Potential Eco-friendly Techniques for the Management of Organic Pollutants from Industry Effluents

V. Uma Maheshwari Nallal, R. Sitrarasi, C. Thamaraiselvi, and M. Razia

Abstract Bioremediation techniques have become noticeable and valuable tools to reduce, reuse, and recycle different industrial effluents through eco-friendly practices. Industries are well known to release anthropogenic-related chemicals into the environment over the century and consequences are witnessed as contamination of soil, water, and air, respectively. The untreated or impertinently treated wastewater effluents are known to be toxic to plants and animals, including humans that lead to negative impacts on the earth. Remediation has emerged for degrading contaminants using physical, chemical, and biological methods. Bioremediation techniques are used nowadays around the world meticulously. It is technology based along with the combined action of plants and associated microbial communities to degrade, remove, transform, or immobilize toxic compounds in effluents. This chapter discusses the classes of organic effluents, toxicological mechanism, and its environmental impact and also emphasizes the current and advanced eco-friendly techniques in the remediation of organic effluents through microbial, algal bioremediation and phytoremediation. Bioremediation techniques are potential, cost-effective, and in addition to that remains as a solution to the challenge of treating many classes of contaminants, compared to the conventional chemical and physical methods, which are often very expensive and ineffective compared to biological methods.

Keywords Bioremediation · Effluent · Microbes · Nanomaterials · Phytocompounds

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1 Introduction

Environmental pollution has been well defined in various ways and implies to the release of unwanted substance by man into the environment that alters the surrounding and damages either their own health or the resource in turn (Moschella et al., 2005; Wasi et al., 2012). It is regarded that pollutants directly or indirectly have a detrimental effect on the human health when they occur in higher concentrations than the natural levels (Richards & Shieh, 1986). The two major classifications of pollutants are biodegradable and non-biodegradable pollutants: sewage effluents and organic matters constitute the biodegradable pollutants and they are decomposed quickly, whereas plastics, detergents, and heavy metals are considered non-biodegradable and cannot be easily decomposed in natural ways. The major source of anthropogenic wastes that enter water bodies are through industries. Release of xenobiotic compounds has been tremendously influenced by the fast-growing wave of urbanization and simultaneous industrialization that occurs to meet the demands of the population (Tabrez & Ahmad, 2010). Industries cannot be solely blamed for the environmental degradation; utilization of fertilizers, gasoline, aerosol sprays, and pesticides remain a major reason for the direct addition of organic pollutants into the surroundings (Richards & Shieh, 1986).

Among the various types of pollutions, organic pollutants are undeniable contributors of water pollution. Effluents from different industries such as textiles, oil mills, paper and pulp industry, and metal industry are the significant contributors of water pollution (Tripathi et al., 2007; Anjaneyulu et al., 2005). Direct water pollution occurs through point sources, and indirect water pollution is through non-point sources. Pollutants affect the developmental characteristics, reproduction, and behavior of biotic communities. Water is a prerequisite for various activities and purposes such as drinking, irrigation, agricultural use, industrial use, and sanitation entirely depends on these water bodies in developing countries such as India. As the global demand for water increases, improper disposal of residues into water bodies has become a major health concern that has inculcated the need for waste water treatment; reuse of water and improvement in water quality have become overwhelming concerns in the present scenario (Gadipelly et al., 2014; Ahmad et al., 2008).

Expansion of modern society has paved ways for the amplified disposal of organic pollutants that results in increased toxicity of wastes (Gavrilescu et al., 2015). Illegal dumping, inadequate disposal techniques, accidental spillage, careless dumping of hazardous waste, and poor choice of landfall are the main causes of xenobiotic contamination and can result in emergence of fatal disease spreading microorganisms (Aboulhassan et al., 2006). This downfall augments the need of potential and effective methods to protect human life and the ecosystem. The conventional physical and chemical methods that are already in existence and practice demand high cost, are less effective, and can serve as a source of additional residue producers that contaminate the surroundings. Physicochemical methods have a narrow range of selection among pollutants to be removed from industrial effluents and are rarely environmental friendly (Banat et al., 1996; Chen et al., 2015). As the concern toward pollution control increases, the need for environmental friendly, inexpensive, and efficient techniques to remove pollutants has become a notion of many researchers (Petala et al., 2009).

Biological remediation methods have gained attention for their eco-friendly behavior and good performance at affordable costs (Giovanella et al., 2020). Bioremediation involves the absorption, adsorption, degradation, or transformation of pollutants through the use of prokaryotic (microorganisms) or eukaryotes (plants) in a simple, inexpensive, and effective way (Alegbeleye et al., 2017; Ayangbenro & Babalola, 2017). For the past two decades, scientists have developed various bioremediation techniques that operate on both narrow and wide range of pollutants with the ultimate goal to restore the polluted ecosystems in a rather simple and eco-friendly way. It has served as the key in solving various environmental issues that remained a challenge to conventional methods (Verma & Jaiswal, 2016). Degradation, detoxification, mineralization, or transformation of pollutants to an innocuous state has never been too easy through bio-remediation, but requires careful planning and execution of the techniques. The major concerns while planning the techniques are nature of the pollutant (dyes, chemicals, nuclear waste, sewage, and hydrocarbons), degree of pollution, location and type of the environment, and cost and site of application (ex situ or in situ) (Azubuike et al., 2016) The purpose of this chapter is to give a comprehensive idea on the organic pollutants eliminated from various industries, their toxicological mechanisms and their environmental impact, and potential eco-friendly management techniques that are widely being applied along with advantages, limitations, and future prospects.

