.78 | 74% |
| $T_5$:Arhar +Akand | 84.23 | 3.78 | 72% | x | x | x |
| $T_9$:Tulsi + Nayantara | x | x | x | 51.85 | 2.07 | 68% |
| $T_2$:Tulsi (*Ocimum sanctum*) | 85.58 | 3.75 | 70% | 59.22 | 2.28 | 66% |
| $T_8$:Nayantara (*Catharanthus* sp.) | x | x | x | 51.00 | 1.75 | 50% |
| $T_4$:Akand (*Calotropis* sp.) | 63.67 | 2.42 | 40% | x | x | x |
| $T_0$:Without host | 48.28 | 1.71 | 34% | 35.75 | 1.15 | 30% |
| Type of host | Growth in 3rd year (Bagaldhara) | | | Growth in 3rd year (Rangamati) | | |
| | Av. height (cm) | Av. girth (cm) | Survival % | Av. height (cm) | Av. girth (cm) | Survival % |
| $T_3$:Arhar + Tulsi | 325.10 | 16.42 | 76% | 158.0 | 9.10 | 70% |
| $T_1$:Arhar (*Cajanus cajan*) | 300.25 | 15.23 | 74% | 155.0 | 8.73 | 68% |
| $T_5$:Arhar + Akand | 258.57 | 12.71 | 68% | x | x | x |
| $T_9$:Tulsi + Nayantara | x | X | x | 106.87 | 6.50 | 64% |
| $T_2$:Tulsi (*Ocimum sanctum*) | 289.67 | 13.50 | 66% | 123.8 | 7.08 | 62% |
| $T_8$:Nayantara (*Catharanthus* sp.) | x | X | x | 97.50 | 5.33 | 40% |
| $T_4$:Akand (*Calotropis* sp.) | 223.30 | 9.60 | 32% | x | x | x |
| $T_0$:Without host | 131.20 | 6.60 | 20% | 70.12 | 3.50 | 20% |

Source: Das and Tah (2016).

Plant height, collar girth, and survival percentage were measured after 12 months, 24 months, and 36 months of planting. The following Table 7.2 shows that growth (viz. plant height and basal girth) of Sandalwood saplings are better with Arhar + Tulsi combination of hosts followed by Arhar (*Cajanus cajan*) as single host followed by Arhar + Akand combination of hosts followed by Tulsi (*Ocimum sanctum*) as single host followed by Tulsi + Nayantara combination of host followed by Nayantara (*Catharanthus roseus*) and Akand (*Calotropis procera*) as single host both in 1st year, 2nd year, and 3rd year at Bagaldhara. The survival percentage also follows the same trend. The survival percentage varies from 70 to 82% in 1st year and 66 to 76% in 2nd year and 3rd year depending on the type of host at Bagaldhara whereas the survival percentage varies from 66 to 76% in 1st year and 62 to 70% in

2nd year and 3rd year depending on the type of host at Rangamati. The Sandalwood seedlings, which were planted without host, have survived 34% in 1st year and 20% in 2nd year and 3rd year at Bagaldhara whereas it has survival 30% in 1st year and 20% in 2nd year and 3rd year at Rangamati (Table 7.2).

The average height in 1st year at Bagaldhara is 110.58 cm, 99.32 cm, 85.58 cm, 84.23 cm, 63.67 cm with Arhar+Tulsi, Arhar, Tulsi, Arhar+Akand and Akand (*Calotropis procera*) host, respectively, whereas without host species, the average height is recorded as 48.28 cm. In 2nd year, it is recoded as 213.33 cm, 196.83 cm, 158.33 cm, 148.57 cm, 124.17 cm with above hosts, respectively, and 95.32 cm without host. In 3rd year, the corresponding heights are 325.1 cm, 300.25 cm, 289.67 cm, 258.57 cm, and 223.3 cm with above hosts, respectively, and 131.2 cm without host. The average basal girth at Bagaldhara also various from 2.42 to 4.51 cm with hosts and 1.71 cm without host in 1st year, 4.31 to 8.08 cm with hosts and 3.21 cm without host in 2nd year, 9.6 to 16.42 cm with hosts and 6.6 cm without host in 3rd year.

