Role of Mangroves in Pollution Abatement

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Abstract

Mangroves are one of the significant categories of coastal vegetation, distributed in the shorelines of tropical and subtropical regions and performing a dynamic role in coastal ecosystems. The recent developments of coastal cities, industrialization, unplanned recreational activities and expansion of aquaculture at mangrove areas in various regions of the world have generated a threat on such significant ecosystems. Nevertheless, the mangrove vegetation has some adaptive features to mitigate the pollution. These ecosystems act as physical, chemical and biological barriers for the transference of pollutants. They play a vital role in trapping sediments; assimilate the excess nutrients by phyto- or bioremediation of toxic substances. The earlier studies revealed that mangroves can act as possible phytoremediators. They absorb a considerable quantity of toxic metal ions and store them in various parts such as stems and roots, consequently evade the transmission of heavy metal ions. In addition, the mangrove associated microorganisms are responsible for remediation of numerous toxic contaminants present within the mangroves. In view of the above, the present chapter offers a comprehensive discussion on the role of mangrove vegetation on abatement of pollutants.

Keywords

Mangrove ecosystem · Heavy metals · Plastics · Hydrocarbons

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11.1 Introduction

Mangroves forests are composed of 73 species of trees and shrubs that grow along the coasts of temperate regions and are known for their ecological and socioeconomic importance (FAO 2007; Sandilyan and Kathiresan 2012). These comprise of woody trees, shrubs and flowering trees which are well adapted to the estuarine conditions (Spalding et al. 2010). Mangroves have highly adapted morphological and physiological features that acclimatize to the saline and anoxic environmental conditions, which enable the increase of biodiversity and biomass productivity proving to be ecologically and economically beneficial (Mukherjee et al. 2014; Duke and Schmitt 2015). These benefits include fisheries, maintaining coastal water quality, shoreline protection, primary production, aquaculture, tourism and recreation, whereas the most important global service is its role in pollution abatement (Duke et al. 2007; Richards and Fries 2016).

Mangroves have several ecological functions, which contribute to economy and improve quality of human life (Rodríguez-Rodríguez et al. 2016). Mangrove ecologies are regarded as barriers prohibiting the release of terrestrial contaminants into the oceans (Li et al. 2019). Mangroves play an essential role in climate regulation, soil stabilization and controlling erosion, regulating nutrient cycles and protecting seagrasses as well as coral reefs (Alongi 2014).

Mangroves act as protective barriers against several natural disasters however this role is dependent on several factors, viz. tree height, density and species composition, dominant species make up (roots, stems, branches and foliage), diameter of roots and trunks, and habitats elevation, nature of channel, pools as well as status of ecological degradation of the forests (McIvor et al. 2012). These natural barriers are also effective against storms, cyclones and tidal waves in several tropical regions (as reviewed by Sandilyan and Kathiresan 2015).

Over the past half century several diseases have occurred globally where the chief causative agents have been heavy metals. Heavy metal pollution especially in the marine environments is a serious threat owing to their persistence, toxicity and non-degradable nature. Heavy metals originate from mining, aquaculture, smelting, agriculture, printing and from industrial sources, viz. petrochemical and electronic industry while discharge of untreated municipal wastes into the marine environment is also one of the sources (Paz-Alberto and Sigua 2013). All discharges from these sources enter the marine habitats where they get accumulated in the organisms and are biomagnified to higher organisms (Rainbow and Luoma 2011). The primary sources for pollution in the mangroves include trace metals, oil residues, pesticides and untreated wastewater. These pollutants affect photosynthesis and growth of plants ultimately leading to mortality (Lovelock et al. 2009).

In short, it can be stated that mangroves offer numerous benefits; however, these may become retarded due to anthropogenic activities that affect mangroves. The following section describes some of the services rendered by the mangroves.

11.2 Solutions from the Mangroves to Pollution Problems

Mangrove ecosystem is of vast ecological, traditional and socioeconomic values (Kathiresan and Bingham 2001). They are actively involved in controlling of marine toxicants, such as heavy metals, pesticides, oils & greases, nutrients and plastics (Wang Q et al. 2019b). They are also involved in carbon sequestration and coastal production. Furthermore, the mangrove residing microorganisms are actively involved in degradation of a wide array of pollutants (Fig. 11.1).

