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A REVIEW PAPER ON FLOATING TREATMENT WETLANDS: WORKING PRINCIPLES AND APPLICATIONS FOR RIVER WATER REMEDIATION

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ABSTRACT

As the world grapples with water scarcity, Floating Treatment Wetlands (FTWs) offer a beacon of hope for sustainable water management. These innovative systems redefine wastewater treatment by utilizing emergent plants on floating mats. FTWs act as biofilters, removing pollutants through a multi-pronged approach: direct plant uptake, microbial breakdown by root-associated biofilms, and sedimentation. Notably cost-effective and requiring no extra land as they can fit in existing water source, FTWs are well-suited for diverse water sources, including secondary effluents, stormwater, and even polluted rivers. Their ability to function in rivers without disrupting existing ecosystems makes them particularly promising for in-situ river water remediation, offering a green solution to restoring vital waterways. The (FTW) effectively addresses technical and operational issues in river water treatment by adjusting to varying water levels and varied flows through its revolutionary buoyant hydroponic design, which depends on integral components such as plants and biofilms anchored beneath the floating mat. The idea of FTWs, their structural layouts, their applicability to river water, and the processes of plant absorption for pollution removal are all covered in this paper. It examines FTWs function in extracting nutrients, heavy metals and new emerging pollutants seriously. The review also emphasizes the significance of vegetation covering, vegetation type, water depth and seasonal variation in improving system performance since an understanding of the hydraulics and other aspects of FTWs is essential for good design.

Keywords: *Floating Treatment Wetland, River Water, Macrophytes, Nutrient Removal, Heavy Metal*

1. Background

The modern scarcity of water has spurred a rethinking of resource management, leading researchers to seek sustainable solutions integrating clean technologies and circular economy principles. With water's critical role in social, environmental, and economic spheres, there's a growing emphasis on developing wastewater treatment and reuse technologies, especially vital for sustainable water management in developing nations with limited infrastructure [1]. Water quality is drastically reduced by the uncontrolled release of raw sewage and wastewater, endangering human health and rendering the water unsuitable to drink. Rivers are essential for irrigation and drinking, but as industrialization grows, direct industrial discharges from rivers decrease the quality of the water, since many rivers serve as handy locations for the dumping of effluents. To maintain environmental sustainability and safeguard public health, solid waste and sewage systems require immediate management and control [2]. Many scholars are investigating novel and sustainable approaches that fuse clean technology with a circular economy. Numerous technologies have surfaced for the treatment of wastewater and reuse of water, tackling important facets of sustainable water management, especially in developing countries without the infrastructure for wastewater treatment [1].

The pursuit of eco-friendly methods for water quality restoration has demonstrated the potential of mimicking natural phenomena, such as the cleansing properties of wetlands, to enhance the physical, chemical, and biological aspects of contaminated water. Floating treatment wetlands (FTWs) exemplify this approach, serving as a soil-less planting technology that integrates agronomy and ecological engineering in a systematic and cost-effective manner [3]. FTWs harness the inherent cleansing abilities of plants to enhance aquatic environments and swiftly eliminate pollutants from water sources. Functioning akin to constructed wetlands (CWs), FTWs leverage the interactions among water, microorganisms, plant components, algae, and pollutants to effectively purify water. Integral to wastewater treatment within FTWs are the roots, rhizomes, leaves, and shoots of hydrophytic plants, which form a floating mat. This mat accumulates nutrients such as nitrogen (N), phosphorus (P), and heavy metals, while also fostering conditions conducive to the biological breakdown of organic waste [4,5]. Since most studies are focused on N & P, very less studies have been done on Potassium (K) removal which is also considered as a food source of many plant. It is not considered a significant pollutant in municipal wastewater, but it is a worry in fertilizer industrial effluent or agricultural runoff that may end up in natural bodies of water [6]. Potassium did not significantly affect organic load reduction or nitrogen elimination, but it was crucial for plant development, as demonstrated by higher growth in the N_2K_2 bioreactor [6,7].

FTWs are widely used to treat secondary effluents, stormwater, sewage discharges, agricultural and airport runoff, polluted rivers, and industrial wastewater. They are known for their affordability and ease of construction, and their potential in treating urban stormwater is becoming more widely acknowledge[1,4]. FTWs utilize buoyant artificial mediums to foster root growth in the water, with emergent macrophytes growing atop a floating mat on the surface rather than being rooted in sediment, distinguished by the large aerenchyma in their roots and rhizomes, enhancing their buoyancy [8–10]. A large surface area is made available by plant roots for the development of the associated biofilm and the trapping of dispersed particulate particles [8]. Since the plants aren't anchored in the sediment, they must absorb nutrients directly from the water, leading to an accumulation of nutrients within their biomass [11]. FTWs are being used more and more for stormwater treatment, agricultural runoff, secondary effluent treatment, and even river remediation because to their simple and low-cost construction [12]. The elimination processes rely on the interplay between floating emergent plants, microorganisms, and atmospheric conditions. These processes include the capture, settling, and clumping together of suspended solids, absorption of pollutants by plant components, various chemical reactions like assimilation, redox, and anammox, as well as nitrification-denitrification processes, decomposition, mineralization, immobilization, breakdown of organic pollutants, and the secretion of extracellular enzymes [4,13]. The intricate network of roots offers a vast surface area for bacterial colonies to flourish, leading to enhanced plant vitality, conversion of nutrients into usable forms, mitigation of metabolic strain, and ultimately, improved breakdown of pollutants [5].

