REVIEW

Enhanced remediation of pollutants by microorganisms–plant combination

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Abstract

The pollutants have become ubiquitous in the total environment (water, soil and air) due to human activities and they are hazardous to all forms of life on the earth. This problem has made scientists focus on mitigating or complete reduction in pollutants by several means. Microorganism and plants are known to scavenge pollutants. Both are studied enormously in reducing, refining, and removing pollutants from the environment successfully. But, their slow process for removal is disadvantage. However, according to recent advancements in the abatement of pollutants, a combined system of both microorganisms and plant has shown to enhance the remediation of pollutants to an efficient level. In a nutrient-depleted pollutant-rich environment, when suitable plant and microorganisms are introduced, the plant interacts with the rhizosphere and root associate with microorganisms to survive in toxic conditions. The chemicals released by plants signal the microorganisms for interactions. This interaction leads in higher germination efficiency and enhanced root elongation which results in enhanced degradation of pollutants in both rhizosphere and phyllosphere. In this background, the current review article provides an overview of the recent advancement in microorganisms plant combined systems in enhanced removal of several recalcitrant pollutants. The conclusion highlights the challenges and future perspectives in this area of research.

Keywords Bioremediation · Environment · Pollutants · Pollution

Introduction

The total environment, which includes water, soil, and air ecosystems, has been adversely affected by the activities carried out by human beings around the globe, and his activities are changing the earth due to pollution (Hill 2020). The effect of environmental pollution (water, soil, and air) is increasing due to accelerated industrialization and urbanization throughout the world. This has resulted in more than twelve million deaths worldwide and twenty-two percent of the global burden of disease in 2012. More than one million children younger than five years of age die each year due to living in a polluted environment (Xu et al. 2018a). There are numerous reports on the effect of pollution on human health.

Some effects include, (1) usage of synthetic chemicals, and the presence of heavy metals in nature threatens integral reproducibility in males (Jenardhanan et al. 2016). (2) Environmental pollutants lead to change in gut microbiota which alters the host immune system and influences in host's energy metabolism, nervous system, cardiovascular system, and endocrine system, either directly or indirectly (Jin et al. 2017). (3) Human milk has been detected with polychlorinated biphenyls and heavy metals such as arsenic, lead, cadmium, and mercury (Pajewska-Szmyt et al. 2019). These effects result in several physiological, mental, economic, and social status of society. As the pollution level increases, health expenditures also increase (Hao et al. 2018). Pollution will impact societal development and condemns future generations to continue poverty and endless poor health encourages social unrest, war, and migration (Landrigan and Fuller 2015). The only solution to these problems is to bring down the pollution levels. From recent lockdown around the globe due to the outbreak of COVID-19 pandemic where most human activities were halted, resulted in the reduction in pollution and nature reclaiming itself. This showed the world how to reduce pollution on a long-term basis (Muhammad

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et al. 2020). However, the total shutdown or lockdown of human activities to bring down the pollution levels cannot be accepted by stakeholders or policymakers owing to an economic crisis. The next best option to remove is through biological means. Biological methods include microbial bioremediation (bacterial remediation, mycoremediation, phycoremediation), enzymatic remediation, vermiremediation, phytoremediation, and zooremediation. Microorganisms alone have the potential to remove pollutants to some extent. Literature studies state that, bioremediation using microorganisms and phytoremediation using plants is the cheapest method employed for the removal of pollutants. Their slow process for removal is a disadvantage. However, a combined system of both plants and microorganisms can enhance the remediation process to an efficient level. The Plant–Microbe rhizoremediation provides several advantages, including the degradation of pollutants, uptake by plants, sorption of pollutants, and enhancement of plant tolerance towards pollutants (Nasr 2019). Considering this, this review focuses on recent research on the microorganisms–plant combination in the successful enhancement of remediation of pollutants of the total environment.

Remediation of pollutants

Active management strategies (Physical and Chemical) can help preserve and restoring conservative total environment systems. However, these methods are not efficient, cost-effective, and not enough to mitigate pollutants due to the continuous regeneration of recalcitrant pollutants by anthropogenic activities (Dangi et al. 2019). Phytoremediation of contaminants by plants and biodegradation of contaminants by microorganisms alone is often not complete because of phytotoxicity and/or evapotranspiration of pollutants. However, a biological process performed by microorganisms and plants could be combined to clean up the hazardous pollutants in the total environment (Mandal et al. 2016; Mishra et al. 2020; Weyens et al. 2009). Microorganisms can be employed in the biodegradation of all types of pollutants and recalcitrant molecules of complex nature (Thakur 2018). In a nutrient-depleted polluted-rich environment, plants interact with the rhizosphere and root associate with microorganisms to survive in toxic conditions. The chemicals released by plants signal the microorganisms for interactions. Microaerophilic conditions will be provided by plants and also exudate from roots enhances the degradation of contaminants. Plant roots stimulate microorganisms by making pollutants available for microorganisms by first providing the substrates and secondly by altering the pH (Hussain et al. 2018). The pollutants accumulated in plants can be degraded by microorganisms introduced into the tissues of the plant. When suitable microbial strain is introduced into the pollutant environment with a suitable plant (more absorbance and strong tolerance), the combined system of both plant and microbe together combine with the indigenous population to enhance the bioremediation process by several mechanisms and environmental factors (Erguven, Yildirim and Adar 2017; Kuiper et al. 2004; Lee et al. 2020; Saravanan et al. 2020; Truu et al. 2015; Fig. 1). This Microbe-Plant combined system can revolutionize the industry by bringing economic, environmental, and social benefits to all stakeholders (Abhilash et al. 2012).