11.2.1 Reducing Nutrient Loads

The ocean waves and currents constantly change the shapes of coastlines as sediment accretion and removal occurs during each wave. This may cause soil erosion along the coasts and this is where mangroves prove to be essential as they help to prevent soil erosion and bind the soil. The mangroves decrease wave intensity thereby reducing sediment discharge into the oceans. Decreased wave flow enables the deposition of bulk mass of sediment along the shores. Mangroves provide organic matter such as leaves and twigs which bind the sediments together and prevent subsidence (Spalding et al. 2014).

The domestic and industrial effluents are discharged into the estuaries; however, the mangroves are capable of purifying and improving the water quality thereby minimizing the effects of these discharges. However, if the pollutant concentrations in these discharges increase, it may harm the mangroves and surrounding environments (Sri Dattatreya et al. 2018). Mangroves can maintain the quality of

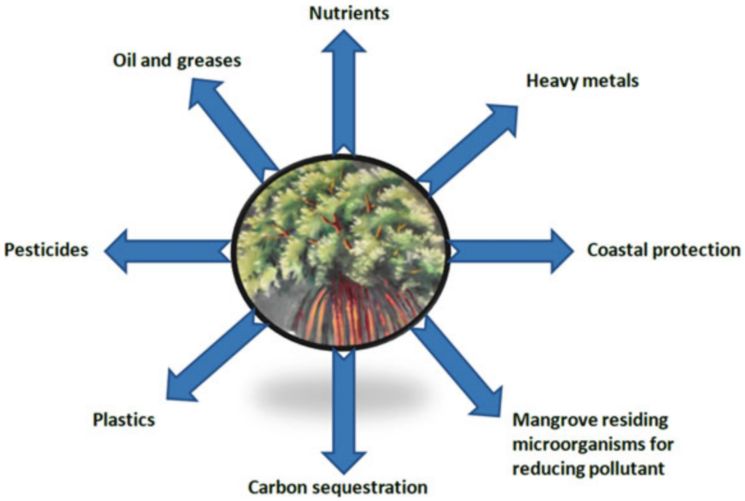

Fig. 11.1 Mangroves on pollution abatements

Table 11.1 Mangrove sources in carbon sequestration

Source	Common/Scientific name	Role in pollution abatement	References
Plant	*Ceriops decandra*	Carbon sequestration	Clough (1998), Alongi et al. (2000)
Plant	*Rhizophora stylosa* and *Avicennia marina*	Carbon sequestration	Alongi et al. (2003)
Plant	*Sonneratia caseolaris*	Carbon sequestration	Alongi et al. (2004b)
Plant	*Rhizophora apiculata,*	Carbon sequestration	Alongi et al. (2004a), Alongi (2009)
Plant	*Kandelia candel*	Carbon sequestration	Alongi et al. (2005)
Soil	–	Carbon sequestration	Ren et al. (2010)
Sediment	Mangrove peat	Carbon sequestration	Ezcurra et al. (2016)

estuaries by eliminating pollutants from effluents and transforming them into useful compounds (Wu et al. 2008).

The sedimentary characteristics such as soil grain, salinity and soil nutrients are also essential in regulating the benthic macro-organisms (Safahieh et al. 2012). Regions with fluctuating soil nutrients prevent growth of soil associated fauna. Hence, the soil nutrients are also detrimental in the mangrove productivity (Kathiresan and Bingham 2001). Dissanayake and Chandrasekara (2014) clearly explained the importance of physicochemical characteristics on the abundance of benthic organisms.

Nitrates and ammonia are two important compounds that have a role to play in regulating water quality. Nitrates are regularly maintained by the nitrogen cycle where nitrates are converted to nitrites, which are consumed by several organisms as nitrogen source. Excess concentrations of ammonia may prove toxic to the surrounding. During nitrification, ammonia is converted to nitrates by ammonia oxidizing bacteria such as *Nitrosomonas* sp., *Nitrococcus* sp. and *Nitrosospira* sp. (Purkhold et al. 2000; Ward and O'Mullan 2002; Purkhold et al. 2003). These species are abundantly found in all ecosystems including the mangroves. Moreover, *Nitrosopumilus maritimus* also plays a decisive role in eliminating ammonia from the mangrove ecosystems (Cao et al. 2011) (Table 11.1).

