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REVIEW ARTICLE

# Plant–microbe interaction in aquatic system and their role in the management of water quality: a review

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**Abstract** Microbial assemblage as biofilm around the aquatic plant forms a firm association that largely depends upon the mutual supplies of nutrients, e.g., microbes interact with plants in an aquatic system most likely for organic carbon and oxygen, whereas plants receive defensive immunity and mineral exchange. Apart from the mutual benefits, plant–microbe interactions also influence the water quality especially at rhizosphere providing inherent ability to the aquatic system for the mitigation of pollution from the water column. The review presents and in-depth information along with certain research advancements made in the field of ecological and bio/chemical aspects of plant–microbe interactions and the underlying potential to improve water quality.

**Keywords** Plant–microbe interaction · Aquatic plants · Biofilm · Rhizosphere · Pollution mitigation · Bio/chemical interaction

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## Introduction

Wetlands are the transitional zones between land and water bodies characterized by shallow overlying water-logged soils harboring rich floral and faunal diversity. The floral diversity of freshwater ecosystem includes rich diversity of macrophytes and microphytes such as phytoplankton, diatoms and other algae dominating the freshwater regimes. Aquatic macrophytes are the large plants growing in the water and at the transitional zones of land and waterways. The principal chemical constituents of surface water required for the proper growth of macro and microphytes include the optimum concentrations of major nutrients such as N (>45 mg $L^{-1}$) and P (>0.25 mg $L^{-1}$) along with organic C and other nutrient elements (Srivastava et al. 2008). Besides the macro and microphytes, microbial consortia exist at various levels of community generally observed as detrital microbial mat, biofilm, and planktonic-microalgal-bacterial assemblages (Paerl and Pinckney 1996; Battin et al. 2003) and contribute substantially to the nutrient cycling (nitrification, denitrification, sulfate reduction, methanogenesis and metal ion reduction) and energy flow in aquatic ecosystem, as a feed of the zooplanktons, altering water quality and degrading the environmental pollutants (Cotner and Biddanda 2002; Battin et al. 2003; Hahn 2006). Microbial assemblage as a biofilm commonly occurs on the leaves of submerged plants, rhizosphere, especially on rhizoplane and on the solid surfaces of sediments. Several environmental conditions, such as excessive nutrients (eutrophication) their availability (Giaramida et al. 2013) and presence of toxic substances in the water affect biofilm and their structure (Calheiros et al. 2009).

Water quality of freshwater aquatic systems is subjected to the natural degradation, processes of eutrophication and the impacts of human activities. Voluminous research literature is available addressing the issues of aquatic pollution (Nagai et al. 2007; Camargo and Alonso 2006; Khan and Srivastava 2008; Shukla et al. 2009) and its biological remediation (Sooknah and Wilkie 2004; Nahlik and Mitsch 2006; Hadad et al. 2006; Srivastava et al. 2014) and the references therein. Furthermore, earlier scientific researches apparently indicate that most of the water quality improvement studies have been carried on the environmental pollutants and their removal either by aquatic plants (in situ and ex situ) or by microbes alone and only few reports are available indicating direct impact of the interaction of the aquatic macrophytes and microbes (Stout and Nüsslein 2010; Sharma et al. 2013; Lamers et al. 2012; Lu et al. 2014) and its possible influence on water quality (Stottmeister et al. 2003; Radhika and Rodrigues 2007; Srivastava et al. 2007; Toyama et al. 2011; Chakraborty et al. 2013). In this paper, most of the technical concepts related to the aquatic macrophytes and their interactions with microbes have been reviewed. Several aspects related to the microbes, microbial assemblages and their role in aquatic regimes have been discussed with a gist of their cumulative impact on the quality of freshwaters.

## Microbial assemblage (biofilm) and its role in aquatic ecosystem

Microorganisms, numerically and biochemically dominate all inland water habitats (Hahn 2006) and proper functioning of an aquatic ecosystem is supported by the rich microbial diversity depending upon the nutrient and prevailing environmental conditions (Zehr 2010). Microbial diversity in freshwaters belongs mainly to the culturable bacterial group viz., actinobacteria, alpha-proteobacteria, beta-proteobacteria, gamma-proteobacteria, firmicutes, bacteriodetes (Calheiros et al. 2009) and archaea (Wang et al. 2008; Wei et al. 2011). Microbial assemblages are found as biofilm on solid substrata and on plant surfaces (Gagnon et al. 2007). Figures 1 and 2 show the major bacterial groups often present in the assemblage mostly in the freshwaters and the graphical structure of biofilm (the circles represent the group of bacteria and the diversity, whereas the size of circles represent the population density of different bacteria belonging to a particular group). Biofilm is a porous meshwork of slime matrix (Weber et al. 1978) formed of extracellular polymeric substance (EPS) (Fig. 2) (Branda et al. 2005), comprised of polysaccharides, proteins, nucleic acid and lipids in which microbial cells remain embedded. In biofilm, microbial cells live in a customized micro-niche in a complex microbial homeostatically stable community having a firm metabolic cooperation, which renders ecologically different characters to the microbes (Costerton et al. 1995). Microbial assemblage in a biofilm is robust and vulnerable to be altered substantially with the change of habitats and the environmental conditions (Hahn 2006; Yannarell and Triplett 2004; Kierek-Pearson and Karatan 2005). Crump and Koch (2008) showed different plant species hosting different bacterial communities. Moreover, molecular techniques such as denaturing gradient gel electrophoresis (DGGE) and terminal restriction fragment length polymorphism (TRFLP) fingerprints of PCR amplified 16S rDNA fragments can easily provide the information of overall pattern of microbial community of biofilm (Truu et al. 2009). Metagenomics studies revealed that microbes perform well in the community, i.e., consortia (Srivastava et al. 2014). In general, microbial communities in a biofilm provide plenty of opportunities to bacterial cells for exchange of genetic information through horizontal gene transfer (HGT) conferring resistance, tolerance and chemical degrading ability (Srivastava et al. 2014). Moreover, HGT is often held responsible for enhancing the competitiveness of bacteria in the natural environments (Ventura et al. 2007). The genetically stable populations of microbes in a biofilm generate varied sensitivities and responses to various anthropogenic pressures (Mcclellan et al. 2008). $PO_4^{3-}$ ions particularly influence the sensitivity of bacterial community in biofilm for toxicants (Kamaya et al. 2004; Guasch et al. 2007; Tlili et al. 2010). Additionally, Tlili et al. (2010) demonstrated the shift in the microbial community in response to toxicants such as Cu and diuran (herbicide), especially in conditions of nutrient deficiency.