2 Organic Pollutants in Industry Effluents

Organic pollutants from industry effluents play a major role in water contamination when compared to other surfaces. Polycyclic aromatic hydrocarbons (PAHs), phenols, aliphatic and heterocyclic compounds, pesticides, herbicides, PCB, and PBDEs are the various organic pollutants that are toxic and deleterious to the environment (Fig. 1). Industries that eliminate a major amount of organic pollutants through effluents that contaminate water bodies are sugarcane industries (Razia et al., 2020; Thamaraiselvi et al., 2019; Parvathi et al., 2015), textiles (Parvathi et al., 2018), tanneries (Vaishnavi et al., 2019), and related industries. The probability of treated waste water from industries containing organic pollutants is also high. Their elimination into the nearby water bodies are a major concern for public health. Treatment of the industrial effluents cannot be entitled to specific organic compounds since they can be a heterogeneous mixture of complex organic pollutant with various concentrations. Other than the effluents from the industries, pesticides and herbicides from the farmlands, municipal sewage that contains food, dissolved organic compounds, oils, detergents, and surfactants also alter the environment.

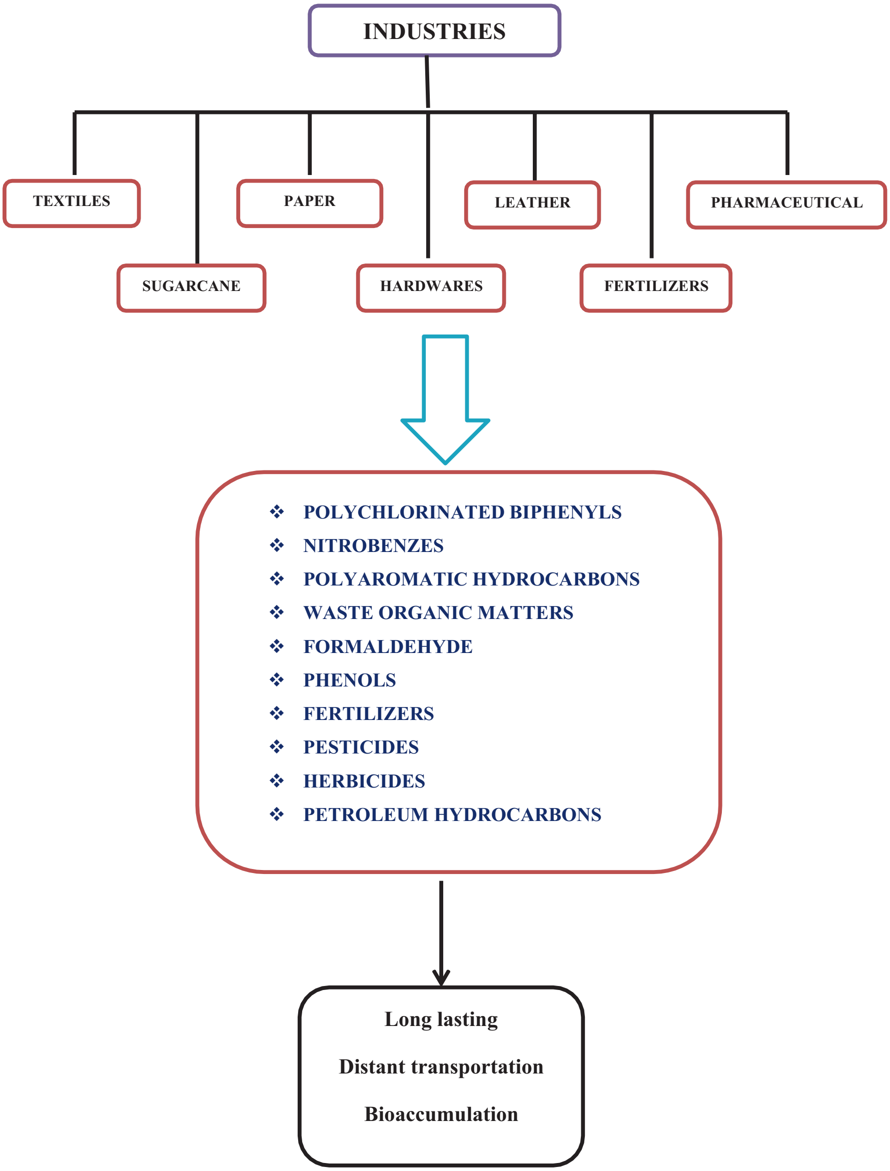

Fig. 1 Organic pollutants from industry effluents and their characteristic features

These organic pollutants not only damage the environment but they also pose a serious threat to the health of humans (Zheng et al., 2013).

The ability to degrade differs from one organic pollutant to another, which is influenced by their structures. Compounds that have simple structures and hydrophobic nature can be degraded readily. Microorganisms such as bacteria, fungi, and algae can easily degrade organic pollutants such as methanol, sugars, and ketones that can only cause acute toxicity when prevalent in water at higher concentrations. Similarly compounds that have complex structures and hydrophobic nature are degraded in a slow phase; they can exist in nature for longer periods that are toxic. For example, compounds such as PAHs, DDT, and PCB degrade very slowly (Clara et al., 2005). Such organic pollutants that can thrive for years are persistent and can enter and get transported in the food chain. Some of the persistent organic molecules are neurotoxic and carcinogenic. Propensity for long-distance travel and higher retention time in the surface without degradation is the major reason that draws attention toward the persistent organic pollutants (POPs). A number of these compounds are major health risk factors as they can cause serious damage to the endocrine system (Hossain et al., 2012). Bioaccumulation and biomagnification with the advantage of circumvention to degradation techniques display POPs as a major threat to human survival (Chiron & Minero, 2007).

The archetypal toxic organic pollutants in industry effluents are as follows.

2.1 Waste Organic Matter (WOM)

WOM consists of sediments and waste water present in the industry effluents. Organic compounds such as protein, carbohydrate, and organic acids are the main components of WOM. Waste organic matter in water bodies can affect their physicochemical properties and the quality of the water that are required for domestic purposes. They are major hindrances in water purification, degradation, and transformation processes (Dignac et al., 2005).