Enhanced removal of excess nutrients/pollutants in aquatic environment

Nutrient removal from surface water is attracting attention as eutrophicated water can cause severe environmental concerns and even threaten human health (Jiang et al. 2019). A plant–microbe interaction in an aquatic system especially on rhizoplane is common (Srivastava et al. 2017), which can be used in the removal of excess nutrients/pollutants by dual potential candidates. The enhanced removal of various pollutants from water by the combination of microorganisms and plants is given in Table 1.

Combination of plants (*Lolium perenne* var. Top One (LPT) and *Lolium perenne* var. respect (LPR) and microbial species (*Bacillus* sp. MOE1 and *Microbacterium* sp. MOE2) enhanced the removal of ammonium nitrogen (NH_4^+-N), Phosphorus, and COD_{Mn} from eutrophicated water (Li et al. 2011). Success in removal of pollutants depends upon concentration of pollutants and presence of plants and plants association with planktonic bacterial communities in water. The study conducted by Xu et al. (2018b), showed that plant species *Phragmites australis*, *Nymphaea alba*, and *Myriophyllum verticillatum* were able to remove organophosphorous pesticide chlorpyrifos from eutrophicated water in which there was influence of planktonic bacterial communities. Enhancement of plant growth was attributed by making carbon available to submerged plant species *Vallisneria natans* by inoculation of bacterial species *Pseudomonas putida* KT2440. The Photocooperation between *V. natans* and *P. putida* KT2440 increased the carbon availability (Gan et al. 2018). In another study, four macrophytes (*Brachia mutica*, *Typha domingensis*, *Phragmites australis,* and *Leptochala fusca*) were used to remove trace elements (Fe, Mn, Ni, Pb, and Cr) from polluted river water by floating treatment wetlands (FTWs). Enhanced removal of elements was reported when FTWs was inoculated with endophytic bacterial strains *Aeromonas salmonicida*, *Pseudomonas indoloxydans*, *Bacillus cerus*, *Pseudomonas gessardii*, and *Rhodococcus* sp. The work showed combination of different species increased in removing heavy metals efficiently than single species (Shahid et al. 2020).
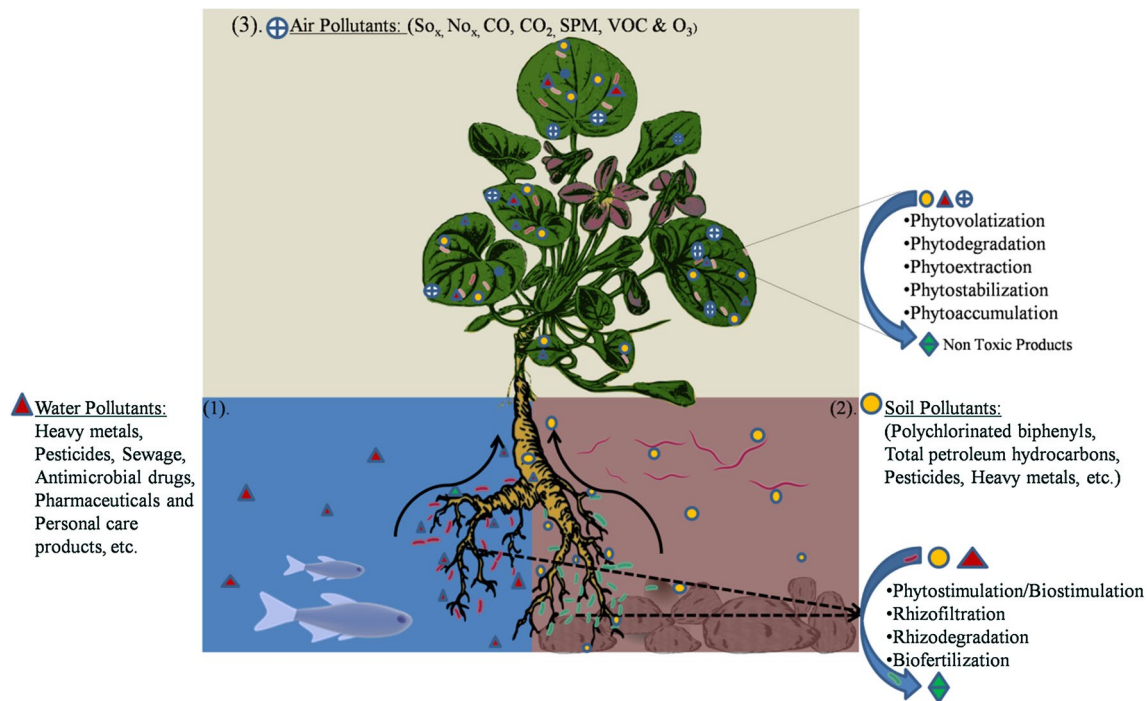
Fig. 1 Mechanism of Microorganism plant interaction in enhanced degradation of pollutants in (1). Water, (2). Soil and (3). Air

