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Floating treatment wetland with microbial fuel cell for removing pollutants, energy utilization, recovery of nutrients – Review on sustainable technology

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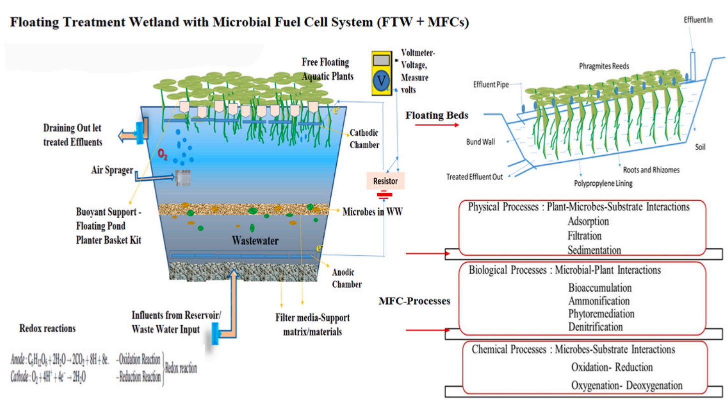
HIGHLIGHTS

- A review on Floating Treatment Wetland (FTW) integrated with Microbial Fuel Cell (MFC) technology.
- Understanding operational parameters and design views of FTW and MFC.
- Allied challenges of FTW-MFC and advanced applications.
- Electrochemically Active Biofilms (EABs) as Bio-electrocatalysts catalyzing effective exclusion of Pollutants.

GRAPHICAL ABSTRACT

Floating Treatment Wetland integrated with Microbial fuel Cell - A Sustainable Technology for Wastewater Treatment



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ABSTRACT

The existing article reviews the state-of-the-art methods for wastewater treatment using Floating Treatment Wetlands (FTW) and Microbial Fuel Cells (MFC). It aims to compile and consolidate current literature while promoting further scientific discussions regarding FTW and MFC. Various concerns are addressed, including building materials, plant species, vegetation, mechanisms, strategies for removing harmful waste, and control schemes. These cohesive technologies are organized effectively for wastewater treatment and natural water purification. However, further research is necessary to enhance their performance, deepen our understanding of the mechanisms involved, and improve overall efficiency. The integrated FTW-MFC approach efficiently converts organic biomass into electricity through a bioelectrochemical process. This method utilizes biochemical reactions and successfully removes pollutants using floating plants in a process known as biosorption. It also involves biological oxidation-reduction facilitated by electroactive biofilms (EABs). Recent advancements in floating

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treatment wetlands with microbial fuel cells (FTW-MFC) have shown their potential as an alternative for generating ecological and renewable bioelectricity. Currently, this technology is interconnected with various other methods for wastewater remediation and ecosystem restoration, allowing for the simultaneous generation of bioelectricity. This nature-based solution enhances water quality and safety while supporting the circular economy, sustainable development, and effective water management.

1. Introduction: state-of-the-art and rationale

The floating treatment wetland integrated with a microbial fuel cell (MFC) is an emerging eco-friendly technology. The term "floating treatment wetland" was first introduced by Headley and Tanner [22], who discussed the use of constructed floating wetlands (CFWs) for stormwater management. They also referred to these systems as floating emergent macrophyte wetlands in their study. Additionally, to further classify this natural clean technology, the technical term "FEMTWs" (Floating Emergent Macrophyte Treatment Wetlands) was introduced by Pavlineri et al., [49]. This review aims to demonstrate that floating treatment wetlands (FTWs), when supplemented with selective floating aquatic plants and associated microbial species, enhance the MFC treatment process. This approach is a favorable methodology for the restoration and sustainable management of contaminated wastewater. FTWs provide active and improved biological treatment through microbial remediation (bioremediation), which aids in the removal of nutrients and helps remediate surface water affected by eutrophication. The plant-microbe associations used in this system are vegetated on a floating mat, with their roots extending into the contaminated water to function as biofilters. The combination of FTWs and MFC technology represents an effective and ecologically sustainable approach for wastewater treatment.

This technology is highly beneficial for extracting clean energy from biomass, such as organic waste, and falls under the category of Green Energy Conversion Systems. It is widely accepted for managing various types of contaminated water, including agricultural runoff, stormwater, and industrial effluents. Due to their operational efficiency and environmentally friendly nature, which does not impose additional burdens on current urban land use, these technologies hold significant global importance and provide effective solutions for stormwater management. The Floating Treatment Wetlands (FTW) system for wastewater treatment effectively reduces the residual concentration of pollutants that remain in the Microbial Fuel Cell (MFC) treatment system by utilizing floating aquatic plants. These plants play a crucial role in two processes: bioaccumulation (where pollutants accumulate within the living plant biomass) and biosorption (where pollutants are absorbed by deceased plant biomass). The use of free-floating aquatic plants in stabilization ponds for the treatment of secondary effluent has become increasingly popular in recent years, as it offers a more economical solution for wastewater management. Broadly, these treatment systems are used in wastewater management and treatment. Microbial Fuel Cells (MFCs) require a large surface area designed to support bio-floc and biofilm formation on the surface of the anode. An effective design is necessary to create electrodes that are resistant to fouling, which involves using anti-fouling electrically conducting rods [11]. It is unrealistic to expect the power density produced by an MFC to match that of a chemical fuel cell, such as a hydrogen-powered fuel cell. In an MFC, the fuel primarily consists of relatively low-energy biomass present at the anode. Another limitation is the relatively slow catalytic rate at which microorganisms operate; they grow at a limited rate. However, Coulombic efficiencies above 90 % can be achieved in optimized environments. While foundational knowledge in MFC research is expanding, significant work remains to be done regarding large-scale applications of Microbial Fuel Cells, particularly in on-site remediation processes [53]. MFCs utilize bacteria as biocatalysts to generate electricity by consuming biodegradable organics found in organic waste materials through biocatalytic reactions in anaerobic conditions. This approach has garnered considerable attention for its potential to simultaneously treat wastewater and produce energy. This research contributes to the treatment of synthetic and industrial wastewater with a high organic load. Additionally, biomass removal from vegetated plants has been utilized for producing biogas, which can also serve as animal feedstock.

A floating wetland system is a treatment method utilizing floating aquatic plants. This review article discusses the integration of floating treatment wetland systems with microbial fuel cells, presenting a cohesive approach for sustainable wastewater treatment. This review paper discusses the technological aspects, operating principles, and scientific applications of combining phytotechnology (FTW) and microbial fuel cell technology (MFC). It evaluates the current state of knowledge on sustainable practices within the context of a circular economy, focusing on the integrated approaches of microbial electrochemical processes and phytotechnology. The assessment highlights advancements in hydraulic systems and the limitations of this technology, along with the mechanisms involved, to improve resource management for effectively removing nutrients and metals [22]. The principles of a low-carbon economy were integrated with a floating treatment wetland (FTW) and a microbial fuel cell (MFC) to develop an innovative combined system designed at enhancing electricity generation and pollutant removal study. The FWT-MFC technology is a comprehensive method that influences the combined treatment effects of pollutants. This system converts organic biomass and energy into electricity through a bioelectrochemical process that involves various biochemical reactions. It effectively removes pollutants using floating plants for biosorption and through biological oxidation-reduction facilitated by electroactive biofilms (EABs). This cohesive approach not only removes pollutants but is also effective in eliminating pathogens from wastewater. Furthermore, the paper outlines innovative strategies to address scientific challenges and emphasizes the importance of these approaches in contributing to the UN Sustainable Development Goals, particularly Goal 6: Clean Water and Sanitation, which aims to ensure the availability and sustainable management of water and sanitation. These efforts include pollutant removal, resource recovery, and the simultaneous production of energy, biomass, and biofuels. The consequences of these techniques are promising for the complete degradation of organic pollutants in wastewater.

2. Floating treatment wetland and microbial Bio-Electrochemical systems

In conservative wastewater treatments, the microbial reactions occur but need the occurrence or influence of the other chemicals. Devoid of them, the treatment cannot resourcefully eliminate the more organic impurities and proceeds for an extended time. The more sludge and the unpleasant odor are formed later the aerobic treatment process. The principal asset, energy, and land necessities are great. The several normal systems including regular ponds and marshlands or wetlands support the wastewater treatment in an organized, ecologically protective, and economical approach. These structures showed great competence owing to modest process operation and conservation [51]. The fabricated wetland is a deep-rooted eco-friendly defensive system for the treatment of wastewater. The binary uncomplicated kinds of assembled wetland systems include the superficial flow-fabricated wetlands and the subsurface flow- fabricated wetlands. The constructed wetland systems practice the aquatic and soil plants to eliminate pollutants from the wastewater [9,10,22,24,61]. In a constructed wetland system, there are numerous physicochemical, biochemical and biological processes proceed to eliminate the contaminants present in the wastewater [69,21,22,57,58].