11.2.2 Reduction of Petroleum Hydrocarbons

Mangroves are known to attract tourists; therefore, the estuaries associated to the mangroves are subjected to constant boating activities apart from regular fishing. Such activities may yield oil spillage. Effluents from the paper and petroleum industries also contribute to oil pollution in mangroves (Lovelock et al. 2009).

Additionally, accidental spillage from oil containers also contributes to contamination of the mangrove system. These contaminations might cause several environmental effects on natural resources. The severity of oil spillages is dependent on volume of discharge, type of discharge and environmental conditions, which varies from season to season (Wang and Stout 2007). Total petroleum hydrocarbons (TPHs) are toxic to the aquatic organisms as they belong to one of the highly toxic group of persistent organic carbons. TPHs are released into various environments as a consequence of extraction, refining and consumption carried out by the petroleum industries (McNioll and Baweja 1995; USEPA 2000). Adequate and effective strategies are required to combat these hydrocarbons which can be achieved by attenuation, biostimulation and bioaugmentation within the soil which is possible in the mangroves. Mangrove areas are subjected to oil spills which affect the soils, plant surfaces and cause sub-lethal and lethal effects (Swan et al. 1994; Duke et al. 1999; Duke and Burns 2003; NOAA 2014). Such disruptions may disturb the socioeconomic benefits rendered by the mangroves.

The ubiquitous hydrocarbons are persistent in the environment due to anthropogenic activities which include oil and gas operations. Polycyclic aromatic hydrocarbons (PAHs) are the most common form of organic pollutant persistent in the environment (Tam and Wong 2008; Lu et al. 2011). Oil spillage may transpire during transportation of crude oil, discharges from petroleum products and during emissions from industries (Tam and Wong 2008). These petroleum hydrocarbons adhere to soil particles, hence degradation is tedious (Barathi and Vasudevan 2001).

Bioremediation of TPHs is a time consuming process since most of the TPH compounds are of high molecular weight (McNioll and Baweja 1995; Huang et al. 2005). Numerous environmental and physicochemical factors including nutrient availability, sunlight, temperature, soil grain size as well as microbial community influence the bioremediation of TPHs (Colombo et al. 2005; Lacerda 2006; Moreira et al. 2011). Some TPH removal by ex-situ methods such as Thermal Desorption, Chemical Oxidation and Incineration have been conducted with limited success. In situ technology involving air sparging, land farming, biosparging, bioventing, bioremediation, and phytoremediation has been carried out successfully (Seabra 2008). Among these, phytoremediation in combination with biotechnology has provided excellent results (Espinosa et al. 2005; Huang et al. 2005; Parrish et al. 2005; Doumett et al. 2008). Mangrove sediments enable to capture, transform and rhizodegrade TPHs during phytoremediation. Mangrove soils contain microbial communities suitable for rhizodegradation of TPHs and make it less bio-available to plants and other biota (Kamath et al. 2004). A former study (Moreira et al. 2011) has exhibited that phytoremediation using mangrove plants is more efficient than bioremediation.

Once an oil spill has occurred, the plants take some time to grow. However, plant recovery is faster than animal recovery as animals require the toxicity to be completely eliminated (Salmo and Duke 2010). Similarly, new seedlings can be planted only after the complete removal of toxicity (Duke 2001). Erosion and elevation are also important components which influence mangrove growth after an oil spill (Lewis 2005). Biotic and abiotic components are also essential to determine the mangrove recovery after each oil spillage. The biotic components include propagules and tolerances of the species towards oil spillage, whereas the chief abiotic components include erosion and elevation (Duke 2016).

11.2.3 Pesticides Degradation

Plants have been progressively used in bioremediation as a probable solution to pollution. Certain plants including mangroves are known to eliminate heavy metals from soil and water, while some grasses can provide a remedy for problems due to petroleum hydrocarbons (USEPA 2000). One such problem is pesticide spillage which may occur during its manufacture, distribution, formulation and application in the field. Excess levels of pesticide in soil may cause several problems such as leaching and running off into ground and surface water, respectively, while also affecting the soil organisms.