Eight plant species *Syngonium podophyllum*, *Sansevieria trifasciata*, *Euphorbia milii*, *Chlorophytum comosum*, *Epipremnum aureum*, *Dracaena sanderiana*, *Hedera helix*, and *Clitoria ternatea* were evaluated for removal of benzene in hydroponic conditions. Among them *C. comosum* showed highest efficiency in removal, a non-sterilized plant which was associated with both endophytic and epiphytic bacteria (Sriprapat and Thiravetyan 2016). Selection of suitable microorganisms in remediation of pollutants plays an important role to reduce the opposite effects of insecticides in agricultural areas (Tatar et al. 2020). Total nitrogen present in eutrophic water body was reduced by combination of immobilized nitrogen cycling bacteria (INCB) with aquatic macrophytes in the study carried out by (Chang et al. 2006). The two seasonal plants *Eichhornia crassipes* and *Elodea nuttallii* provided favorable conditions in roots to INCB to colonize. The microorganisms plants jointly removed total nitrogen (TN) by 70.2%, nitrite and ammonium by 92.2% and 50.9%, respectively. Sauvêtre et al. 2018 worked on removal of pharmaceutical frequently categorized as a recalcitrant pollutant Carbamazepine (CBZ) from aquatic environment by a plant species A*rmoracia rusticana* in combination with *Rhizobium radiobacter* and Diaphorobacter *nitroreducens* (10%). The dual system enhanced the pollutant removal significantly.

Lolium perenne L. and *Arabidopsis thaliana L* in association with endophytic bacteria *Pseudomonas* sp. reduced Total petroleum hydrocarbon (TPH)- Diesel significantly.

Application of bacteria reduced phytotoxicity and suggested that inoculation had a positive effect on plant growth under stress conditions as compared to control (without bacteria) Iqbal et al. 2019. The plant *Halonemum strobilaceum* growing in hyper saline conditions of Arabian Gulf harbor constituted oil utilizing bacteria in phyllosphere and rhizosphere. Frequent genera included yeast *Candida utilis* and the two proteobacteria *Ochrobactrum* sp. and *Desulfovibrio* sp. In rhizosphere, *Halobacterium* sp. and *Halococcus* sp., the firmicute *Brevibacillus borstenlensis*, and the proteobacteria *Pseudoalteromonas ruthenica* and *Halomonas sinaensis* was found. All the strains except yeast were found to be excellent degraders of polluted oil. The study concluded that *H. strobilaceum* could be used to phytoremediation of oil-polluted hypersaline environments via rhizosphere technology (Al-Mailem et al. 2010).

Under hydroponic conditions, *Dracaena sanderiana* inoculated with two plant growth-promoting (PGP) bacterial strains, *Bacillus thuringiensis* and *Pantoea dispersa*, removed one of the most abundant endocrine-disrupting compounds Bisphenol A (BPA). The Microorganisms–Plant combined system enhanced removal of BPA up to $92.32 \pm 1.23\%$ (Suyamud et al. 2018). Wu et al. 2016 worked on removal of nitrogen from water by hydroponic condition using three macrophyte species *Typha augustifolia*, *Phragmites australis*, and *Acorus calamus L.* The three species were fed with synthetic waste water. From the result, it was evident that there was co-relation between

Table 1 Microorganism–plant combined system in enhancing nutrients/pollutants removal from aquatic water systems