The floating treatment wetland (FTW) combined with microbial fuel cells represents a collective technological advancement designed at the simultaneous treatment of wastewater and energy recovery. This approach offers several advantages over conventional biotreatment methods. It is particularly effective for handling high levels of organic contaminants, operates more quickly, and results in reduced sludge production post-treatment. Additionally, there is no requirement for further post-treatment processes. Moreover, this method is environmentally friendly and visually appealing due to the flora involved, and it holds promise for ecological restoration when implemented on a large scale. Therefore, it serves as a sustainable and cleaner methodology for wastewater treatment. The reed beds are artificially constructed wetlands through promising plants that have remained recycled to clean sewage in different portions of the world. This research has been approved based on the kind of wastewater treatment system for household wastewater [1] and brewery industrial effluent [6]. The reed beds remain perfect for hot countries where plants grow fast and have small operational costs, however, they need an allocation of land. The floras used characteristically common reed (Poaceae) species *Phragmites australis* or *Phragmites communis* are full-grown in rows in cradles of soil and or gravel lined with a resistant mud or synthetic inside layer. The wastewater or effluent needing action for treatment which is nourished into the bed usually has a deepness of 600 mm. After treatment, the reed bed base has a slope to permit the pool of the wastewater (Fig. 1). Then the effluent is disseminated over the pipelines and taps onto the reed bed, and then it permeates downcast to the roots and rhizomes, through horizontal underground stems of the reeds. The system of root and rhizome delivers a combination of aerobic and anaerobic atmospheres that boost a range of microorganisms in the soil. As a consequence, the system of reed beds is likely to clean an extensive range of pollutants. Though microbes that are accomplished of biodegrading numerous artificial chemicals (including pesticides) originate in soil, they do not typically exist in the effluent treatment plants, consequently, the reed beds can be active for treating effluents that comprise compounds of chemicals. The reed bed systems are a type of vertical flow system that lets the water flow below the gravel surface. It is a free-draining batch flow system, and it is not constantly flooded. To accomplish a batch, flow the effluent is disseminated to the bed over a pump or siphon-type system and the effluent is circulated over the bed where it progressively drains down. The substrate drives over periods of being saturated with effluent, then aerated as it drains through. As the effluent permeates down it is composed of drainage pipes at the bottom and can be fed to auxiliary reed beds for further processing or discharge. The core plant species in reed beds is the collective reed plant (*Phragmites australis*) and be treated to increase nutrient removal [44,46]. The forced bed aeration (FBA™) or aerated wetland is a valuable technology that includes single or added constructed wetland beds of either horizontal or vertical fitted out by an airing scheme using a blower. The enforced air inside the system optimizes the removal by oxidation processes rising within the constructed wetlands, producing a worthy aerial footprint decrease in comparison to classically constructed wetlands. The energy intake remains less, assessed as lower in association with conservative biological reactors. The FBA™ is patented by Scott D. Wallace, the specialist worldwide specialist of constructed wetlands completely projected by IRIDRA in Italy. The aerated wetlands were fetched together 15 years ago by Scott D. Wallace in the US, an individual professional on wetland treatment globally. The greatest dispersed aerated wetland technology is the one patented with the word forced bed aeration (FBA™), for which IRIDRA is the leader in Italy (eubrdialogues.com).

3. Floating treatment wetland with microbial fuel cells system (NBS-natural based solution)

The synergistic effect of combining floating treatment wetlands (FTW) with microbial fuel cells (MFC) is a groundbreaking technology that addresses the issues of nutrient overflow, pollutants, petroleum products, and other organic materials entering freshwater lakes worldwide. Many of these lakes, especially shallow ones, are under severe stress due to these factors. Therefore, biotreatment presents a promising solution by harnessing the natural abilities of plants and microorganisms to absorb nutrients, such as phosphorus and nitrogen, which leads to the breakdown of contaminants through biological processes known as bioremediation. Wetlands are commonly utilized for biological remediation to eliminate harmful waste and to uptake excess nutrients. These natural wetlands act as biofilters, improving water quality by managing stormwater runoff and regulating nutrients in the watershed, as well as treating wastewater and industrial effluents. Wetlands function as biological filters for water, allowing it to flow through areas with dense aquatic vegetation and permeable soils. Additionally, constructed wetlands equipped with microbial fuel cells enhance pollutant management techniques and enable the harvesting of green energy. The operational mode and electric field present in these systems can further improve both bioremediation and energy harvesting [54].

Plant-integrated microbial fuel cells (PMFCs) have been developed to address sanitization and power generation in micro-contaminated water. These innovative approaches provide valuable techniques for remediating micro-polluted water in real-world scenarios [85]. The key mechanisms for nutrient recovery include biotransformation or biosorption by microorganisms and plants, acclimatization, absorption into

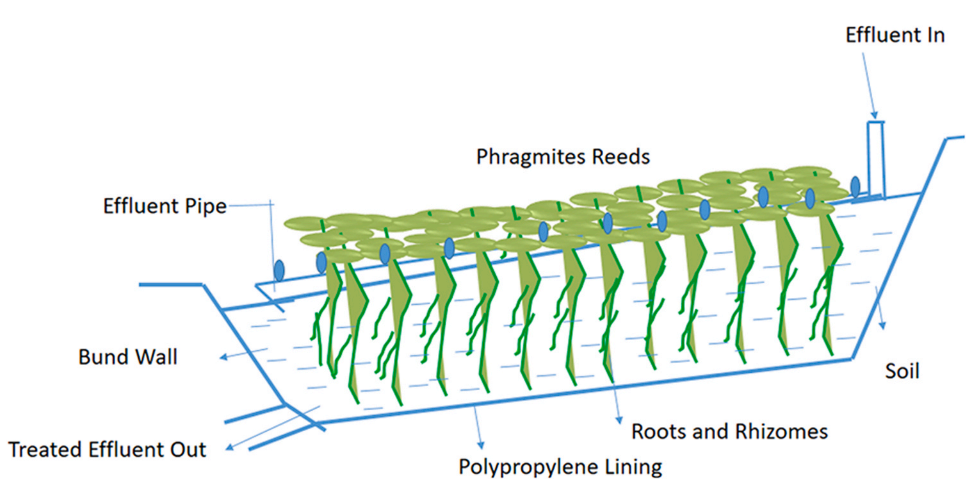

Fig. 1. The reed bed system.

organic and inorganic sediments, and conversion to gas through volatilization. Submerged and surface water plants can utilize and remove pollutants from soil sediments and the water column, integrating them into their biomass. Constructed floating aerated treatment wetlands (FTWs) represent a promising technology for treating complex wastewater. They are particularly effective for wastewater polluted with hydrocarbons, commonly produced by refineries or found at contaminated sites, as well as airport stormwater runoff affected by de-icing products. They are also suitable for remediating groundwater contaminated from mining activities, wastewater with high organic loads (such as effluents from dairies, piggery, wineries, and sugar or sago industries), and wastewater with high ammonia levels (such as swine wastewater). FTWs combined with microbial fuel cells form a cutting-edge system that utilizes nature-based solutions for the sustainable management and cleanup of pollutants. These engineered systems mimic natural wetlands and are designed to efficiently treat wastewater from various sources, including household and industrial sources like petroleum refineries, pulp and paper industries, textile factories, sugar plants, sewage water, greywater, and agricultural runoff, under optimized conditions.

The system consists of a filter bed made up of sand, gravel, and soil, along with native microorganisms, support media, and floating or aquatic plants that thrive in the wetland bio-network. Additionally, grass and manure are utilized to eliminate metal contaminants present in the wastewater. Fabricated wetlands play a crucial role in the treatment, recycling, decontamination, distillation, and storage of water. They operate without the need for energy input, resulting in reduced costs for maintenance and operation. This versatile system also helps control flooding and sequester carbon. Floating treatment wetlands (FTW) are created using floating rafts that support plant propagation through hydroponic techniques [16]. These rafts float on the surface of wetland ponds and improve water quality by filtering, absorbing, and breaking down pollutants, including nutrients, sediments, and metals.

The FTW may represent a cost-effective and sustainable engineered system that serves as a best management practice for reducing pollution in storm water management. Floating treatment wetlands are plant-based systems designed to remove pollutants from wastewater and purify contaminated water bodies. These artificial platforms are typically made from materials such as bamboo and are supported by aquatic floating plants. The platforms consist of floating rafts that hold these plants, which act as biofilters to effectively eliminate pollutants from the water. The roots of the plants extend over the floating islands and into the water, creating dense root structures with a large surface area that enhance their ability to filter and purify the water. FTW-MFC biosystems combine the wastewater treatment capabilities of floating treatment wetlands (FTWs) with the electricity generation of microbial fuel cells (MFCs). The typical experimental setup consists of an FTW box, which features a buoyant support system for aquatic plants and often includes cathodes. This is paired with an MFC that contains an anode chamber and, in some cases, a cathode partition. This configuration enables the simultaneous treatment of wastewater and the production of bioelectricity. For preliminary wastewater treatment, a model setup with a batch-flow anaerobic biofilter (AF) is used, which has a capacity of 1500 liters. Additionally, an FTW box with a capacity of 1000 liters is utilized, along with a 200-liter plastic drum that serves as a settler for the treatment process. The experimental setup, as shown in Fig. 2, Floating treatment wetland with Microbial Fuel Cells (FTW-MFC) System includes the key mechanisms and the following components:

i. FTW Component:

Floating Raft or Box: This is a raft or box, usually made from plastic or another buoyant material, which serves as the floating wetland.

Buoyant Support: This floating raft system enables the FTW box to float on the water's surface, supporting both the plants and their root systems.

Plants: Aquatic plants like *Canna indica* and *Phragmites* are cultivated within the FTW system to facilitate wastewater treatment. Both floating and non-floating plants have the potential for pollutant removal; however, this review highlights that floating aquatic plants are more effective for treating surface wastewater. Additionally, they can be harvested easily after the treatment process. Floating aquatic plants are especially effective for surface wastewater treatment and can be easily harvested after the treatment process.

The selection of floating plants is crucial, and they should be chosen based on the types of pollutants, their concentrations, and loads in the wastewater. Some effective options include:

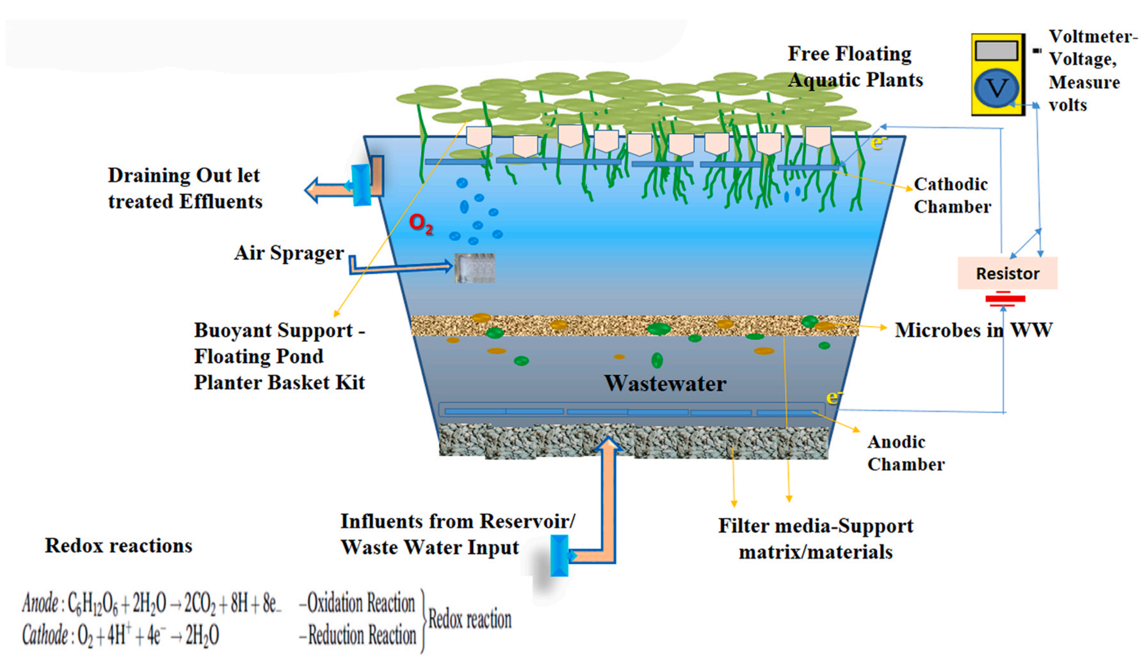

Fig. 2. Floating treatment wetland with microbial fuel cells (FTW-MFC) system.