It is well known that bioremediation using plants is a time consuming process. During this extended time the pesticides may gradually be eliminated or become less bio-available to the biota. In certain cases, the pesticides may transform the soil structure which may cause drastic changes to such environments. A study (Belden et al. 2004) was conducted to upsurge the phytoremediation efficiency by employing prairie grasses along with mulberry trees. The study showed increased efficiency which suggested that similar techniques can be employed to the mangroves ecology to decrease the pollution due to pesticides.

Persistent Organic Pollutants (POPs), such as DDTs, chlordanes, endosulfans, etc. are ubiquitously found in waters or sediments in mangroves of the tropical areas. Even though these contaminants have been detected in various ecosystems globally, very little knowledge is available on the consequences of these compounds on the mangrove ecosystems (Bayen 2012).

The estuaries bring in these toxicants that are sprayed on to the agricultural fields. Since some estuaries inundate the mangroves, certain pesticides are deposited (Chilundo et al. 2008; Nagelkerken et al. 2008). However, the exact composition of these pollutants and their effects on various metabolic processes of the mangroves are largely unknown. This is where biosurfactants come into and play to combat the effects of several pollutants. Biosurfactants are bio-molecules that are retrieved from bacteria and fungi (Maier and Soberon-Chavez 2000; Mukherjee et al. 2006) and aid as natural choices to remove surface chemicals (Banat et al. 2010; Cameotra et al. 2010). Some studies have proved the ability of bio-surfactant as an effective surface agent (Kheiralla et al. 2013). However, their significance in complete degradation of pesticides is still under research.

11.2.4 Heavy Metals Remediation

Mangroves are essential in combating pollutants as they are known to sink anthropogenic pollutants and toxicants. In the mangrove soils, metal contaminants generally accumulate in the superficial water and pore water, and in solid phases like abiotic and biotic components (Lewis et al. 2011). A former study has highlighted the depletion of oxygen owing to the inundation of mangroves (Bayen 2012). The presence of sulphides and decreased oxygen concentration may contribute to co-precipitation of heavy metals in mangrove soils. In addition to sulphides, physicochemical concentrations are also associated with trace metals (Bayen 2012). Some mangrove plants like *Rhizophora* sp. can accumulate up to 95% more trace metals than other plants, thereby enabling the mangroves to retain and prevent heavy metals from infiltration into the environment (Silva et al. 1990). Salinity exchanges in the estuaries are also responsible for metal retention. The major cations such as Na, K, Ca and Mg intensify in the water during increased salinity and these ions bind with heavy metals (Laing et al. 2009).

Phytoremediation employing mangroves is used to remove/detoxify contamination due to heavy metals. The mangroves are employed to eliminate heavy metals and certain harmful organic compounds from soil while some volatile-organic compounds can be removed from the groundwater (Paz-Alberto and Sigua 2013).

An aggregate of 33 species of mangrove plants are adapted at consuming heavy metals. *Avicenna marina* has the utmost potential to degrade heavy metals than other mangrove plants. In general, roots are known to take up more heavy metals than the aerial parts, hence the upper plant tissues are not good indicators of metal pollution. However, in a study *A. marina* leaves had consumed 10% more metals than roots. The study had revealed that *A. marina* plants act as an indicator of Cu, Zn and Pb, as these metals were preferred (MacFarlane and Burchett 2002; MacFarlane et al. 2003).

The biodiversity of mangroves is also dependent on magnitude of pollution in the particular environment. Increased pollution causes the rise of pollution tolerant species while other species do not grow in these areas. *A. marina* plants are identified as superlative pollution tolerant species hence may be abundantly present in areas of high pollution. In simple words, it can be said that pollution hampers the mangrove biodiversity (Maiti and Chowdhury 2013).

The dispersion of metals varies with depth, coastal distance and typology of above ground mangrove vegetation (Kehrig et al. 2003; Marchand et al. 2006; Chatterjee et al. 2009). Trace metals may arise from natural and anthropogenic sources hence the exact source of the respective metals is difficult to differentiate. The anthropogenic sources of metals include mining (Marchand et al. 2006), gas (Antizar-Ladislao et al. 2011; Kruitwagen et al. 2008) and textile dye industries (Machado et al. 2002). The metals are brought to mangroves by rivers (Kehrig et al. 2003), or tidal exchange (Kruitwagen et al. 2008) or by atmospheric transfer (Rumbold et al. 2011). Mangroves efficiently retain the metals in plant tissues, hence reduce the metal bioavailability to the fauna.