Sl. no	Xenobiotics	Plant species	Microorganisms	References
1	Ammonium nitrogen (NH_4^+ -N) Phosphorus, and COD_{Mn}	*Lolium perenne* var. Top One (LPT) *Lolium perenne* var. respect (LPR)	*Bacillus* sp. MOE1 *Microbacterium* sp. MOE2	Li et al. (2011)
2	Chlorpyrifos	*Phragmites australis* *Nymphaea alba* *Myriophyllum verticillatum*	Planktonic bacterial communities	Xu et al. (2018b)
3	Carbon dioxide	*Vallisneria natans*	*Pseudomonas putida* KT2440	Gan et al. (2018)
4	Fe, Mn, Ni, Pb, and Cr	*Brachia mutica, Typha domingensis, Phragmites australis* and *Leptochala fusca*	*Aeromonas salmonicida, Pseudomonas indoloxydans, Bacillus cerus, Pseudomonas gessardii,* and *Rhodococcus* sp.	Shahid et al. (2020)
5	Benzene	*Syngonium podophyllum, Sansevieria trifasciata, Euphorbia milii, Chlorophytum comosum, Epipremnum aureum, Dracaena sanderiana, Hedera helix,* and *Clitoria ternatea*	*Enterobacter EN2, Cronobacter EPL1,* and *Pseudomonas EPR2*	Sriprapat and Thiravetyan (2016)
6	Decaclorobiphenyl PCB-209 by	*Ocimum basilicum L*	*Acinetobacter, Bacillus, Lysinibacillus, Novosphingobium, Pseudomonas, Rhizobium, Sphingobium, Stenotrophomonas,and Terribacillus as well as bacterial strains Pseudomonas taiwanensis BS-1, Rhizobium nepotum BS-2, Terribacillus sacharophilus BS-3, Stenotrophomonas rhizophila BS- 4, Bacillus arybhattai BS-5,* and *Lysinibacillus macroides BS-6*	Sánchez-Pérez et al. (2020)
7	Nitrogen	*Eichhornia crassipes* *Elodea nuttallii*	Immobilized nitrogen cycling bacteria (INCB)	Chang et al. (2006)
8	Carbamazepine (CBZ)	*Armoracia rusticana*	Rhizobium radiobacter Diaphorobacter nitroreducens	Sauvêtre et al. (2018)
9	Total petroleum hydrocarbon (TPH)-Diesel fuel	*Lolium perenne L.* *Arabidopsis thaliana L*	*Pseudomonas* sp.	Iqbal et al. (2019)
10	Oil	*Halonemum strobilaceum*	*Ochrobactrum* sp., *Desulfovibrio* sp., *Halobacterium* sp., *Halococcus* sp., *Brevibacillus borstenlensis, Pseudoalteromonas ruthenica* and *Halomonas sinaensis*	Al-Mailem et al. (2010)
11	Nitrogen	*Typha augus tifolia, Phragmites australis, and Acorus calamus L*	Microbial Community	Wu et al. (2016)
12	Nitrophenols (NPs)	*Spirodela polyrhiza*	*Pseudomonas* sp. (strain ONR1) *Cupriavidus* sp. (MFR2) *Rhodococcus* sp. (PKR1) *Rhodococcus* sp. (DNR2)	Kristanti et al. (2014)
13	Phenol and Cr (VI)	*Brassica napus*	*Pantoea sp. FC 1*	Ontañon et al. (2014)

plant biomass and total nitrogen removal with involvement of microbial community. Water contaminated with nitrophenols (NPs), 2-NP, 3-NP, 4-NP, and 2,4-dini- trophenol (2,4-DNP) was rhizoaugmented with NP-degrading bacteria to giant duckweed (Spirodela polyrhiza). The four NP-degrading bacterial strains were found to colonize *Spirodela* roots resulted in complete removal of NPs within each cycle (Kristanti et al. 2014). The bacterial strain *Pantoea* sp. FC 1 resistant to phenol and Cr (VI) used phenol as sole carbon source and also able to reduce Cr (VI) to Cr (III). The strain was inoculated into rhizosphere *Brassica napus* hairy roots (HRs). The efficiency in removal of phenol and reduction from Cr (VI) to Cr (III) was improved with combination of both microorganisms and plant (Ontañon et al. 2014). The pollutants included organic substances such as nitrogen and phosphorous, various heavy metals, pesticides, hydrocarbons, phenolic compounds, pharmaceutical wastes, and personal care products.

From the above discussed studies, it is evident that the combination of microorganisms and plant species was successful in enhancing the removal of aquatic pollutants such as excess nutrients, benzene, total petroleum hydrogen (TPH), phenol and pharmaceuticals pollutants. The mechanism behind the removal of these pollutants includes phytostimulation/biostimulation, rhizofiltration, rhizodegradation, and biofiltration.

Enhanced removal of excess nutrients/pollutants in terrestrial environment

Soil is the ultimate sink for all pollutants that has been neglected, which resulted in the deterioration of its quality in several sites across the world (Sakshi et al. 2019). The management of soil contaminated with persistent organic pollutants (POPs) by plant–microbe interactions is a low-cost prospective biotechnological approach (Sarma et al. 2019). Microorganisms partnership with plants can be used to overcome problems related to the soil such as salinity, fertility, degradation, and habitat loss (Pandey et al. 2019). There are several successful attempts in the removal of pollutants from the soil by microorganisms–plant combination. The enhanced removal of various pollutants from the soil by the combination of microorganisms and plants is given in Table 2.