3.1. Canna, typha, phragmites, and cyperus

- Poaceae family (Lollium sp., Zizania sp., and Chrysopogon sp.)
- Phragmites, Carex, Acorus, and Juncus, which have been successfully utilized in floating treatment wetlands (FTWs) and can adapt to various locations

It is noteworthy that the root development of Phragmites australis may be limited to a depth of 40 cm after three years of growth due to the toxic effects of the digestate liquid fraction. Furthermore, *Limnobium laevigatum* is effective for treating total petroleum hydrocarbons (TPH), while *Lemna paucicostata* is suitable for crude oil removal. The phytotreatment process, along with the biomass produced from cultivated plants, can provide valuable feedstock and generate energy for poultry farms, particularly when the wastewater is free from harmful chemicals.

ii. Electrodes: MFC Components:

The graphite rods or other conductive materials are placed in the root zone of the plants to function as cathodes, facilitating electricity generation.

a. Anode Chamber: This chamber, typically made of plastic, houses the anode electrode, which is usually constructed from graphite or carbon material.

   Anode Electrode: Exposed to wastewater, the anode electrode allows bacteria to oxidize organic matter, thereby generating electrons.
b. Cathode Compartment (Optional): Some FTW-MFC systems may include a separate compartment for the cathode electrode, which can be made from graphite, granular activated carbon (GAC), or other conductive materials.

iii. System Integration:

Wastewater Feeding: Wastewater is introduced into the FTW box either through batch feeding or continuous flow.

Electrode Placement: The cathodes are strategically positioned to enhance electron transfer from the plant roots to the anode, thus generating electricity.

Monitoring: The open circuit voltage and power density are typically measured to assess the performance of the MFC.

Water Quality Analysis: Parameters such as Biological Oxygen Demand, Chemical Oxygen Demand, and pH are monitored to evaluate the wastewater treatment performance of the FTW.

An effective design is essential for creating electrodes that resist fouling, which involves using electrically conductive anti-fouling rods. Electrodes are selected according to the types and concentrations of pollutants present in the wastewater, as well as the specific pollutants that need to be removed or recovered. Additionally, the selection of plants and their combinations is determined by the types of pollutants that need to be addressed and the preferences for recovery. The FTW box is planted with a selection of varied plant species and fitted with graphite rod cathodes in the root zone, as well as anode chambers at the bottom. Open circuit voltages are measured daily over a six-week period, and subsequent closed circuit measurements are taken using a resistor (1000 Ω).

4. The following are the significant characteristics of the FTW,

- These cleaner green technologies are sustainable and suitable for water clear-out and decompose organic matters or pollutants into non-toxic constituents (Eco-friendly)
- These technologies do not release new or further chemical matters into the environs (Toxic end products)
- Comparatively modest and relaxed to achieve and stress-free adapted to the local/community needs (Community need-based sustainable development)
- Applying these technologies does not involve a large investment to be virtually introduced
- They can be competent to remove numerous contaminants in grouping, sustainable and inexpensive process (Economically sound)
- They are applicable for small and large-scale levels of in-situ and ex-situ bioremediation of noxious waste
- These technologies are quickly emergent as a sustainable and conservative treatment approaches and its techniques are also best appropriate for emerging contaminants.

5. Support components prominence in FTW

The support components are essential for the operation of a Floating Treatment Wetland. The three foremost pollutant reduction mechanisms that have been recognized in Floating treatment wetland are as follows,

1. The aquatic plants uptake pollutants directly, particularly nutrients from the aquatic system using a process well-known as biological uptake.
2. The microbes rise on the floating rafts, and plant roots and take part in the breakdown then ingest organic matter in the aquatic system over microorganisms via decaying and degradation process.
3. The plant roots filter out soil sediment and related pollutants. These removal mechanisms organize a scheme that might be a less expensive, supportable method for eliminating noxious waste from stormwater.

The Floating treatment wetland can creditably remove waterborne contaminants, and it might be employed on utmost surviving lakes and ponds, several FTW placed in built-up settings remain recycled as stormwater catchment basins. However, while used in grouping with a stormwater wet pond, these FTW are frequently positioned near the coastline wherever stormwater arrives at the pond moreover complement the buffer area otherwise over an inflow pipe. They will interrupt the maximum polluted runoff inflowing the system. The FTW positioned close to the coastline diminish surf action and decrease challenging and coastline erosion. The principal constituents of the fabricated wetland scheme comprise a inferior impermeable layer, a layer of gravel or sand or support matrix, an upper layer of aerobic zone, a lower layer of anaerobic zone, and plants. The resistant layer is that precludes penetration and decreases the undesirable consequence of waste on the aquifers. The gravel layer acts as a supportive level that offers nutrients to the zones of flora and roots. The flora zone covers plant material that enables phytoremediation and recovers the quality of water. Moreover, the root zone helps with the biological remediation and denitrification processes. The aerobic and anaerobic schemes are involved, an aerobic zone where the plants grow and aerobic bacteria for the biodegradation of organic and inorganic constituents present in the water are found. In the anoxic zone, anoxic bacteria are established to destroy the pollutants [73]. The Floating treatment wetlands progressively achieved admiration and outstanding to agreed valuable topographies including wastewater treatment below varied environmental circumstances, ecology quality conservation, landscape protection, and beautiful welfare. This system is phytotechnology- based, in this the macrophytes propagate on a floating raft utilizing their roots in a stable interface with an aquatic system and eliminate contaminants over several biological, chemical, and physical processes. It is greatly accomplished and solves technical as well as functioning challenges that arise in stormwater treatment owing to the unpredictable atmosphere of hydrologic input of contaminant loads since this advanced buoyant or floating hydroponic design can change up and down with moving water altitudes in the stormwater pond and treat extremely moveable flows. The aquatic plants and microbial biofilms associated with adherence to the root system droopy underneath the floating mat performed a central functional part in this eco-technology. The existing exploration comprises the idea of FTW, their operational designs, their significance in stormwater controlling, and plant uptake mechanisms for contaminant elimination or clean-up. The part of the floating treatment wetlands is to eliminate the metals, elements, and nutrients that are too favorably investigated. Understanding the hydraulics and other constraints of FTW is active to real operational design. Therefore, the portion of plant life coverage, plant type, sorption support media, exposure to air or aeration frequency, force, and plant mass to recover the treatment system competence are moreover emphasized. Owing to their functioning tractability and sustainable operation with no extra problem on current urban terrestrial usage, these treatment Wetland systems attract comprehensive global interest and deal with rational solutions for stormwater running. The assessment provides the hi-tech analysis of the present thoughtful of hydraulics and other constraints of FTW, and related mechanics to augment the management competence of FTW for nutrients recovery as well as heavy metals removal. To alleviate runoff from the rural developments and the construction of post-user polymer fibers and corresponding vegetation with native plants. The Floating treatment wetland imitator the capability of normal wetlands to clean up water by appealing an "intense wetland effect" to ponds, also restoring the marshlands. The Lake Freshwater Region Stormwater Management Commission entitled this mission "Best Management Practice or BMP (www.floatingislandinternational.com). The built floating treatment wetlands are fabricated engineered systems aimed to improve the developments and interfaces that take place in natural wetlands among water, plants, microbes, earth, and the air to eliminate pollutants from contaminated waters in a comparatively inert and accepted way. The fabricated Floating treatment wetland characteristically include the movement of polluted water ended the shoot systems (superficial flow), (Fig. 2) or root system and its zone (immersed bed or sub-surface flow; Fig. 2) of evolving aquatic species of reeds, rushes, and sedges. The method cast-off for wastewater treatment involves the usage of free-floating water plants that float either as thin layers on the aquatic surface (e.g., *Lemna minor, Azolla*) or have exclusively modified floating leaf-bases (e.g., Water Lettuce, Water Hyacinth, *Salvinia*) as illustrated in Fig. 2. The Floating treatment wetland are an alteration of the treatment systems that are active with rooted, emergent plants growing as a floating mat on the surface of the water comparatively than in the rooted sediments. In FTW, the plants sustained on a floating raft assembly or rooted in roughly sort of matrix or soil support media, or normal floating swamplands play a substantial part in self-buoyed on interweaved mats of their floating roots, its tubers, and stored plant litter as well as carbon-based matter [22].

Since they drift on the aquatic surface, the FTW remain a little pretentious through variations in aquatic levels that might immerse and unfavorably stress bottom-rooted plants. FTW might be associated with an aquaculture system or hydroponics farming, as the plants obtain their nourishment openly from the water pole in which the roots are adjourned, quite than from the soil profile. The hydroponic system that reports iron metal pollutants in water resources can be employed through wastewater hydroponics, by combining wastewater treatment with plant-based nutrient biosorption. These phytotreatment approaches can effectively remove heavy metals like iron and other pollutants. The study was conducted in a hydroponic system that affords a simple, worthwhile solution to stabilize the ecosystem through an iron metal pollutant, a bottleneck problem in public water resources and normal waterways [70,71].

