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Implementation of Floating Treatment Wetlands for Textile Wastewater Management: A Review

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Abstract: The textile industry is one of the most chemically intensive industries, and its wastewater is comprised of harmful dyes, pigments, dissolved/suspended solids, and heavy metals. The treatment of textile wastewater has become a necessary task before discharge into the environment. The textile effluent can be treated by conventional methods, however, the limitations of these techniques are high cost, incomplete removal, and production of concentrated sludge. This review illustrates recent knowledge about the application of floating treatment wetlands (FTWs) for remediation of textile wastewater. The FTWs system is a potential alternative technology for textile wastewater treatment. FTWs efficiently removed the dyes, pigments, organic matter, nutrients, heavy metals, and other pollutants from the textile effluent. Plants and bacteria are essential components of FTWs, which contribute to the pollutant removal process through their physical effects and metabolic process. Plants species with extensive roots structure and large biomass are recommended for vegetation on floating mats. The pollutant removal efficiency can be enhanced by the right selection of plants, managing plant coverage, improving aeration, and inoculation by specific bacterial strains. The proper installation and maintenance practices can further enhance the efficiency, sustainability, and aesthetic value of the FTWs. Further research is suggested to develop guidelines for the selection of right plants and bacterial strains for the efficient remediation of textile effluent by FTWs at large scales.

Keywords: bacteria; floating treatment wetlands; plants; textile effluent

1. Introduction

The major sources of water pollution are industries, domestic discharges, urbanization, pesticides, fertilizers, and poorly managed farm wastes [1,2]. The textile industry significantly contributes to the

economy of a country. However, it consumes a large amount of water, and thus generates a larger quantity of wastewater [3]. Textile industry wastewater contains harmful dyes, different pigments, oil, surfactants, heavy metals, sulphates, and chlorides [4]. All these pollutants unfavorably affect the quality of water and aquatic life.

Dyes are key constituents of textile effluent. Textile dyes are considered as one of the worst polluters of our environment, including water bodies and soils [5]. These dyes also have adverse effects on human health. The dyes in textile wastewaters are carcinogenic, mutagenic, and genotoxic for all life forms [6]. Dyes in wastewater hinder the sunlight reaching to water, and thus decrease photosynthetic activity, reduce transparency, and disturb the ecosystem [3,4]. Additionally, different chemicals are used in the textile industry and cause problems for life forms, as well as the environment upon direct contact with them [7]. Existing wastewater treatment technologies are inefficient for the removal of dyes and associated pollutants from wastewater because of their persistent nature and resistance to degradation [8].

Incompletely treated or untreated water is harmful to the environment and other living creatures [9,10]. All types of wastewater should be treated before dumping into open water bodies in order to minimize the spread of water pollution [11]. Textile wastewater can be treated by various methods based upon physical, chemical, and biological approaches. However, the by-products of these treatment processes can be toxic and difficult to dispose of safely [6,12]. Consequently, it is essential to devise and adopt an environmentally friendly and sustainable technique to treat textile wastewater.

Phytoremediation, i.e., use of plants to remove pollutants, is one of the best economical and sustainable approaches for wastewater treatment [13,14]. Plants can take up contaminants from water, soil, and air [15]. Over the past years, different plants have been used to remediate dyes from textile wastewater. Different plants species have different nutrients/pollutants removal potential, and could exhibit great phytoremediation and stress tolerance [15–17]. Along with the applications of plants, different eco-friendly mechanisms are now being adopted to treat textile wastewater, and they include plant seeds [18], bacteria [8], fungi [19,20], yeast [21,22], and microalgae [23]. Recently, helminths have also been used to degrade dyes, for example, the nematode *Ascans lumbncoides* and the cestode *Momezia expansa* have been found to reduce azo dyes by anaerobic methods [24,25].

Although dyes are resistant to degradation, many microorganisms can completely decolorize and mineralize them [26]. The application of bacteria is an efficient way to treat dyes, as they are not harmful for the environment. Different bacteria have a high ability to degrade different dyes; for example, *Pseudomonas* sp. and *Sphingomonas* sp. have been found useful in the degradation of dyes [3]. The specifically adaptive bacteria can produce reductase enzymes that can reductively cut the dyes in the presence of molecular oxygen [27]. In the current scenario, we must seek efficient, eco-friendly, and economical technologies to treat textile wastewater with a minimum generation of waste materials [3]. Application of plants and bacteria has become a sustainable approach for wastewater treatment [18].

2. Potential Pollutants in Textile Wastewater

Textile wastewater contains highly variable dyes that have structural varieties including basic, acidic, reactive, azo, metal complex, and diazo dyes [28]. Typical characteristics of textile effluents include high temperature, the extensive range of pH, chemical oxygen demand (COD), biological oxygen demand (BOD), heavy metals, and a variety of contaminants such as dyes, salts, surfactants, dissolved solids, and suspended solids (Table 1) [28–30].

Table 1. Characteristics of textile wastewater.

Reference	[12]	[31]	[4]	[32]	[29]	[33]	[34]	[35]	[36]	[37]	[38]
Country	India	India	Iraq	Canada	Pakistan	Pakistan	India	Pakistan	Pakistan	India	Pakistan
Temp (°C)	35–45		33–45	35–45	25.4	42			38		38
pH	6.0–10.0	9.2–11	5.5–10.5	6–10	8.5	12.93			7.8	10.7	8.8
EC (µS/cm)						8.07		7.1	8.4		8.2
DO (mg/L)					0.84						
Color (Pt–Co)	50–2500			50–2500	456	53 (m^{-1})		35.5 (m^{-1})	68 (m^{-1})		66 (m^{-1})
COD (mg/L)	150–10,000	465–1400	150–10,000	150–12,000	433.7	813	1090	471	493	1734	513
BOD (mg/L)	100–4000	130–820	100–4000	80–6000	224.6	422	141	249	190	1478	201
Total solids (mg/L)		3600–6540				5125		4961	5420		5420
TSS (mg/L)	100–5000	360–370	100–5000	15–8000	244	391	1004	391	324	6438	324
TDS (mg/L)	1800–6000	3230–6180	1500–6000	2900–3100	2570	4834		4569	5164	9060	5251
Total Alkalinity (mg/L)	500–800	1250–3160									
Hardness (mg/L)						410			380		
Total settleable solids (mg/L)						24			38		
Total Organic Carbon (mg/L)						301		166	230		201
TN (mg/L)					55.8						
TP (mg/L)					13						
Phenol (mg/L)									0.86		0.85
Chlorine (mg/L)				1000–6000		600					
Chlorides (mg/L)	1000–6000		200–6000		846				1382		1383
Free chlorine (mg/L)				<10							
TA (mg/L) as CaCo3			500–800								
TH (mg/L) as CaCo3											
TKN (mg/L)			70–80	70–80							
Phosphate (mg/L)				<10							16.4
Sulphates (mg/L)			500–700	600–1000	412				310		311
Sulphides (mg/L)			5–20								
Oil and grease (mg/L)			10–50	10–30	28						