Enhanced removal of phenylurea herbicide (PH)- isoproturon (IPU) from contaminated sites was achieved by the action of plant–microbe interactions. Transgenic *Arabidopsis thaliana* plant converted IPU into to 3-(4- isopropylphenyl)-1-methylurea (MDIPU). The released intermediate was further metabolized by the combinedly inoculated MDIPU— mineralizing bacterium *Sphingobium* sp. strain 1017–1 in the rhizosphere, resulting in an enhanced and complete removal of IPU from soil (Yan et al. 2018). Synergistic activity between plant (*Saccharum* sp.) and yeast (*Candida* VITJzN04) enhanced removal of organochlorine pesticide lindane (~ 100 mg/kg) in ex-situ remediation carried out by (Salam et al. 2017). In another study *Cytisus striatus* in association with different dual bacterial inoculants was assessed for dissipation of the insecticide hexachlorocyclohexane (HCH). Interaction between the dual bacterial species with *Cytisus striatus* enhanced the removal of insecticide up to 53% (Becerra-Castro et al. 2013). Similarly, a recent study on biodegradation of monocrotophos (MCP) by Dash and Osborne 2020 showed enhancement in removal of MCP by *Bacillus aryabhattai* VITNNDJ5 and *Liriope muscari* in combination. Two actinobacteria *Streptomyces* sp. Z38 and *Streptomyces* sp. Z2 was grown with maize root exudates to remove pesticide lindane and metal Cr (VI). Good performance in removal of mixed contaminants was observed and also improved plant establishment (Simón Solá et al. 2019).

Shi et al. 2019 also analyzed efficiency of Ectomycorrhizal (ECM) fungi *Hebeloma vinosophyllum* (Cr (VI)-sensitive strain) and *Pisolithus* sp1 (Cr (VI)-tolerant strain) along with Japanese black pine (*Pinus thunbergii*) in removal of Cr (VI) from soil. *Pisolithus* sp1 had a significantly higher accumulation of Cr than *H. vinosophyllum* in mycelium under the same Cr (VI) treatments in liquid culture experiment. Accumulation of 17α-ethynylestradiol (EE2) in soil and environment due to land application of sewage sludge and animal manure as influenced on human and animal health. He et al. 2019 isolated EE2-degrading bacteria *Hyphomicrobium* sp. GHH and inoculated with plant *Lolium perenne*. Inoculation of bacterial isolate increased accumulation of EE2 significantly in the plant and removal of EE2 up to 99%. The interaction between two candidates is having a synergistic effect on the EE2 removal.

Plant-Microorganisms joint interaction in crude oil degradation showed higher efficiency in the rhizospheres of *Scorzonera mongolica Maxim.*, *Atriplex centralasiatica*, and *Limonium bicolour* by larger shoot and root biomass than non rhizospheric soil (Ying et al. 2011). Chloronitroaromatic pollutant, 4-chloronitrobenzene (4CNB) was degraded by application of bacteria strain *Comamonas* sp. strain CNB-1 isolated from activated sludge into rhizosphere of Alfalfa. The pollutant 4CNB was removed within two days (Liu et al. 2007). Four plant growth promoting bacteria (PGPB) *Arthrobacter* sp., *Bacillus altitudinis*, *Bacillus megatherium* and *Sphingomonas* were investigated to check the effects of these PGPB on plant growth and Cd accumulation of oilseed rape (*Brassica napus*) plants grown on aged Cd-spiked soil. Enhanced uptake of Cd was seen in *Brassica napus* and also there was significance in shoot biomass and Plant Analyzer Development (SPAD) due to combination of both PGPB and Plant (Pan et al. 2017).

Table 2 Microorganism–plant combined system in enhancing nutrients/pollutants removal from soil environments