Table 7.2 also shows that growth of sandal saplings (viz. plant height and basal girth) at Rangamati are better with Arhar as single host followed by Arhar + Tulsi combined host, followed by Tulsi as single host followed by Tulsi + Nayantara combined host followed by Nayantara (*Catharanthus roseus*) as single host both in 1st year, 2nd year, and 3rd year. The survival % also follows the same trend. The survival percentage varies from 50 to 76% in 1st year and 40 to 70% in 2nd and 3rd year depending on the type of host. The sandal saplings, which were planted without host, have survived 30% in 1st year and 20% in 2nd and 3rd year, respectively. The average height at Rangamati varies from 51.0 to 61.57 cm with hosts and 35.75 cm without host in 1st year, 70.33 to 109.33 cm with hosts and 42.5 cm without host in 2nd year, 97.5 to 158.0 cm with host and 70.12 cm without host in 3rd year. The average basal girth also varies from 1.75 to 2.78 cm with hosts and 1.15 cm without host in 1st year, 2.67 to 4.33 cm with hosts and 2.0 cm without host in 2nd year, 5.33 to 9.10 cm with hosts and 3.5 cm without host in 3rd year.

The growth of Sandalwood saplings are better (almost double) in Bagaldhara than in Rangamati because the soil of Bagaldhara is loose and contains more of mica but the soil of Rangamati is slightly rocky, compact and full of laterite. Akand (*Calotropis procera*) and Nayantara (*Catharanthus roseus*) seem to be poor host as survival percentage is 40% and 50%, respectively, though combination of host of Arhar + Akand (76%, 70%, and 70% in 1st year, 2nd year, and 3rd year, respectively) and Tulsi + Nayantara (68%, 64%, and 64% in 1st year, 2nd year, and 3rd year, respectively) performed better (Das 2014).

It has been observed that Tulsi (*Ocimum sanctum*) combined with Arhar (*Cajanus cajan*) gave the best performance as host plants in all the locations for the growth and development of the Sandalwood plants. In some cases, Nayantara (*Catharanthus roseus*) gave the significant result for the growth and development of the sandal plants, though it has also been proved that Sandalwood plants can survive without any host plant association. This might be the effect of soil environment which will be explored in near future. However, it is clear that there is a certain edaphic factor for the growth and development of Sandalwood plant.

**Table 7.3** Average Plant height and girth of Sandalwood trees at different age

| S. no. | Age (year) | Plant height (m) | Girth of the plant (cm) | Remarks |
|---|---|---|---|---|
| 1 | 1st | 0.45 | 0.4 | Basal girth |
| 2 | 2nd | 0.93 | 1 | Basal girth |
| 3 | 3rd | 1.35 | 3.2 | Basal girth |
| 4 | 4th | 1.75 | 5 | Basal girth |
| 5 | 5th | 2.2 | 6 | B.H.G. |
| 6 | 6th | 2.8 | 8 | B.H.G. |
| 7 | 7th | 3.4 | 11.5 | B.H.G. |
| 8 | 8th | 3.85 | 15.2 | B.H.G. |
| 9 | 9th | 4 | 20.5 | B.H.G. |
| 10 | 10th | 4.6 | 24.4 | B.H.G. |
| 11 | 13th | 5 | 32 | B.H.G. |
| 12 | 15th | 6.2 | 40.3 | B.H.G. |
| 13 | 20th | 7.5 | 53 | Av. b.h.g of 21 trees |
| 14 | 25th | 8.8 | 64.5 | Av. b.h.g of 10 trees |
| 15 | 30th | 9.7 | 72 | Av. b.h.g of 8 trees |
| 16 | 35th | 10.2 | 83 | Av. b.h.g of 10 trees |

Das (2013)

The survival percentage of Sandalwood did not decline in 4th year and were growing well even after the removal of host plants after 3rd year of planting. It proves that sandal needs the support of host plants for its better growth and establishment in the initial stage due to its parasitic nature. In another field investigation in different forest gardens of the Bankura (South) Division, a lot of Sandalwood population in different age have been observed and enumerated for height and girth of the plants (Das 2013). Those observations were taken into consideration for highlighting the magnitude towards edaphic factors of this region especially for the growth and development on the yield of Sandalwood. All these observations have been exhibited in the following tabular form (Table 7.3).