Table 1. *Cont.*

Reference	[12]	[31]	[4]	[32]	[29]	[33]	[34]	[35]	[36]	[37]	[38]
Nitrogen (mg/L)									28.6		28.7
Zink (mg/L)			3–6	<10							
Nickel (mg/L)				<10		2.0		0.125	7.6		7.57
Manganese (mg/L)				<10							
Iron (mg/L)				<10		3.3		1.171	14.3		14.4
Copper (mg/L)			2–6	<10				0.503			
Boron (mg/L)				<10							
Arsenic (mg/L)				<10					0.025	0.90	
Silica (mg/L)				<15							
Mercury (mg/L)				<10							
Fluorine (mg/L)				<10							
Chromium (mg/L)			2–5			0.21		0.812	9.7	3.7	9.67
Potassium (mg/L)			30–50			858			242		
Sodium (mg/L)	610–2175		400–2175	7000		1656			1560		
Cadmium (mg/L)						0.27			0.88	0.80	0.88
Calcium (mg/L)						80.16			110		
Magnesium (mg/L)						48.6			65		
Sulfate (mg/L)						412.54					
Phosphate (mg/L)						10.08					
Nitrate (mg/L)						24					
Lead (mg/L)								0.880		0.40	
Phosphorous (mg/L)									16.4		
Aluminum (mg/L)									2.5		

EC: Electrical Conductivity; DO: Dissolved Oxygen; COD: Chemical Oxygen Demand; BOD: Biological Oxygen Demand; TSS: Total Suspended Solids; TDS: Total Dissolved Solids; TN: Total Nitrogen; TP: Total Phosphorus; TA: Total Alkalinity; TH: Total Hardness; TKN: Total Kjeldahl Nitrogen.

2.1. Dyes

Discharge of wastewater from the finishing and dying process in the textile sector is a substantial cause of environmental pollution [39]. Discharge of dying effluents in the environment is the primary cause of a significant decline in freshwater bodies [40]. Dyes are the substances that, when applied, give color to the substrate by altering the crystal structure of the colored materials. Textile industries extensively use extensive dyes primarily due to their capacity to bind with the textile fibers via formation of covalent bonds [41]. Moreover, dyes are those contaminants that are not only toxic, but they also can change the color of the wastewater [42]. The main environmental risk associated with their use is their subsequent loss during the dying process. Consequently, significant quantities of unfixed dyes are regrettably discharged into the wastewater. The release of toxic textile wastewater causes adverse health risks to humans, plants, animals, and micro-organisms [43].

Colored textile dyes not only degrade the water bodies, but also hamper the penetration of sunlight via water, which causes a decrease in the rate of photosynthesis and level of dissolved oxygen, thereby affecting the whole aquatic ecosystem [44]. Textile dyes are composed of two key elements, auxochromes and chromophores. Chromophores are responsible for coloring the dyes, while auxochromes provide chromophores with additional assistance [45]. Azo dyes are most commonly used among all textile dyes in coloring multiple substrates. They have the large molecular structure, and their degradation products are sometimes more toxic [46]. When they get adsorbed by the soil from the wastewater, they can easily alter the chemical and physical characteristics of the soil. It may lead to a reduction of flora in the surrounding environment. The presence of azo dyes in the soil for a longer period dramatically disturbs the productivity of the crops and also kills the beneficial microbes [44]. Different studies reported that textile dyes also act as carcinogenic, mutagenic, and toxic agents [47,48]. An increase in textile industry means more use of dyes that may lead to severe toxicity disturbing the surrounding environment. Textile dyes pose a major risk to healthy living due to their xenobiotic effects [7]. The textile sector releases huge concentrations of colored effluents into the water bodies without prior treatment. Therefore, saving water from pollutants and prior treatment of textile effluents has indeed received emerging attention.

2.2. Dissolved Solids

Textile wastewater is contaminated heavily with dissolved and suspended solids [28]. Total dissolved solids (TDS) are consistently associated with conductivity and salinity of the water. Estimation of solids in water is a vital factor in making it safe for drinking purposes [49]. The World Health Organization (WHO) sets a minimum limit of 500 mg/L for TDS and 2000 mg/L as a maximum limit [50]. A higher value of TDS corresponds to the extensive use of several human-made dyes [51]. In TDS, soluble salts usually exist as cations and anions. Slight changes in the physiochemical characteristics of wastewater completely change the nature of deposit and ions concentration in the bottom. Higher values of TDS result in extreme salinity upon discharging into the water streams used for irrigation [52]. Much higher values of TDS can significantly produce harmful impacts on the biological, chemical, and physical characteristics of water bodies [51].

2.3. Suspended Solids

Suspended solids are considered as major pollutants in textile wastewater. They contain phosphate, chlorides, and nitrates of K, Ca, Mg, Na, organic matter, carbonates, and bio-carbonates [53]. A higher concentration of suspended solids hinders the prolific transfer setup of oxygen between air and water. Excess of a suspended solid released from the textile effluents can block the breathing organs of aquatic animals [54]. Suspended solid in aquatic medium leads to increasing turbidity, which subsequently results in depletion of oxygen. Likewise, suspended solids also can restrict the necessary penetration of light into the aquatic system, which decreased the capability of various algae and different flora to produce oxygen and food. Suspended solids directly absorb the sunlight, which enhances the temperature of the water and, at the same time, reduces the amount of dissolved oxygen [28].

Durotoye et al. (2018) conducted a study to examine the quality of effluents discharged from the textile industry [55]. It was found that the total suspended solids (TSS) exceeded the set limits specified by the national standards for textile effluents by 10 to 110% in all analyzed samples. Similarly, Ubale and Salkar [56] also reported a higher value of TSS (1910 mg/L) in cotton textile effluents [56]. Discharge of untreated textile wastewater with a higher concentration of TSS may potentially be very toxic for all living organisms.

2.4. Heavy Metals

Effluents from the textile industries comprise of several organic and inorganic chemical, organic salts, dyes, and heavy metals [42]. Heavy metals are more evident and non-biodegradable when released into the surrounding environment. Heavy metals can easily accumulate in the food chain as well [57,58]. High non-biodegradability, toxicity, and biological enrichment of heavy metals pollution has gravely threatened the sustainability of the ecological system and human health [59]. High risk of deterioration in water quality is prominent due to the heavy metal pollution [60].

The existence of heavy metals that greatly characterizes textile effluents. Heavy metals present in untreated textile wastewater can easily accumulate into the bio-system leading to various health repercussions [61]. Discharge of untreated textile wastewater is primarily associated with the concentration of several heavy metals such as Arsenic (Ar), Copper (Cu), Zinc (Zn), Cadmium (Cd), Lead (Pb), Mercury (Hg), Nickel (Ni), Chromium (Cr), and many others [62]. Because of the health hazards of heavy metals, numerous regulations and standards have been introduced to avoid any accumulation of heavy metals that would otherwise be lethal to human. Unfortunately, the discharged untreated textile effluents exceed the admissible limits set for heavy metals, especially in developing countries. As reported by Noreen et al. [63] and Mulugeta and Tibebe [64] the discharge of heavy metals from textile wastewater was high as compared to the permissible limits. Similarly, Wijeyaratne and Wickramasinghe [65] also reported that the concentration of Cu and Zn were higher than the permissible limits. Therefore, it is a matter of extreme importance to remediate these metals from the textile effluents before their discharge into the surrounding environment in order to prevent water pollution.