Sl. no	Xenobiotic	Plant species	Microorganisms	References
1	Phenylurea herbicide (PH)-isoproturon (IPU)	*Transgenic Arabidopsis plant*	*Sphingobium sp. strain 1017–1*	Yan et al. (2018)
2	Lindane	*Saccharum* sp	*Candida VITJzN04*	Salam et al. (2017)
		Cytisus striatus	*Rhodococcus erythropolis ET54b* *Sphin- gomonas sp. D4*	Becerra-Castro et al. (2013)
3	Monocrotophos (MCP)	*Liriope muscari*	*Bacillus aryabhattai VITNNDJ5*	Dash and Osborne (2020)
4	Lindane and Cr(VI)	maize root exudates	*Streptomyces sp. Z38* *Streptomyces sp. Z2*	Simón Solá et al. (2019)
5	Cr(VI)	*Pinus thunbergii*	*Hebeloma vinosophyllum* *Pisolithus sp1*	Shi et al. (2019)
6	17α-ethynylestradiol (EE2)	*Lolium perenne*	*Hyphomicrobium sp. GHH*	He et al. (2019)
7	Crude oil	*Scorzonera mongolica Maxim., Atriplex centralasiatica, and Limonium bicolor*	growth-promoting rhizobacteria	Ying et al. (2011)
8	4-chloronitrobenzene (4CNB)	Alfalfa	*Comamonas sp. strain CNB-1*	Liu et al. (2007)
9	As, Cd, Pb and Zn	Acacia saligna and Eucalyptus camaldulensis	rhizosphere microorganisms	Guarino and Sciarrillo (2017)
10	Nitrobenzene	Phragmites australis-JS45 system	Proteobacteria and Firmicutes	Chi et al. (2018)
11	Bisphenol A (BPA)	*Dracaena sanderiana*	*Bacillus thuringiensis* and *Pantoea dispersa*	Suyamud et al. 2018
12	Cadmium (Cd)	poplar (clone "I-214")	*Pseudomonas fluorescens*	Cocozza et al. (2014)
13	Dioxin	*Trifolium repens L*	*Comamonas sp.* strain KD7	Wang and Oyaizu (2011)
14	Polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Cd and Zn)	ryegrass	*Microbacterium sp. KL5* *Candida tropicalis C10 in*	Chen et al. (2016)
15	Lead (Pb)/zinc (Zn)/ cadmium (Cd)	*Sedum plumbizincicola* *Sedum plumbizincicola*	*Bacillus sp. SC2b*	Ma et al. 2015
16	Ni, Cr, and Cd	*Brassica juncea*	*Pseudomonas aeruginosa KP717554* *Alcaligenes feacalis KP717561* *Bacillus subtilis KP717559*	Ndeddy Aka and Babalola (2016)
17	As, Cd, Cu, Pb, and Zn	*Lupinus luteus*	*Serratia sp. MSMC541*	El Aafi et al. (2012)

Integrated Phytoremediation System (IPS) was applied for removal of heavy metals As, Cd, Pb and Zn in soil. The two plant species *Acacia saligna* and *Eucalyptus camaldulensis* along with rhizosphere microorganisms showed considerable amount of pollutants removal (Guarino and Sciarrillo 2017). (Chi et al. 2018) conducted experiments for removal of nitrobenzene from sediments using *Phragmites australis*-JS4. The efficiency of removal of nitrobenzene was not significant by *Phragmites australis*-JS4 alone. However the pollutant was degraded with twenty days by indigenous microorganism which was quantified using real-time polymerase chain reaction. Enhanced remediation of dioxin contaminated soil by dibenzofuran-degrading bacterial strain *Comamonas* sp. KD7 and Plant *Trifolium repens L* was reported by (Wang and Oyaizu 2011). After twelve weeks of growth, significance in reduction in dioxin

was achieved. Green house study conducted by Chen et al. 2016 to remove polycyclic aromatic hydrocarbons (PAHs) and heavy metals (Cd and Zn) from soil by microbe-plant combination revealed that, ryegrass with *Seduce alfredii* inoculated with microbial strains *Microbacterium* sp. KL5 and *Candida tropicalis* C10 removed the pollutants in to be below standard limit.

Removal of oil refinery sludge by association of plant growth-promoting rhizobacteria and polycyclic aromatic hydrocarbon-degrading bacteria in combination with pasture plants was carried out by (Pizarro-Tobias et al. 2015). The combination of both microorganisms and plant was able to remove total hydrocarbons within seven months compared to control soil site which was carried out only by plant. Presence of three grass species *Cymbopogon ambiguus, Brachiaria decumbens,* and *Microlaena stipoides* increased the

efficiency of microorganisms in removing remediation of diesel/oil contaminated soil, without any requirement for nutrient supplementation (Gaskin and Bentham 2010). Plant growth-promoting bacteria (PGPB) *Bacillus* sp. SC2b was used as metal mobilizing bioinoculant for rhizoremediation of soils polluted with metals lead (Pb)/zinc (Zn) and cadmium (Cd). The bacterial strain was inoculated into rhizosphere of plant *Sedum plumbizincicola* and *Brassica napus* which resulted in mobilization of high concentration of heavy metals from soils (Ma et al. 2015). Another study carried out by (Kanat et al. 2018) showed control and preventive measures of heavy metals contamination. Similarly heavy metal (Ni, Cr, and Cd) was removed by combination of *Brassica juncea* and three bacterial strains *Pseudomonas aeruginosa* KP717554, *Alcaligenes feacalis* KP717561, and *Bacillus subtilis* KP717559. Inoculation of these three bacterial strains improved germination of *B. juneca* and also significance in solubilization of heavy metals (Ndeddy Aka and Babalola 2016). The plant Lupinus luteus grown in soil and was supplemented with heavy metal along with inoculation of bacterial strain *Serratia* sp. MSMC541. Inoculation of bacterial strain improved the tolerance of plant species to heavy metals (El Aafi et al. 2012). Apart from these pollutants, solid waste generation is another major problem encountered across the globe. The organic waste which accounts for 40–70% of total municipal solid waste (MSW) requires attention for its management (Kanat and Erguven 2020).