Numerous reviewers have evaluated floating treatment wetland technology on multiple occasions [1,4,9,10]. Nonetheless, this assessment focuses on the most recent advances in floating treatment wetlands (FTWs). It delves into the core idea, operational concepts, and major design elements of FTWs, as well as the plant's function in pollution removal. Furthermore, it provides a thorough explanation of the techniques used by FTWs to remove nutrients and heavy metals.

However, there has been limited exploration into the joint application of plants and bacteria for purifying polluted river water in Floating Wetlands (FWs) [14]. Thus, this review paper is also centered on the remediation of contaminated river water utilizing FTWs.

2. Review Methodology

To conduct a comprehensive review analysis, an extensive literature review was performed using Google Scholar, Scopus and other search engine with the search terms "Floating Treatment Wetlands", "Floating Islands", “Wastewater Management” and related terms spanning the years from 2000 to 2023. To determine the scale of each study, several factors were evaluated, including the size of the developed system, whether environmental conditions were controlled, and if the treated water was synthetic or real samples. Experiments were categorized as "Bench Scale," "Pilot," or "Real".

Regarding FTWs, most studies concentrate on enhancing system efficiency by optimizing various design features, including system size, inflow parameter and pollutant concentrations, and climatic conditions [15]. In this context, key design and operational parameters for FTWs include the choice of vegetation, the extent of vegetation coverage on the water surface, the growth media (if used), water depth, and buoyancy methods [5].

3. Floating Constructed Wetland: Details

3.1 Working Principle of FTWs

Roots, rhizomes, associated biofilms, and plant shoots play a crucial role in FTWs, with the interaction between the underground network of roots and rhizomes and the microbial assemblages being the primary mechanism for removing pollutants from wastewater [16]. FTWs work by growing biofilms that release extracellular enzymes, produce a large surface area that is biologically active, and aid in physical and biochemical reactions that lead to the breakdown of organic pollutants, the entrapment of solids, the filtration of suspended matter, and the uptake of nutrients and metals [4,17]. This biofilm provides a habitat for diverse bacterial communities, playing a crucial role in nutrient sequestration from water by facilitating nitrogen removal through nitrification and denitrification, retaining phosphorus through adsorption [15], and reducing water flow and turbulence to enhance sedimentation and trap suspended particles [18]. FTWs operate effectively in both aerobic and partially anoxic/anaerobic environments, with superior pollutant removal in aerobic conditions, and can be further improved by incorporating endophytic and rhizospheric bacteria to alleviate plant stress and enhance pollutant degradation [19]. Metals are removed through various processes, including entrapment in biofilms, binding to clay particles or particulate matter, chelation, micro-precipitation, precipitation, ion-exchange, redox reactions, formation of metal sulfides/hydroxides, and uptake by macrophytes [18,20].

3.2 Design parameters of FTWs

Key design and operational parameters for FTWs include the type of vegetation, the percentage of water surface covered by vegetation, the growth media, water depth, and the methods used to achieve buoyancy [5]. Additionally, some researchers have combined FTWs with artificial Aeration System (Aerators) to enhance dissolved oxygen (DO) levels in the water column [21,22].

Buoyancy, a crucial design parameter, can be achieved by creating a floatable raft or mat on the water surface [23]. Materials like as foam, coconut peat, bamboo, and artificial matrix such as Biohaven are utilised as buoyant mats in built FTWs [8,11,24].

When planning an FTW, water depth is a crucial factor; ideally, it should be maintained at 0.8 to 1.0 meters to optimize root exposure to pollutants, with shallow depths facilitating enhanced removal of fine particles and suspended solids due to increased root, water, and microorganism interaction, while deeper water promotes the formation of a free water zone beneath the floating mat, facilitating the removal of coarse suspended solids through sedimentation [18]. The water level also directly influences the diffusion of oxygen from the atmosphere and the hydraulic retention time (HRT) [9]. Headley & Tanner [10] recommended water depth ranging from 0.8 to 3 meters to prevent plant roots from reaching benthic sediments, thereby ensuring proper segregation of accumulated solids from the roots to minimize the need for system maintenance over extended periods. HRT is also an important factor in removing pollutants, since it is possible to build an appropriate microbial population in constructed wetlands (CWs) that will allow for enough contact time to eliminate pollutants over an extended HRT [25,26]. Since the removal of nitrogen often takes a longer HRT than the removal of organic matter, a short HRT may result in inadequate denitrification of wastewater [27].