Moreover, it shares nearly resemblances with a sub-surface system of FTW, in this management transpires as water movements over the root region of the plants, quite than between the stems. The terms cast off in identifying the system of Floating treatment wetland for together regular and non-natural are tremendously diverse. Almost all the key regular FTW, these ecotypes around the world have specified an altered term. Since, the comparatively innovative eminence of non-natural FTW used for the water treatment, there are quite no reliable terms that have remained largely useful. Man-made Floating treatment wetland are progressively practiced for wastewater treatment and here is essential to develop a frequently appropriate term, FTW gives the impression of being largely valuable. However, these floating marshes retaining promising plants must be distinguished since treatment systems using aquatic free-floating plants (including, duckweed or water hyacinth), though the distribution of several likenesses, both architecturally and functionally dissimilar from the schemes exist are conferred.

In, Table1, the comparison of various plants and electrodes used in the FTW-MFC system, along with their effective substrates and the benefits of power generation were discussed. It was noted that various plants and electrodes used in the FTW-MFC system were compared, highlighting their effective substrates and power-driven benefits. The various type of supportive components are utilized in this biosystsem based on the different pollutants, taking into account their concentrations, the types of recovery metals, and nutrients involved. Electrodes are chosen based on the specific pollutants present in the wastewater and the concentrations of these pollutants, focusing on the ones that need to be removed or recovered. Furthermore, the selection of plant species and their combinations is influenced by the types of pollutants that need to be addressed and the preferences for recovery. The type of wastewater is crucial for selecting the right supportive component.

The FTW are notable since aquatic free-floating plants through the circumstance that they use superior developing marshland plants rising on a to some extent combined moving mat, as different to an uncombined mass of minor, separate floating plants requiring some important mat. Notwithstanding the changes, the aquatic free-floating plant schemes predominantly use superior species comprising the water hyacinth which can provide a valuable vision into in what way a Floating treatment wetland system strength purpose and accomplish. The aquatic free-floating plant schemes have remained cast off to decrease particulate and organic pollution loads in industrial wastewater and domestic sewage water. The avoidance of algal bloom growth through darkening or absence of light and the lessening of wind, as well as thermal mixing, can incline to create arrangements additional operative at eliminating suspended solids, and organic loads comparatively to a consistent system of facultative pond [52]. The wide root arrangement dangling underneath water hyacinth plants delivers a great surface area for the growth of microbes. The great growth and acceptance rates of nutrients of many aquatic free-floating plants can also affect in noteworthy elimination of nutrients and metals if near is a sufficient land-living area obtainable and the plants are frequently reaped. The metal elimination also takes place completed the precipitation and adsorption chemically on the substrate present in plant surfaces, by the ripe plant's meshing root material that grows in the bottom benthic sludge zone [52]. Numerous of these reaction processes are also likely to be significant in Floating treatment wetland using promising macrophytes. The FTW is widely used for secondary wastewater treatment to remove pollutants and is also effective in treating sediments under suitable environmental conditions, requiring continuous water quality analysis and electrochemical monitoring and thorough assessment of retention time.

6. Principal reactions occurring in MFC chambers of an FTW-MFC system

The plant-integrated MFC is an innovative treatment system that converts organic matter into energy, and electricity by living plants and microorganisms in the soil. The probable practices involve the desalination of saline as well as salty waters, electricity generation, reduction of methane, conserving nature, and sustainable management. The scheme of treatment systems consequently addresses the diverse community-based challenges including the worldwide energy transition, scarcity of water, linking remote groups, and supportable production of foods [28,65]. The innovative sustainable method can be functional in altogether assembled wetlands as well as maritime environs deprived of damaging the bionetwork or adapting the ecological zone. Then subsequently not at all exterior energy storage or input is vital and the

Table 1
The comparison of various plants and electrodes used in the FTW-MFC system and its effective substrate and power-driven benefits.

Plants Used	Substrate	Microbial community	Anode	Cathode	Maximum Power	References
FTW-MES. Iron based nanomaterials could improve the electrochemical performance of FTW-MES-Fe.	surface water applications. low-carbon wastewater	Nitrogen-converting bacteria, *Zoogloea*、*Acinetobacter*、*Flavobacterium.,* Electroactive bacteria(EAB) *Thauera*、*Pseudomonas, Flavobacterium)*	Carbon cloth,	Carbon brush, cathode loaded nano iron oxide	maximum current density and maximum power density of FTW-MES-Fe were 107.6 ± 27.4 mA/m3 and 38.8 mW/m3, respectively., external resistance was 200 Ω, the maximum TN removal load of FTW-MES-Fe was 1.86 g/(m2•d). Current density and potential promoted the enrichment of nitrogen-converting bacteria.	Zhengyu [82]
CW-MFC Equisetum hyemale plant.	domestic wastewate	*Lactobacillus plantarum,* Synergistic interaction of microbes, plant aeration, and electrochemicalprocesses.	graphite electrodes	graphite electrodes	bioelectricity production 990.8 mW/m^2 on day 15 BOD removal efficiencies 91 %, COD removal efficiencies of 93 % on day 15, Removal pH was 25–33 %.	[2].
Plant-microbial fuel cell (PMFCs) *Pistia stratiotes L., Oenanthe javanica, Ipomoea aquatic, Hydro cotylevulgarisL* (Enrichment of the exoelectrogen in the rhizosphere) Aquatic plants	micro-polluted water remediation	Proteobacteria, Actinobacteriota, Firmicutes, Bacteroidota and Chloroflexi	polyacrylonitrile-based (PAN-based) carbon fibre felt with the size of 30 cm in width and 20 cm in length	polyacrylonitrile-based (PAN-based) carbon fibre felt with the size of 30 cm in width and 20 cm in length	1.27–2.01 mA m^2 2.45–6.29 mA m^2, 1.3–4.71 mA m^2, 1.08–3.4 mA m^2, 3.76–8.74 mA m^2, Optimal removal rates of 53.17 % for COD, 88.35 % for TN, 80.51 % for NO3 −-N, 98.56 % for NO2 −-N, and 9.89 % for NH4 + -N,	[85]
Plant-microbial fuel cell (PMFCs) Withania somnifera (L.) Dunal	Soil organic wastes soil-based p-MFC	Rhizobacteria, Soil microbes	graphite circular cathode (56.76 cm^2 surface area), graphite fibre	graphite circular anode (50.28 cm^2 surface area), graphite fibre	cell voltage achieved was 1260 ± 140 mV and peaked at 1400 mV.	Debajyoti [11]
MFC	Sugr industry wastewater	Exoelectrogenic microbes, microbial biofilm	carbon yarn-based brush	Activated Carbon	MFC generated cell OCV of around 870 ± 20 mV with power density of 563 ± 30 mW/m2. Current density of around 0.79 mA/m2 with COD removal of 81 % and BOD removal of 86 %	Debajyoti [11]
CW-MFC *Phragmites australis*	Municipal wastewater, Synthetic wastewater	Microbial consortium or microbes in municipal wastewater	Graphite granules layer (anode), graphite felt-connector for the anode, Sand, Separator,	Graphite granules layer (cathode), graphite felt for connecting cathode, Resistance, Copper wire	highest voltage, current, and power densities reached 687 mV, 4000 mA/m3, and 785.86 mW/m3,	Hoda *et al.*, 2024
CW-MFC *T. latifolia* plant species *Canna indica, Typha latifolia, and Eichhornia crassipes*	Textile wastewater	Microbes in wastewater	Graphite	Graphite	voltage, and current, 1.04 mA and 0.178 V.	[62]
CW-MFC with Phragmites Planted	Hexavalent chromium (Cr(VI)) in the aqueous solution	electrochemically active microorganisms (EAB), activated sludge, *Chloroflexi* and *Proteobacteria* *Exiguobacterium* *Geobacter*	-‘	-‘	power density and output voltage 0.375 V and 0.144 W/m3 , respectively total Cr: 97.5 %, Cr(VI): 99.2 % COD 90.5 %, P 96.7 %	[45]
FTWonly *Equisetum hyemale* FTW microcosms under the influence of abiotic stressors	Synthetic wastewater	*Serratia*	-no mfc	-no mfc	removes Pb (up to 98 %) and As (up to 79 %) presence of As suppresses PO4-P removal	[46]
FTW only *Distichlis spicata* (L.) Greene (saltgrass), *Juncus roemerianus Scheele* (needlegrass rush), *Spartina alterniflora Loisel.* (smooth cordgrass), and *Spartina patens (Aiton)*	Brackish waters, adjacent estuary	Microbial consortium or microbes in native brackish water. *S. patens* and *S. alterniflora* grew well in the oligotrophic water quality exposures	-no mfc	- no mfc	0.089 mg·L−1 TN, 0.017 mg·L−1 PO4-P	[5]

(*continued on next page*)

Table 1 (*continued*)