Soil pollutants included pollutants such as pesticides (herbicides, weedicides and insecticides), heavy metals, total hydrocarbons and other recalcitrant compounds. The combination of microorganisms and plants with single species or combination of several species enhanced the removal of pollutants from soil effectively.

Enhanced removal of excess nutrients/ pollutants in atmosphere

Air pollution is a major culprit that enhances pulmonary disorders such as asthma, chronic obstructive pulmonary disease, lung cancer, and respiratory infections in susceptible populations, such as children, the elderly, and those of low socio-economic status affecting nine of 10 individuals living in urban areas worldwide (Kurt et al. 2016). Plant–microorganisms combined system can be used to clean up both indoor and outdoor air systems to remove major air pollutants (O_3, PM_{10}, NO_2, SO_2, and CO). This can be accomplished by selecting appropriate plant species and specific microbial communities to remove pollutants maximum (Irga et al. 2020). The enhanced removal of various pollutants from atmosphere by the combination of microorganisms and plant is given in Table 3.

Indoor gaseous air pollutant formaldehyde (colorless flammable gas at room temperature with a pungent odor) was removed by interaction between endophytic bacteria *Bacillus cereus* ERBP and plant species *Clitoria ternatea*. Sterile seedlings of *Clitoria ternatea* inoculated with bacterium inoculant increased the efficiency of seed germination and seedling growth under increasing levels of

Table 3 Microorganism–plant combined system in enhancing nutrients/pollutants removal from air

Sl. no	Xenobiotic	Plant species	Microorganisms	References
1	Gaseous formaldehyde	*Clitoria ternatea*	*Bacillus cereus* ERBP	Khaksar et al. (2016)
2	Formaldehyde	*Helianthus annuus Linn, Lycopersicon esculentum Miller, Oryza sativa, Sansevieria trifasciata, Prain, Bryophyllum pinnatum, Mesembryanthemum cor- difolium L. f. Most*	Rhizobacteria	Zhao et al. (2019)
3	O_3	*Zamioculcas zamiifolia*	*Bacillus cereus* ERBP	Pheomphun et al. (2019)
4	Formaldehyde	*Tradescantia zebrina Bosse (T. zebrina)* *Aloe vera (Haw.) Ber (A. vera)* *Vigna radiata (Linn.) Wilczek (V. radiata)*	Rhizosphere microorganisms	Yang et al. (2020b)
5	Toluene	*vetiver grass in*	*Achromobacter xylosoxidans* F3B	Ho et al. (2013)
6	Phenanthrene, acenaphthylene, acenaphthene, and fluorine	*Ornamental Plants*	*Acinetobacter, Pseudomonas, Pseudoxanthomonas, Mycobacterium, and uncultured bac- teria. Bacterial*	Yutthammo et al. (2010)
7	Formaldehyde	*Epipremnum aureum*	dynamic microbial community	Wang et al. (2014)
8	Toluene	*Fittonia verschaffeltii var. argyroneura and Hoya carnosa,*	Toluene-Metabolizing Bacteria	Zhang et al. (2013)
9	Chloromethane	*Arabidopsis thaliana was*	*Hyphomicrobium* sp.	Nadalig et al. (2011)

formaldehyde (Khaksar et al. 2016). In another study, formaldehyde removal by plants and with or without soil microorganisms were evaluated for removal. The result showed that plant-microorganisms system increased by 0.24–9.53 fold compared to the plant-only systems (Zhao et al. 2019). In one of the study, O_3 was effectively removed in a continuous system by *Zamioculcas zamiifolia* after addition of endophytic bacteria *Bacillus cereus* ERBP into *Z. Zamiifolia*. The bacteria protected plant against O_3 stress conditions (Pheomphun et al. 2019). (Yang et al. 2020a) developed an efficient plant–microbe technology to remove formaldehyde by adding cultured microorganism into the rhizosphere of three plant species, *Tradescantia zebrina Bosse (T. zebrina), Aloe vera (Haw.) Ber (A. vera)* and *Vigna radiata (Linn.) Wilczek (V. radiata)*. Results showed that the plant–microbe system removed efficiently than plant alone. Phenolic pollutant, toluene was removed by vetiver grass in association with endophytic bacteria *Achromobacter xylosoxidans* F3B by the study conducted by (Ho et al. 2013). The strain F3B protected plants against toluene stress and maintained chlorophyll content of leaves, and a 30% reduction in evapotranspiration through vetiver leaves. Similarly in another study, toluene was removed by foliage plants, *Fittonia verschaffeltii var. argyroneura* and *Hoya carnosa* along with group of rhizosphere bacteria. The study showed rhizosphere microbial community contributes to the phytoremediation potential of indoor foliage plants (Zhang et al. 2013).