3. Available Technologies for Treatment of Textile Effluent

Textile effluent can be treated by several chemical, biological, and physical methods and reused for irrigation and industrial processes [66,67]. All methods work in some ways, but they all have some constraints. Textile wastewater remediation techniques include, but are not limited to, filtration, chemical oxidation, flocculation, Fenton's reagent oxidation, foam flotation, fixed-film bioreactors, anaerobic digestion, and electrolysis [68,69]. Among these coagulation-flocculation are the most commonly used methods [70]. Coagulation is the addition of a coagulant into wastewater to treat it, and is also a popular method of textile wastewater removal [71]. Electrodialysis, reverse osmosis, and ion exchange process are some of the tertiary treatment processes for textile wastewater treatment [72]. Adsorption is remarkably known as an equilibrium separation process and is widely used to remove contaminants [73,74]. Furthermore, advanced chemical oxidation processes are also commonly used for such purposes [66]. In many effluent treatment plants, first chemicals are added to make the wastewater constituents biodegradable. Then biological methods are applied, as biological methods alone cannot treat textile wastewaters up to the standard [67].

In certain cases, a combination of two or more techniques can be used to improve water quality, such as the aeration and filtration after coagulation. Filtration is applied as a tertiary treatment to improve the quality of treated wastewater. Carbon filter and sand filters are used to eliminate fine suspended solids and residual colors [75] Recently, a combination of coagulation and ultrafiltration has been applied for better results [76].

Biological treatments include aerobic treatments (activated sludge, trickling filtration, oxidation, ponds, lagoons, and aerobic digestion) and anaerobic treatment (anaerobic digestion, septic tanks and

lagoons) [72]. It also includes the treatment by fungal biomass, such as *Aspergillus fumigates*, effectively used to remove reactive dyes from textile wastewater [77]. A large number of microbes can degrade dyes, and this approach is gaining momentum [78]. Some of the techniques used previously for textile wastewater treatment, along with their disadvantages, are shown in Table 2.

Table 2. Various techniques for the treatment of textile wastewater and their drawbacks.

Type	Technique	Drawbacks	References
Chemical	Combined Electrocoagulation	The pH should be maintained below 6 during the process	[79,80]
	Coagulation and Adsorption by Alum	Increase the concentration of sulfate and sulfide	[81]
	Ozonation	It has low COD reduction capacity	[82]
	Chemical coagulation	It is a slow technique and large amount of sludge is produced	[83,84]
	Electrochemical oxidation	Secondary salt contamination	[66]
	Coagulation	Coagulants can be associated with diseases like cancer or Alzheimer's	[85,86]
	Electrochemical technology	Produce undesirable by-products that can be harmful for environment	[87,88]
	Ion exchange method	Not effective for all dyes	[89]
	Photochemical Sonolysis	Requires a lot of dissolved oxygen, high cost, and produces undesirable by-products	[90]
	Coagulation-photocatalytic treatment by nanoparticles	Sludge production, difficulty of light penetration in dark and colored wastewaters, high costs of nanoparticles preparation, and limited cycles of nanoparticles usage	[91]
	Fenton and Photo-Fenton process	Sludge production, accumulation of unused ferrous ions, and difficult maintenance of pH	[92]
Physical	Adsorption/filtration (commercially activated carbon)	High cost of materials, costly operation, may not work with certain dyes and metals, performance depends upon the material types	[11]
	Adsorption	It is a costly process	[93]
	Membrane based treatment	Membrane failing may happen, and costly method	[67,94]
	Pilot-scale bio-filter	Bio-filter has low efficiency to metabolize hydrophobic volatile organic compounds because of the massive transfer limitations	[95]
	Pressure-driven membranes	Sensitivity to fouling and scaling	[96,97]
Biological	Constructed wetlands	High retention time and large area required for establishment	[66,98]
	Use of White-rot fungi along with bioreactor	It has long hydraulic retention time and requires large reactors	[99,100]
	Microalgae	Conditions hard to maintain, selection of suitable algae is critical	[101]
	Duckweed and algae ponds	Inefficient removal of heavy metals	[102,103]

Though many of these technologies have excellent performance, they have many limitations [67,104]. Many physicochemical treatment options are costly because of the equipment [67]. Conventional treatment methods achieve incomplete removal of dyes and produce concentrated sludge, which causes issue of

secondary disposal [72]. In flocculation, the floc is difficult to control, and sludge underneath can re-suspend solids in water [54]. Trickling filters also have drawbacks such as high capital cost and a heavy odor [105].

Comparatively, biological methods have various advantages. They are cost-effective, produce a smaller amount of sludge, and are eco-friendly [106,107]. Ecological engineering has the advantage of being cheap. They are also able to treat non-point source wastewater effluents [107,108]. Though some biological processes also have many limitations, such as they are somewhat lengthy processes, some dyes can be a non-biodegradable, and a large amount of heavy metals in wastewater may hamper the microbial growth [54].

4. Floating Treatment Wetlands for Textile Effluent Treatment

Constructed wetlands are engineered systems composed of emergent plants and microbes with tremendous potential to remediate wastewater. Microbes proved great potential in enhancing phytoremediation potential and tolerance of plants to various environmental stresses [109,110]. Floating treatment wetlands (FTWs) are an innovative variant of constructed wetlands that make use of floating macrophytes and microbes for treatment of wastewater [111,112]. The application of FTWs (Figure 1) is a practical, eco-friendly, sustainable, and economical approach for the treatment of wastewater [112,113]. In addition to their high economic importance [114,115], plants have a key role in wastewater treatment. Mats float on the water surface, and plants are grown on these mats in such a way that the plant's roots are completely submerged in water and the plant's aerial parts are above the water [116]. Vegetation is supported on buoyant mats, which make these mats easy to retrofit in any water body where they need to be used [112]. Mostly halophytic grasses are explicitly selected for FTWs due to their rhizome, which can trap air [108,117]. FTWs share properties of both a pond and a wetland system. There is a hydraulic gradient between the bottom of the pond and the plant roots, so that the pollutants are degraded, trapped, and/or filtered by the plant roots and associated bacteria [118]. FTWs make use of plants and associated biofilms to reduce the nutrients load; that is why they are described as biofilm reactors with plants [117].

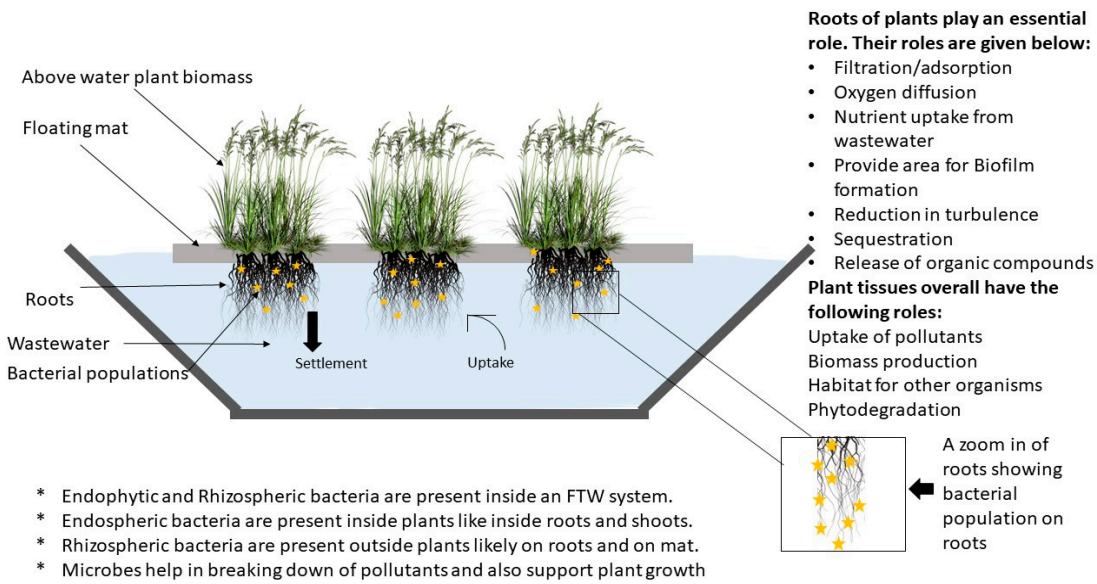

Figure 1. Schematic representation of floating treatment wetlands (FTWs) and pollutants removal process.