Choosing appropriate vegetation for FTWs is pivotal, relying on specific fundamental traits of plant species, necessitating plants that are acclimatized to local climates, aesthetically pleasing, non-invasive, buoyant, preferably perennial, capable of flourishing in hydroponic environments, and featuring ample aerenchyma tissues to facilitate enhanced oxygen diffusion from above ground to underground parts [1,3,9,28]. Plants should possess a strong capacity for nutrient absorption, the capability to thrive and expand, and develop dense, submerged root systems [9]. In FTWs, predominantly emergent species are favored, but their placement must consider the balance of the floating structure; utilizing a mix of plants of different heights is often advantageous, although taller species may pose a risk of tipping over the FTW, thus requiring a sturdy foundation to maintain plant positioning. However, species selection is contingent upon the climate of a specific region and the objectives for contaminant removal [4]. Plants absorb and retain pollutants in various components, necessitating periodic harvesting and regeneration of wetland vegetation to completely eliminate absorbed contaminants from the system, thus preventing the reintroduction of nutrients into the water and mitigating potential pollution issues [3]. Emergent macrophytes from the genera *Canna, Carex, Cyperus, Juncus, and Typha* are the most commonly used ones in FTWs. To enhance the visual appeal of FTWs, ornamental plants, particularly those from the Canna genus, are often incorporated, especially in areas designated for the treatment of river water, ponds, or stormwater. Although FTWs have demonstrated proficiency in pollutant removal, there has been limited exploration into the utilization of herbaceous ornamental plants; hence, Barco & Borin [29] conducted research to investigate their capacity for improving both water quality and aesthetic appeal in urban water bodies. Since the roots of FTWs must stay out of contact with benthic sediments or soils, these plants have to take up nutrients directly from the water column, and they may do so at a higher rate than sediment-rooted artificial wetlands [10]. While numerous research endeavors have examined nutrient absorption by plants in FTWs, several crucial aspects require further investigation for the effective application of FTWs, including plant adaptation, upper mass and root growth, pollutant tolerance thresholds in the water, and the development of symbiotic relationships between plants and various microorganisms [5].

Biofilms are naturally existing slimy, sticky colonies of bacteria, fungus, protozoa, and algae that are adhered to plant roots and other stable living and non-living surfaces of FTWs in a body of water [30–33]. According to Xiao & Chu [34], biofilm carriers possess a specific surface area that is 60–430 times greater than that of plant roots, allowing them to mitigate fluctuations in water flow and effectively trap pollutants [4]. Biofilms improve removal efficiency by offering additional biologically active surfaces for contaminant biochemical transformation, binding trace metals to clay particles or particulate matter for subsequent uptake or precipitation, providing mechanical stability, increasing water retention, complexing metals, trapping suspended solids, enhancing nutrient sorption (adsorption or absorption by roots of plant), and protecting against viruses by providing barrier or certain microorganism feed on these viruses which are known as enteric virus (example: notovirus, rotavirus) that are usually found in wastewater [8,10,35,36]. The amount of pollutants present, the water body's metabolic activity, the development and shape of the roots, and the root exudates all affect the concentration of bacteria in biofilms [14,37]. When FTWs modified with artificial biofilm carriers are compared to those enhanced with natural biofilms, the removal efficiency of pollutants is consistently greater [38]. Figure 1 summarize the process involved in FTWs along with the parameters involved in FTWs.