2.2 Formaldehyde

Formaldehyde is made up of organic molecules such as carbon, hydrogen, and oxygen. This organic compound is identified in the effluents of chemical industries, textile industries, paper and pulp manufacturing industries, and paint and fiber industries. Formaldehyde is capable of combining with a multitude of other compounds, which makes the degradation process of formaldehyde tiresome. Moreover, they can affect the skin and the mucous membrane through which they gain entry into the central nervous system of the human body and cause neurodegenerative disorders. The chances of retinal damage are also high when exposed to high amounts of formaldehyde (Panchanathan et al., 2016).

2.3 Nitrobenzene

Nitrobenzene is a similar organic compound such as formaldehyde that consists of carbon, hydrogen, oxygen, and nitrogen. It is one of the important organic compounds used in the chemical industry. Large-scale manufacturing of aniline is possible with the presence of nitrobenzene. Nitrobenzene is the precursor of aniline, and in turn it is indirectly involved in the manufacturing process of phenols. Aniline is also eliminated from chemical industries in their effluents as they are the precursors to phenol manufacture. These organic compounds smell like rotten fish thereby rendering an unpleasant smell to the water bodies and are a major hindrance in the use of water for drinking purpose. Chemical industries are largely involved in the manufacture of such organic compounds due to their use in laboratories as solvents for the preparation of electrophilic reagents. Continuous and long-term exposure of nitrobenzene can cause fatal damage to the human body (damage of central nervous system, vision impairment, lung irritation, and blood-related issues) and is identified as carcinogenic substance (Guo et al., 2014).

2.4 Phenols

Phenolic compounds mainly exist in water surfaces due to the elimination of effluents from the industries. They are highly toxic and can remain on the surface for a long period of time. Phenols are organic compounds with OH as their main functional group that is directly bonded aromatic hydrocarbons. The major sources of phenols are coke plants, oil refineries, industries that manufacture insulation materials, paper and pulp industries, and chemical industries. Many phenolic compounds that enter the water bodies and other environmental surface are carcinogenic in nature. The reason that they have become major health concern is due to the fact that they are toxic even in low concentrations. Phenols can cause serious health issues and can impair the reproductive capacity of aquatic organisms as well as human beings (Villegas et al., 2016).

2.5 PCBs

Polychlorinated biphenyls (PCBs) are biphenyl groups attached to at least two or more than two to ten chlorine atoms. PCBs are commonly employed in industries that manufacture machinery since they are used as coolant fluid and dielectrics in the machines. For example, PCBs are commonly used in transformers, electric motors, and capacitors. Industries that make use of such machineries also tend to discharge PCBs into the environment in their effluents. As far as persistent organic pollutants are considered, PCBs are a major concern to human health. They can cause serious damage to the immune system. Over exposure to these compounds can lead to the accumulation of these compounds in the adipose tissues of the skin. Spread of these compounds from the skin can damage other internal organs such as the brain, kidney, and liver and result in their impairment. They have been reported to cause nervous disorders and affect the immune system. Reproductive issues are of great concern when it comes to these organic pollutants, they act as mutagens that can interfere with the hormones, and studies showed that they can inhibit as well as imitate estradiol. Moreover, they are stable, long persistent, and can withstand extreme temperature and pressure. It is the chemical makeup of the PCBs that determine their degradation process. This manmade chemical has now become a major threat to mankind itself (Yao et al., 2014).

2.6 PAHs

Polycyclic aromatic hydrocarbons (PAHs) occur in clusters, angular or linear arrangements. They are made up of two or more benzene rings and are recalcitrant organic pollutants. PAHs are released during burning of coal, trash, solid wastes, tobacco, wood, and gasoline. High-temperature cooking can release PAH into the environment. They consist only of carbon and hydrogen moles, they are manufactured in several chemical industries, and they are the most common carcinogenic compounds that are used in laboratories for cancer experiments. Coke industries, aluminum manufacturing industries, and motor manufacturing industries are the common sources that eliminate PAH in their effluents. Accidental leaks and tar deposits must also be considered for the deposition of PAH into the environment. PAHs that have high molecular weight are a major threat to the environment and human health as they can accumulate in the environment. They can threaten the life of organisms by causing acute toxicity, mutagenicity, and carcinogenicity (Euvrard et al., 2017).

2.7 Fertilizers, Pesticides, and Herbicides

Pesticides and herbicides are a major threat to water bodies as they are washed away from the farmland and reach the water source thereby contaminating them. Since this chapter is dedicated to the organic pollutants present in the effluents from industries, pesticides and herbicides can be given less importance. The industries that manufacture fertilizers, pesticide, and herbicides are the source of such organic pollutants as the wash off water from such industries can contain them. Organophosphorus pesticides can exist in the water for a long period of time and cause serious environmental pollution. They can be easily degraded in the environment by simple techniques, and they possess acute toxicity on people and livestock (Younas et al., 2017).

2.8 Petroleum Hydrocarbons

The major source of petroleum hydrocarbons is industrial waste water and municipal sewage. Oil manufacturing industries, their refinement, and transportation entertain their presence in the waste water that is eliminated from such industries. They are highly toxic to aquatic organisms as they could deteriorate the water quality and decrease the oxygen exchange between the water surface and the environment (Kuyukina et al., 2020).

3 Toxicological Mechanism of Organic Effluents

Industries are legally bonded to install effluent treatment facilities, yet a significant amount of organic pollutants enter the water bodies and soil surfaces. The major industries that eliminate POPs into the surroundings are petroleum industries, chemical industries, steel manufacturing industries, pulp and paper manufacturing industries, and fertilizer industries (Richards & Shieh, 1986). Fatima and Ahmad (2006), and Tabrez and Ahmad (2010) have reported from India the presence of organic pollutants such as phenols, pesticide, heavy metals, PCBs, and PAHs. Roane et al. (1996) report the presence of pesticides at 37% of sites in the USA. It is not only the large-scale industries that significantly contribute the waste accumulation in the environment; small scale industries also play a major role. Tabrez et al. (2011) have reported large amount of heavy metals into the sewage from industrial effluents from small- and large-scale industries. Heavy metals can amalgamate with the ground water and cause fatal adversities in human bodies. These metals can also disturb the metabolic functions, hormones, and enzymatic reactions.