4.1. Role of Plants

The success of pollutant removal from water largely depends upon the selection of the plant species [119]. Plants play an essential role in the removal of pollutants from a water body. The roots of plants play a significant part in this process. The roots act as a physical filter in a FTWs system.

Roots filter the suspended particles in water and settle the filtrates at the bottom of the tank or water pond [111].

The key functions of plant in a FTW are:

1. Direct uptake of pollutants by the roots [120].
2. Extracellular enzyme production by roots [113].
3. Provide a surface area for the growth of biofilm [117].
4. Roots secrete root exudates that help in denitrification [121].
5. Suspended particles are entrapped in the roots [111].
6. Macrophytes also enhance flocculation of suspended matter [113].

Pollutant uptake by the roots of the plants is a significant process of pollutant removal from wastewater [122,123]. Dyes are phyto-transformed and then absorbed by the roots of plants [124]. The physical characteristics of the roots of plants and the nutrient uptake are interdependent/interlinked. The type of medium and nutrients in which the root exists specify the root's physical characteristics. In FTWs, the roots of the plants remain hanging in water and obtain their nutrition directly from the water. It leads to faster movement of nutrients and pollutants in the water towards the roots, thus leading to their accumulation in plant biomass. In a comparison between original plants and only plant roots in FTWs, the plants exhibited an excellent percentage of pollutant removal than artificial roots [111,125]. It suggests that the roots of the plants release some bioactive compounds in the water, and there is also a change in physicochemical processes in water. These bioactive compounds help in the change of metal species to an insoluble form, and it also enhances sorption characteristics of the biofilm, which help in pollutant removal from water [108]. Plants in FTWs support the activities of microbes already present in the wastewater as plant-microbe interactions play a prominent role in the treatment of water [113,126]. Plant roots provide spaces for the microbial growth that are necessary for water treatment [127].

Nitrogen and phosphorus are important pollutants of wastewater discharged by the textile industry. Several plants in FTWs have found efficient in removing total nitrogen (TN) and total phosphorus (TP) from wastewater [128]. Nitrogen is extracted from water by denitrification and sedimentation, while phosphorus is removed by plant uptake [129,130]. FTWs can also remove particle bind metals easily [130]. The ammonia-oxidizing bacteria and archaea on the rhizoplane have a major role in the nitrification and denitrification process [130,131].

Heavy metals are also present in textile wastewater. Macrophytes can take up these metals from the contaminated water effectively. *Phragmites australis* has excellent capacity for heavy metals removal from water, which is also a significant constituent of textile effluents [132]. FTWs vegetated with *P. australis* achieved 87–99% removal of heavy metals from textile wastewater [121]. The vegetation and floating mats minimize the penetration of sunlight in the water and stop the production of algal blooms in the water [133].

4.2. Role of Microorganism

Microbes are a key component of the biogeochemical cycle and energy flow in the aquatic ecosystem [134]. Microbes can decompose and demineralize the organic/inorganic pollutants and play a crucial role in pollutant removal from textile wastewater (Table 3) [135]. Microorganisms possess a different mechanism for the remediation of contaminated water, likely bio-sorption, bio-accumulation, bio-transformation, and bio-mineralization of organic and inorganic pollutants [127,135]. The presence of bacteria and their survival in FTWs, along with their activities, is mainly dependent on the type of plants [35]. In addition to the roots, mats also serve as a growth point for microbes [103]. These bacteria in FTWs can be rhizospheric and endophytic [136]. Rhizospheric bacteria reside outside the plant, and are sometimes attached to plant roots or on floating mats. Whereas endophytic bacteria reside inside the roots and shoots of plants [137]. The microorganisms present on roots and inside the plant tissues aid in the pollutant removal process of plants [138]. Microbes also promote plant

growth by stimulating plant growth promoting activities like the release of indole-3-acetic acid, siderophore, and 1-amino-cyclopropane-1-carboxylic acid deaminase. They also solubilize inorganic phosphorous [138,139].

Bacteria have a unique ability to adhere and grow to almost every surface, and form complex communities termed biofilms [117]. The rhizoplane of FTWs release roots exudate to attract microbial cells to form biofilms and maintain large microbial biomass. In biofilms, bacterial cells grow in multicellular aggregates that are contained in an extracellular matrix, such as polysaccharide biopolymers together with protein and DNA produced by the bacteria [140]. This biofilm formation is very beneficial for bacteria themselves, such as resistance to many antimicrobial, protozoan, and environmental stresses [141].

In FTWs, different groups of bacteria have been identified; however, the nature and abundance of the bacterial community may vary depending upon the growth conditions, substrate, growth medium, and plant species [142]. In a study on floating wetland's plants with *Eichhorina crassipes*, 40 phyla of bacteria were identified, among these most common was Proteobacteria, followed by Actinobacteria, Bacteroidetes, and Cyanobacteria [143]. In another study, Actinobacteria were found dominant in water samples, while proteobacteria were the largest group of bacteria in roots and biofilms samples of a floating wetland planted with *Canna* and *Juncus* [142]. The second-largest group of bacteria found in water and roots samples was Cyanobacteria, but was not found in biofilm. The roots of floating macrophytes also harbored the sulfate-reducing and sulfur-oxidizing bacteria [144]. In FTWs, the production of reduced sulfide acts as potential phytotoxin and sulfur oxidizing bacteria contribute in the detoxification of plants [142,145]. The presence of nitrosamines on the plants roost also confirms the abundance of nitrifiers in the aquatic system that contribute to the ammonia-oxidation process [142]. The anoxic and anaerobic microbes ubiquitous on floating mats, soil, and roots contribute to denitrification and retain metals, and thus remove pollutants from contaminated water [146,147]. The metals acquired by bacteria can be sequestered through bioaccumulation and adsorption by binding to different functional groups such as carboxylate, hydroxyl, amino, and phosphate offered by cell walls [148].

Table 3. Application of bacteria for dye removal from textile wastewater.