Yutthammo et al. 2010 studied on diversity and activity of Polycyclic aromatic hydrocarbons (PAHs) degrading bacteria in the Phyllosphere of ornamental plants. About 1–10% of Phyllosphere bacteria were able to remove PAHs. Bacterial species such as *Acinetobacter*, *Pseudomonas*, *Pseudoxanthomonas*, *Mycobacterium*, and uncultured bacteria enhanced the removal of phenanthrene from the leaves. In addition, phyllosphere bacteria on *Wrightia religiosa* were able to reduce other PAHs such as acenaphthylene, acenaphthene, and fluorine which are considered major urban air pollutants. Botanical filtration of formaldehyde was achieved by combination of dynamic microbial community and plant species *Epipremnum aureum*. The plant species maintained microbial community which in turn degraded volatile organic compound adsorbed or absorbed by plant root bed (Wang et al. 2014). Chloromethane a major volatile halocarbon air pollutant in stratosphere, responsible for about 15% of chlorine-catalyzed ozone destruction was degraded by *Hyphomicrobium* sp. which was isolated from leaves surface of *Arabidopsis thaliana* (Nadalig et al. 2011).

From the above studies it is evident that, the air pollutants such as gaseous compounds, volatile organic compounds, ozone, and particulate matter were successfully removed by microorganisms plant interaction by several mechanisms such as phytovolatilization, phytodegradation, phytoextraction, phytostabilization and phytoaccumulation.

Conclusion and future studies

Rapid growth in the economy of countries across the globe and increased human activities on vegetation resulted in the release of several recalcitrant pollutants into the water, soil, and air. The concentration of these pollutants is beyond the threshold limit at present causing several serious health issues to humans and other organisms in the environment.

The success of removing pollutants from polluted sites by biological methods depends on the interaction between appropriate microorganisms and plants. From the above-mentioned studies conducted by several research across the globe, it is evident that, the special characters adopted by microorganisms to tolerate high concentrations of several recalcitrant pollutants and capacity to colonize the roots of plants and their presence in phyllosphere make them excellent candidates for bioremediation of almost all kinds of pollutants present in water, soil and air. These kinds of organisms can be exploited at an industrial level to clean up the pollutants. The removal of pollutants by the combination of microorganisms and plant combine system gives several benefits over other methods in removing pollutants. First, they are cost-effective, eco-friendly, easy to manage and secondly they increase the green cover and provide shelter for many other organisms living in the biosphere. Most of the water bodies and more than 300 sites in India are contaminated by several pollutants and people living in those areas are unaware of it. The need of the hour is to use microorganisms plant combined system to decontaminate those sites.

Another serious problem faced by most of the countries across the globe is air pollution. This is a serious concern because, on an average, a person inhales 6–10 L of air per minute, which amounts to 15,000 l/day (Gawrońska and Bakera 2015). Countries like India and many other countries of Asia are witnessing most of the deaths because of breathing polluted air. The scientific solution has been shown by many. Nowak et al. 2014 reported that the trees and forests in the United States removed 17.4 million tons of air pollutants in 2014. Recent work carried out by Franzetti et al. 2020 states that plant microorganisms interaction can remove the pollutants from urban air. This method of remediation can be exploited commercially by selecting suitable microbial strains and plant species. The commercial scale of remediation of water, soil, and air pollutants using microorganisms plants combination is an emerging concept. The real cost in managing these contaminants should be scaled up and it should be made available in the market so that government, non-government organization, environmentalist, and the public can engage in remediation/managing of pollutants both in indoor and outdoor environments.

Challenges in this field of research are many. Firstly, the combination of multiple species of plants and

microorganisms together enhanced in removing few pollutants and combination of single species of plant and microorganism enhanced in removing some pollutants present in total environment. These observations reveal that, selection of appropriate plant and its associated microorganism in removing pollutants is essential to clean up the specific pollutant. The factors behind these are still unclear and require further attention. For practical application of microorganisms–plant combined system to remediate the contamination in industrial level, it is very much essential to come out with scale-up studies before commercialization. Another challenge in this field lies in the bioaccumulation of pollutants by plants and its disposal after remediation process, which impacts the food chain and environment. Next challenge is biotransformed products. The indiscriminate use of the pesticides has inflicted serious harmful problems to humans in the ecosystem (Yildirim et al. 2018). During the pesticide remediation process, biotransformed products formed should also be studied for its toxicity and affectivity before coming to conclusion of successful remediation because many of the transformed products are toxic or more toxic than their parent compounds (Supreeth and Raju 2017).

Future research should focus on the Plants Microbial Fuel Cells and Constructed-Wetland Microbial Fuel Cells technologies which incorporate plants with combination of bacteria to remove pollutants and also generating bio-electricity. Finally, elucidating actual genes and proteins responsible for pollution remediation and to make the process much easier, faster, and economical by microorganisms and plant combination with the help of genomics, metagenomics, metaproteomics, metatranscriptomics, and metabolomics by omics approaches is required.

Declarations

Conflict of interest The authors declare no conflict of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

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