Organic compounds are the major constituents in pesticides that have become a part of modern agricultural practices. Widespread population has highly increased the need to adopt modern agriculture and alternatively increase the use of synthetic pesticides in the environment. Thus, pesticides have become ubiquitous compounds in the surface and ground waters. Increase in the demand of fertilizers, pesticides, and herbicides among farmers have encouraged such industries to produce large amount of likely products. The effluents from these industries contain the organic pollutants that persist in the environment for a longer period of time. Fatima and Ahmad (2006) report the presence of toxicant organochlorine and organophosphorus in India. Pesticides are highly harmful to aquatic microorganisms as they can enter their body. They can cause neurotoxicity, cardiotoxicity, and ocular toxicity even if exposed to a short period of time. Chronic exposure to pesticides such as endosulfan, DDT, and HCH can attribute to the development of various cancers (Muniz et al., 2008). Herbicide manufacturing industries dispel organic compounds such as 2,4-dichlorophenoxyacetic acid (2, 4-D), 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), and 4-chloro-2-methylphenoxycetic acid in their effluents. Since the ban of chlorinated hydrocarbons to control weed growth, carbamates have gained importance. The mechanism by which the carbamates control the overgrowth of weeds is by inhibiting the cholinesterase enzyme. When these mixtures enter the human body, they can work through the same mechanism and are therefore considered highly toxic to humans (Chaudhaery et al., 2010).

Phenols from chemical industries, petrochemical industries, and pulp and paper industries are commonly found in the effluents that are discharged (Gupta & Ahmad, 2012). The toxic mechanism of phenol involves the disruption of the cytoplasmic membrane in cells. The integrity of the cell wall is lost which leads to the disruption of related functions and cell death (Yap et al., 1999). Phenols can increase the stress levels in microbes that alter their cell membrane fluidity leading to cell death. This has been reported in various microbes such as *Escherichia coli* (Mrozik et al., 2004), *Pseudomonas putida* (Yap et al., 1999; Heipieper et al., 2003), and *Vibrio* species (Heipieper et al., 2003; Mrozik et al., 2004). When stress increases, the degree of saturation of fatty acids increases leading to the conversion of cis-unsaturated fatty acids to trans-isomer and also triggers the alteration of polar groups in phospholipids therefore transforming the stability of the cell membrane.

4 Environmental Impact of Industrial Effluents

Industrial effluents are considered as the manmade curse to the environment. Organic pollutants present in the industrial effluents are the silent killers as they persist in the environment for a long period of time and accumulate on the surface causing permanent impairment to the ecosystem (Alharbi et al., 2018). They are omnipresent in the environment, in water, air, land, animals, plant as well as human beings. Human survival has been possible on earth due to their interaction with the abiotic and biotic components of the environment; any effect on these components can directly or indirectly question the ultimate survival of humans. It is not only the environment that is being affected, but also, we are forced to face interferences in social, cultural, and technological perspectives (Pariatamby & Kee, 2016). Organic pollutants that are eliminated in the industrial effluents deteriorate the ecological balance; thereby, threatening the life of plants, animals, humans, and other organisms leading to mortality. As organic pollutants can persist in the environment for a longer period of time, their resistance toward photolytic, chemical, and biological degradation makes them a great menace to the environment. Organic pollutants have turned out to be a major global concern due to their long-range transport, bioaccumulation in adipose tissues of mammals, and persistency and toxicity at meagre concentration (Tang, 2013). Organic pollutants are not restricted to certain geographical area of earth; they are even identified in the Arctic region as they can travel to longer distances due to their small size, low molecular weight, and stability (Brown & Wania, 2008).

Due to our smart and insane expeditions, humans have tried to conquer and pacify nature, seize infectious agents, and caused extinctions with the discovery of organic chemical compounds. Only in the later years, man has started to realize the harmful effects of these organic compounds that are dispersed into the environment as they begun to cause serious health issues. Myers (2002) suggests that we lag behind in knowledge of the boons and banes of these toxic chemical, and it is highly necessary to adhere to traditional risk assessment. Nevertheless, traditional risk assessment is always subdued since it prevents commercialization of the product in the global market. Sarkar et al. (2003) reported that in India high levels off persistent organic pollutants were detected in fish samples collected from the rivers of Kumaon, Himalayas, Uttarakhand. Some studies were performed in the late 1990s in India that demonstrated the presence of elevated levels of PCBs, DDTs, and HCHs in *Plantanista gangetica* (Ganges river dolphin). Karuppiah et al. (2005) reported that Irrawaddy dolphins contained low concentrations of PCBs when compared to the Bay of Bengal dolphins. High levels of organic pollutants are reported in the Himalayan glaciers (Kang et al., 2009); Kumaon Himalayan region (Sarkar et al., 2003); Kolkata, West Bengal (Purkait et al., 2009); Assam (Bishnu et al., 2009); Karnataka and Andhra Pradesh (Begum et al., 2009); and the Tamiraparani river, Tamilnadu (Kumarasamy et al., 2012). Organic pollutants have unarguably exceeded the limits as contaminants globally, and improper disposal or lethargic remediation strategies can lead to higher level damages in the environment and human health.