Bacteria	Dye	Reference
Bacillus firmus	Reactive Blue 160	[149]
Oerskovia paurometabola	Acid Red 14	[150]
Pseudomonas aeruginosa and Thiosphaera pantotropha	Reactive Yellow 14	[151]
Enterobacter sp. CV–S1	Crystal Violet	[152]
Serratia sp. RN34	Reactive Yellow 2	[153]
Paracoccus sp. GSM2	Reactive Violet 5	[154]
Staphylococcus hominis RMLRT03	Acid Orange	[155]
Bacillus cereus RMLAU1	Orange II (Acid Orange 7)	[156]
Enterococcus faecalis strain ZL	Acid Orange 7	[157]
Pseudomonas aeruginosa strain BCH	Orange 3R (RO3R)	[158]
Anoxybacillus pushchinoensis, Anoxybacillus kamchatkensis and Anoxybacillus flavithermus	Reactive Black 5	[159]
Citrobacter sp. CK3	Reactive Red 180	[160]
Bacillus Fusiformis kmk 5	Disperse Blue 79 (DB79) and Acid Orange 10 (AO10)	[161]
Pseudomonas sp. SUK1	Red BLI	[162]
Brevibacillus sp.	Toluidine Blue dye (TB)	[163]
Bacterial strains 1CX and SAD4i	Acid Orange 7	[164]
Pseudomonas luteola	Azo Dye RP2B	[165]

5. Removal of Pollutants

5.1. Removal of Dissolved and Suspended Solids

Textile effluents usually contain a high concentration of total dissolved solids (TDS) as compared to the other industrial discharge mainly due to dying, bleaching, and fixing agent. TDS is correspondingly related to conductivity and salinity of the water [49,166]. Similarly, total suspended solids (TSS) consist of nitrates, phosphates, carbonates, and bicarbonates of K, Na, Mg, Ca, salt, organic matters, and other particles. The maximum concentration of TSS in textile effluents is due to the increased concentration of suspended particles, which increases the turbidity of the water [111,124]. It also erases the level of oxygen from the aqueous medium, resulting in the disturbance of principal food chain balance in the aquatic ecosystem [166]. The much higher value of TDS was observed in textile wastewater from an extended range of 1000–10,000 mg/L [167].

In general, total dissolved solids (TDS) and total suspended solids (TSS) are removed via the filtration and physical settling in FTWs. Plant roots have a crucial role in extracellular trapping of suspended solids and the pollutants in order to neutralize the risk and avoid cell injury [168]. In FTWs, plant roots provide a living, high surface area for the effective development of successive biofilms that hold several communities of micro-organisms responsible for entrapping and filtering of suspended particles [111,169]. The root-related network of biofilms has proven active in physical trapping of fine particulates [170]. The presence of disturbance-free atmosphere and unrestricted water layers among the floating roots provides idyllic conditions for sedimentation of particles [171]. Floating treatment wetlands demonstrated productive potential to remediate TDS, TS, TSS, and other suspended pollutants from various types of wastewater [139,172]. Tara et al. (2019) reported an effectual decline of TSS from 391 to 141 mg/L, TDS from 4569 to 1632, and TS from 4961 to 1733 by using FTWs for textile wastewater treatment [35]. Another report showed the achievement of FTWs applied for textile wastewater remediation, showing a significant decline in TDS and TSS after the end of the experiment [173]. The presence of microbial community directly affects the treatment performance of wetland treatment systems [174]. Key role of microbial communities in the effective removal of suspended solid particles is evident by different studies of FTWs [132,146,175].

5.2. Removal of Organic Matter

In textile wastewater substantial organic matter load is present in terms of biological oxygen demand (BOD) and chemical oxygen demand (COD). Wastewater effluents from the dyeing and printing systems are distinguished by significant BOD and COD fluctuations. Dye wastewater with high concentrations of COD and BOD will lead to eutrophication in the receiving water bodies, and raise environmental concerns about possible toxicity [176]. Various recent studies reported a high concentration of BOD and COD in textile wastewater effluents [177–179].

In different forms of wastewater, effective removal of organic matter by application of FTWs has been achieved. Darajeh et al. 2016 reported 96% and 94% reduction in BOD and COD from palm oil mill effluents treated with FTWs [180]. Queiroz et al. (2019) treated dairy wastewater by employing eleven different species of floating aquatic plants and observed a considerable reduction in both BOD and COD [71]. Recently, plant-bacteria partnership in FTWs proved to be very promising in the successful removal of organic matter. The maximum reduction in BOD is attributed to the microbial degradation of organic components coupled with the ample oxygen supply in the root zone [181]. Adsorption, sedimentation, and microbial degradation are the primary mechanisms for the effective removal of BOD [182,183]. Meanwhile, reduction of COD is credited to microbial degradation of substrate through plant roots [146,184]. Microbial activities are usually more vigorous in the root zone [158]. Plants roots provide an active settling medium and surface area for essential attachment and food for microbial population [185].

5.3. Removal of Heavy Metals

In FTWs, different processes such as adsorption, the formation of metal sulfide, direct accumulation by plants, algae, bacteria, and entrapments by biofilms in the roots zone play a promising role in successful remediation of heavy metals [123,130]. Various potentially toxic heavy metals settle down in the system bottom once they bind with minute clay particles in the roots zone [186,187]. Endophytic and rhizospheric microbes performed a variety of important chemical reactions, including adsorption, chelation, complexation, sulfide formation, and micro-precipitation, reduction-oxidation, and ion exchange [188]. Root exudates in the root zone speed up these reactions for the subsequent formation of metals hydroxide and sulfide, which in turn improve the sorption of trace heavy metals [189,190].

Recent studies have shown that successful inoculation of various degrading bacteria improves the efficiency of aquatic wetland plants in removing metal ions/metalloids from textile wastewater, resulting in safe disposal or reuse of treated wastewater [172,191]. When bacteria enter into plant tissues, they offer more productive effects for plants as compared to those bacteria present outside the plant body. Endophyte bacteria increase contaminant accumulation and reduce their phytotoxicity in the host plant by mineralizing recalcitrant elements that would be otherwise not degradable by plants [136]. Combining use of plant and endophyte bacteria is a promising approach in the remediation of heavy metals [126,192]. In line with the prospect mentioned above, Tara et al. (2018) determined the positive impacts of bacterial augmentation on two FTWs plants, *Phragmites australis* and *Typha domingensis*. Bacteria partnership with *T. domingensis* reduced copper to 0.009 mg/L, nickel to 0.034 mg/L, chromium to 0.101 mg/L, lead to 0.147 mg/L, and iron to 0.054 mg/L, while *P. australis* decreased copper to 0.007 mg/L, nickel to 0.027 mg/L, chromium to 0.032 mg/L, lead to 0.079 mg/L, and iron to 0.016 mg/L from their initial concentrations [35].

6. Factors Affecting the Performance of FTWs

6.1. Plant Selection

The selection of the right plants at floating mats is essential to achieve optimal remediation of pollutants. The plants for the vegetation of FTWs should be a non-invasive, native species, perennial, with a quick growth rate, extensive root system, high biomass yield, high tolerance to pollutants, and high ability to uptake and accumulate pollutants in above-ground parts, and which can grow in a hydroponic environment [118,193,194]. The roots' morphology, plant tolerance to pollutants, and root exudate profile play a major role in determining the plant's potential for phytoremediation [119]. Many kinds of grass are selected for phytoremediation due to their dense root structure that can harbor a vibrant microbial community. The production of root exudate and its quality also vary significantly even in closely related genotypes. It results in substantial differences in associated microbial community and their stimulation in the rhizoplane [195,196]. Thus, the selection of the right plant in FTWs increases the remediation performance, such as cattails (*Typha* spp.) are specially used for the treatment of acid mine drainage [197,198]. However, FTWs are planted with several species, and there is no precise pattern of using specific species for certain types of wastewater or pollutants [199,200]. In the past, various plant species have been used effectively in FTWs (Table 4).