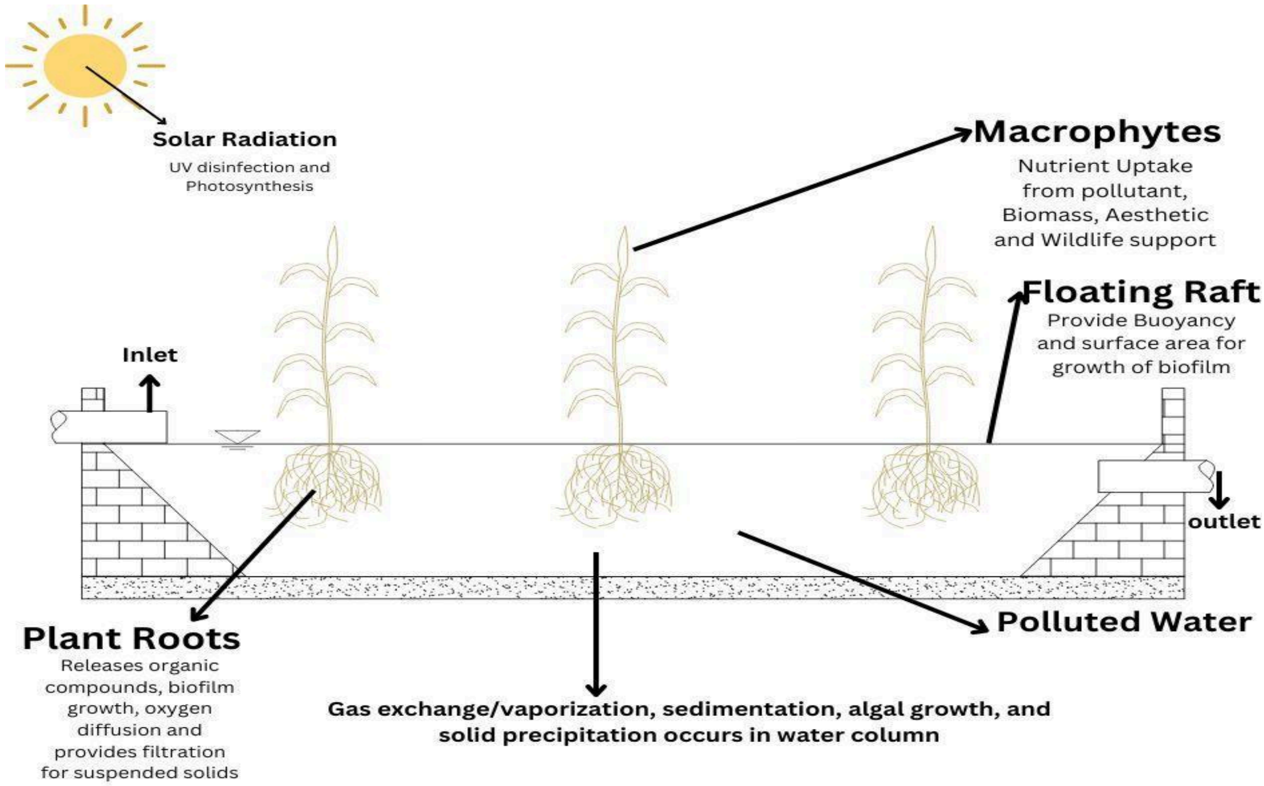

Fig 1: Working Drawing on Horizontal Floating Treatment Wetland

4. Application of FTW in treating polluted river water

FTWs are mainly constructed for the treatment of polluted water sources and improve the quality of water. FTWs can be applied to treat eutrophic lake water [39], stormwater [39], petrochemical refinery wastewaster [40], agricultural runoff [41,42], aquaculture effluent [43], river water [14,44,45]. Table 1 summarizes numerous FTW studies, detailing the types of water and wastewater treated, the plants used for remediation, and the average pollutant removal efficiencies, encompassing sources such as lake and river water, industrial wastewater, Aqua-culture wastewater, nutrient-rich wastewater, and groundwater.

The escalating industrialization is significantly compromising river water quality, exacerbated by the direct discharge of effluents, particularly in regions worldwide where rivers serve as dumping sites for industrial waste, coupled with the connection of household effluents and drainage to these water bodies [14]. FTWs are an attractive answer to issues related to river water pollution as they are affordable and, most significantly they require no land. Limited studies has been performed in actual river water. The large surface area of biofilms in FTWs enhances their capacity to remove pollutants from river water more efficiently, making FTWs an effective and innovative solution for managing river water pollution. Peterson et al. [45] found that installing a 90 m^2 artificial floating wetland on the

Chicago River reduced nitrate and phosphate concentrations by 6.9% and 6.0%, respectively, during the growing season. In the study conducted by Shahid et al. [14], FWs effectively treated the Ravi River's contaminated water to satisfy irrigation requirements. Saeed et al. [37] found the FCW primarily removed nitrogen via nitrification-denitrification, phosphorus through filtration and sedimentation, with nutrient and E. coli removal higher in dry periods and greater organic mass removal in wet periods due to higher influent concentrations. Arivukkarasu & Sathyanathan [46] among the four floating wetland systems (FWTs), those with *C. indica* and Vetiver grass significantly reduced the initial concentration of E. coli, dropping to 850 and 870 MPN/100 mL, respectively, with an efficiency of 46.88% and 45.63% when compared to other treatments.

Table 1: An overview of FTW studies for several forms of wastewater remediation

Wastewater type	Plant used	Key findings (average removal rate in %)	Scale of study	References
River water	*Festuca arundinacea*	TN: ~90; TP: ~72; NH_4: ~86	Microcosm	[47]
	Equisetum sp., Ipomoea aquatic Forsk	TP: 87.5; COD: ~79; NH_4: ~84	In-situ	[48]
	Brachia mutica, Leptochala fusca, P. australis, and T. dominigenesis (inoculated with bacteria	Maximum removal with P. australis; reduced Fe, Mn, Ni, Pb, and Cr to 0.53, 0.2, 0.09, 1.04, and 0.07 mg/L in 35 days.	Mesocosm	[14]
	Phragmites australis and Canna indica	TIN: 38; TP: 70; NH_4: 28;	Batch	[37]
	Acorus calamus, Caltha palustris , Carex bromoides , Carex comosa , Carex stricta , Decodon, verticillatus , Filipendula rubra , Hibiscus moscheutos , Iris virginica var. shrevei , Juncus effusus , Justicia americana , Rumex altissimus, Saururus cernuus , Scirpus cyperinus and Verbena hastata	NO_3-N: 6.9 $PO_4{}^{3-}$: 6	Field-Study	[45]
Aqua-culture wastewater	*Typha latifolia, Chrysopogon zizaniodes, Sparganium erectum*	TP: 65; BOD5: 52; COD: 66	Field-study	[49]