5 Eco-Friendly Techniques in the Remediation of Organic Pollutants

The progress in the remediation of organic pollutants from industrial effluents is slower than the progress in the invention of organic pollutants. Organic compounds were discovered for the betterment of human survival, which has now become a major hindrance to the ecosystem and the existence of plants, animals, and humans. Few developed as well as developing countries have new technologies that can effectively degrade the organic contaminant from polluted sites. On the other hand, the cost incurred in developing such physicochemical methods account for rates higher than that which was required to develop the same (Azubuike et al., 2016). These magnified problems in the management of organic pollutants from industrial effluents create the need for eco-friendly and cost-effective methods that can target multiple contaminants at a particular contaminated site. Bioremediation has become the apple of our eye when it comes to successful biological and safe method for degradation of pollutants (Fig. 2).

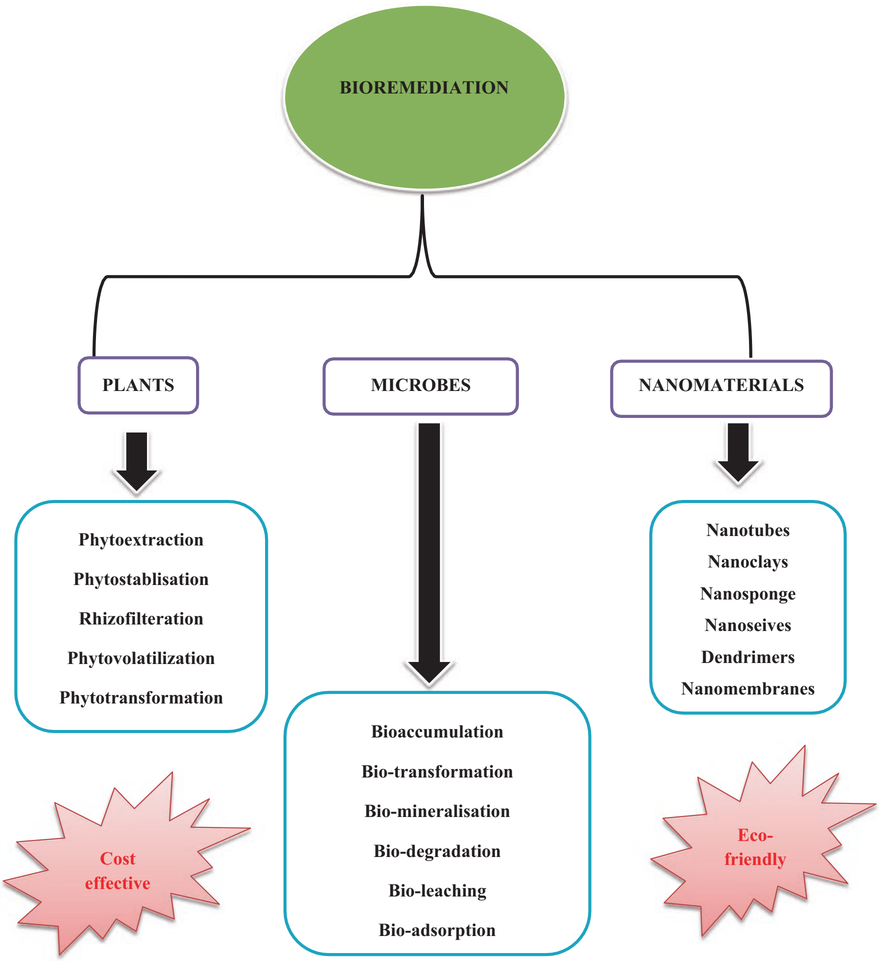

Fig. 2 Potential eco-friendly techniques for the management of organic pollutants and their types

5.1 Phytoremediation

Phytoremediation is a technique to eradicate pollutants and that came into existence approximately three decades ago. Plants have been identified as a unique agent to accumulate and immobilize persistent organic contaminants. The success of phytoremediation in degrading petroleum-based contaminants has been appreciable when compared to other physical and chemical methods that are being employed at contamination sites. Very little success has been achieved in breaking down metal and persistent organic compounds or contaminants, but phytoremediation has been a promising candidate in degrading heavy metal and organic contaminants. It is a common phenomenon for plants to metabolize the substances that are available to them in the surroundings; plants accumulate and degrade complex substance into simpler ones by nature to obtain their requirements from the abiotic environment (Vidali, 2001). Phytoremediation has gained the attention and trust of many researchers to effectively clear the contaminants from the site in a safe and cost-effective manner. Phytoremediation is not limited to the removal of impurities and contaminants from soil alone, but the field has also extended its service in removing the contaminants from water and effluents eliminated from the industries into the surroundings (Raskin & Ensley, 2000).

In the past years, phytoremediation has taken roots in different ways based on the fate of the contaminant. Several classifications of phytoremediation have been evolved and are unique in treating various types of organic contaminants. Either one of these techniques is used at the site of the contaminant, or combinations of the techniques are used to achieve better results. The most commonly employed technique of phytoremediation is phytoextraction or simply known as phytoaccumulation. In this method, the plants take up the contaminant from the site where they are planted through their root system up to their shoots. Heavy metals are accumulated within the plants through this method, and precious metals such as silver, gold, and platinum can also be accumulated within the plant and extracted through laboratory procedures. One of the best ways to remove poisonous heavy metals such as mercury, arsenic, etc. is through phytoaccumulation technique. The next method is phytodegradation or phytotransformation where organic contaminants are ingested from the soil or the site of contamination and transformed or broken down into a less poisonous or less transportable form. Through this method, it is easier to convert hexavalent chromium to trivalent chromium which is less carcinogenic and immobile.

Reducing the mobility and transportability of the contaminants in the location can be achieved by phytostabilization. Leaching of the contaminants from one surrounding into another is a major hindrance in maintaining the quality of the ecosystem. Here leachable particles bind to the plant root or shoot and form a stable mass through absorption. This makes sure that the particles will not re-enter the environment. Rhizospheres found in the roots of the plants help in degrading the particles in the soil to a simpler form which can be easily degraded. The ability to breakdown contaminants in the surrounding through the rhizosperes of the plant roots is known as rhizodegradation. Here a special relationship between microorganism and plants is observed. The mechanism of degradation is facilitated by proteins and enzymes that are associatively produced by soil organisms and plants.