Each plant species has a different phytoremediation potential and different metals uptake mechanisms such as accumulation, exclusion, translocation, osmoregulation, distribution, and concentration [201]. Different types of vegetation can be used in FTWs such as terrestrial, aquatic emergent, sub-emergent, and free-floating species. However, emergent plants are most widely used in FTWs due to their extensive root structure [201,202].

The terrestrial and emergent plant species have mostly long and extensive root structures as compared to free-floating aquatic plants, and provide ample surface area for the pollutant removal process [203,204]. The dense root structure and ability of plants to grow hydroponically are important to obtain maximum pollutant removal by FTWs [116].

Table 4. Use of various species of macrophytes in floating treatment wetlands.

Country	Plant Name	Wastewater	Removal Efficiency	Reference
Argentina	*Typha domingensis*	Synthetic runoff effluent	Achieved 95% removal of total phosphorus, soluble reactive phosphorus, NH_4^+ and NO_3^-	[205]
Australia	*Carex appressa*	Runoff from low density residential area	The pollutants removal performance was 80% for TSS, 53% for total phosphorus, 17% for total nitrogen	[206]
China	*Iris pseudacorus*	Synthetic secondary effluent	Achieved 89.4% removal of TN in one day retention time	[207]
China	*Cyperus ustulatus*	Domestic wastewater	The average removal efficiency for total microcystin-RR and microcystin-LR were 63.0% and 66.7%, respectively	[208]
Indonesia	*Chrysopogon zizanioides*	Textile wastewater	The average removal rate for chromium was 40%, BOD was 98.47%, and COD was 89.05%	[209]
Italy	*Phragmites australis, Carex elata, Juncus effusus, Typha latifolia, Chrysopogon zizanioides, Sparganium erectum,* and *Dactylis glomerata*	Resurgent water	The COD, BOD, and TP were reduced by 66%, 52%, and 65%, respectively	[210]
New Zealand	*Carex virgate*	Storm water	The pond with FTWs achieved 41% TSS, 40% particulate zinc, 39% copper, and 16% dissolved copper removal more than pond without FTWs	[111]
New Zealand	*Carex virgate*	Domestic wastewater	The removal rate for both TSS and BOD was more than 93%, TP and dissolve reactive phosphorus removal rate were 44.9% and 29.7%	[211]
Pakistan	*Phragmites australis*	Synthetic diesel oil contaminated water	The hydrocarbons concentration was reduced to 95.8%, COD to 98.6%, BOD to 97.7%, and phenol to 98.9%	[212]
Pakistan	*Phragmites australis, T. domingensis, Leptochloa fusca* and *Brachia mutica*	Oil contaminated stabilization pit	Reduced COD 97.4%, BOD 98.9%, TDS 82.4%, hydrocarbons 99.1%, and heavy metals 80%.	[108]
Pakistan	*Brachia mutica and Phragmites australis*	Oil field-produced wastewater	The COD, BOD, and oil contents reduced by 93%, 97%, and 97%, respectively	[139]
Pakistan	*Phragmites australis and Typha domingensis*	Textile wastewater	The color, COD, and BOD were reduced by 97%, 87%, and 92%, respectively	[35]
Pakistan	*Brachiaria mutica*	Sewage effluent	The COD, BOD, and oil contents were approximately reduced by 80%, 95%, and 50%	[112]
Pakistan	*Typha domingensis, Pistia stratiotes* and *Eichhornia crassipes*	Textile effluent	The average reduction rate for color, COD, and BOD was 57%, 72%, and 78%, respectively	[138]
Pakistan	*Phragmites australis, T. domingensis, Leptochloa fusca* and *Brachia mutica*	Oil contaminated stabilization pit	The COD, BOD, and TDS contents were reduced by 79%, 88%, and 65%	[213]
Sri Lanka	*Eichhornia crassipes*	Sewage water	The removal rate was 74.8% for TP and 55.8% for TN	[214]

Table 4. *Cont.*

Country	Plant Name	Wastewater	Removal Efficiency	Reference
Sri Lanka	*Typha angustifolia* and *Canna iridiflora*	Sewage wastewater	Achieved 80% reduction in BOD and NH_4^+-N, and 40% reduction in NO_3^--N	[215]
USA	*Spartina patens*	Synthetic marine aquaculture effluent	The TP concentration was dropped to ranging from 17–40%	[216]
USA	*Pontederia cordata* and *Schoenoplectus tabernaemontani*	Urban runoff	The TP and TN concentration were dropped to 60% and 40% in treated wastewater	[217]

It is well reported that plants with small root structure and slow growth rates are not suitable for phytofiltration [218]. The dense root structure also favors the bio-adsorption and biochemical mechanism essential for the pollutant removal process [219]. Although terrestrial plants demonstrated good potential for phytoremediation in the hydroponic system, they were not commonly used in FTWs [201]. Species with good potential for rhizo-filtration, such as *Brassica juncea* and *Helianthus annus*, can be used in FTWs. The most commonly used emergent plants genera/species are *Phragmites* (*Phragmites australis*), *Typha* (*Typha angustifolia*, *Typha latifolia*), *Scripus* (*Scripus lacustris*, *Scripus californicus*), *Juncus*, *Eleocharis*, *Cyperus*, and *Elode* [33,146,220]. Among all these *Phragmites australis* is the most frequently used species in free water surface wetlands followed by *Typha* (*T. angustifolia* and *T. latifolia*) [221]. The features such as perennial, flood-tolerant, toxic pollutants tolerant, extensive rhizome system, and rigid stems make it the best contestant for wetlands [204].

A combination of more than one species of plant has also been used many times to see the effect of using multiple species instead of one. Moreover, different plants have different pollutant capacities that vary from species to species. Under same conditions *Typha angustifolia* removes more nutrients from wastewater as compared to *Polygonum barbatum* [133]. *P. australis* produced the highest amount of biomass, followed by *T. domingensis*, *B. mutica*, *L. fusca*, *C. indica*, and *R. indica*, whereas *L. fusca* showed the highest plant density followed by *B. mutica*, *P. australis*, *T. domingensis*, *C. indica*, and *R. indica* [108,213]. Plants can uptake dyes, which are the principal constituent of textile wastewater. Previously, *Myriophyllum spicatum* and *Ceratophyllum demersum* species of plants efficiently removed dyes from synthetic textile wastewater [10].

6.2. Plant Coverage

Plant coverage on a floating mat has a prominent role in the wastewater remediation process. An increase or decrease in plant density may also increase or decrease the decontamination process. However, an increase in plant density does not equate with an increase in pollutant removal [118]. The increasing plant density will ultimately decrease the dissolved oxygen level of water under the floating mats. In a constructed wetland dominated by cattails and reeds, results indicated that microbial community and nitrate removal rates were high in wetlands with 50% plant coverage than 100% plant coverage [222]. Chance and White [223] reported that non-aerated floating wetlands with 100% planting coverage had a low dissolved oxygen level as compared to floating wetlands with 50% planting coverage. The dense plant coverage limits the gaseous exchange, which mostly occurs through the uncovered portion of the system [223]. There is little information in the literature on plant density, but plant coverage is suggested to be less than 80 percent for most FTWs [224].