Wastewater type	Plant used	Key findings (average removal rate in %)	Scale of study	References
Synthetic wastewater	*Iris pseudacorus*	TN: 43.8, Plant uptake nutrient: 7.7	Lab-scale (green-house)	[50]
Nutrient enriched lake water	*Canna flaccida, Juncus effusus*	TP: 45.5–75; TN: 58–83.5	Mesocosm	[39]

5. Contaminants removal using FTWs

5.1 Nitrogen Removal

Various nitrogen forms in wastewater (org-N, NH_4^+-N, NO_2-N, NO_3-N) are removed mainly through denitrification (microbial reduction of nitrate to nitrogen gas under anoxic/anaerobic conditions), ammonia volatilization at high pH, and plant uptake, while other processes like nitrification, ammonification, and microbial assimilation merely convert nitrogen into different forms [28]. Plant harvesting can permanently remove inorganic nitrogen that has been taken by roots and deposited in plant tissues. Through mass transfer, ammonia volatilization which takes place in an alkaline environment removes NH_3 gas from the water's surface and releases it into the atmosphere [51]. Ammonium removal ranges from 24% to 100%, influenced by plant species, influent load, and environmental conditions. While sedimentation removes some nitrogen, a significant portion remains; denitrification handles 80% of nitrogen removal, with the rest managed by biological accumulation and sedimentation, potentially enhanced by thiosulfate-driven denitrification [12]. Shahid et al. [14] in their river water treatment reported that *Phragmites australis* shows total nitrogen was reduced from 37.5 to 2.07 mg/L^{-1} , nitrate from 33.3 to 1.23 mg/L^{-1}. In another study [41,42] *Pontederia cordata and Juncus effusus* were observed to remove 84.3% and 88.9% of total nitrogen (TN) from stormwater at high nutrient loading rates, and 35.5% and 66.3% at low nutrient loading rates, respectively. White & Cousins [39] reported that *J. effusus and C. flaccida* contributed to 28.3% and 16.4% of total nitrogen (TN) removal, respectively. Chua et al. [52] shows the TN uptake rates as 16.2 mg/m²/day for *T. angustifolia*, 1.74 mg/m²/day for *Chrysopogon zizanioides*, and 2.82 mg/m²/day for *Polygonum barbatum*. The FTW ecology efficiently processes decomposing plant matter and circulates nutrients from man-made sources, therefore managing extra nitrogen from plant leaf debris sedimentation and maintaining low nitrogen levels in water [53].

Adding external carbon and sulfur sources to the water can enhance the removal efficiency of FTWs. Carbon sources facilitate complete denitrification, converting NO3- to N2, thereby significantly reducing N2O emissions and enhancing the system's overall performance [12]. Adding sulfur sources is another effective method to enhance total nitrogen (TN) removal efficiency [54]. Shahid et al. [14] in their river water treatment reported that *Phragmites australis* shows total phosphorus was reduced from 2.63 to 0.53 mg/L^{-1}.

5.2 Phosphorus Removal

In FCW systems, phosphorus removal typically occurs through direct uptake by macrophyte roots, storage in plant biomass, and filtration of phosphorus-bound sediments by hanging roots, which then settle at the bottom [37]. Phosphorus can be found in wastewater as dissolved inorganic orthophosphate PO_4^{3-}P and organic-P. The permanent elimination of the system's stored phosphorus is made possible by harvesting plant biomass. Microorganisms use enzyme phosphatases to convert organic phosphorus into inorganic dissolved forms, which are then assimilated by plants and biofilms [48]. Seasonal variations influence phosphorous uptake in certain plants; for instance, *Typha domingenesis* exhibits peak phosphorus accumulation in leaves during summer and winter, while the highest accumulation occurs in roots, attributed to nutrient redistribution towards rhizomes in preparation for dormancy, serving as storage for the upcoming growing season [4]. In a study conducted by White & Cousins [39] *J. effusus and C. flaccida* were responsible for 41.6% and 25.5% of total phosphorus (TP) removal, respectively. Shen et al. [55] demonstrated that the FTW-PS, comprising plants and substrates, exhibited the highest performance, with a soluble reactive phosphorus removal efficiency of 62.5 ± 7.4% and a soluble non-reactive phosphorus conversion rate of 90.7 ± 13.7%. FTW removal efficiencies with *Canna indica, Ocimum tenuiflorum, Chrysopogon zizanioides*, and *Hibiscus rosasinensis* were from around 45% to 74% (average 66.46%), 50% to 72% (average 61.50%), 60% to 85% (average 72.15%), and 25% to 66% (average 53.25%), respectively [46]. Peterson et al. [45] demonstrated that a small, 90 m^2 AFW installed on the Chicago River reduced phosphate concentrations by 6.0% during the growing season.

