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# Emerging and ecofriendly biological methods for agricultural wastewater treatment

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**Abstract**
The quest for sustainable agricultural practices has led to a surge in research focused on innovative wastewater treatment methods. This review explores the emerging biological treatment approaches designed to address the challenges of eco-friendly agricultural wastewater treatment and subsequent reuse. The investigation centers around three novel techniques: constructed wetlands, algae-based systems, and microbial fuel cells. Constructed wetlands (CWs) mimic natural processes to treat agricultural wastewater, providing habitat for various plant species that collaboratively remove contaminants. Algae-based systems(ABs) harness the photosynthetic prowess of algae to absorb nutrients and pollutants, producing biomass that can be repurposed. Meanwhile, microbial fuel cells (MFCs) employ microorganisms to break down organic matter in wastewater while generating electricity as a valuable byproduct. This review aims to provide insights into the potential of these biological treatment methods to revolutionize wastewater management in agriculture. By mitigating environmental impact, conserving water resources, and yielding reusable outputs, these techniques will offer a sustainable pathway towards addressing the pressing challenges of agricultural wastewater treatment and enhancing the overall ecological balance.

**Keywords** Agricultural wastewater, Biological methods, Wastewater treatment, Constructed wetlands, Algae-based systems, Microbial fuel-cell

## Introduction

In the delicate balance between human agricultural needs and the ecological well-being of our planet, the efficient treatment and sustainable reuse of agricultural wastewater emerge as crucial challenge. As global water scarcity intensifies and environmental concerns loom larger, the imperative to develop innovative and environmentally friendly solutions has become paramount (Abdelfattah and El-Shamy 2024). In wastewater management, the agricultural sector has long been a significant contributor to pollution and water depletion. As agricultural activities intensify to meet growing food demands, they inevitably produce vast quantities of wastewater laden with nutrients, pesticides, and other contaminants. This agricultural runoff poses significant threats to water quality, disrupts ecosystems, and jeopardizes human health. In response, traditional wastewater treatment methods have been employed, yet their efficacy in terms of resource efficiency, energy consumption, and environmental impact remains limited. Thus, the search for novel approaches that can address the multifaceted challenges of agricultural wastewater management has become imperative.

The past two decades have witnessed a burgeoning interest in harnessing the power of biological processes to address the challenges of agricultural wastewater

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treatment and reuse. This interest has culminated in the development of innovative biological treatment methods that mimic nature's intricate mechanisms, providing a well-rounded and long-lasting solution. Various biological methods have been employed in the treatment of wastewater. They include activated sludge process (Magalhães et al. 2021), trickling filters (Żyłka et al. 2018), constructed wetlands (de Campos and Soto 2024), anaerobic digestion (Ferrer et al. 2024) and membrane bioreactors (Han et al. 2024), etc. However, for this review, the methods under scrutiny covers constructed wetlands, algae-based systems, and microbial fuel cells, each presenting unique characteristics that contribute to the eco-friendly treatment and utilization of agricultural wastewater. Constructed wetlands, algae-based systems, and microbial fuel cells are mostly used in Agro-waste treatment because they are cost-effective, high rate of nutrient recovery, sustainable, lower energy consumption, adaptable, require fewer chemicals compared to conventional wastewater treatment methods it also provide habitat and support for various wildlife species, contributes to biodiversity conservation in agricultural areas and enjoys wide acceptability (Al-Jabri et al. 2020; Malik et al. 2023; Mohsenpour et al. 2021; Retta et al. 2023).