11.2.5 Act as a Plastics Trap

Plastics are widely used in our day to day lives which have led to the improper disposal of plastics and the resultant mismanagement of wastes. The mismanaged plastic wastes accumulate in the beaches, mangroves and other aquatic ecosystems (Lebreton et al. 2017). Plastic debris has always garnered attention due to its low degradation rate, accumulation and bioavailability to the aquatic organisms (Iñiguez et al. 2016). Approximately 60–90% of marine debris constitutes plastics owing to its high production (Li et al. 2016). The plastic conundrum arises from mismanagement which according to a study ranged between 4.8 and 12.7 million metric tons in 2010 (Jambeck et al. 2015). In nature, compounds such as phthalates and persistent organic pollutants may adhere to plastic debris by virtue of which bioaccumulation and biomagnifications may occur (Moore and Phillip 2011; Jang et al. 2016; Clukey et al. 2018).

The larger plastic debris persists in these marine systems for a long period of time, thereby undergoing breakdown to minor particles referred to as microplastics which pose a bigger threat than larger plastics (Li et al. 2016). Microplastics are ingested by various organisms such as mollusks, crustaceans, fishes and others due to its smaller size and attractive colours (Wright et al. 2013; Antão-Barboza et al. 2018). Microplastics adsorb POPs and heavy metals leading to the bioaccumulations and biomagnifications, thereby causing their entry into the food chain (Ríos et al. 2007; Andrady 2011; Kühn et al. 2015; Bennecke et al. 2016; Wang et al. 2016; Massos and Turner 2017). Microplastics can release toxic materials which are consciously added during the manufacture of plastics, thereby causing environmental threat (Gallo et al. 2018). Moreover, microplastics are potential transporters of exotic species (Rech et al. 2016) and pathogenic microorganisms (Kovač Viršeka et al. 2017). However, information on the complete effects of microplastics on the marine environment is still insufficient (Auta et al. 2017).

Estuaries provide several ecological benefits to man (Barbier et al. 2011); however, they are constantly polluted due to domestic sewage discharges which act as an entry pathway for microplastics into the marine environment (Browne et al. 2011; Cesa et al. 2017). Cordeiro and Costa (2010) explained that the litter in the mangroves originated from terrestrial and freshwater sources. Mangroves are unique with regard to their retention and transformations capabilities of land-based litter and pollutants due to intense biomass and productivity (Fourqurean et al. 2012; Li et al. 2016; Booth and Sear 2018), hence are garnering much research attention (Martin et al. 2019). Some of the terrestrial origins of microplastics include personal care goods, for example, facial scrubs, cleansers, creams and toothpaste which reach the aquatic systems through municipal sewage and wastewater treatment plants (Auta et al. 2017; Murphy et al. 2016).

Mangroves have a complex root system consisting of pneumatophores and prop roots which enhance turbulence and wave energy (Horstman et al. 2014; Norris et al. 2017). These roots act as a filter system which traps materials transported by waves and currents. An earlier report exhibited the different retention capacities of various objects dumped in the mangrove forests (Ivar do Sul et al. 2014).

Plastics trapped by mangrove roots cause external damage which affects the tree and the dependent fauna. These plastics also prevent gas exchange, meanwhile release absorbed chemicals to the mangrove ecosystem (Cole et al. 2011). A number of natural factors such as estuarine hydrodynamics, mangrove characteristics, sediment grain size along with human activities such as tourism, mariculture and coastal dumping are some of the determining factors for plastic distribution and retention in the mangroves (Ivar do Sul et al. 2014; Lima et al. 2016). Ivar do Sul et al. (2014) explained that retention capacity of the mangroves is reliant on the hydrodynamics of the plastic materials while also mentioned that plastic bags are retained the most owing to its hydrodynamic property. Thus the hydrodynamics of semi-enclosed mangrove habitats are a regulating factor for the distribution of plastics (Boelens et al. 2018).