5.3 Metal Removals

Heavy metals pose severe environmental and health risks, necessitating their urgent removal; bio-methylation (e.g., mercury, arsenic) and biomagnification (e.g., cadmium, lead) exacerbate these threats, and using FTWs with emergent macrophytes offers an eco-friendly and cost-effective solution [4]. Through active and passive processes including rhizofiltration, rhizodegradation, and phytostabilization, the root networks of floating plants take up heavy metals from the surrounding water and transfer them to their aerial portions. Certain metals, such as arsenic (As) and mercury (Hg) undergo the phenomenon known as phytovolatilization, in which these metals are taken up by roots, transformed into a volatile state inside the plant, and then released into the atmosphere through the leaves [56]. Translocated heavy metals accumulate in plant tissues (phytoaccumulation) [57], which can then be harvested (phytoextracted) and sediment dredged to eliminate them from the system. Plants' ability to absorb metals is influenced by their morphology, biomass development, growth rate, heavy metal tolerance, and environmental adaptability [58]. *Juncus effusus and Carex riparia* are commonly utilized in FTWs for the removal of heavy metals due to their readily harvested root biomass [51]. Shahid et al. [14] reported that in their river water treatment study, *Phragmites australis* reduced trace metals by up to 79.5% for iron, 91.4% for nickel, 91.8% for manganese, 36.14% for lead, and 85.19% for chromium.

5.4 Emerging Pollutants Removal

Floating Treatment Wetlands (FTWs) are well-known for their ability to remove heavy metals and nutrients from wastewater. Now, they are also showing promise in the fight against new contaminants including pharmaceuticals and textile industries effluents, which present serious problems for conventional wastewater treatment systems.

In this recent study, Karki & Philip [59] examines how well *Chrysopogon zizanioides* (Vetiver) and *Colocasia esculenta* (Taro) work in hydroponic settings to reduce pharmaceutical and personal care product (PPCP) pollutants like metronidazole (MNZ), naproxen (NAP), and methylparaben (MeP). The results show that both plants have similar uptake potentials (5.23 to 5.76 mg/g biomass dry weight) and low pollutant accumulation (<10%), with a sizable portion of the pollutants undergoing metabolism (66.27% to 78.42%). The study conducted by Lyu et al. [60] examined the potential of floating treatment wetlands (FTWs) as a nature-based remedy for treating water contaminated with propylene glycol, exploring various removal mechanisms quantitatively. Results showed that FTWs containing *Acorus calamus* and mixed species exhibited the highest average glycol mass removal efficiency (99%), followed by *Carex acutiformis* (98%), *Juncus effusus* (93%), compared to the control group without plants (10%), all tested over a one-week period.

Nawaz et al. [61] studied, synthetic dye-enriched effluent—which was produced by adding three distinct colours to tap water separately—was treated using FTWs containing *Phragmites australis* and certain bacteria. Along with mitigating dye-induced toxicity and promoting plant growth, the FTWs significantly reduced metal concentrations (Cu, Ni, Zn, Fe, Mn, Pb) by 75% to 89.7% across all three dyes when supplemented with Acinetobacter junii strain NT-15, Rhodococcus sp. strain NT-39, and Pseudomonas indoloxydans strain NT-38. This indicates that FTWs are a viable treatment option for textile wastewater that is dye-rich.

6. Factors affecting FTWs

6.1 Water Depth

The efficiency of FTWs improves with increased depths because deeper water during flow events prolongs the detention time of stormwater pollutants, allowing for more treatment per unit surface area [10]. However, in a study by Chang et al. [53], increasing water depth led to higher removal of total nitrogen and nitrates, while the remediation of total phosphorus and orthophosphate decreased. Increasing water depth beyond a certain level can cause more flow to bypass the root-biofilm network of FTWs, potentially reducing treatment efficiency despite the greater depth [10]. To optimize root growth and enhance its exposure to pollutants, it is recommended to maintain a water depth of at least 0.8 to 1.0 meters [1]. Various studies employing FTWs have reported water depths ranging from 0.25 meters in a bench-scale study [62] to 2.5 meters [63] and 3 meters [64] in real-scale investigations, reflecting the diverse range of depth parameters examined across different research contexts.

6.2 Vegetation Coverage

Vegetation coverage is an important factor which can affect the performance of FTW. FTWs with 5% to 10% floating vegetation cover effectively reduce TP by 54%, OP and nitrate by 48%, and TN by 32%, though exceeding 5% coverage may block sunlight from reaching the bottom in large ponds [53]. Vegetation cover exceeding 50% in FTWs can create anoxic conditions by blocking oxygen diffusion, while a low cover of 9-18% offers minimal treatment efficiency [9,13,47].

6.3 Function and types Vegetations

Plant selection is crucial for FTW systems as macrophytes enhance treatment performance through nutrient uptake, sediment trapping, organic matter degradation, and by offering aesthetic appeal and food for wildlife [24]. The most common emergent macrophytes used in FTWs are from the genera *Canna, Carex, Cyperus, Juncus, and Typha*, with ornamental *Canna* species often chosen for aesthetic enhancement in populated areas; these plants, absorbing nutrients directly from the water rather than from sediments, may exhibit higher rates of nutrient and metal assimilation than sediment-rooted constructed wetlands [10]. Although FTWs have demonstrated proficiency in pollutant removal, there has been limited exploration into the utilization of herbaceous ornamental plants; hence, Barco & Borin [29] conducted research to investigate their capacity for improving both water quality and aesthetic appeal in urban water bodies and found that *C. indica*, *P. cordata* and *T. dealbata* were the most suitable species for FTW. According to Keizer-Vlek et al. [65], removal efficiencies in FTW studies vary widely due to loading rates, ranging from 6% to 83% for TP and 25% to 40% for TN. Using *Iris pseudacorus L.*, plant uptake accounted for 60% of TN and 74% of TP removal, while