Plants Used	Substrate	Microbial community	Anode	Cathode	Maximum Power	References
Muhl. (saltmeadow cordgrass). plant species must tolerate salinity						
CW-MFC microcosm reactor, pplant used *Cyperus altrnlifolius*	Synthetic wastewater (500 mg/L acetate-COD, 30 mg/L NH4Cl-N, 8 mg/L K2HPO4-P, CaCl2, MgSO4, and trace element solution	activated sludge from Municipal wastewater	stainless steel mesh sandwiched with carbon fiber	stainless steel mesh sandwiched with carbon fiber	Voltage out put 301.8 ± 149.1 mV. COD removal was found at 12 h (79.6 ± 6.3 % and 88.6 ± 2.75 % under the Open Circuit and Closed Circuit, respectively)	Jun Yan et al. [81]
CW-MFC with native macrophyte Dieffenbachia sp	Synthetic melanoidin effluent, palm oil mill effluent (POME), Melanoidin	Lactic bacteria *Lactobacillus plantarum, Lactobacillus casei and Pediococcus parvulus,* oxidoreductase-producing bacterium Bacillus lichenformis	graphite plate	graphite plate	maximal power density of 0.18 ± 0.01 mW/m3 was generated, melanoidin removal of 93.59 ± 0.10 % and 95.12 ± 0.15 % were achieved	[14]
Microbial fuel cell integrated into a hydroponic system (MFC-Hyp) *Allium tuberosum Cymbopogon citratus*	synthetic potato-process wastewater 2673 ± 74 COD mg/L, pH 6.88 ± 0.01	EAB-electroactive bacteria, proteobacteria, firmicutes, and bacteroidetes	bamboo charcoal	carbon cloth with platinum	maximum power density of 130.2 ± 45.4 mW m−2 removal of organics (as COD) was 96.3 %,	[56].
MFC	Domestic wastewater, Grey water, blackwater substrate	Microbes in wastewater	stainless-steel electrodes	Aluminum electrodes	voltage output of 118.93, 144.84, and 89.76 mV COD reduction (65.83 %) BOD5 removal (69.18 %)	Tensay [33]
MFC only	Wastewater, Synthetic wastewater	Electroactive biofilm fermentative bacteria	Carbon felt	Carbon felt	Current Density of 2.5 ± 0.2 A m^{-2}	Diana [41]
Windmill grass, goldfish algae, water hyacinth, and water spinach	Wastewater	Electrochemically active microorganisms, Sludge as inoculum	Stainless-steel mesh and carbon felt	Stainless-steel mesh and carbon felt	99 mV- 161 mV	[83]
Typha orientalis and *Iris pseudacorus Scirpus validus*	Gravel	Electrochemically active bacteria (EAB)- *Geobacter, Ferruginibacter* NB-degrading bacteria (e.g., Comamonas, *Pseudomonas*)	GAC	GAC distance between the cathode and anode was 17 cm	19.5 mW/m^2, 590 mV)	[40]
Pennisetum setaceum Iris pseudacorus, Hyacinth pink, and *Phragmites australis*	Red soil Municipal wastewater with constructed wetland matrix Graphite gravel	*Bacteria* Electrochemically active bacteria	Graphite plate Multi-anode Graphite gravel Stainless steel mesh	Graphite plate Graphite gravel Stainless steel mesh	163 mW/ m^2 25.14 mW/m^2	([15] [84].
Epipremnumaureum Dracaena braunii	Garden soil,	*cow dung Bacteria*	Carbon fiber brush	Carbon fiber cloth	15.38 mW/ m2, 12.78 mW/ m^2	Sarma, Mohanty [55]
Chasmanthe floribunda, Chlorophytumcomosum Papyrus diffuses	Garden soil	*Pseudomonas, Enterobacter, Bacillus*	Graphite	Graphite	0.21 mW/ m2, 18 mW/m^2, 1.083 mW/ m2	Azri *et al.*, 2018
Puccinelliadistans	Potting mix, sandy loam soil	*Low bacterial content*	Carbon felt	Manganese-based cat analyzed carbon	83.7 mW/ m^2	(Md Khudzari *et al.*, 2018)
Typha latifolia	wastewater treatment zeolite wetland system	Electrogenic bacteria-zeolite media-	graphite surface	graphite surface	1.008 ± 0.14 V, 15.1 mWatt/m^2,	[7]
Epipremnumaureum Dracaena braunii	Garden soil, cow dung	*Bacteria*	Carbon fiber brush	Carbon fiber cloth	15.38 mW/ m2, 12.78 mW/ m^2	Sarma, Mohanty [55]
Sedum hybridum	Sand, silt, clay, and organic matter	*Proteobacteria, Actinobacteria, Chloroflexi*	Graphite fiber felt/ activated carbon granules	Graphite fiber felt	0.092 mW m^2	Tapia et al., [67]
Brassica juncea, Trigonellafoenumgrae	cum, Canna stuttgart Compost soil mix	*Bacteria*	Carbon brush	Hydrated Carbon cloth	69.32 mW/m^2 80.26 mW/ m^2 222.54 mW/ m^2	Sophia, Sreeja [64]
Spartina alterniflora aerenchyma	Wastewater, gravel layer (100-mm high),	Electrochemically active bacteria	Aanode layer (100-mm high), gravel layer (100-mm high) granular activated carbon	Cathode layer (25-mm high). granular activated carbon layer (GAC, 3–5 mm in diameter	Coulombic Efficiency of 14.9 % and current density of 187 mA/m^2	[38]

(*continued on next page*)

Table 1 (*continued*)

Plants Used	Substrate	Microbial community	Anode	Cathode	Maximum Power	References
			layer (GAC, 3–5 mm in diameter			
Typha latifolia L. *T.latifolia*	Organic-based peat and sand mixture	Sludge contains essential minerals such as Ca, Mg, Na, K, N, P, and various Microelements plants and active microorganisms	Graphite anodes	Graphite anodes	78 mWatt/m^2 and 105 mA/m^2	[47]
Canna indica plant species	Wastewater glucose, KH2PO4, Na2HPO4, MgCl2, ZnCl2, CaCl2, CH3COONa, CuSO4, NaNO3, and tap water	Activated Sludge		Carbon fiber felt (CFF), stainless steel mesh (SSM), graphite rod (GR), and foamed nickel (FN) were used as air-cathode and anode for each system	5.11 mWm^{-2} 253.3 GJ ha^{-1} $year^{-1}$	[75]
Oryza sativa *Epylobium* and *Lycopius europeanus* herbs *Calamintha nepeta*	A layer of clay; layer of soil Coconut fiber panel (Separator)	Bacteria	Flat Carbon cloth	carbon cloth	10 and 35 mWh/d.	[4]
Loliumperenne	Hoagland sol.	*Cyanobacteria, Proteobacteria, Bacteroidetes*	Graphite granules	Carbon felt	55 mA/ m^2	[20]
Canna indica plant	Wastewater gravel	Fermentative bacteria (e.g., Anaerolineaceae) and electrochemically active bacteria (e.g., Geobacter). Denitrifying bacteria and acetotrophic methanogens	A graphite disk anode	A graphite disk anode	105 mA/m^2	Lu [42]
Typha latifolia	Sludge from glove manufacturing company gravel for support	*Bacteria*	Carbon felt	Carbon felt, porous air spargers	6.12 mW/ m^2	[48]
Juncus effuses, L.	Groundwater	Sand bed; Quartz sand	Graphite rod	Graphite rod	Power density−0.86 mW m^{-2} at a current density of 3.62 mA m^{-2} (module.3) and 1.74 mW m^{-2} at a current density of 5.75 mA m^{-2} (module.4)	Manman [76]
Cyperusinvolucratus	Wastewater, lotus soil	*Bacteria*	Graphite felt	Graphite felt	5.9 mW/ m^2	[34]
Ipomoea aquatica	Anaerobic sludge from municipal wastewater	*Geobactersulfurreducen, Betaproteobacteria*	Granular activated carbon	Stainless steel with GAC	12.42 mW/ m^2	Liu *et al.*, 2013
Lemnaminuta	Potable water	*Low bacteria content*	Carbon felt	Graphite granules	380 § 19 mW/m^2	[26]
Canna indica	Marine sludge	*Bacteria*	-	-	15.73 mW/m^2	Yadav et al., [80]
Eichhorniacrassipes	Wastewater	*Bacteria*	Graphite disk	Graphite disk	224.93 mW/ m2	Venkata Mohan et al., [72]
Spartina anglica	Hoagland sol	*Bacteria*	Graphite rod in graphite grains	Graphite felt	222 mW/m^2	Helder et al., [23]
Arundinellaanomala	Hoagland sol	*Bacteria*	Graphite rod in graphite grains	Graphite felt	22 mW/m^2	Helder et al., [23]
Arundo donax	Hoagland sol	*Bacteria*	Graphite rod in graphite grains	Graphite felt	System breakdown	Helder et al., [23]
Oryza sativa	Rice straws barnyard matter	*Natronocellaacetinitrilica, Beijerinckiaceae Rhizo biales, Rhodobactergluconicum*	Graphite felt	Graphite felt	6 mW/m^2	Kaku et al., [32]
Gylceria maxima	Hoagland sol	Bacteria	Graphite granules	Graphite felt	67 mW/ m^2	Strik et al., [66]

expertise can be useful in remote areas deprived of electrical substructure keeping cost effective. The scientific value of the plant-integrated MFC is an energy cell that deeds the organic load and its matter that is obtainable in the system of wetlands. This organic load and its matter can transform in the form of exudation or through added mechanisms which comprise microbial conversion, hydrolysis, or rhizo-deposition as a common process and certain of these will act in response to oxygen and also be excessively free by the roots of plants. The microorganisms in the oxygenic soil profile of marshes can change the remaining exudates from the plant roots or decayed plant material into carbon dioxide (CO_2), electrons, protons, etc. The produced electrons can be collected by employing an anode in the nearness of the microbes that are attached over an exterior circuit to an additional electrode, where a redox reaction of the reduction process takes place. With the decreasing oxygen level and the protons to water at the cathodic zone (aerobic regions), also the electrons will flow through the circuit because of the difference in potential property (www.wur.nl). The roots of plants discharge oxygen and produce exudates from roots (rhizo-deposition), ventilating the rhizosphere and stimulating microbial activity. The ammonia-oxidizing and nitrite-oxidizing microbes or bacteria transform NH_4^+ (ammonium) into NO_2^- (nitrite), and NO_2^- (nitrite) into NO_3^- (nitrate), correspondingly. The exudates of plant root and organic loads extant in the wastewater are anoxygenically assimilated in the anode compartment (anodic zone, anaerobic regions) and are prominent to the discharge of electrons which are transported to the compartment of the cathode through an exterior circuit. The chemical species of nitrite or oxygen acts as an electron acceptor in the cathode compartment [63,25]. A MFC is a biological-electrochemical scheme of a system that contains cathodic (cathode, aerobic regions) and anodic (anode, anaerobic region) chambers and disjointed by a membrane called a proton exchanger (Fig. 2). The bioprocess of oxidation of organic substances in anaerobic conditions in the anodic compartment or chamber is achieved by electro-chemo-genic active microbes or bacteria that discharge electrons, and protons with CO_2. The released protons travel across the membrane called proton exchange membrane (PEM) and move into the cathodic chamber while the electrons are transported to an exterior circuit and are recycled to produce energy as electricity [68]. The microorganisms including *Shewanella*, and *Geobacter* (exoelectrogenic bacteria) can execute electron transference, in any direct or indirect ways over microbial biomass or biofilm [17].