## Aquatic plant–microbe interaction and its role in freshwater ecosystem

Aquatic macrophytes are limited to the macroscopic flora including the members of four different groups: (1) emergent (e.g., *Phragmites australis*), (2) floating leaved (e.g., *Hydrilla* spp.), (3) free floating (e.g., *Pistia stratiotes*) and (4) submerged macrophytes (e.g., *Chara* spp.) (Figure 3) (Srivastava et al. 2008). The distribution of aquatic plants and microbial species largely depend up on the nutrient status of freshwaters (Wu et al. 2007; Buosi et al. 2011) in the following order: oligotrophic > mesotrophic > eutrophic > hypertrophic. The rhizoplane (the part of root remaining in contact with water or soil) of all macrophytes is the most active zone (Davies et al. 2006; Münch et al. 2007) because of the presence of various microbial communities. Macrophytes do not affect the microbial community structure in the microcosm, providing strong evidence in support of the higher activities of natural plant–microbe interactions even in the sediments (Ahn et al. 2007). Roots of aquatic plants provide extended

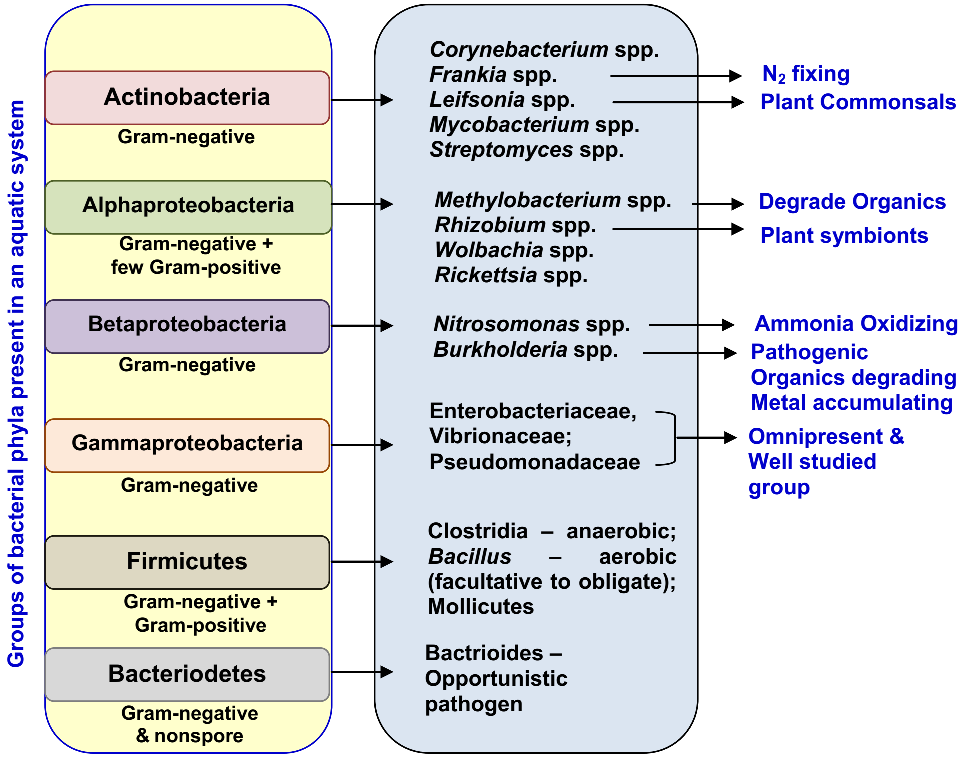
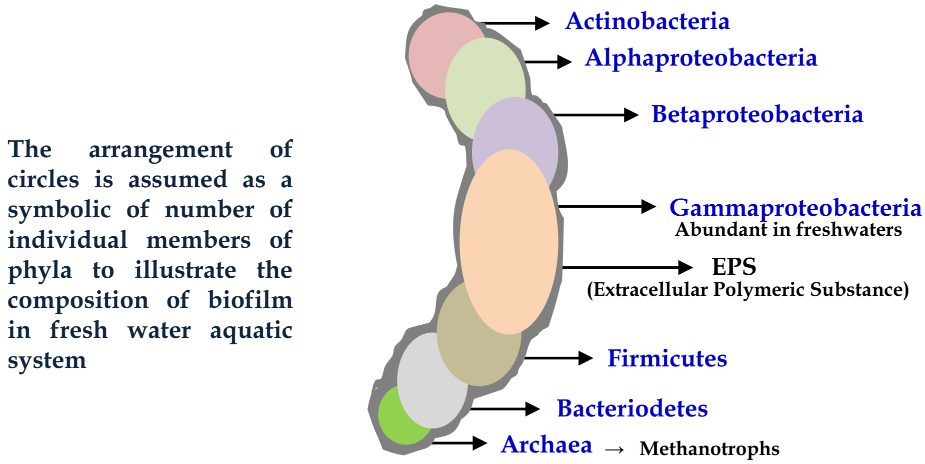