Typha angustifolia L. showed 49% for TN and 99% for TP, emphasizing the critical role of plants in the treatment process. X. Zhang et al. [50] found that phosphorus removal increased over time, with TP removals reaching 50.9% to 74% by the end of the experiments, attributed to plant growth. Nitrogen removal efficiency was directly influenced by DO concentrations; systems with higher DO (2.03 and 1.6 mg/L) achieved better TN removal (80.7% and 79.2%), while lower DO systems (1.27 and 0.67 mg/L) had poorer nitrification levels (47% and 10.1%).

The accumulation of heavy metals in plant tissues varies by species; Ladislas et al. [66] found that in a FTW system with *Juncus effusus* and *Carex riparia*, Cd concentrations were 0.1 mg/g for both, Ni concentrations were 44 and 64 mg/g, and Zn concentrations were 210 mg/g in the roots and 80 mg/g in the aerial parts of *Juncus effusus*. T. Headley & Tanner [67] used *Carex virgata*, *Cyperus usitalis*, *Juncus edgariae*, and *Schoenoplectus tabernaemontani* in their study, and in floating wetlands treating stormwater, they were able to achieve a removal rate of 65–75% for copper (Cu) and 10–35% for zinc (Zn).

6.4 Seasonal Variation

Basically it is seen that warmer temperatures enhance nutrient removal due to increased plant biomass and microbial degradation, whereas colder temperatures inhibit these processes as plants become dormant and microbial activity slows as studied by different researchers [47,68]. Ge et al. [68] study shows due to the high temperatures between August and October, plant biomass increased; however, when air temperatures decreased towards the conclusion of the experiment, plant biomass started to diminish, which was consistent with seasonal changes noted in earlier research [69,70] Seasonal fluctuations have a direct impact on nutrient removal and plant development, as warmer temperatures stimulate higher biomass and microbial activity in the rhizosphere, improving nutrient absorption and biodegradation, whereas colder conditions, particularly in December, impede plant and microbial functions, resulting in reduced nutrient assimilation during the mature and senescence phases due to decreased metabolic activity, particularly in plant enzymes [68]. In other studies Wang et al. [71]found that nutrient removal rates increased significantly during warmer seasons while decreasing during colder seasons, indicating that temperature plays an important impact in nutrient removal efficiency.

According to Chang et al. [53], *P. elephantipes and P. cordata* have higher below-ground biomass and lower aerial biomass in the winter, which results in higher nutrient concentration in the aerial parts and lower in the below-ground parts. This suggests that there is an inverse relationship between biomass and accumulation potential, which reverses in other seasons. Ge et al. [68] discovered that seasonal fluctuations had no substantial effect on *C. indica, T. dealbata, or L. salicaria* in their phosphorus intake. Thus, various research utilizing different plant species have had varied outcomes, so this element must be considered while working on FTW.

6.5 Aeration

Aeration in FTWs increases the elimination of oxygen-demanding contaminants by encouraging root development under floating mats and producing aerobic conditions conducive to biofilm production in a variety of substrates, hence increasing total pollution removal [72,73]. Numerous studies have attempted to integrate FTWs with additional equipment, such as active air diffusion, in order to improve root development from floating mats, increase the surface area for biofilm growth, and ensure adequate dissolved oxygen levels for aerobic treatment processes such as nitrification and BOD degradation, which are frequently required for wastewater discharge [72]. Garcia Chance & White [22] observed that non-aerated FTW systems outperformed aerated ones in nitrogen and phosphorus removal from the water column, despite the latter showing higher dissolved oxygen concentrations, although aerated systems exhibited greater nitrogen uptake by plants compared to non-aerated systems. Nevertheless, in field-scale trials, aeration may be necessary in FTWs for nitrification, as observed by Keizer-Vlek et al. [65], yet the absence of oxygen could result in nitrogen loss due to denitrification, as noted by [39].

6.6 Plant Harvesting

For development and reproduction, macrophytes in FTWs immediately absorb nutrients from the water; hence, harvesting the biomass is frequently used to improve the intake and removal of nitrogen and phosphorus [74]. Olguín et al. [75] suggests recognising and managing possible plant diseases and pests as well as trimming macrophytes aerial parts two or three times a year. On the other hand, Borne [8] draws attention to the challenges associated with collecting biomass in various FTW systems and recommends that it be done just once a year, ideally in the early summer. Colares & Celente [76] conducted vegetation harvesting (*Hymenachne grumosa*) after 10 months of operating an FTW system for treating secondary effluent from a university campus and found that pruning or harvesting improved the removal efficiency of TN, N-NH3, and total organic carbon (TOC). Harvested biomass obtained from treating pond water may be used for a variety of things, such as cow feed, energy generation, composting for fertilization and soil correction, and as a raw material for regional craft industries that employ dried biomass to make a range of goods [75].