The biofilm is essential for transferring electrons from bacteria to the anode. Extracellular polymeric substances (EPS), a component of the biofilm, serve as a conductive matrix that enhances electron movement. The process of biofilm formation is influenced by several factors, including the types of microorganisms present, the availability of nutrients, and the electrostatic interactions between the microorganisms and the anode material. Microbial biofilms, especially those formed by electroactive bacteria, are crucial for electron transfer in microbial fuel cells (MFCs). These biofilms consist of bacteria, extracellular polymeric substances (EPS), and additional components that aid electron transfer to the anode. Electroactive biofilms (EABs) play a crucial role in biological oxidation-reduction reactions by facilitating electron transfer between microorganisms and the anode electrode. These biofilms, composed of electroactive bacteria, help oxidize organic matter, releasing electrons that can be harnessed to generate electricity. The anode biofilm functions as a biological catalyst, enabling the conversion of chemical energy into electrical energy.

In the anode chamber, microorganisms oxidize organic substrates, which leads to the release of electrons. These electrons are then transferred to the anode electrode through the biofilm, while protons are simultaneously released into the solution. Once the electrons reach the anode, they travel through an external circuit to the cathode chamber. At the cathode, oxygen, typically acting as the terminal electron acceptor, accepts the electrons. This process completes the redox reaction and generates an electric current.

Bioelectrochemical systems (BESs) utilize microorganisms to catalyze oxidation and/or reduction reactions at the anode and cathode electrodes, respectively. At the anode, oxidation of organic and inorganic electron donors occurs. Common examples of these electron donors include waste organics and sulfides. At the cathode, an electron acceptor, such as oxygen or nitrate, can be reduced. The anode and cathode are connected through an electrical circuit. If electrical power is harvested from this circuit, the system is referred to as a microbial fuel cell. Conversely, if electrical power is supplied to the system, it is called a microbial electrolysis cell.

The following reactions occur in FTW/ CW-MFCs:

Anode Chamber: $C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$

Cathode Chamber: $6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O$

Overall Reaction: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ + Electric Energy

The carbon, organic load, and its matter are the main pollutant in the wastewater and the treatment processes involved are to oxidize into inoffensive by-products, including carbon dioxide and water [75]. The wastewater treatment plants (WWTPs) are often intended for certain effluent water quality necessities deprived of adequate thought assumed to energy necessities, which signify around 25–40 % of the working rate of WWTPs. The sustainable substitute is to excavation of energy from the wastewater itself throughout the treatment, and the wastewater has great potential energy as well as anoxygenic assimilation that will castoff to harvest methane and biogas. The amalgamation of MFCs in the wastewater treatment process is a substitute technique for producing sustainable energy and a system to widespread the combination of MFCs with the accepted redox reaction gradient of constructed wetlands (CWs). The CWs permit the elimination of contaminants and organic load with its matter from wastewater through bioprocesses comprising of filtration, adsorption, and accumulation by aquatic plants, also through microbial transformations through biodegradation [75]. The CW-MFC can serve as a sustainable treatment process for leachate while simultaneously generating electricity and facilitating the environmentally friendly removal of various harmful compounds in wastewater. Power generation in CW-MFC systems ranges from 25 to 1600 mV. In previous studies, the treatment efficiency of leachate using CW-MFC was reported to be 90.6 % for COD (Chemical Oxygen Demand), 92.6 % for ammonia, and 96.7 % for total phosphorus (TP) [8]. Yan et al. [81] found that integrating a microbial fuel cell (MFC) into the constructed wetland resulted in a higher rate of COD removal. It was noted that the MFC integration initially facilitated the entrapment of organics before the subsequent dissimilating metabolism occurred.

The network of interactions and its processes involved FTW-MFC in wastewater treatment in contaminant removal is shown in Fig. 3.

The environment of the wetland which contains various mediums including soil or charcoal, sand or pebbles, also helps in the physical parting of adjourned solids in wastewater to about a certain range. These ecosystems produce oxygenic and anoxygenic regions that can be employed by MFCs to produce electricity. The constructed wetland integrated through fuel cells is a combination of wetland ecosystem with microbial electrochemical fuel cell prototypes having the prospective to manage and clean the wastewater effectively, also concurrently produce clean energy of electricity. The production of electricity proceeds due to the bio-electrochemical reactions, accumulation of substrate, and the corresponding biological interactions produced through exo-electrogenic microorganisms flourishing on organic loads and its matters in waste in the anoxygenic regions of the wetland ecosystems. The microbial activity and interactions enhanced in constructed wetlands functioned as bioelectrochemical systems [43]. The regular or else fabricated wetland, this one comprises in cooperation of oxygenic and anoxygenic regions and conditions that produce a reduction-oxidation reactions gradient. These reaction gradients allow the movement of electrons (formed by anoxygenic metabolism and assimilation by microorganisms) into the preferred way and therefore prominent to the stream of current as in MFCs. Hence, the combined method of constructed wetlands integrated with MFCs has remained recognized as active and eliminates the level of COD, BOD, Total Nitrogen, and Total Phosphorus, furthermore for removing unsafe pollutants includes dyes, pharmaceuticals, pesticides, hydrocarbons, metals, heavy metals, and energy production in the scheme of electric flows [74,37,50].

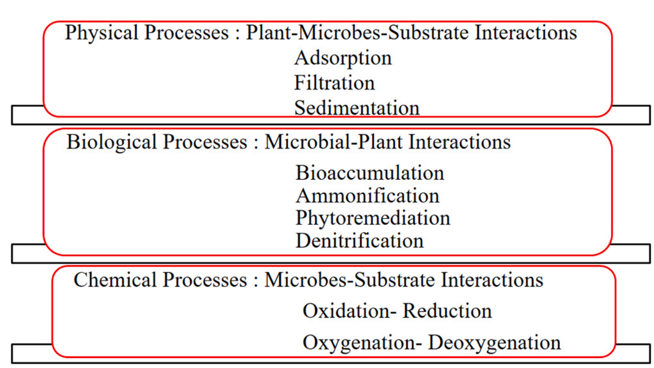

Fig. 3. Networking interaction processes involved FTW-MFC in wastewater treatment in contaminant removal.

Consequently, the built wetlands combined with MFCs deal with an active elucidation for ecological, economical, and energy-prospective technological knowledge for the management of wastewater with parallel biological electricity (biofuel) generation. The chief problems connected with mounting and bio-hydrogen production or bio-hydrogen damage owing to methanogenic microbes, the process and scheme, pattern, and an absence of thoughtful microbes' control, need to be resolved before further upscale processing. These glitches are non-essentially established in the minor scaling process of MFCs or MECs, but then they are thoughtful when advancing to the experimental scale, wherever the topping dynamics increase the threats. The methanogenic microorganisms might substantiate being solitary of the existing confines, as these microbes were established in several of the experimental scalings of MECs. It includes the MECs disjointed through a sheath or membrane and was established to afford the maximum hydrogen purity on a laboratory measure. Conversely, in an experimental scale of MEC, the designs and amplified density result in the formation of methane at the cathodes. The complications comprise electrode spaces and optimal design of the microbial electrochemical cells (MEC), the operation of mixed feedstock [27], prominent to reduced nourish store or feedstock conductivity, and the biohydrogen loss although consecutively and sustaining a greater facility [29] wholly of which prime to reduced current masses and biohydrogen generation. The ultimate arrangement between the electrodes and cumulative surface-area-to-reactor-volume proportion can be elucidated by effecting a modest scheme design prone to relative topping. An additional upfront scheme that might reduce the price of engineering owing to the least-expensive materials and original outline agreeing for stress-free conservation [27]. As reported previously, the one-chamber structure was supposed to have the greatest option for industrial topping, letting relaxed conformation for uninterrupted manufacture and letting down the price.

6.1. *Design criteria for FTW and its determination of surface area covered in the MFC system*

The first-order socket stream kinetic model was functional to compute the surface area of the marshland or wetland as previously practiced by diverse investigators [30,31,52]. The reed bed technique remained castoff to analyze the area of the floating wetland, influx loads, influent or effluent biochemical oxygen demand (BOD) loads, constant temperature, permeability, and water deepness remained designated as strategy constraints or parameters.

$$A = \frac{Q\ln\,(C_i \div C_o)}{KT \times d \times nv} \tag{1}$$

$$KT = K20 \times Ø^{(Tw-20)} \tag{2}$$

where the symbol 'A' represents the surface area of the wetland (m^2), Q denotes the quantity of inflow (m^3/day), Ci is the influent load or concentration of BOD (mg/L), Co signifies the effluent load or concentration of BOD (mg/L), d refers the depth of water (m), "nv" denotes the porosity connected to the part of wetland and is not engaged by the plants, KT indicates the temperature constant (day^{-1}), K20 refers the temperature constant at temperature 20°C (day^{-1}), Tw denotes the temperature of wetland (∘C) and Θ represents the temperature coefficient for the rate constant and its value depends on the type or nature of contaminants to be removed. The standards of K20 and Θ rest on the type or nature of contaminants. The period to maintain the wastewater and its hydraulic loading rate in a moving wetland can be considered for calculation using Eqs. (3) and (4) correspondingly.

$$\begin{aligned} t &= [A \times d \times nv] \div Q \\ HLR &= Q \div A \end{aligned} \tag{3}$$

$$\text{Removal Efficiency} = \{1 - C_e \div C_o\} \times 100\% \tag{4}$$

Where't', represents the time to hold wastewater in the wetland (day), "A", refers to the area of the wetland (m^2); "d" signifies the depth of water in the wetland; "n" is the porosity or permeability (typically 75 %), "Q" denotes the average inflow (m^3/d) and HLR indicates the hydraulic loading rate (cm/day or m/day). The BOD removal competence of the entire scheme is estimated and measured using the formula (3).

The simple scheme parameters comprise the area of the wetland, rate of loading (loading rate), time for retention (retention time), plant type, and temperature. To each parameter has its identifiable importance in this system, the plants substantially grasp up the passageway of wastewater improving the sedimentation of solids in suspended formations. The wetland warmness is a significant scheme of constraint since BOD and several additional pollutant elimination hinge on the temperature. The aquatic plants are the foremost accumulator for contaminant elimination and their biomass or growth rate also be subject to temperature. By way of the plants available, the appropriate temperature they propagate adds rapidly and absorbs additional pollutants from the wastewater (www.iaees.org). To define the proportion of surface area concealment of Floating treatment wetland in linking to a preferred proportion of phosphorus decrease established on plant's shoot uptake and root uptake; and also, microbial biomass or biofilm purging (as in below Eq. 5), where only aboveground plant shoot uptake was considered for harvesting (as in below Eq. 6). The manifold floating treatment wetlands, the surface area attention situations are accessible for Pelican Lake through investigating a grouping of goals for the decline of total phosphorus (TP) load (%) and mean TP load in aboveground plant tissue detected and microbial TP decrease in-lake were calculated. The nutrient load of TP and water quality and characteristics properties of Pelican Lake are then cast in assessment to that of floating wetland management applications for in-lake investigation globally. This type of treatment system has the prospective of in-lake clean-up action suitable for algal bloom-rich eutrophic lakes in Manitoba and in other parts of the global biosphere. The influence of floating treatment of wetlands on nutrient lessening in Lake was evaluated over the average value of TP load or concentration rates from reports of case studies that remained castoff to assess the proportion of nutrient decline in linking to FTW surface area enclosed (www.iisd.org).