The study shows that at Hirbundh nursery of Khatra Range under Bankura (South) Forest Division, Sandal trees attain a height of 2.2 m, 4.6 m, 6.2 m, 7.5 m, 8.8 m, 9.7 m, and 10.2 m and a girth of 6.0 cm, 24.4 cm, 40.3 cm, 53.0 cm, 64.5 cm, 72.0 cm, and 83.0 cm in 5th, 10th, 15th, 20th, 25th, 30th' and 35th year of age, respectively. Age—height and age—girth curves were drawn and shown in Figs. 7.3 and 7.4, respectively (Das 2014). The sigmoid curves reflect the growth of Sandalwood trees with age.

### 7.14.1 Factors Affecting Growth

The following factors generally have important effects on growth in most plantations.

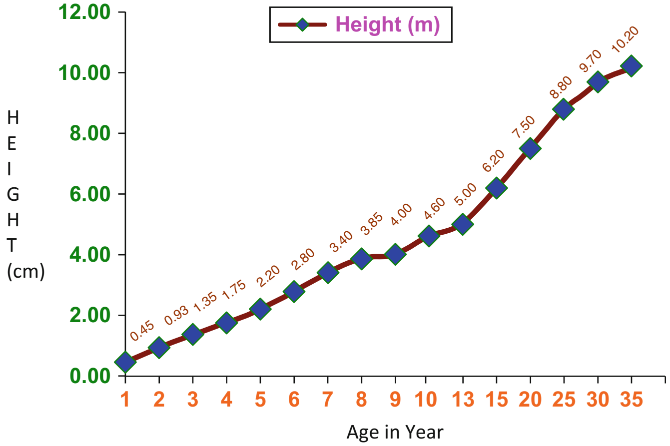


**Fig. 7.3** Age—height curve (Das 2014)

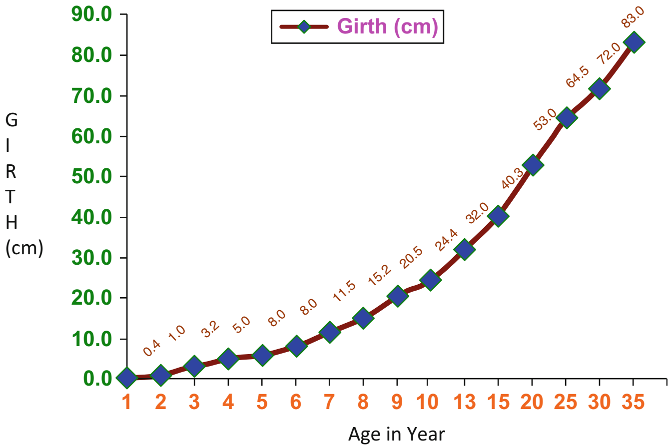


**Fig. 7.4** Age—girth curve (Das 2014)

- Site condition and soil,
- Climatic condition,
- Initial specing and treatment,
- Silvicultural operations,
- Artificial thinning and pruning,
- Internal condition (genetic and physiological).

### 7.14.2 Influence of Soil on Growth and Heartwood Formation

Red ferruginous loam is the most common soil on which Sandalwood trees occur, the underlying rock is often metamorphic and is chiefly gneiss. Sandalwood requires good drainage and does not withstand waterlogged ground. Best growth of tree is on rich fairly moist soil such as garden loam and well drained deep alluvium on river banks (Troup 1921). In a study carried out by Jain et al.(1988) on soil properties and their relationship to the growth of Sandalwood in three locations, it was observed that lime status, water holding capacity, pore space, volume expansion on wetting, exchangeable calcium and magnesium and available potash, exerts positive influence on the increment in girth and height.

Heartwood in Sandalwood is the economically important product, and is the source of oil. It is believed that the heartwood with premium scent can be obtained from the trees, growing in dry regions, especially on red or stony grounds (Gunther 1952) and quantity of oil will be comparatively higher when compared to those grown in the fertile territories (Bhatnager 1965). The growth of Sandalwood seedlings is better in porous and well drained soils which help the seedlings for better root respiration and root-shoot growth in comparison to the soils which is hard specially when dry, slightly rocky, compact, and full of laterites (Das et al. 2018). Their experiment also proved that the availability of organic compound in the soil was responsible for stimulating the Sandalwood plant's growth and development. It is also reflected that higher the total nitrogen (N) and available nitrogen (N) content, better is the growth both height and girth (Das et al. 2018).