7. Advantages and Disadvantages of FTW

This low-cost technology's main benefit is its capacity to float on the water's surface and adjust to changing water depths in the event of heavy or moderate rains [77]. Emergent plants that are floating or have bottom roots may float or submerge in the water as needed thanks to their buoyancy. FTWs increase wetland surfaces without requiring more land, while also providing habitat for fish, birds, and macro invertebrates by enhancing the quality of the water. Since use of FTWs provide habitat for both native and foreign fish species they can be used for larval control, especially in areas where mosquito breeding grounds are well-defined and have appropriate water conditions due to the fish's proven larvivorous capacity [78]. Floating mats, extensive root and rhizome networks, and biofilms are just a few examples of the biological biomass that contaminants might interact with on FTWs. By facilitating metabolite exchange, microbial organic degradation, biochemical pollutant transformations, and enhanced breakdown of refractory chemicals, these biofilms further increase pollutant removal. The diverse shapes and vegetation of various colors, morphologies, and patterns on floating structures serve as points of attraction, offering additional benefits such as wildlife habitat, bird shelters, and protection from predators [79]. As they function within their ecosystem, naturally resolving problems without human intervention, and are sustainable over time with adequate knowledge and experience, floating wetlands have lower maintenance demands than larger constructed wetlands. These demands include vegetation management and periodic platform adjustments, which are less labor-intensive and costly.

Along with the advantages there are limited problems that might occur from FTW, as mentioned by T. R. Headley & Tanner [10], the intrusion or migration of wildlife can detrimentally affect water quality in aquatic systems by introducing fecal matter, specific nutrients, and disturbances, while excessive grazing and trampling may disrupt or eradicate vegetation cover, hindering plant establishment on floating structures. Another significant issue encountered in the treatment process is the proliferation of invasive plants and excessive vegetation growth in FTWs designed for treating sewage effluents or urban stormwater, which can result in decreased dissolved oxygen (DO) levels or even deoxygenation

[80]. Thus, it is essential to regulate vegetation cover according to the type of effluents treated in a specific FTW system.

8. Conclusion and Recommendation

Because of its easy installation and practical use for bioremediation, stormwater management, and wastewater treatment, floating treatment wetlands (FTWs) are an emerging technology. By successfully eliminating heavy metals, nutrients, suspended particles, and other new emerging pollutants, FTWs may be installed into existing water bodies to improve treatment performance without requiring structural improvements. This also addresses issues posed by unpredictable storm occurrences and pollution loads. FTWs eliminate pollutants by physical, chemical, and biological methods by combining plant life, helpful microorganisms, and biofilms. Although more study is required to tailor FTWs to certain contaminants and situations, there are a lot of potential advantages. FTWs have a bright future ahead of them, particularly when they combine with other technologies and go through long-term assessments. All things considered, FTWs offer a workable and environmentally beneficial method of treating water, and they have the potential to revolutionize impoverished countries' sustainable water management. Growing urbanization and inadequate waste management have seriously contaminated river water, endangering the health of people and animals as well as harming the ecosystem and the surrounding area's visual appeal. Since FTWs are quickly built without requiring extra land, they can withstand flood inundation and improve the aesthetic appeal of water bodies, making them especially well-suited for purifying river water. Heavy metals are removed through processes like biofilm trapping, chelation, precipitation, adsorption, and plant uptake. Nitrogen is removed via plant uptake, volatilization, and denitrification. Phosphorous is eliminated through plant uptake, adsorption, and precipitation. Regular pruning or harvesting is essential to prevent pollutant reintroduction, manage plant detritus, and support macrophyte regeneration.

Despite tremendous advancements, there is still much to investigate in this area because the majority of the work is focused on pilot or laboratory sizes rather than practical applications. In order to more fully assess the behavior of floating supports and macrophytes in more demanding environmental conditions including plant death, deformation, sinking, and plant predators one of the primary research challenges is to put these bench-tested systems into practice on a larger, more realistic scale by installing the system in actual water sources like river or lakes. There has been little study on potassium and sulphate removal using FTWs, thus further research may be undertaken in these areas. Additional research should be done on the concepts of plant adaptations, biomass development above and below ground, and symbiotic relationships between flora and micro fauna. Further study is also needed on the variables influencing large-scale floating wetlands removal efficiency, the connection between root biomass and FTW treatment potential, biochemical and ecological processes, and long-term cost-effectiveness. Additionally, the optimal harvesting cycles for different plant species should be carefully considered, and their nutrient uptake capacities should be thoroughly studied. The biomass that is gathered from FTWs may be utilized for animal feeds or processed into compost or biofuel, which might result in a source of revenue.

Therefore, although there have been an increasing number of papers in the past few years, more study is required to fully understand the removal processes that are intrinsic to FTW as well as the variables that are critical for maximizing treatment effectiveness, improving durability, and reducing expenses. In addition, research into the use of FTWs to remove different pollutants highlights the critical necessity to deal with new toxins in order to support sustainable development and protect the environment and public health.

9. Declaration of competing interest

The authors declare that none of the work described in this publication may have been impacted by any conflicting financial interests or personal ties.

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