6.3. Aeration and Dissolve Oxygen

In constructed wetlands, the dissolved oxygen level is an essential factor that can influence the pollutant removal process. In traditional wetlands, often the problem of insufficient oxygen supply and inappropriate oxygen distribution are found [225]. The atmospheric reaeration is one of the most important sources of oxygen supply in wetlands. Plants produce oxygen during the

photosynthesis process, which can be released from plant leaves and roots into their surrounding environment [226]. The microbial degradation of organic matter can be achieved under both aerobic and anaerobic conditions. The aerobic degradation is mostly applied for less polluted wastewater to achieve high removal efficiency, and anaerobic conditions are favorable for the treatment of highly polluted wastewater [227]. It is well reported that higher oxygen contents in wetlands enhance the organic pollutant degradation process [228]. In wetlands, mostly oxygen is consumed by the organic matter degradation and left insufficient oxygen for the nitrification process and total nitrogen removal process [229]. The phosphorus removal bacteria in constructed wetlands can uptake more phosphorus in aerobic conditions as compared to anoxic conditions [230].

The leakage of oxygen from roots facilitates oxygen in FTWs. The extensive roots system, attached microbial communities, organic growth media, and organic pollutants under floating mats develop a substantial requirement of oxygen [223]. In addition, the photosynthesis process in water, gaseous exchange, and aeration may be reduced due to limited sunlight and air circulation, depending on the coverage area of the floating mat. It may lead to a low oxygen level under the floating mats [118]. It is widely reported that water under planted floating mats had a low dissolved oxygen level as compared to floating mats without plants or with artificial roots [111,116,217].

However, an increase in oxygen level does not mean an equal increase in the pollutant removal process. In some cases, the increasing level of oxygen in wetlands did not result in increased removal of total nitrogen and total phosphorus [231,232]. Similarly, in FTWs augmented with biofilm, the increased aeration improved the ammonium and phosphorus removal from polluted river water. In contrast, this increasing dissolved oxygen level decreased the denitrification process and overall total nitrogen removal [233]. In another study, while treating the nutrients enriched agricultural runoff, the aerated water column achieved less nitrogen and phosphorus removal as compared to the non-aerated water column [223]. Although aerated and non-aerated systems removed an almost similar amount of ammonia and nitrate, the aerated system showed higher uptake of nitrogen by plants than the non-aerated system. Park et al. (2019) treated the domestic wastewater through aerated and non-aerated FTWs coupled with biofilms and concluded that aerated FTWs with biofilms enhanced the organic matter, nitrogen, and *E.coli* removal [211]. Furthermore, it showed that FTWs can effectively perform under aerobic as well as anaerobic conditions.

6.4. Bacterial Inoculation

Plants-microbes interaction in FTWs has been widely studied [211,234,235], and signified the crucial role of plants-microbes interaction in mitigating the pollutants from wastewater. The plants and microbe interaction in wetlands largely depend upon plant species, availability of nitrogen, phosphorus, and various nutrients and minerals. Many plant species could cope with the adverse impacts of heavy metals and other abiotic stresses via regulating their antioxidants and nutrient uptake [236–238]. In FTWs, the hanging roots of the plants provide surface area for microbes' attachment and biofilm formation. Where these bacteria contribute to pollutant removal process and, in return, get organic carbon and oxygen from plants for their growth and survival [169]. Often, these symbiotic bacteria are not competent enough to remediate the diverse and potentially toxic pollutants from the wastewater [231]. The remediation potential of FTWs can be enhanced by inoculating the plants with purposefully isolated bacterial strains [232]. These inoculated bacteria not only enhance the pollutants remediation process, but also reduce the pollutants induced toxicity in plants and favor the plant growth by secreting multiple plant growth promoting hormones.

Rehman et al. [175] reported that the inoculation of FTWs with hydrocarbon-degrading bacteria enhanced the remediation of oil field contaminated water. Further, this plant-bacteria synergism improved the plant growth by reducing level of hydrocarbon induced toxicity in plants by producing siderophores and indole acetic acid and some other enzymes. Similarly, the inoculation of plant roots with rhizospheric and endophytic bacteria enhanced the removal of potentially toxic metals from the polluted river water and metals uptake and accumulation by plants [123]. Tara et al., 2019

applied FTWs vegetated with *P. australis* in combination with three dye degrading and plant growth promoting bacteria to treat textile effluent. The combined application of *P. australis* and bacteria enhanced the organic and inorganic pollutant removal and showed a reduction of 92% in COD, 91% in BOD, 86% in color, and 87% in trace metals [35]. Dyes degrading bacteria with the ability to degrade dyes can be isolated from the effluent of textile mills. Bacteria were isolated from textile effluent to degrade reactive dyes and it was found that three bacterial species, *Alcaligenes faecalis*, *Bacillus cereus*, and *Bacillus* sp., exhibited the potential to achieve more than 25% decolorization [239]. The bacteria can also be isolated from the plant parts to use as inoculum in FTWs for the degradation of textile effluent [38]. Some examples of successful application of bacteria in FTWs are given in Table 5.

Table 5. Inoculation of bacteria in floating treatment wetlands to enhance remediation potential.

Wastewater	Plant Specie	Inoculated Bacteria	Pollutant Removal	Retention Period	Reference
River water	*Phragmites australis*, *Typha domingensis*, *Brachia mutica*, *Leptochloa fusca*	*Aeromonas salmonicida*, *Pseudomonas indoloxydans*, *Bacillus cerus*, *Pseudomonas gessardii*, and *Rhodococcus* sp.	Significant reduction in trace metals contents (Fe, Mn, Ni, Pb, and Cr)	5 weeks	[123]
Diesel contaminated water (1%, *w*/*v*)	*Phragmites australis*	*Acinetobacter* sp. BRRH61, *Bacillus megaterium* RGR14 32, and *Acinetobacter iwoffii* AKR1	95.8% hydrocarbon, 98.6% chemical oxygen demand (COD), 97.7% biological oxygen demand (BOD), 95.2%, total organic carbon (TOC), 98.9% Phenol removal	3 months	[212]
Textile effluent	*Phragmites australis*	*Acinetobacter junii*, *Pseudomonas indoloxydans*, and *Rhodococcus* sp.	97% color, 87% COD, and 92% BOD removal	8 days	[38]
Oil contaminated water	*Phragmites australis* *T. domingensis* *Leptochloa fusca* *Brachiaria mutica* inoculated with bacteria	*Ochrobactrum intermedium* R2, *Microbacterium oryzae* R4, *Pseudomonas aeruginosa* R25, *P. aeruginosa* R21, *Acinetobacter* sp. LCRH81, *Klebsiella* sp. LCRI-87, *Acinetobacter* sp. BRSI56, *P. aeruginosa* BRRI54, *Bacillus subtilus* LORI66, and *Acinetobacter junii* TYRH47.	97.43% COD, 98.83% BOD, 82.4% TDS, 99.1% hydrocarbon content, and 80% heavy metal removal	18 months	[108]
Phenol contaminated water	*Typha domingensis*	*Acinetobacter lwofii* ACRH76, *Bacillus cereus* LORH97, and *Pseudomonas* sp. LCRH90	COD was reduced from 1057 to 97 mg/L; BOD5 from 423 to 64 mg/L, and TOC from 359 to 37 mg/L Phenol removal of 0.166 g/m2/day	15 days	[235]
River water	*Phragmites australis*, *Brachia mutica*	Aeromonas Salmonicida, Bacillus cerus *Pseudomonas indoloxydans*, *Pseudomonas gessardii*, and *Rhodococcus* sp.	85.9% COD, 83.3% BOD, and 86.6% TOC reduction, respectively	96 h	[146]
Oil field wastewater	*Brachiara mutica* and *Phragmites australis*	*Bacillus subtilis* LORI66, *Klebsiella* sp. LCRI87, *Acinetobacter Junii* TYRH47, *Acinetobacter* sp. LCRH81	97% COD 93%, and 97% BOD reduction, respectively	42 days	[139]
Oil field produced wastewater	*Typha domingensis*	*Bacillus subtilis* LORI66, *Klebsiella sp.* LCRI87, *Acinetobacter Junii* TYRH47, and *Acinetobacter* sp. BRSI56	95% Hydrocarbon, 90% COD, and 93% BOD content removal	42 days	[175]
Sewage effluent	*Brachiaria mutica*	Acinetobacter sp. strain BRSI56, Bacillus cereus strain BRSI57, and Bacillus licheniformis strain BRSI58	Reduction in COD, BOD, Total nitrogen (TN), and phosphate (PO_4)	8 days	[112]