## 7.15 Yield of Sandalwood and Revenue

### 7.15.1 Heartwood Formation

Heartwood formation starts from 10 to 12 years of age and is rapid up to 20 years and reached its peak when the trees are 30 years and above (Kumaravelu et al. 2007). The yield of heartwood varies from locality to locality and with the age of the tree. In India, trees of 100 cm girth have been reported to yield between 85 kg and 240 kg of heartwood according to the locality from which they come (FAO 1995). Cameron (1894) reported that the tree attains commercial maturity at 27–30 years and at this period the heartwood is well developed at a depth of 5 cm below the surface. Ranganathan and Wilson (1934) observed that trees obtained from edges of plantation or open fields harvest more heartwood compared to those of proportional size obtained from the neighboring forests. Rama Rao (1911) from his investigations inferred that hosts influence heartwood formation also, in addition to growth and development. Srimathi and Kulkarni (1980) were of the view that heartwood formation is dependent on genetic factors of the individual tree and the phenotypic factors play only a secondary role.

Heartwood/sapwood ratio in sandal trees in different sandal tracts of Tamil Nadu was studied by Nayar (1984). He found that in the higher elevations of

**Table 7.4** D.B.H and volume of wood, heartwood diameter, and volume of Sandalwood

| S. No. | Diameter at breast height (cm) | Volume of 1 m log ($m^3$) (i) | Diameter of heartwood at breast height (cm) | Volume of heartwood of 1 m log ($m^3$) (ii) | Volume of sapwood (i – ii) |
|---|---|---|---|---|---|
| 1 | 16 | 0.0201 | 10 cm | 0.0078 | 0.0123 |
| 2 | 14 | 0.0154 | 8 cm | 0.0050 | 0.0104 |
| 3 | 10 | 0.0078 | 5 cm | 0.0020 | 0.0058 |
| 4 | 12 | 0.0113 | 8 cm | 0.0050 | 0.0063 |
| Total | | 0.0546 | | 0.0198 | 0.0348 |

Source: Das (2013).

**Table 7.5** Total and average volume of stem timber, small timber, volume and weight of Sandalwood trees

| No. of sandalwood trees felled = 51 no. | |
|---|---|
| Total volume of stem timber = 7.2584 $m^3$ | Average volume of stem timber/tree =0.1423$m^3$...(i) |
| Total volume of small timber = 2.7416 $m^3$ | Average volume of small timber/tree =0.0537$m^3$...(ii) |
| Total weight of stem timber = 8845 kg | Average weight of stem timber/tree =173.43 kg... (iii) |
| Total weight of small timber = 2095 kg | Average weight of small timber/tree =41.08 kg.... (iv) |
| Weight of stem timber/$m^3$ = 1218 kg. | Average weight of timber/tree =214.51 kg.... (iii + iv) |
| Weight of small timber/$m^3$ = 764 kg | Average volume of timber/tree =0.196 $m^3$..... (i + ii) |

Source: Das (2014).

Mettupalayam Range where soils are fairly rich and trees are of good proportion, the heartwood formation is relatively poor. In Coimbatore where xerophytic conditions prevail even in the trees of smaller girth class (10–18 cm), the heartwood formation was good. But in Forest college campus, where the soil is shallow and has pebbles and boulders, the sandal trees of even 30–45 cm girth had little or no heartwood (Nayar 1984).

In convention, the yield of timber is expressed by means of volume of wood. The volume of 1 m log ($m^3$), diameter of stem at breast height, and the diameter of heartwood at breast height denote the volume of heartwood and sapwood in this case. A brief tabulated form is given below (Table 7.4).

From the above table, it was calculated that the ratio of Sapwood: Heartwood = 1.75:1 and Total Wood: Heartwood = 2.75:1.

A small observation of 51 Sandalwood trees when felled, crosscut, and converted into stem timber, small timber and their weights were noted and presented in Table 7.5.

### 7.15.2 Girth Vs. Yield

Tree girth of Sandalwood is directly proportional to yield of heartwood. Venkatesan (1980) reported that probable average heartwood yield that can be expected under Tamil Nadu Forest conditions and suggested that each tree can yield at least 1 kg of heartwood per year after 20 years. His estimation of heartwood with girth is presented below.