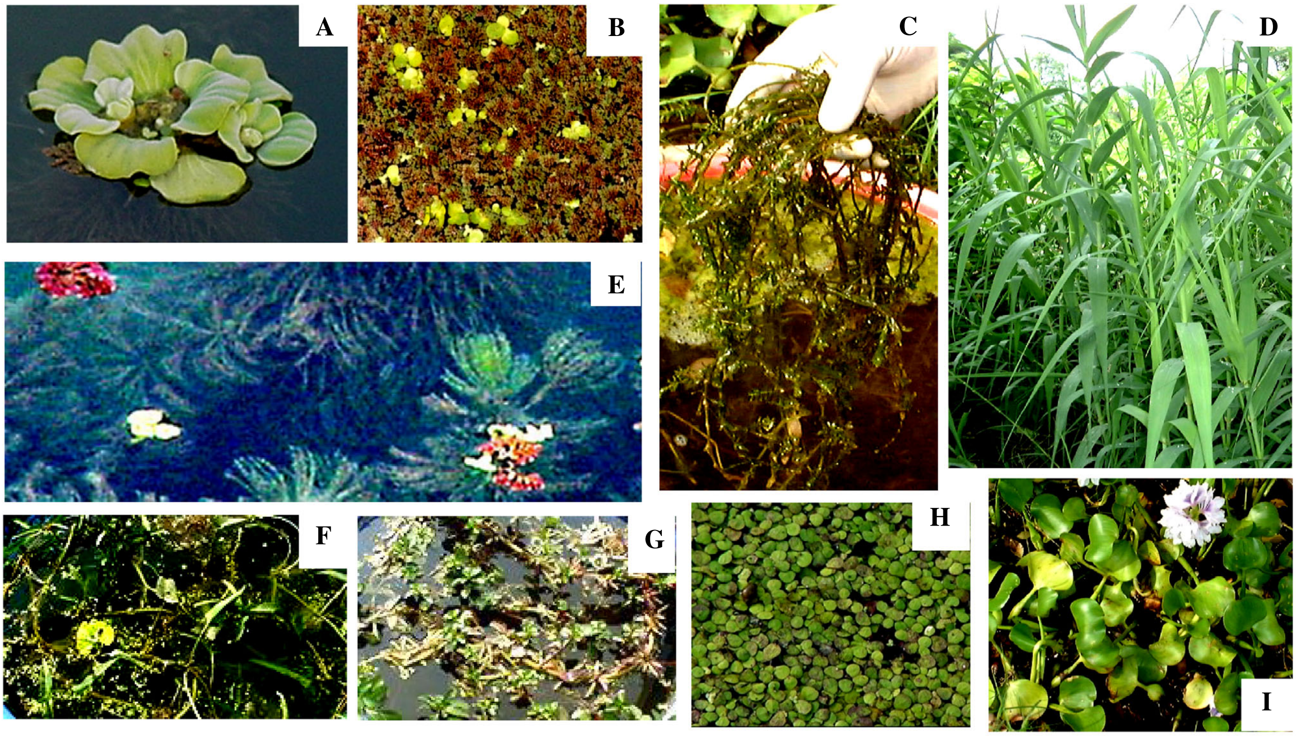
**Fig. 1** Commonly present bacterial groups with most common examples in an aquatic system



The arrangement of circles is assumed as a symbolic of number of individual members of phyla to illustrate the composition of biofilm in fresh water aquatic system

**Fig. 2** Pictorial representations of microbial assemblages in a biofilm

surface for benthic microbial community to rest and act as a customized niche for each microbe ensuring the continuous supply of nutrients, organic carbon and oxygen (Stottmeister et al. 2003). Similarly, aquatic plants get mineral nutrients and defensive immunity in return from the microbes forming firm interrelationships between these two. Stout (2006) demonstrated the impact of plant–microbe interaction on *Lemna minor* whereby bacterial association within the roots of the plant negatively influence the uptake of Cd metal ions to avoid the entry of this toxic metal into the plants. Plant–microbe interaction in fresh water bodies depend on several factors such as water chemistry (pH, electrical conductivity, salt concentrations, dissolved oxygen, dissolved organic matter, and toxic organic pollutants) (Schauer et al. 2005), redox conditions (Gray et al. 2004) and the availability of nutrients (Buosi et al. 2011; Ahn et al. 2007). Very limited information is available on the significance of plant–microbe interaction in aquatic ecosystem however; some of the typical examples of aquatic plant–microbe interactions and their role in the aquatic system are presented in Table 1. Table 1 also indicates the microbial interaction with aquatic macrophytes contributing mainly in nitrogen cycle. Rhizoplane of aquatic plants is the zone of influence which has