The Equations. (5 and 6) are a consistent formulation to evaluate the percent or proportion of water surface area enclosed by FTW to decrease phosphorus loads in eutrophic waterbodies. The Eqs. 5 and 6, Percent (%) Surface Area coverage by FTW (Stanley 2015).

$$\left(\frac{\text{Total P in lake water }(g\cdot L^{-1}) \times \text{Lake volume (L)} \times \text{Percent of P reduction} \times 0.01}{\text{Total P above ground plant tissue }\left(g/m^2\right) \times \text{Total P FTW }\left(g/m^2\right) \times \text{Surface area of lake }\left(m^2\right)}\right) \times 100 \tag{5}$$

$$\left(\frac{\text{Total P in water } (\text{g}\cdot\text{L}^{-1}) \times \text{Site volume (L)} \times \text{Percent P reduction desired} \times 0.01}{\text{Total P in above ground tissue } (\text{g/m}^2) \times \text{Surface area of lake } (\text{m}^2)}\right) \times 100 \quad (6)$$

The floating macrophytes stimulate the hydraulic flow of the water beneath and use the plants through the root system functioning as a regular filter (Chen *et al.*, 2016; [16]). The nutrient-loading bases may be the greatest dynamic and give additional optimistic help to the well-being of the aquatic environment [36].

Bio-Concentration Factor

The Bio-Concentration dynamic Factor was calculated according to Zhuang *et al.* (2007) as follows:

$$\text{Bio} - \text{Concentration Factor (BCF)} = \text{C}_{\text{harvested tissue}}/\text{C}_{\text{substrate}} \quad (7)$$

Where,

C-harvested $_{\text{tissue}}$ is the concentration of the target pollutant in the plant-harvested tissue.

C $_{\text{substrate}}$ is the concentration of the same compound in the hydroponic nutrient solution.

The estimation of the above factor for samples collected at different time intervals after the treatments of the experiments helped detect the bioconcentration of the plant biomass.

7. Significant prospective advantages: ecosystem sustainable development & management

The estimation of the above factor for samples collected at diverse time intervals after the experimental treatments helped to detect the bioconcentration of the plant biomass.

- It affords scheme flexibility and can be sized to be suitably obsessed by nearly any pond or lake.
- It enriches the contaminant elimination effectively on existing wet ponds of stormwaters.
- It provides a maintainable contaminant elimination scheme and nature living habitat.
- It deals with resiliency and can endure storm-event-driven water-level variations if they are involved to the bottom or tied to the shoreline, so it is not spoiled or vanish by rolling from side to side the vent construction of the pond.
- It progresses aesthetics, and can also be castoff to advance the pictorial charm of surface water topographies together with ponds and lakes
- It can be able to be fed by gravity (low energy use)

7.1. It enhances the biodiversity enhancement

(i) **Retrofit existing wetlands or detention ponds**

It is not continuously possible to raise the scope of a wetland or connect source controls to take the reason of extra contaminants given the cost of land procurement or the cost of substituting the current substructure. The Floating treatment wetland will reduce the contaminants deprived of needful changes outside the current ponds or wetlands.

(ii) **Design to target the required level of treatment**

The floating treatment wetlands are a prefabricated system, so they can be topped up to encounter the preferred level of water quality treatment, or removed if water quality treatment is no longer essential and repositioned the matured mounted floating treatment wetlands (FTW).

(iii) **Maintain treatment despite fluctuating water levels**

Through contrast, the floating wetlands will increase and drop with water levels, which permits them to be cast off in circumstances where water levels cannot be retained at a similar level.

(iv) **Recovery of sediment and sludge**

The floating treatment wetlands can be stimulated near the waterbody, consequently, the sludge and sediment can be aloof deprived of affecting destruction to the substructure. This might be a significant improvement when treating waters more in suspended solids.

(v) **Algal Bloom Control**

The floating treatment wetlands are active in decreasing the extreme biomass of phytoplankton and filamentous algae, triggered by high concentrations and loads of phosphorus inflowing into the water body. It is commonly supposed that the motive for this decline is owed to the collective effects of being devoid of light or shading and heat or temperature decline.

(vi) **Provide a food source and refuge for fish**

The Floating treatment wetlands are cast off in entertaining fishing ponds to maintain a biologically varied range of autotrophic and heterotrophic organism's immovable on the root systems.

(vii) **Enhance landscape amenity**

The floating treatment wetlands can be sized and intended as a convenience feature. They can be considered as an island, mount a ruined island, or about the boundary of waterbodies that are too subterranean or sharp, shallow wetland.

(viii) **Installation of a low-maintenance treatment system**

There are no extraordinary measures that are essential for upkeep when associated with other water treatment actions. The key condition for upkeep will be the elimination of weeds or rubbish.

8. The carbon sequestration and carbon footprint

8.1. The short-term energy requirements for earthworks

8.1.1. The acts as a net carbon sink

a. **Less areal footprint**

This system is also a valued technology for urban wastewater. Certainly, the usage of oxygenated or aerated wetlands decreases the demanded operation area in association with constructed wetlands.

b. **Low energy consumption**

The support of airing needs an extra contribution of energy in association with built wetlands. On the contrary, the energy intake leftovers are fewer than other technological interpretations (for example, ACS-activated sludge systems). The practice of inverter and programmable logic controller devices allows the regulation of oxygen transfer, optimizing energy consumption.

c. **From passive to active regulation**

Even though the built wetlands, are inert treatment technologies with the least probability of guideline, airing systems give the option to improve control of the treatment processes over the parameter of oxygen transference. Though the working and upkeep activities continue simple, upholding the well-known benefits of nature-based solutions.

d. **Refurbishment FBA,**

It is too well right for the refurbishment of undersized treatment of wetlands and the plants involved in treatment facing a rise in influent wastewater pollutant loads. Certainly, the airing system can be additional to a current wetland plant deprived of the elimination of filling media, and recognition of the usage of appropriate equipment.

9. Substantial and significant parameters

The efficiency was measured founded on the enhancement of substantial physicochemical characters that include the following parameters color of water, its conductivity, pH, turbidity, COD, BOD, TOC, TS, BOD/COD ratio, C: N ratio, NPK value, etc.,) nutrients (Nitrogen, Ammonia, and Phosphorus: NO_3^-, PO_4^-, SO_4^-, $NH4^+$, etc.); metals and heavy metals (zinc, chromium, copper, lead, and cadmium); resistant plant types and their adaptability (Tolerance level and Bio-accumulation) and acute ecotoxicity tests (fish, Phytoplanktons, Zooplanktons, Microtoxicity study) to assess the reduction of toxicity after wastewater treatment.

9.1. Effective time and its performance

9.1.1. The gravel filtration will instantly eliminate suspended sediment

- The exclusion of nutrients and organic matter will first prerequisite vegetation to become established
- The performance can be kept at optimum with a well-established maintenance schedule
- The performance fluctuates with seasonal change wells; inferior in autumn/winter, utmost in spring/summer

9.2. Maintenance of the system

- The needs to be monitored frequently to ensure there is no bio-clogging
- The gravel medium needs to be renewed as required
- The suggested cutting back of plants and removal of litter at the termination of each growing season

9.3. Scaling considerations

The size of the reed beds and the number of reed bed stages are essential and are correlated to the load of nutrient removal. The design criteria to meet the following

- The monitoring of the required inlet and outlet concentrations and a population equivalent must be evidenced
- The hydraulic and the mass loading determination directly impact sizing, aspect ratio, and depth
- The commitment considers climate factors and climate change including droughts and dry weather, water gains from rainfall, etc. And the seasonal dynamics and variances in flows through different seasons
- The requirement considers seasonal efficiency tied to plant growth

10. Significant prospective limitations

❖ Attaching floating treatment wetlands-FTW can be a challenging task.

❖ Has extreme nutrient reduction efficiency, the FTW need to be reaped or eliminated seasonally. The existing environmental policy would probably need the yield of plant material in the drop to obtain nutrient elimination as a management. This involves a feasibly important labor strength.

❖ The Floating treatment wetland inhabit the open water surface, and influence block entree or decrease the obtainable zone for lakes and ponds used for recreation. The least water deepness should be no lower than three feet (from 4 to 5 feet is commended). The plants used on the FTW can root into the bottom residues or remain in shallow water causing the floating rafts to be immersed when the pond water level rises throughout storm events.

❖ Approximately contaminants including oil residues and herbicides in urban runoff might harm the plants and microorganisms.

❖ The invasive species and non-native plants must not be planted on the FTW and weeded out of this treatment system to evade adversative effects on local bionetworks.

❖ The main disadvantages include, the compressed by climate conditions and *exsitu* environmental factors.

❖ In certain cases, the osmotic microbial fuel cells with forward osmosis membranes, is difficult to integrate with wetland systems to improve the removal of nutrient elements in the soil system. The inclusion of soil in wetland systems can lead to severe clogging of forward osmosis membranes, while floating wetland systems may have good applications in osmotic microbial fuel cells because they do not require soil substrate (Hengliang [86]).