Agricultural lands containing herbicides, pesticides, metals and selenium, industrial sites containing organics, metals and arsenic, mine tailings with metals, and wood treatment sites containing PAHs can also be successfully remediated with plants (Banuelos, 2000; Ferro et al., 1999; Olson et al., 2003; Rock, 2003; Winter & Redente, 2002). Contaminated waters that can be phytoremediated include sewage and municipal wastewater comprising nutrients and metals, agricultural drainage water with fertilizer residues, metals, arsenic, selenium, boron, organic pesticides, and herbicides, industrial wastewater containing metals and selenium, coal pile run-off containing metals, landfill leachate, mine drainage, and groundwater plumes with organics and metals (EPA pub., 1999; Ferro et al., 2001; Hansen et al., 1998; Horne, 2000; Lin et al., 2000; Rock, 2003). Plants can also be used to filter air containing NO, SO_2, ozone, CO_2, dust or soot particles, nerve gases, and/or halogenated volatile hydrocarbons in both outdoor and indoor conditions (Jeffers & Liddy, 2003; Morikawa et al., 2003).

Phytoremediation is solely photo-driven as plants are autotrophs and photosynthesis is a natural process that aids phytoremediation. Phytoremediation is tenfold cheaper when compared to physical and chemical methods. In situ phytoremediation is cost effective and is safe as it reduced the exposure of the workers to the pollutants as well as reduces the exposure of wildlife to deadly contaminants (Glass, 1999). It is a green and clean initiative as bulldozers or harmful chemicals are not employed in this technique. Advantages are greater than the disadvantages in this technique and is popular among the public as mere ethical issues arise in this case (Flechas & Latady, 2003; Negri et al., 2003).

5.2 Microbial Bioremediation

Microbial remediation is an eco-friendly technique to remove the organic contaminants from the industry effluents that are eliminated into the surroundings (Singh & Nagaraj, 2006). Special concern is growing toward the microbial enzyme-based bioremediation techniques that involve oxidoreductase, hydrolases, and other such enzymes (Karigar & Rao, 2011).

Bacterial Remediation

Oil-degrading microorganisms produce biosurfactants that have low molecular weight. This property helps in degrading oils at contamination site and ocean oil spills. The water-oil interfacial tension is reduced through the biosurfactants produced by the microbes. Even high molecular weight biosurfactants can work as biodispersants by preventing amalgamation of oil in water. Lipids and proteins are the active components of the biosurfactants with high molecular weight. The surface area of the hydrophobic water-insoluble contaminants is increased by these surfactants that help in the remediation process. Overproducing bacteria with biosurfactant property is preferred for cleaning the water-insoluble lipid and oil contaminants at the site. Certain bacteria can indirectly help by stimulating the growth of the oil-degrading bacteria as well as improve their ability to degrade the hydrocarbons (Ron & Rosenberg, 2002). Degradation of PAH has been possible in the past years only through the use of bacteria, fungi, and algae that have the ability to degrade such complex molecules and immobilize them. Bacteria are less efficient in degrading PAH when compare to other microorganisms (Albert & Ravendra, 2000).

Poisonous substances can be easily degraded by microorganisms and have a high potential for bioremediation. The effect of bioremediation depends on the modifications that are included to suit the site of contamination. Chemical attraction plays a major role in effective degradation of pollutants (Sudip et al., 2002). Heavy metal contamination is considered as a crucial environmental problem due to the threats that it possesses. They can amplify through the food chain and lead to severe ecological and health-related issues in terrestrial and aquatic organisms. Employing physical and chemical techniques would be expensive and unsafe for the elimination of heavy metals and organic pollutants. Bioremediation using microbes is a safe and cost-effective method (Anushree, 2004).

Mycoremediation

Fungi including mushrooms have many enzymes that are effective in degradation of organic contaminants from industrial effluents. Numerous pollutants of various sizes can be effectively degraded using fungi, and this effective remediation method is known as mycoremediation (Purnomo et al., 2013; Kulshreshtha et al., 2013). Degradation of the impurities by mushrooms improves their biomass and the ability to secrete oxidizing and hydrolyzing enzymes (Kuforiji & Fasidi, 2008; Zhu et al., 2013). Ligninolytic enzymes that are produced by white rot fungi can degrade substrates specifically and have the capability of mineralization and transformation of POP that have analogous structure as lignin. Fungi are effective in degrading effluents from industries such as textiles, paper and pulp industry, chemical industry, etc. (Pointing, 2001).

Phycoremediation

The elimination or deduction of persistent organic pollutants from the surroundings by algae is recognized as phycoremediation and is an encouraging eco-friendly practice for the management of contaminants. More than being eco-friendly, it is a sustainable technique and a natural way to clean the decontaminated sites (Baghour, 2019). Phycoremediation is an effective method to remove heavy metals from the surroundings, and this can be achieved in two processes: biosorption and bioaccumulation. In biosorption technique, the heavy metals are passively bound to the nonliving biomass in an aqueous solution, such as the effluents from the industries, whereas in bioaccumulation technique, the metals are removed or accumulated by the algae through its metabolic activity. Green algae have gained immense interest due to its ability to bioaccumulate or biodegrade organic pollutants at major contaminated sites such as aquatic ecosystems (Iriti et al., 2009). Singh and Olsen (2011) reported that photoautotrophic organisms such as algae are important bioresources that have the ability to grow faster, have easy cultivation methods, and require less water and land resources.