**A** – *Pistia stratiotes*; **B** – *Azolla* spp.; **C** – *Hydrilla* spp.; **D** – *Phragmites australis*; **E** – *Chara* spp.; **F** – *Ipomea aquatic*; **G** – *Ludwigia repens* ; **H** - *Spirodela polyrhiza*; **I** – *Eichhornia crassipes* *Photo by Dr. Jatin Srivastava*

**Fig. 3** Some aquatic macrophytes of common occurrence in wetlands of North India

different water chemistry than rest of the water column because of high microbial activity (Stout and Nüsslein 2010). Clear evidence is apparent from the researches, e.g., Stottmeister et al. (2003); Hoang et al. (2010); Calheiros et al. (2010); Zhao et al. (2014) and from the work referred therein, for the independent and random plant–microbe interactions. This implies that in most of the aquatic regimes including the engineered wetlands, aquatic plants interact with microbes from symbiotic to parasitic, irrespective of the species of plant and microbe. Terrestrial plants release an array of chemical signals to interact with other organisms (Badri et al. 2009), whereas aquatic plants depend more on the offerings such as organic carbon and $O_2$ (especially at rhizoplane) required primarily by the microorganisms to survive. In general, microbes form two types of symbiotic relationship with plants: (1) endophytic, involving the colonization of internal tissues of plants (Weyens et al. 2009) such as $N_2$ fixing diazotrophs (Nielsen et al. 2001) and other nutrient assimilators AMF (arbuscular mycorrhizal fungi) (Sřaj-Kržič et al. 2006) and (2) ectophytic (microbes remain outside of the plant) such as ammonia-oxidizing bacteria (Wei et al. 2011) and methanotropic bacteria (Sorrell et al. 2002). Ectophytic interaction involving both roots as well as leaves is an important plant–microbe interaction as several biochemical reactions occurring at the interactive surface influence the elemental cycles in aquatic ecosystem (Laanbroek 2010). Figure 4 shows a comprehensive illustration of plant–microbe ectorhizospheric (ectophytic zone of influence) interaction. The oxygen is transported from shoot to root through inter-connected lacunae (Sand-Jensen et al. 2005) a part of which is released from the roots either by humidity-induced pressurized flow through or by wind-driven venture mechanism (Soda et al. 2007), also known as radial oxygen loss (ROL) (Brix 1997; Inoue and Tsuchiya 2008). The ROL depends largely on plant species (Brix 1997; Stottmeister et al. 2003) and on the redox potential of water (Wiessner et al. 2002) accounting for 90 % of rhizospheric oxygen stimulating the growth of aerobic nitrifying bacteria (Reddy et al. 1989; Brix 1997) and aerobic decomposition of organic matter present as plant exudates by heterotrophic bacteria. Oxygen is utilized mostly as a primary electron acceptor for energy generation (Bodelier 2003) and to carry out number of beneficial oxidation processes (Laanbroek 2010). Further the diagenesis of organic matter in sediments takes place via oxic and anoxic microbial activities with the consumption of electron acceptors such as oxygen causing an oxygen deficient zone. Under such anoxic conditions bacterial cells (facultative anaerobes) capable of using $NO_3^{1-}$, $SO_4^{2-}$ and $CO_2$ as terminal electron acceptor to decompose the organic matter (Steenberg et al. 1993)