The Sandalwood trees attained a height of 12–15 m and a girth of 1–2.4 m in dry deciduous forest of Deccan Plateau (Singh and Shankar 2007). Growth of Sandalwood tree was reported by Lahiri (2010) from Mahammad Bazar Range of Birbhum Forest Division that Sandalwood trees attained 60 cm B.H.G (over bark) in 21 years and the height revealed 7.0 m and heartwood girth revealed 26 cm. Heartwood formation was rapid in 20 years and reached its peak when the trees were above 30 years (Kumaravelu et al. 2007). The yield of heartwood varies from locality to locality and with the age of the tree. In India, trees of 100 cm girth have been reported to yield between 85 and 240 kg of heartwood according to the area from which they come (FAO 1995).

### 7.15.3 Revenue to Exchequer

The above Sandalwoods are sold in open auction in 2009 and in tender in 2010. Price of Sandalwood stem timber (including sapwood) in 2009 and 2010 was Rs. 750–950 per kg and Rs. 900–1400 per kg, respectively, depending on the quality (average price = Rs. 982/kg.) and price of small timber varies from Rs. 450 to 650/kg. (Average price = Rs.485/kg). So average price per tree is coming Rs. 1,90,000.00 and revenue earned from the sale of the above Sandalwoods is Rs. 97,00,000.00 (Das 2013).

### 7.15.4 Rotation Age

Under natural conditions, Sandalwood tree at 27–30 years would yield 25–30 kg of heartwood. But, under managed plantation conditions, rotation period of Sandalwood is considered as 15 years because with scientific approach like initial watering at seedling stage, periodical pruning, and fertilizer application, Sandalwood trees easily yield at least 15 kg of heartwood at the age of 15 years with the diameter at breast height (dbh) of approx. 15 cms (Mishra et al. 2018). According to recent studies, heartwood initiates at the age of 6–8 years and sizable heartwood is formed at 15 years which is worth harvesting. As per Viswanath et al. (2014), comparison of overall financial indicators at 15 and 20 years proved that a rotation period of 15 years is more economically viable than 20 years for all the Sandalwood cultivation models under study.

## 7.16 Production of Sandalwood in India

In its natural zone of occurrence in southern states and other states large tracts of plantations have been raised. The price trend in the international market has increased drastically. In 1999 the rate of Sandalwood (heartwood) in International market was Rs. 650.00/kg, whereas this rate has gone up to Rs. 3700/kg in 2007 and Rs. 4100/kg in 2010–11 and Rs. 9000/kg in 2019–2020. The average sale value for the wild Indian Sandalwood's heartwood increased from US$ 9400 per tonne in 1990 (Rai 1990) to around US$ 150,000 per tonne in July 2014 (on small volumes based on an auction held in Tamil Nadu, India), indicating a momentous yearly compounded growth rate (TFS 2015b). It is projected that the world demand for Sandalwood is about 5000 to 6000 tonnes per year, and for its oil, it is about 100 to 120 tonnes per year (Gairola et al. 2007). The country's production during 1930s through 1950s was around 4000 tonnes of heartwood per year which has now decreased to a meager 500 tonnes of heartwood per year. Karnataka and Tamil Nadu together accounting for nearly 90% of total Sandalwood production in India while Andhra Pradesh, Kerala, Orissa, Madhya Pradesh, and Maharashtra contribute the rest. All India Sandalwood production figures show substantial decline over the years. Mortality due to spike disease and other factors, extensive smuggling from restricted zone to free zone, dwindling forest cover and existence of non-uniform legislative provisions on movement of Sandalwood from one state to another, are some of the causes for decline in the production of Sandalwood. As a result the present production of sandalwood is very low.

Annual production of Sandalwood in Karnataka from 1958–1959 to 2010–2011 and the annual production of Sandalwood in Tamil Nadu from 1980–1981 to 2011–2012 was given by Kumar et al. (2012) along with its sky rocketed price for the same period.

According to unofficial reports, compared to 89 tonnes of smuggled Sandalwood in 1982–1983 in Karnataka, the seizure during 1987–1988 increased to 370 tonnes. The stock of wood in depots which was 100 tonnes in 1984–1985 has risen to 213 tonnes in 1988–1989. The fact is that extraction of trees is not taking place in an organized or prescribed manner. The production of Sandalwood has come down to 450–900 tonnes/year from 1990–1991 to 2010–2011. It was only 300 tonnes in 2011. The shortage is so severe that there was no auction of Sandalwood in Karnataka in the past 2 years. There is some recognition of this at the Government level. State-owned Karnataka Soaps and Detergents Ltd., maker of Mysore Sandal Soap, has launched a Grow More Sandalwood campaign that involves the company entering into agreements with farmers to increase Sandalwood cultivation.