7. Care and Maintenance of FTWs

FTWs can be constructed by using different types of materials including polyvinyl chloride (PVC) pipes, bamboo, polystyrene foam, wire mesh, fibrous material, and many more [116,127]. The most critical factors that should be considered while selecting appropriate material are buoyancy, durability, performance, eco-friendly, local availability, and cost [116,206]. In general, buoyancy is provided by floating mats/rafts, which also provide the base for plantation of vegetation. Sometimes plants can be grown in other structures such as wire mesh structure, and buoyancy can be provided by different materials such as PVC pipes [116,240]. The floating mats should be strong enough to support the load of plants, growth media, and be resistant to damage by sun, water, and heavy wind for long term sustainability. Floating mats should be designed to extend over the width of the retention pond, making a closed area between the inlets and FTWs for better flow distribution and to prevent short-circuiting [118,223].

The plants can be established on floating mats by direct seeding, planting cuttings and seedlings of the plants. The choice of method depends upon plant species, the structure of the floating mat, and environmental conditions, and availability of plants [118,171]. Direct seeding may be a cost-effective and rapid method for the vegetation of large-scale FTWs. The species, such as *Typha* and *Phragmites*, are commonly vegetated on floating mats through their cuttings [146]. The planting of seedlings may be an expensive approach in the sort-term, however, it results in rapid establishment of plants and a high growth rate. For plants establishment, selection of appropriate growth media is very important, especially during the initial stage of the plant vegetation. The most commonly used growth media are coconut fiber, peat, and soil [118,127]. The organic and inorganic fertilizers are also often applied to ensure better growth and development of plants on floating mats [136]. Care should be taken that growth media must have the ability to hold enough water for plant uptake and air circulation to maintain aerobic conditions, be resistant to waterlogging, and have ideal pH for plant growth [118,223].

It is suggested to avoid tall plants for FTWs, as during windy periods, these plants may cause the floating mat to drift, and laying of these plants in one direction may cause the salting or turnover of the floating mats [118,171]. Further, the plants with lose and large above-ground biomass should be avoided to limit the accumulation of dead plant biomass and release of accumulated pollutants in the water column [118]. Care should be taken while planting that plant roots should be able to reach the water column to ensure the availability of water during the initial stage of development [119,127]. After initial days of plantation, some plant may die due to unfavorable environmental conditions or toxicity of polluted water. Additionally, plants may die back during regular weather changes and by severe deoxygenation conditions below the floating mats. This issue can be solved by replanting the new plants at the free area of the floating mats [130]. Periodic trimming and harvesting of the plants may boost plant growth and prevent the accumulation of plant detritus and biomass on the floating mats [168].

Floating mats should be secured appropriately in the aquatic ponds to prevent drifting due to wind and waves [116]. The floating mats can be supported by fastening the floating mat's corners to the side of the ponds and anchoring them. Care must be taken to ensure that there should be some flexibility in the anchored ropes to adjust floating mats with changing water levels to the prevent sinking or submerging of floating mats during rising water level. In the windy area, the chances of over-turn of floating mats can be minimized by installing small floating mats rather than a large one with low height vegetation [118]. In a warmer climate, vegetation on floating mats may become a habitat for mosquito and other similar insects. This problem can be controlled by maintaining aerobic conditions in the pond, water spray on plants, frequent harvesting of the plants, and by use of approved chemical and biological control agents for these insects [241,242]. The periodic harvesting of the plants also improves the ability of plants to uptake nutrients and phosphorus from the polluted water.

The growth of invasive species on the FTWs may pose a potential issue for specific vegetation. The predominance of selected species can be maintained by regularly checking and pulling the weeds from the floating mats [243,244]. Regular monitoring of the FTWs is also vital to maintain the aesthetic

value and prevent the clogging of inlet and outlet by the accumulation of plastic bottles, plant branches, and other non-biodegradable materials [118].

8. Conclusions and Recommendations

FTWs can be a viable option for remediation of textile wastewater as an alternative to costly and partially effective conventional wastewater treatment methods. The combined action of plants and associated biofilm in FTWs can efficiently remove the solid particles, organic matter, dyes, pigments, and heavy metals. The *P. australis* and *T. domingensis* have been widely used for FTWs and found efficient for remediation of textile effluent. FTWs are cost-effective, but need proper care and maintenance for long term performance. The harvesting of plants on floating mats can further boost the pollutant removal process and reduce the addition of litter and plant material in water.

The manipulation of characteristics such as plant selection, biofilms, plant coverage, and oxidation/aeration can be used further to enhance the remediation potential of FTWs. The development of guidelines for the right selections of plants for specific types of textile effluents can increase the success rate of FTWs. Further research is required to isolate and characterize the specific bacterial strains capable of colonizing the plants for remediation of textile effluent according to pollutant load. One of the main hindrances in the application of FTWs is the availability of land, which can be solved by the installation of FTWs on already existing water ponds.

Most of the studies conducted on the application of FTWs for treatment of textile effluent were on lab or pilot scale for a short duration. Therefore, it is suggested to research large scale application of FTWs for remediation of textile wastewater under natural environmental conditions. Further, the effect of weather should be deeply observed to analyze the performance of FTWs under changing temperature, precipitation, and other environmental conditions. The proper disposal of harvested plant biomass and litter also needs extensive research for safe disposal of extracted pollutants from the treated wastewater. The use of harvested grasses from the floating mat as the fodder of livestock needs careful investigation of nutritional values of plants, accumulated pollutants in plant parts, and the ultimate effect on animal and animal products and transportation in the food chain.

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