**Table 1** Common aquatic plant–microbe interaction and their role in the aquatic ecosystem

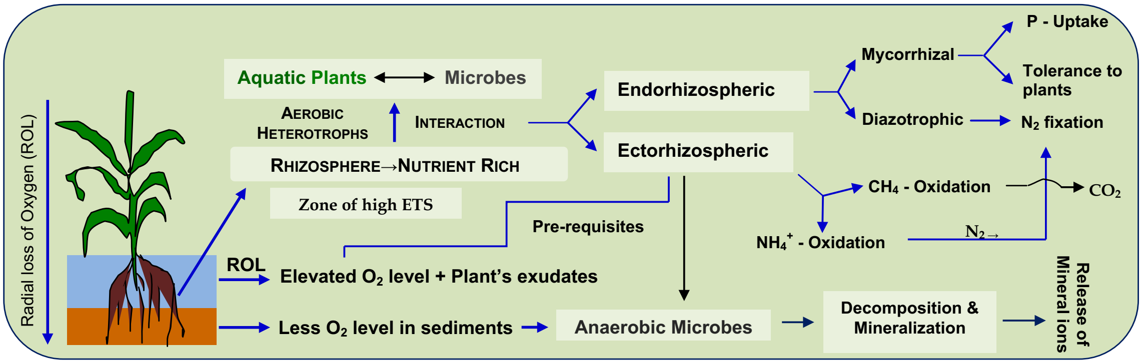
| Plant species | Microbial species | Role in ecosystem | References |
|---|---|---|---|
| *Azolla filiculoides* | *Anabaena azollae*[1]; *Arthrobacter* spp.[2] | $N_2$ fixation | Carrapiço, (2002)[1]; Stirk and van Staden (2003)[2] |
| *Chara aspera* | Members of *Cytophaga-Flavobacteria-Bacteriodetes* | Allelopathic activity against algae and Cyanobacteria | Hempel et al. (2008) |
| *Lemna minor* | *Pseudomonas* sp. RWX31 | Denitrification | Ying-ru et al. (2013) |
| *Vetiveria ziznioides* | *Arbuscular mycorrhiza* | Allelopathic activity on members of Enterobacteriacae | Srivastava et al. (2007) |
| *Phragmites australis* | *Nitrosomonas* | Ammonia oxidation | Okabe et al. (2012) |
| *Ulva australis* | *Pseudoalteromonas tunicate*<br>*Roseobacter gallaciencis* | Allelopathic effect on other Alage | Rao et al. (2006) |
| *Neptunia natans* | *Devosia neptuniae* sp. nov. | Nitrogen fixation | Rivas et al. (2003) |
| *Utricularia* spp. | [*Scenedesmus* spp.<br>*Characiopsis* spp.][a] | Improving P supplements[b] | Plachno et al. (2012)[a]<br>Sirová et al. (2009)[b] |
| *Hemiaulus hauki*** | *Richelia intracelluaris* | Nitrogen fixation | Hay et al. (2004) |
| *Typha latifolia* (L.) | *Bacillus* spp. | Nitrogen fixation | Biesboer (1984) |
| *Chlorella vulgaris* | *Azospirillum brasilense* | PGPB | Gonzalez and Bashan (2000) |
| *Scenedesmus bicellularis* | *Pseudomonas diminuta* | PGPB | Mouget et al. (1995) |
| *Nuphur* spp. | *Mesorhizobium loti* | Nitrogen fixing | Wagner (2012) |
| Rooted macrophytes* | *Sinorhizobium meliloti* P221 | IAA production in roots | Golubev et al. (2009) |

*PGPB* plant growth promoting bacterium

* Usually *Pistia* spp. do not have any symbiotic relation, *Bacillus* strain was introduced in the rhizosphere

** Marine alga

[1,2;a,b] superscripts corresponds to the reference as given on the extreme right of the table



Aquatic macrophytes replenish the oxygen in the deep waters by radial oxygen loss whereby oxygen is released from the roots moving via inter connected lacunae. ROL and root organic exudates initiate aerobic microbes to perform metabolic action for their own survival using $O_2$ as an electron acceptor and organics of exudates as carbon. Most of the plant-microbes interaction (endorhizospheric and ectorhizospheric) in fact based on these prime requisites. In return plants get nutrient minerals and protection from toxic pollutants and pathogens. In the deepest zone of low oxygen or as in sediments, the activity of anaerobic life forms decompose the organic matter releasing minerals and gases by utilizing terminal electron acceptor as $NO_3^-$, $CO_2$, $CH_4$, and $SO_4^{2-}$. The action of microbes makes the rhizosplane (internal as well as external rhizospheric zone) as the zone of high electron transport system (ETS) and energy consumption.

**Fig. 4** Plant–microbe interactions at rhizoplane in a fresh water ecosystem

become more active causing a high electron transport system (ETS) activity in the sediments (Germ and Simčič, 2011). Methanogens produce methane ($CH_4$) from $CO_2$ by reducing it with $H_2$. $CH_4$ production, the lowest energy yielding process, predominates the freshwater regimes especially after the complete consumption of all the electron acceptors other than the $CO_2$ (Rejmankova and Post 1996; Conrad 2004).

## Environmental perspectives of plant–microbe interactions in an aquatic ecosystem

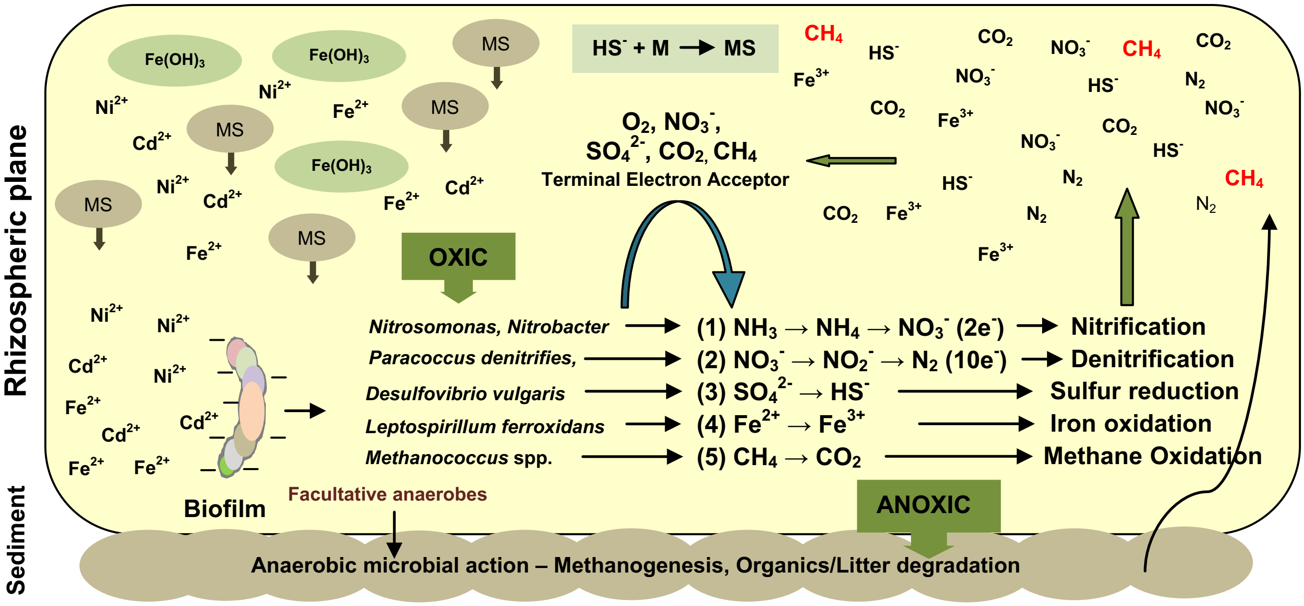
The interaction of plants and microbes in the environment is quite obvious as mentioned in the previous section affecting the quality of media at large. Aquatic ecosystems provide plenty of opportunities to the plants and microbes to interact just for their survival. Environmental pollution mitigation is a cumulative effect of plant–microbe interactions in a broader sense (Pilon-Simts and Freeman 2006), also commonly known as bioremediation, which has been the most researched field in biological and environmental sciences all over the world. In general, plant–microbe interaction relies upon mutual benefits, whereas plants provide oxygen and organic carbon to the microbes in return microbes provide minerals and metabolites required by plants for their growth.