The age of sandalwood tree and color of heartwood influences the content and quality of sandalwood oil. Heartwood from young trees (around 10 years of age, height $<10$ m, girth $<0.5$ m, heartwood diameter 0.5–2 cm) contains 0.2–2% oil and that from the mature trees (30–50 years of age, height 20 m, girth 1 m, heartwood diameter 10–20 cm) contains 2.8–5.6% oil (Zhang et al. 2012). Further, sandalwood oil from young trees contains 85% of santalol and level of santalones is higher compared to oil from mature trees (ICFRE 1992). Sandalwood oil content markedly decreases along the length of the tree (from root to tip) and across the diameter of heartwood (from core to periphery) in various proportions. In general, it has been reported that nearly 45% reduction in oil content from root to tip, and approximately 20% reduction from core to periphery is observed (Shankaranarayana and Parthasarathi 1987). The root contains 3.5–6.3%, stem 3–5%, and branches 1–3% oil. The quantity of oil within the heartwood of a matured Sandalwood tree varies amongst trees, ranging between 0.5 and 5% in *S. album* (Veerendra and Padmanabha 1996), 0.05–8% in *S. austrocaledonicum* (Page et al. 2010), and 0.1–8.2% in *S. lanceolatum* (Page et al. 2007). The price of Sandalwood oil in 1975–1976 was Rs. 899.25/kg whereas in 2005–2006 it has gone up to Rs. 15,992.99/kg. Current rate of Sandalwood oil is Rs. 70,000 to 1,00,000 per kg. As per the Tropical Forestry Services, heartwood is used for extracting essential oil via hydro-distillation. The price for Sandalwood oil was about US$ 5000 per kg in the global market, which further raised to US$ 8000 per kg in 2014–2015 (TFS 2015a). The cost of Indian Sandalwood is ten times higher than that of Australian Sandalwood. The heartwood of Indian Sandalwood produces higher oil, constituting increased levels of α- and β-santalols, the important aromatic compounds of Sandalwood oil compared to any other Sandalwood species (Baldovini et al. 2011; TFS 2015a).

## 7.17 Conclusions and Future Direction

The growth of sandalwood plant without host was observed in some cases the experiment conducted by Das in 2014. In parallel, it was also observed that in some cases, sapling mortality was noticed without host plant. The reason behind this might be the soil environmental factors. From the soil analyses report, it was remarkable that the differences of macro- and micro- soil nutrients were distinctly exhibited. Those organic compounds were responsible for stimulating the sandalwood plant growth and development (Das et al. 2018). Probably fungal and bacterial colony grow in organic matter for their life cycle in each soil environment, though it is a varied factor which depends on the soil characteristics of each and every forest garden. There has been fluctuation in production of Sandalwood year after year due to so many reasons; however, the trend clearly shows a drastic reduction in production. Sandalwood resources in India especially the wild populations is presently under threat, largely due to illegal felling, forest fire, grazing and to some extent spike disease combined with heavy domestic and international demand and with inadequate uniform regulation in the Southern States of the Country. Presently Sandalwood has been categorized as “vulnerable” by International Union for Conservation of Nature (IUCN) in 1998 (IUCN 2015). The dwindling population severely eroded the genetic base and is a cause of concern for initiating tree improvement work. Identifying spike resistant genotypes breeding for disease resistance is to be given equal impetus. Forestry research with reference to tree improvement, forest genetics and breeding should be given priority.

The excessively high demand in the international market of sandalwood has led to continued cost escalations for Sandalwood-based products and accumulative interest in Sandalwood cultivation, both as a commercial crop and on a smaller scale within agro-forestry systems. Effective cultivation of Sandalwood depends on a detailed knowledge about its basic biology and propagation. Knowing fully the conditions like soil types, seed treatments, host-parasite relationship, etc., raising large scale plantations in the natural sandalwood bearing areas as well as in farmlands will add up to the resource building of the valuable tree species.

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