Polycyclic aromatic hydrocarbon (PAH) is a type of organic contaminant found in sediments which are transferred to organisms (Ramdine et al. 2012). The hydrophobic nature of plastics enables POPs such as dichlorodiphenyltrichloroethane (DDTs), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) to get adsorbed onto microplastic surfaces (Endo et al. 2005; Teuten et al. 2007; Frias et al. 2010; Rochman et al. 2013). These adsorbed compounds are consumed when the microplastics are ingested and released into the tissues of organisms (Engler 2012). Similarly, toxic monomers (Saido et al. 2009) and some plastic additives like bisphenol A and phthalates (Fries et al. 2013) leach from the microplastics and affect the marine organisms and environment.

Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), rayon and polyester (PES) are the some of the regular polymers recovered from the mangroves (Li et al. 2018; Zhu et al. 2019). However, Ajith et al. (2020) reviewed that apart from these Polystyrene (PS) and nylon are also commonly found in the marine environment and this could enter the mangroves. PP has a wide use in industrial and household applications which include textiles, stationery, packaging, automobile parts and laboratory equipment (Gewert et al. 2015). PE is used in packaging, plastic bottles, bags (Zhang et al. 2016) and fishing gears (Chen et al. 2018; Wang T et al. 2019a). The other polymers are also dominant, but their origins are not documented well (Ajith et al. 2020).

Plastic polymers are recalcitrant in nature which prohibits rapid microbial degradation enabling the long-term persistence of plastics in the environment (Longo et al. 2011). Additionally, the plastic surfaces act as substrates for microbial colonization (Dussud and Ghiglione 2014). During colonization, microbes initiate biodegradation by secreting extracellular enzymes (Eich et al. 2015; Sekhar et al. 2016). Certain microorganisms produce biofilms which also influence biodegradation of plastics (Sheik et al. 2015; Eich et al. 2015; Jeon and Kim 2016). Microbial enzymes are important in biodegradation of plastic substances, since some enzymes utilize plastics as carbon source (Auta et al. 2018).

11.2.6 Mangrove Residing Microorganisms

Mangroves occur at the interface of marine and terrestrial ecosystems which exemplify a prosperous biodiversity. Microorganisms are essential components of the mangrove ecosystem; they play crucial roles in the creation and upholding of this biosphere. They also supply biotechnologically potential and valuable products (Thatoi et al. 2013). This ecosystem offers a typical environment harbouring different assemblages of microbes, for instance, actinomycetes, bacteria, cyanobacteria, fungi, protozoa, algae, etc. (Sen and Naskar 2003). Among them, bacteria and fungi provide a noteworthy contribution towards reducing the pollutants (Fig. 11.2). These microbes contributing in different steps of decomposition and mineralization of mangrove leaves among other litters significantly contribute to the productivity of the mangrove environment. They play an important role in recycling nutrients, involve in carbon sequestration and devastate pollutants. The microorganisms degrade the pollutants by their enzymatic action while enzymes act as biocatalysts facilitating degradation. Among the mangrove residing microbes, the bacteria are the most dominated group as they are several fold higher than those of fungi (Kathiresan and Qasim 2005). Microbes utilize a broad range of substances to produce energy and nutrients from the surrounding environment for the growth and multiplications of cells. The mangroves are the extremely productive ecosystems hold rich nutrients which support the growth and multiplication of diverse groups of microorganisms.

Domestic wastes and industrial effluents are expelled into the estuaries and channels associated with the mangroves which may release excess nutrients in the surface water and soil. This may instigate eutrophication and algal blooms whilst excess nitrogenous wastes may also be harmful. Certain aquatic biota including bacteria and algae enable mangroves to eradicate the harmful nitrogenous wastes and unused nutrients present on the surface water and soil. This purified water can be reused in aquaculture (Spalding et al. 2014).

Mangroves are one of the main ‘hotspots’ for marine fungi (Shearer et al. 2007). Although the trunks and aerating roots are permanently or intermittently submerged the other parts remain free of salt water interference. The lichens and terrestrial fungi

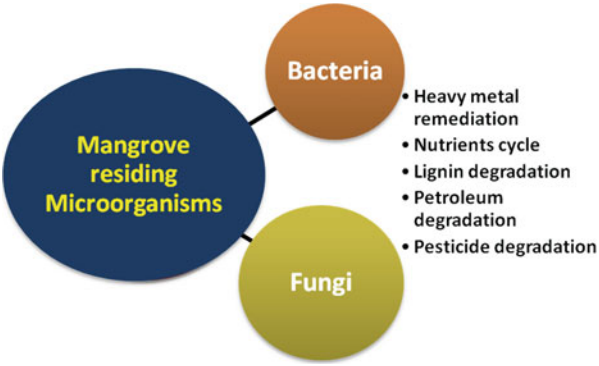

Fig. 11.2 Mangrove residing microorganisms and their dynamic role in pollutants reduction

inhabit the dry parts of plant while marine groups live in the bottom region; middle region overlies the marine fungi (Sarma and Hyde 2001).