### Degradation of organic pollutants

Massive field application of organic compounds such as poly-aromatic hydrocarbons (PAHs), chlorinated organic compounds, poly-brominated biphenyls ethers (PBEs) and poly-chlorinated biphenyls (PCBs) have been a major cause of contaminated environmental media (Srivastava et al. 2014) and the aquatic systems are the most vulnerable of all. Because of the catabolic activity, microbes are well-known bioremediators able to degrade virtually all classes of organic chemicals (Hiraishi 2008; Fennell et al. 2011). Co-metabolism is one of the key mechanisms that microbes follow to catabolically degrade the recalcitrant organic compound to get organic carbon along with electron acceptors, available in plenty at the rhizospheric zone of terrestrial and aquatic macrophytes (Stottmeister et al. 2003). The rate of biodegradation is of second-order kinetics in natural waters and proportional to the number of microbes and amount of xenobiotics (Paris et al. 1981), whereas the microbial community largely depends upon the macrophytic species (Calheiros et al. 2009). In addition, the organic carbon, provided by the plants to the rhizospheric microbes helps degrading the complex recalcitrant organic compounds (Mori et al. 2005) such as PAHs (Mordukhova et al. 2000) and pyrenes (Jouanneau et al. 2005). Golubev et al. (2009) reported the classic example of this concerted mutual benefit whereby plants get a growth hormone indole acetic acid (IAA) as a result of rhizospheric microbial degradation of PAHs. Such observations have also been reported earlier by other researchers (Huang et al. 2004; Escalante-Espinosa et al. 2005) on different aquatic plants and sediments. Gloubev and coworkers isolated and identified the microbe such as *Sinorhizobium meliloti* P 221 forming an ectorhizospheric association with the aquatic plants capable to synthesize IAA via degrading PAHs. Moreover, earlier reports of Gasol and Duarte (2000) suggest the best survival of bacteria within the productive aquatic environment of algae whereby bacteria use the algal derived carbon efficiently to grow and multiply. The increased number of bacteria cause odor and taste problems in the freshwaters (Okabe et al. 2002). Aquatic plant-associated biofilm is capable to degrade the algal-derived organics containing chiefly amines, aliphatic aldehydes and phenolics (Simpson 2009) and dissolved organic matter (DOM) (Tranvik 1998) such as PCBs (poly-chlorinated biphenyls) (Ghosh et al. 1999) and atrazine (Guasch et al. 2007). Additionally, rhizoplane of aquatic plants are also rich in ubiquitous methanotrophs a group of $\alpha$ and $\gamma$ proteobacteria, utilizing methane for energy and as carbon source (Semrau et al. 2010). Particulate methane monooxygenase (pMMO) produced in methanotrophs (e.g., *Methylosinus trichosporium* OB3b, *Methylococcus capsulatus*) degrade a wide variety of toxic organic compounds (Yoon 2010; Pandey et al. 2014), especially chlorinated ethenes (Tsien et al. 1989; Yoon 2010) via a cascade of enzymatic reactions involving the production of formaldehydes that later produce terminal compound $CO_2$.

### Removal of inorganic contaminants

Low levels of metal ions that naturally occur in aquatic systems as a result of slow leaching from soil and rocks havE no deleterious effect on aquatic biota (Zhou et al. 2008). Excessive metal ions in waters are mainly of industrial, agricultural and municipal waste origin in many parts of the world. The mobility of metal ions in the water is influenced by several bio/chemical factors including pH and Eh (redox potential) of water, presence of hydrated oxides of iron, metal carbonates and plant–microbe interaction as biofilm on the rhizosphere of macrophytes (Hansel et al. 2001; Carranza-Álvarez et al. 2008). Most of the metals form cations in water which adhere to the negatively charged EPS of biofilm matrix prevent the entry of metal ions into it and the plants. Most of the aquatic macrophytes possess iron plaque around the roots and submerged parts (King and Garey 1999) and sequester metal ions from water (Hansel et al. 2001). Iron plaque is layer of iron (hydr)/oxide precipitate around the plant parts caused by oxidation of iron by molecular $O_2$ or by iron oxidizing bacteria (e.g., *Ferroplasma* sp. and *Leptospirillum ferroxidans*) (King and Garey 1999). It has been observed that radial oxygen loss depends on the root porosity of the plants which enhances the oxygen level at rhizoplane (Li et al. 2011). Iron oxidizing bacteria may enhance the formation of more iron plaque. Li et al. (2011) have also demonstrated the function of root porosity, ROL, plaque formation and toxic response of As (arsenic) metalloid whereas the later was found substantially decreased