Scenedesmus, *Chlamydomonas*, *Nodularia*, *Arthrospira*, *Oscillatoria*, *Spirulina*, *Botryococcus*, *Cyanothece*, *Chlorella*, *Phormidium*, *Ulva lactuca*, *Kappaphycus alvarezii*, *Desmodesmus* are the few microalgal and macroalgal species used for bioremediation purpose. Macroalgae are utmost beneficial when compared to microalgae as they can assimilate enormous amounts of macro- and micronutrients during their developmental stages. This has an advantage of minimizing the ill effects of anthropogenic activities in regard with eutrophication and algal blooms (Dubey et al. 2013; Rawat et al. 2011). The report of Madadi et al. (2016) shows that *Chlorella vulgaris* is highly potential in treating effluents from industries as they can effectively remove nutrients from petrochemical wastes. The enzymes present in the algae are perceived to play a vital role in the biodegradation of persistent organic pollutants and also the microalgae that are capable of acting as biosurfactants maximize the bioremediation at PAH-containing sites (Baghour 2019). The use of algae as a potential technique in the management of organic pollutants from industrial effluents as an alternative eco-friendly approach will reduce the environmental impact of chemical and physical methods. More than being environmental friendly, they are cost-effective that makes them good candidate in the bioremediation process from an economic perspective.

5.3 Remediation Using Nanomaterials

Nanoremediation methods necessitate the use of reactive nanomaterials of 1–100 nm in size for alteration and decontamination of pollutants. These nanomaterials must retain properties that enable both chemical reduction and catalysis to diminish the impurities of concern. The advantage of this method is the on-site bioremediation of the contaminants; transport of the contaminated soil or water is not required for treating the impurities (Otto et al. 2008). The unique properties of the nanomaterials make them the desired candidate for bioremediation process. Nanomaterials are characterized by small size, large surface area, ability to penetrate through narrow spaces, ability to withstand in ground water, wider distributions, and options of various coating for specific targeting of the pollutants. Their smaller size encourages them to penetrate deep into the ground when compared to large particles of macro size. However, transportation is not possible though penetration can be achieved. Long distance transport of the nanoparticles through the ground cannot be achieved (Tratnyek and Johnson 2006). Zeolites have attracted the researches due to their stubborn character in eliminating the contaminants. Carbon nanotubes and fibers are widely used in removing pollutants at various contamination sites. Enzymes that are biocatalysts and proteins by nature are also used to synthesize nanoparticles that can be effectively used in nanoremediation. Metallic nanoparticles, nanoparticles produced by the amalgamation of two or more metals, by coating polymers unto their surface, titanium dioxide nanoparticle, and nanoparticles synthesized from noble metals are the present stand of researchers worldwide to solve the ever-growing problem of environmental pollution (Theron et al. 2008; Zhang 2003).

Mechanisms through which nanoremediation works is mostly through the Brownian movement or random motion that helps them to move or transport in effluents rather than wall effects. Gravity plays a chief role in controlling the movement of the nanoparticles as they tend to sediment and their movement is further restricted. Density of the nanoparticles is a driving characteristic in nanoremediation as it can force the particle to settle down limiting its ability to degrade the contaminants. Surface electrostatic force does not interfere in manufacturing process since nanosize particles can easily suspend themselves in water which makes these nanoparticles as a versatile remediation tool and provides an option to inject liquid into the surface where the impurities are present. Iron nanoparticles are usually coated with polymers or other substances to improvise their reacting ability and the rate of transport. The small size results in the entrapment of the nanoparticles within the soil, which subsequently restricts their flow along with the groundwater. This has been found as a major setback in in situ bioremediation using nanoparticles (Henn & Waddill 2006).

Aggregation of the synthesized nanomaterials when they are released into the surrounding makes the nanoparticles behave like natural materials. As stated earlier, transport to further areas is a limitation with nanoparticles, but researchers have synthesized nanoparticles taking into consideration the hydrological properties of the water at the site of contamination in order to provide the opportunity of long distance travel to the particles that are used for remediation (Kersting et al. 1999; Novikov et al. 2006; Vilks et al., 1997). Colloids are highly capable of forming nanoclusters that are stable and portable; they can carry the contaminants by absorbing them from the surface. Since they can absorb particles in between the redox zones, they can facilitate the inhibition of pollutant transport. Aggregation, sedimentation, and dispersion are the major factors that determine the effective activity of the nanoparticles without forming clusters to degrade the contaminants in the environment (Waite et al. 1999). Gilbert et al. (2007) reported that inorganic nanoparticles may exhibit the same property of cluster formation as found in natural nanomaterials; hence, it is necessary to study the fundamental properties of the synthesized nanoparticles for better performance. Self-aggregation is regarded as the major problem that hinders the use of the particles in remediation as the fear of particles entering the food chain prevails. They can remain as suspended solids in drinking water through bioaccumulation (Boxall et al. 2007).

Diffusion of nanoparticles to other location generally occurs when the nanoparticles are released into the environment. When nanoparticles such as iron oxide bound to copper are used, they are found to travel for longer distances in mining sites to degrade heavy metals, hydrocarbons, and other organic materials. This shows that these particles can move along and degrade the required particles at the required site (Hochella et al. 2005). Size-dependent reactivity and binding ability is observed in these particles based on their kinetic and thermochemical relationships in regard to the size (Madden et al. 2006). It is studied that nanoparticles are harmless in nature but can possess toxic properties by absorbing the pollutants that they are adhered too and can potentially be toxic to humans, animals, aquatic being, and the environment. Copper which is bound to the iron oxide nanoparticles can be potentially harmful to fungi, algae, and other aquatic plants as they are toxic in general. The only way to surpass copper toxicity is by using mercury or copper which can be harmful in other ways (Sposito 1989). Public believe that nanoparticles that are used for in situ remediation possess risks that are unknown. Nongovernmental and nonprofit groups are against the use of nanoparticles stating that precautions must be taken before the use of these particles for remediation, and until their safety is proved to the public, use of such particles must be restricted. In early 2003, the ETC Group called for the counteractive principle to be functional to the practice of nanotechnology (ETC Group 2003). Their apprehensions were about manifold nanoscale machines that can influence self-replication and change matter into “gray goo” (Drexler 1986).