Bacteria are well known to degrade petroleum hydrocarbons as they have been employed successfully during oil spills (Rahman et al. 2003; Brooijmans et al. 2009). Biodegradation of petroleum hydrocarbons relies on a number of factors, such as the type of compound and availability to microorganisms. Some bacteria consume hydrocarbons as their primary source of supplement (Yakimov et al. 2007). However, high molecular weight hydrocarbons can never be degraded (Atlas and Bragg 2009). Mangrove sediments host a variety of bacteria and fungi among which certain strains may have ability to degrade hydrocarbons. Some of these species include *Bacillus subtilis*, *Pseudomonas fluorescens* and *Rhodococcus erythropolis* (Duke 2016).

The *B. subtilis* is capable of degrading hydrocarbons and can survive in extreme conditions of heat. These spores are advantageous as they have the potential to produce a natural biosurfactant called surfactin which is synthesized in combination with crude oil (Queiroga et al. 2003). The strain *P. fluorescens* is also known to produce biosurfactants which have the potential to degrade hydrocarbons (Kaczorek and Olszanowski 2011). The bacterium *R. erythropolis* has a unique metabolism which consumes carbon from hydrocarbons, thereby degrading various compounds such as chlorinated phenols, steroids, lignin, coal and crude oil (Brandao et al. 2003).

The mangrove fungus has attracted attention of scientists due to their wealthy and diverse potentials. Wu (1993) screened 15 species of fungi from mangroves regions of Tanshui Estuary, Taiwan. He observed that they can secrete different enzymes that have potential to decompose mangrove litter. Xin et al. (2002) found that the marine white-rot fungus can degrade 50% of lignin incubated with entire sugarcanes.

Microorganisms adapt to all kinds of environment (Brooks et al. 2011; Aujoulat et al. 2012) and possess the potential to transform plastic polymers. The mangrove residing microbes can metabolize the pollutants which might enhance biotransformation and subsequent degradation (Luigi et al. 2007). Several studies have articulated their results on microbial degradation of plastic polymers. PET was degraded by *Ideonella sakaiensis* 201-F6 (Yoshida et al. 2016); degradation polystyrene by *Pseudomonas* sp. and *Bacillus* sp. (Mohan et al. 2016); the attenuation of molecular weight of PE under test conditions by a fungus *Zalerion maritimum* (Paco et al. 2017); degradation of PE by *Bacillus cereus* (Sowmya et al. 2014); *Kocuria palustris* M16, *Bacillus subtilis* H1584 and *Bacillus pumilus* M27 (Harshvardhan and Jha 2013). A number of other bacteria are also involved in polymer-degradation which includes *Pseudomonas stutzeri*, *Alcaligenes faecalis*, *Pseudomonas putida*, *Staphylococcus* sp., *Streptomyces* sp. and *Brevibacillus borstelensis* (Ghosh et al. 2013; Caruso 2015). Therefore, it may be affirmed that microbial degradation of plastics is an eco-friendly approach (Boelens et al. 2018). Mangroves host a wide variety of microbes (Kathiresan 2003; Thatoi et al. 2012) due to the suitable conditions of temperature, pH and salinity (Ghizelini et al. 2012).

11.2.7 Carbon Sequestration

Mangroves are the principal carbon-rich habitats of the tropic regions (Kristensen et al. 2008; Donato et al. 2011; Pendleton et al. 2012; Siikamäki et al. 2012b; Alongi 2014). Typically, mangroves garner quadruple amounts of carbon than other floral habitats (Donato et al. 2011). However, mangrove deforestation occurs at a significantly higher rate than the loss of other types of forests (FAO 2007). Mangrove deforestation causes carbon emission and reduces carbon sequestration (Alongi 2014). Carbon emissions coupled with other greenhouse gases (CH_4, N_2O) may have contributed to climate change (IPCC 2014). To combat climate change, it is necessary to prevent deforestation of mangroves and subsequent carbon emission (Kristensen et al. 2008; Donato et al. 2011; Houghton 2012; Alongi 2014).