Plant-microbe interactions involve maximum action at rhizoplane. In the figure a biofilm assumed to be present on rhizosphere of an aquatic plant involve several bio/physico-chemical activities such as nitrification (1), denitrification (2), sulfate reduction (3), iron oxidation (4), and methane oxidation (5) by corresponding microbes, the resultant chemical ions as an outcome of these reactions come in to the water column and further physico-chemical reactions proceed that largely affect the quality of water. Hydrogen sulfide mostly reacts with the metal cations to form metal sulfide (MS) precipitates, which fall on the surface of water body. $Fe^{3+}$ react with water and form $Fe(OH)_3$ that contribute in iron plaque formation on the plant surface. Under anoxic conditions most of the facultative anaerobes degrade organics and plant litter to get carbon and utilize the $CO_2$, $SO_4^{2-}$, and $NO_3^-$ as a terminal electron acceptor

**Fig. 5** Bio/physico-chemical reactions at rhizoplane in an aquatic system

at increased plaque formation. After the oxidation of iron, sulfate reduction in the aquatic system is another important metal removing process (Machemer and Wildeman 1992), whereby sulfate reducing bacteria associated with aquatic macrophytes as biofilm reduce sulfate into sulfides thereby lowering the pH which is required by the microbial cell to biosorb the metal ions (Han and Gu 2010) from the water column. In addition, metal ions react with the hydrogen sulfide in waters (as a result of sulfate reduction) to form metal sulfide which gets precipitated in acidogenic conditions (Webb et al. 1998) and moves down to the sediments (Fig. 5) thereby sequestering metal ions from water column (Machemer and Wildeman 1992). Not only macrophytes but also algae may interact with microbes to remove contaminants from the water, e.g., Muñoz et al. (2006) observed the enhanced adsorption of toxic metals such as Cu(II), Cd(II), Ni(II) and Zn(II) by a microalga *Chlorella sorokiniana* having an association with bacterium *Ralstonia basilensis,* especially for Cu(II) adsorption because of the presence of more Cu binders as compared to the other metals. Mycorrhizae also form association as endophytic symbionts with most of the aquatic plants (Sřaj-Kržič et al. 2006) and enhance the uptake of P and translocation of other nutrients in the plants (Thingstrup et al. 2000). Mycorrhizal associations protect the plants from toxic pollutants such as heavy metals (Srivastava et al. 2010). Srivastava et al. (2010) demonstrated the role of mycorrhizal association in Vetiver grass (a common wetland species of Indian subcontinent, South East Asia and Australia) protecting from the As (III) by blocking the membrane transport system of phosphorus, a chemical analogue of As (Meharg and Hartley-Whitaker 2002).

Plants and microbes in an aquatic system largely depend upon the availability of nutrient ions such as various mineral elements, P and N for their growth. Excessive nutrient ions cause the eutrophication of water body followed by cyanobacterial bloom and toxin production (Giaramida et al. 2013). Aquatic macrophytes take up excessive nutrient ions from the water and inhibit the growth of algae. Free floating macrophytes such as *Pistia stratiotes, Eichhornia crassipes, Ipomea aquatica* and *Spirodela polyrhiza* also play important role in removal of nutrient ions such as dissolved inorganic nitrogen such as ammonium $NH_4^+$. The rhizospheric association of aerobic chemoautotrophic bacteria viz., *Nitrosomonas* and *Nitrobacter* oxidizes ammonium as $NH_4^+ \rightarrow NO_2^- \rightarrow$