6 Advantages and Limitations of Bioremediation

Bioremediation techniques are considered as effective and eco-friendly technique to manage organic pollutants from industry effluents, yet they have their own advantages and limitations. This section discusses the various advantages and disadvantages that are experienced in bioremediation techniques.

In ex situ techniques, biopile technique has constructive feature, effective biodegradation strategy, the ability to control and maintain temperature, and aeration is available. But this technique requires space, and the cost of maintenance is also high. Power supply is a prerequisite; hence, loss of power supply in remote areas can be a hindrance and lead to contamination without uniform distribution of air on the effluents (Sanscartier et al., 2009). Windrow treatment methods show higher rate of hydrocarbon removal than biophile method. They can be the best options to remediate the toxic volatiles, yet they are assumed to release methane into the atmosphere due the reduction reaction that occurs which is a harmful greenhouse gas (Coulon et al., 2010). Phytoremediation is so far considered as a best method to treat organic pollutants. Accumulation, extraction, filtration, stabilization, and degradation are the several mechanisms involved depending on the type of the pollutant. Plants provide an easy platform to remove elemental pollutants such as heavy metals and radionuclides that are toxic in nature. Hydrocarbons and chlorinated compounds are removed by mechanisms such as stabilization, rhizoremediation, and degradation. Meagher (2000) and Kuiper et al. (2004) have reported the removal of hydrocarbons and chlorinated compounds by using willow and alfalfa plants for bioremediation.

The major factors that influence the effect of phytoremediation are root system, above-ground biomass, concentration of the pollutant, toxicity of the pollutant, climatic conditions, and location of the site. The important advantage of using plant as remediation agents is the opportunity of bioaccumulating precious metals that can be recovered by phytotoming. Moreover, they are environmental friendly, require low cost of operation and maintenance, and they can also improve soil fertility (Mench et al., 2009). The few limitations that researchers have overcome while using phytoremediation are longer remediation time, toxicity, and slow growth of the plant and depth of the roots.

7 Current Status and Future Prospects of Bioremediation

Bioremediation techniques have proven to be potential sources for the management of organic pollutants from industry effluents without any doubt. Different types of wastes are being treated with different techniques to manage the pollutants in an effective way. Microbes have gained immense attention due to the crucial role they play in restoring the contaminated sites. There is an increased knowledge in identification of microbes and its metabolic pathways involved in degrading the pollutants through bimolecular techniques such as genomics, proteomics, transcriptomics, and metabolomics (Wang et al., 2012). This helps in overcoming the limitation that is observed in bioremediation sites. Nutrient requirements, compatibility among different microorganisms at the study site, and bioavailability of nutrients are being continuously studied by the researchers. Microbes are cost-effective when compared to other physicochemical methods. The major preference for microorganisms when compared to phytoremediation is the fast multiplication rate. Slow growth observed in plants is often a limitation when it comes to degrading the organic pollutants. Biostimulation and bioagumentation are the recent techniques practiced using microbes to degrade pollutants. In biostimulation, nutrients are added to the polluted sit to stimulate the activity of the autochthonous microbes. This method will reduce the limitation of nutrition availability in polluted sites. On the other hand, the method of bioagumentation aims at increasing the number of microbes with degrading capacity at the site of pollutants. Moreover, it was observed that microbial consortium is capable than pure isolates in degrading the organic pollutants efficiently (Silva-castro et al., 2012; Bhattacharya et al., 2015).

Prospects in bioremediation techniques are increasing in the current scenario, which tends to make bioremediation as the most potential techniques to manage organic pollutants from industry effluents. It is regarded that application of more than a single remediation technique at site can help increase the efficacy and decrease the time required for the bioremediation process. By this way, the limitation of one method can be overcome by the advantage of another. Simultaneous application of eco-friendly multiple remediations can reduce the cost and make it feasible (Cassidy et al., 2015). Banitz et al. (2016) suggest that information regarding the spatial configuration of bacterial dispersal through the application of combined metrics can act as an indicator of biodegradation performance.

Genetically engineered microorganisms (GEMs) have earned the attention of researchers in different fields and applications. Bioremediation efficacy can be enhanced by planning the effective and controlled use of genetically engineered microorganisms. GEMs can act as a biocatalyst and effectively target pollutants as well as recalcitrant compounds and degrade then. They can incorporate novel metabolic pathways or use existing pathways for the purpose of degradation. Use of horizontal gene transfer is also a promising approach; use of suicide systems in GEM can kill the microorganisms that try to escape the contaminated sites, and this will help in gaining public acceptance. GEMs can be engineered with special degrading pathways to target a particular compound in a short span of time (Paul et al., 2005). The future of nanomaterials in remediation techniques can reach great heights if the methods are executed precisely. Nanomaterials have increased surface area and require low activation energy, which can help in increasing the potential of nanoparticles at degradation sites. The overall time and cost of remediation can be reduced with the strategic use of nanoparticles (Rizwan et al., 2014; Azubuike et al., 2016).

8 Conclusion

Organic pollutants from industry effluents have become a major stress to the environment. Though industries are installed with treatment plants in recent days, a large amount of the organic pollutants reach the surroundings through the effluents that are eliminated from the industries. Physicochemical methods that have been conventionally used for the management of organic pollutants are costly and require superior maintenance. Eco-friendly techniques such as bioremediation require low cost of installation and maintenance. Microorganisms and plants have been employed as potential bioremediation technique for the management of organic pollutants. The type of the organic pollutants present in the effluent and location of the polluted site are the major factors that determine the efficacy of the bioremediation site. The bioremediation technique that has to be applied must be carefully determined by taking into consideration the nature of the pollutant, feasibility of the procedure, cost of installation, and performance of the particular technique. The effectiveness of the method entirely depends on proper planning and execution of the suitable method.

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