Blue carbon emissions can be reduced significantly by the mangrove restoration programs (Pendleton et al. 2012; Siikamäki et al. 2012a). Through mangrove restoration, several environmental activities such as photosynthesis, respiration, water purification, decomposition and predation may also be restored (Cardinale et al. 2011; Parrotta et al. 2012). Blue carbon sequestration through mangrove restoration is gaining popularity due to its importance in climate change (Le 2008; Joffre and Schmitt 2010). Blue carbon sequestration enables to promote and safeguard mangroves as well as provide a solution to climate change (Robledo et al. 2004). However, mangrove restoration is possible only with an ecologically beneficial design and socioeconomic support for its construction (Mazda et al. 2006).

In the early days, carbon accumulation was conducted as short-term studies and the results expressed that a large amount of carbon is stocked in the soil. However, over time it was proved that short-term studies do not portray the actual picture of carbon sequestration. This is evidenced in a study where short-term assessment of 137Cs, 222Th and 210Pb radionuclides suggested a high carbon accumulation rate of 1.25 tC ha^{-1} $year^{-1}$ (Alongi et al. 2004). However, ground-truth studies and imaging studies have showed a lesser carbon accumulation rate of 0.5 tC ha^{-1} $year^{-1}$ (Alongi et al. 2004). This is due to simultaneous accretion and erosion of mangroves forests. The actual picture of carbon sequestration can be projected only by carrying out long-term studies (Alongi 2011).

Despite the numerous services provided by the mangroves, they are constantly subjected to human pressures as over 120 million people are known to inhabit areas surrounding the mangroves (UNEP 2014). A large area of mangroves is converted to aquaculture as this provides an income and means of food. The loss of mangroves may lead increased concentration of carbon in the atmosphere. Mangroves are essential sources of blue carbon sinks. Blue carbon is the organic carbon stored, sequestered, and released from mangroves, salt marshes, seagrasses and other marine environments (Nellemann et al. 2009; McLeod et al. 2011; Murray et al. 2011; Pendleton et al. 2012; Duarte et al. 2013; Alongi 2014). Annually, mangroves contribute to 30% of global carbon sequestration (Siikamäki et al. 2012a). Mangroves need to be restored by carrying out effective restoration programs such as Reduced Emissions during deforestation and degradation (REDD) (Ahmed and Glaser 2016) (Table 11.2).

Table 11.2 Mangrove sources in regulation of nutrient load/water quality

Source	Common/Scientific name	Role in pollution abatement	References
Soil	–	Treatment of water quality	Tam and Wong (1995)
Plant	*Kandelia candel, Bruguiera gymnorrhiza*	Salinity and nutrient removal	Ye et al. (2001)
Plant	*Kandelia candel*	Treatment of municipal wastewater	Wu et al. (2008)
Soil	Glomalin related protein	Improves water quality	Wang et al. (2018)

11.2.8 Coastal Protection

Mangroves act as natural barriers that prevent storms and cyclones or resist their intensity, thereby minimizing the damage on the inner areas. The constant exchange of sediments between oceans and mangroves strengthens the mangrove soil thereby preventing soil erosion. The dense mangroves growing along the coastal regions can act as a natural shield, help to reduce the impact of natural calamities like cyclone, tsunami and coastal storm by engrossing the waves' energy because of the flexibility of the mangrove stem. The study conducted by Kathiresan and Rajendran (2005) scientifically proved that the mangroves play a significant role in coastal protection. During excessive high tides or tsunamis, the coasts are protected by the mangroves, which reduce the wave intensity, hence the waves do not enter too far into the terrestrial areas (Spalding et al. 2014).

11.3 Conclusion

Though the mangroves provide solutions for several pollutants, the tolerance of mangroves towards toxicity necessitates testing to comprehend the toxicity threshold level of mangroves. This may be accomplished by testing the various stages of mangroves right from their juvenile stages. By such experiments, the information on tolerance of mangroves towards toxicity can be documented. Such information extends knowledge of the scientific community to apprehend effects of chemical and non-chemical stressors.

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