**Table 2** Environmental perspectives of plant–microbe interaction in aquatic ecosystem

| Plant | Microbe | Interaction type | Environmental significance | References |
|---|---|---|---|---|
| *Pistia stratiotes* | *Bacillus cereus* GXBC1 | Ectorhizospheric | Enhanced Cr(VI) Uptake | Chakraborty et al. (2013) |
| *Phragmites austrails* | *Hydrogeno phaga S1*; *Agrobacterium radiobacter S2* | Ectorhizospheric | Degradation of Acid Orange-7 | Davies et al. (2006) |
| *Phragmites australis* | *Mycobacterium gilvum* | Ectorhizospheric | Degradation of bezo[a]pyrine | Toyama et al. (2011) |
| *Ipomea aquatic* | AMF | Endorhizospheric | Enhanced Cd uptake | Bhaduri and Fulekar (2012) |
| *Typha latifolia* (L.) | α, β, γ proteobacteria; Bacteroids; Pseudomonads | Endorhizospheric + Ectorhizospheric | Reduction of Fe(III) into Fe(II); enhanced Cu uptake | Ye et al. (2001); Carranza-Álvarez et al. (2008); Li et al. (2011) |
| *Lemna aoukikusa* | *Acinetobacter calcoaceticus* | Ectorhizospheric | Active phenol degradation | Yamaga et al. (2010) |
| *Eichhornia crassipes* M. | *Nitrobacteria irancium* | Ectorhizospheric | Enhance Cr and Zn uptake (aerial) | Abou-Shanab et al. (2007) |
| | *Bacillus cereus* | | Enhanced Mn uptake in roots | |
| | *Ochrobactrum anthropi* | | Enhanced Cr and MN uptake in roots | |
| *Phragmites communis* | *Microbacterium* sp. | Endorhizospheric | Degrade Chloropyriphos (<60 %) | Chen et al. (2012) |
| *Nymphaea* spp.<br>*Najas* spp.<br>*Potamogetone crispus* | *Pseudomonas* spp.; *Paenibacillus* spp.; *Enterobacter* spp. | | Degrade pesticides such as Chloropyrifos and Fenpropathria. Depend largely on the plant's part of isolation | |
| *Chlorella sorokiniana* | *Pseudomonas migulae*, *Sphingomonas yanoikuyae* | Ectorhizospheric | Enhanced degradation of Phenol, Phenanthrene, salicylate | Borde et al. (2003) |
| *Chlorella sorokiniana* | *Ralstonia basilensis* | Endophytic symb. | Enhanced uptake of Cu metal | Muñoz et al. (2006) |
| Rooted macrophytes | *Methylosinus trichosporium* | Ectorhizospheric | Degrade trichloroethylene | Tsien et al. (1989) |

$NO_3^-$ (Wetzel 2001). The presence of predominant ammonia-oxidizing bacteria (AOB) (Wei et al. 2011) and archaea (AOA) on the rhizoplane having *amoA* gene (Herfor et al. 2007) plays a vital role in nitrification and denitrification (Wang et al. 2009). Environmental significance of the plant–microbe interactions have been widely studied in engineered (constructed) wetlands (Kadlec et al. 2000; Vymazal et al. 2001; Stottmeister et al. 2003; Truu et al. 2005; Nahlik and Mitsch 2006; Vymazal 2007; Münch et al. 2007). Table 2 presents examples of plant–microbe interaction of aquatic environment and their ability to mitigate pollution in the waters depending on the type of interactions.

## Future studies

Future studies on plant–microbe interaction and its role in environmental remediation and/or restoration in general are of utter importance and may include the metagenomics and characterization of microbial population associated with rhizoplane of aquatic plants needing lot of technological knowledge advancements. Second, it would be quite interesting to know the behavior of plant–microbe interaction at rhizoplane of free floating aquatic macrophytes under elevated atmospheric $CO_2$ and at elevated ambient temperature and on the development of new interactive combinations in freshwater regimes. More studies are required to understand the structure and function of microbial community in a biofilm interacting with particular plant species, e.g., influence of any toxic chemical on microbial assemblages present in the vicinity, microbial community 6shift during climate change and environmental perspectives of newly developed transgenic plant–microbe interactions.

## Conclusion

In aquatic systems plant–microbe interaction is common, especially on the rhizoplane. Plants secrete several organic chemicals (plant exudates) containing aminoacids, polysaccharides, lipids, phenolic compounds and nucleic acids in their surroundings for protecting the growing soft tissues, for mineral uptake depending upon the local electrochemical environment and to attract microbes forming an association of characteristic features performing specific actions. The nature of these interactions varies from positive to negative, depending upon their relationships. Additionally, several microbial communities interact with each other including members of actinobacteria, α, β, γ and Δ proteobacteria, firmicutes, bacteriodetes and archaea and remain in a continuous layer of exo-polymeric substance (EPS) forming a matrix of microbial network (biofilm). The structure of microbial assemblage differs on different plant species depending upon the nature and availability of organic carbon and oxygen level at rhizoplane. In deep waters, rooted macrophytes continuously replenish the loss of oxygen as a result of microbial and chemical consumption by supplying through the plant's interconnected lacunae right from shoot to root where the $O_2$ is released, also known as radial oxygen loss (ROL). The ROL at rhizoplane render it a high electron transport (ETS) zone where $O_2$ acts as electron acceptor required for the survival of aerobic life forms; however, in the absence or in low oxygen level (as in sediments) several other electron acceptors such as $CO_2$, $CH_4$ and $NO_3^-$ support anaerobic life forms. There is a sharp oxic-anoxic interface near the rhizoplane as most of the facultative anaerobes survive at this zone and are critical for water chemistry (Fig. 4). In an aquatic system, rhizoplane is the site of active nitrification, denitrification, sulfur reduction, iron oxidation, methanogenesis, methanotrophism and many more bio/physico-chemical reactions. Apart from the bio/physico-chemical actions, individual aquatic plant species possess a unique and a set pattern of micro-flora whereas both the specie interact for their survival making the resources present in the surrounding available and indirectly helps remediating the environmental pollutants to a greater extent. For example, bacterial species degrade PAHs to synthesis indole acetic acid (IAA) which is plant growth promoting hormone, and mycorrhizal interaction enhances the nutrient uptake and protects the plants from toxic metals by avoiding their direct entry presumably by altering membrane transport channels.

### Compliance with ethical standards

**Conflict of interest** There is no conflict of interest of any kind.

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