11. Expected cost-benefit analysis as per literature review

The benefit-cost analysis or the cost-benefit analysis (CBA) is a moderately modest and shared procedure for creating conclusions and assessing impacts of environmental. This system is grounded on the "inclination-to-pay" standard code that states the principles of ecological organizations carefully be contingent on human thoughts. The financial exploration revealed that the wetland treatment system is additional sustainable and economical than the common management system of effluent. The studies revealed that the floating treatment wetland system is less expensive, economically feasible, and energy-competent than the industrial effluent management system, and the wetland system too affords extra environmental benefits. With the less expensive cost-benefit quotient of replacing the effluent management system with a Floating treatment wetland system, the energy cost will considerably drop. Though this research is continuing the primary cost estimates for floating treatment wetlands-FTW rafts range from 1 to 24 dollars per square foot. The lesser value is for home-based FTW rafts made moreover of second-hand materials or waste PVC pipes; the greater worth signifies the cost of commercially obtainable, registered FTW rafts. The costs for the flora/plants plugs for implanting the Floating treatment wetland system and are needy on the plant species and sources, the type of FTW system (harvested or permanent), and their persistence of application including nutrient management, nursery production, habitat restoration, etc. An estimate of upkeep costs can be prepared constructed on the size of the floating treatment wetland system, the labor for plant reaping or standby, weed controlling, etc. If certainly not structure restoration is essential the annual costs are predicted to be lesser than those for constructed or built wetlands (3–5 %) of the assessed assembly cost [13].

12. Challenges and existing research breaches of FTW and MFC

The practice of using ecological floating beds (EFBs) to regulate water contamination has gained worldwide recognition due to the severe issue of eutrophication in various water bodies [18]. Floating treatment wetlands (FTWs) can be somewhat challenging because variations in water levels may submerge plants, putting unnecessary pressure on those with bottom-rooted systems. FTWs can be likened to conventional hydroponic systems, as the plants obtain their nutrients directly from the water in which their roots are suspended, rather than from soil. They also share similarities with subsurface flow treatment wetlands, where water moves over the root zone of the plants rather than between the stems. The terminology used to describe floating treatment wetland systems, both natural and artificial, varies considerably. Around the world, natural floating wetland ecosystems are known by a wide range of terms. However, for the relatively new category of non-natural or constructed floating treatment wetlands used for wastewater treatment, there remains a lack of consistent terminology that is widely accepted [19]. One of the challenges faced by FTWs is the lack of harvesting options. The pond water treatment process is complicated by the need for approximately a 500-meter walk over unpaved terrain for material transfer, making harvesting and transporting collected materials difficult. Phyto-accumulated substances, such as metals, may be released back into the water, with some settling in the sediment of the aquatic system. Although this process has a net positive effect, the overall results are less than optimal compared to what could be achieved. Therefore, the primary function of the floating wetland should be enhanced sedimentation of various contaminants, including heavy metals and phosphorus (P), along with the removal of nitrate and nitrite through bacterial denitrification [60,59].

Consequently, the constructed wetlands combined with microbial fuel cells (MFCs) offer an effective solution for sustainable, cost-effective, and energy-efficient wastewater treatment, along with simultaneous bioenergy and electricity generation. However, significant challenges related to hydrogen production and retention arise from methanogenic microorganisms, the design and operational structure, and the lack of adequate microbial controls. These issues must be addressed before scaling up the process. While these problems are not typically encountered in smaller MFCs and microbial electrolysis cells (MECs), they become pronounced when transitioning to experimental-scale systems, where scaling factors increase the associated risks. An effective design is essential for creating electrodes that resist fouling, which involves using electrically conductive anti-fouling rods. In laboratory settings, microbial fuel cells (MFCs) have demonstrated the ability to produce substantial amounts of bioelectricity while also effectively removing contaminants. However, this area of research is continually advancing, especially in the pursuit of better electrode materials. Researchers are concentrating on identifying anode materials that exhibit uniform conductivity and cathode materials that are more resistant to fouling [11,12]. Electrodes are selected according to the types and concentrations of pollutants present in the wastewater, as well as the specific pollutants that need to be removed or recovered. The microorganisms in the wastewater or added to the treatment system were key factors influencing process efficiency. Additionally, the selection of plants and their combinations is determined by the types of pollutants that need to be addressed and the preferences for recovery.

The methanogenic microorganisms may prove problematic within the current settings; in fact, they have been observed at several experimental scales of MECs. These MECs often utilize a membrane or sheath designed to maximize hydrogen purity in laboratory-scale processes. However, at larger scales, design complexities and operational factors can lead to increased methane production in the cathodic chamber. Problems such as electrode spacing, optimal MEC design, and the operation of various feedstocks can lead to decreased feedstock efficiency, reduced conductivity, and biological hydrogen loss, all of which contribute to lower current densities and hydrogen generation [27,29]. The arrangement between electrodes and the surface area-to-reactor volume ratio must be carefully considered. A simpler design can reduce fabrication costs through the use of cheaper materials and straightforward structures that facilitate easy maintenance.

Previous studies suggest that a single-chamber design may be the most favorable for industrial-scale processing, allowing for seamless continuous operation at a lower cost. According to the review, using multiple electrodes is more efficient for large-scale on-site wastewater treatment applications [3], and operating in a closed-circuit mode also enhances efficiency [39]. In some studies, polymer tubes have been employed to hold the anodic electrodes together and protect them from impacts. These materials are not only inexpensive but also easy to work with. Additionally, covering the electrodes with a polymer material can enhance conductivity while maintaining sufficient surface area for biofilm growth, using structures like grids. Some research has implemented multiple cathodes alongside a single anode compartment, while others have utilized four pairs of electrodes connected in parallel. However, many of the developed systems are quite complex and challenging for real-time upscaling and analysis under practical conditions. In certain cases, the separation of materials between the anode and cathode is solely reliant on the diffusion of oxygen. Other studies have used materials like glass wool for separation [78,77,79]. The choice of membranes for separating the anode from the cathode, as well as modifications to electrodes, plays a critical role in the potential economic viability of transitioning the system from prototype to pilot scale [3]. In a recent study on the microbial electrochemical coupling of floating treatment wetlands (FTW) and microbial electrochemical systems (MES) for low-carbon wastewater remediation, Zhengyu Yan et al. [82] highlighted that external resistance is a critical factor for the efficient purification of low-carbon wastewater using FTW-MES. This research serves as an important technical reference for enhancing in-situ remediation with FTW-MES. Using a membrane for separation helps to settle solids and sludge at the bottom of the reactor, facilitating the transfer of treated wastewater from the anode to the cathode for further treatment. The sustainable options discussed in these reviews highlight the possibility of simultaneous pollutant removal and resource recovery, along with concurrent energy utilization and biomass production. Most studies report that biological wastewater treatment and energy generation can effectively occur in parallel, often resulting in improved treatment outcomes and electricity generation.

13. Future directions and prospects

The combination of microbial fuel cells (MFCs) in wastewater treatment represents an innovative approach for generating sustainable energy. This system integrates MFCs with natural reduction-oxidation reactions, as well as with constructed wetlands or floating treatment wetlands. Constructed wetlands facilitate the removal of contaminants and organic matter from wastewater through biological processes, including filtration, adsorption, and phytoremediation, where plants play a key role. Additionally, microbial biotransformation aids in biodegradation [75]. The support medium for these wetlands consists of various materials such as soil, sand, charcoal, gravel, and pebbles. These materials help separate suspended solid matter in wastewater, enhancing treatment effectiveness. Kong et al. [35] reported the enhanced effects of zero-valent iron and a static magnetic field on pollutant removal and power generation in electroactive constructed wetlands. The design of the wetland creates both oxygen-rich (oxic) and oxygen-poor (anoxic) zones that MFCs can utilize to produce electricity. In this combined system, the constructed wetland with an MFC stands out for its potential to treat wastewater while simultaneously generating clean energy. The electricity produced is a result of chemical reactions, the accumulation of organic substrates, and biological interactions driven by exoelectrogenic microorganisms that thrive on organic loads in the anoxic regions of the wetlands.

Both regular and constructed wetlands have a unique synergy of oxic and anoxic regions that promote reduction and oxidation reactions, which facilitate the movement of electrons produced by microbial metabolism. This electron movement ultimately leads to the generation of electrical current, similar to how traditional MFCs operate. The biochemical bioprocesses involved in wastewater treatment encompass various processes: physicochemical processes such as sedimentation, adsorption, and precipitation; biological and microbiological processes including biodegradation, assimilation, denitrification, and nitrification; and plant-mediated processes like phytoremediation and assimilation. These collectively contribute to the effective removal of mixed pollutants within treatment systems. The combined methodology of Constructed Wetlands (CW) and Microbial Fuel Cells (MFC) is recognized for its capability to eliminate wastewater parameters, including Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), total nitrogen, and phosphorus. Additionally, it is effective in removing hazardous emerging contaminants such as pharmaceuticals, dyes, pesticides, oils, hydrocarbons, metals, and heavy metals, all while producing energy [37,50,74]. Furthermore, the strengths of these engineered biosystems, which utilize floating treatment wetlands (FTW) and MFCs, reflect their capacity as multi-tasking bioremediation systems. They not only support the growth of floating plants but can also be adapted to diverse ecosystems and integrated with innovative techniques to enhance their efficiency. This improves the treatment of various water bodies, including domestic and industrial wastewater, surface and groundwater, stormwater, highway runoff, irrigation water, buffer areas, and drainage canals.

The use of engineered remediation biosystems combining FTW and MFC with microbial electrochemical processes effectively reduces or eliminates harmful ecological pollutants. The key areas of focus include long-term field performance and management, biofilm composition and contributions, validation of identified plant traits and ecotypes, and practical implications. At the laboratory level, microbial fuel cells (MFCs) have shown the capability to produce significant amounts of bioelectricity and facilitate contamination removal. This is still a rapidly evolving field, particularly in the search for uniformly conductive materials for the anode and materials for the cathode that are less prone to fouling. These research work supports the sustainable development goals (SDGs), specifically SDG 6 (clean water) and SDG 7 (clean energy). This innovative, nature-based treatment system promotes clean and safe water, leading to improved water quality. The significant outcomes contribute to the circular economy, sustainable development, and effective water management, aligning with the United Nations Sustainable Development Goal Six, which promotes "Clean Water and Sanitation" to ensure access to water and sanitation for all.

CRediT authorship contribution statement

Usharani Rathinam Krishnaswamy: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gustavo Henrique Ribeiro Da Silva:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper Usharani Rathinam Krishnaswamy reports financial support was provided by Coordination of Higher Education Personnel Improvement. Co-author employed by UNESP, Gustavo HRD Silva If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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