Constructed wetlands, Microbial Fuel Cells (MFCs), and algae-based systems are superior choices for agricultural wastewater treatment due to their cost-effectiveness, sustainability, and additional benefits, effectively addressing the significant drawbacks of traditional methods like bioremediation, composting, activated sludge, anaerobic digestion, and phytoremediation. Constructed wetlands are particularly advantageous because they mimic natural processes, providing a sustainable and environmentally friendly treatment option with minimal energy and maintenance requirements (Waly et al. 2022), in contrast to the high operational costs and sludge disposal issues associated with the activated sludge process (Apollo 2023). Furthermore, constructed wetlands enhance local biodiversity by creating habitats for various species and effectively remove a wide range of pollutants, including nutrients, heavy metals, and organic matter (Rana and Maiti 2020; Zhang et al. 2020a, b) which bioremediation (Saravanan et al. 2024) and phytoremediation (Sophia and Shetty Kodialbail 2020), limited by slow processing rates and site-specific conditions, often fail to address adequately. Microbial Fuel Cells offer the dual benefits of wastewater treatment and renewable energy production by generating electricity from waste, a feature absent in traditional methods (Elhenawy et al. 2022). MFCs produce less sludge compared to the activated sludge process and anaerobic digestion, reducing disposal challenges and associated costs, and can treat various types of waste, including domestic, industrial, and agricultural, providing versatility and broader applicability (Hamedani et al. 2024; Khan et al. 2024). Unlike anaerobic digestion, which requires controlled temperature conditions and has long start-up times (Garkoti et al. 2024), MFCs operate more straightforwardly and sustainably by integrating waste treatment with energy recovery, significantly reducing the environmental footprint. Algae-based systems are highly efficient in nutrient removal, effectively preventing eutrophication, a problem inadequately addressed by composting and anaerobic digestion (Kumar et al. 2024; Sakarya et al. 2023). They also offer the potential for biofuel production from algae biomass, providing a valuable byproduct not available in traditional methods. Additionally, algae capture and sequester carbon dioxide, helping to mitigate greenhouse gas emissions and contribute to a circular economy by recovering valuable byproducts such as bioplastics, fertilizers, and animal feed (Paul et al. 2020; Sarwer et al. 2022). Thus, these advanced technologies present a holistic and efficient solution to the challenges of agro wastewater management, surpassing the limitations of conventional approaches.

There are existing systematic reviews on the application of Constructed wetlands (Hassan et al. 2021; Parde et al. 2021), MFCs (Apollon et al. 2024; Pandit et al. 2021), and algae-based systems (Catone et al. 2021; Singh et al. 2023a, b; Vishwakarma et al. 2022) in treating agricultural and aquaculture wastewater treatment. However, no single review has comprehensively examined all these biological treatment methods together. This gap justifies the focus of this review article, which discusses the potential of emerging biological treatment methods: namely constructed wetlands, algae-based systems, and microbial fuel cells; for eco-friendly agricultural wastewater reuse. The significance of these innovative biological treatment methods in promoting a more sustainable future is emphasized in the review. The review details the key performance attributes of these three methods compared to other biological methods of agro-wastewater treatment. Additionally, insights into the economics of biological wastewater treatment, process integration, and the future outlook of these processes are provided.

## Agricultural wastewater

Agricultural activities are essential for sustaining human life by providing food, fiber, and other raw materials. However, they also generate significant amounts of wastewater, which poses environmental challenges if not managed properly. Agricultural wastewater comprises various pollutants, including organic matter (Jagaba et al. 2024), nutrients (Singh 2024), pesticides (M. Rani and Shanker 2024), and pathogens (Park et al. 2023), derived from irrigation, livestock operations, and crop processing. Agricultural wastewater is a heterogeneous mixture containing a diverse array of contaminants originating from different sources within farming operations. Organic matter such as plant residues (Abonyi et al. 2021, 2022, 2023; Ohale et al. 2023), animal manure (Abbaspour et al. 2024), and food processing waste (Matei et al. 2021) constitutes a substantial portion of agricultural wastewater. These organic compounds undergo microbial degradation, consuming oxygen and potentially leading to oxygen depletion in receiving water bodies, thereby threatening aquatic ecosystems. Moreover, agricultural activities often involve the use of fertilizers containing nitrogen and phosphorus compounds (Abonyi et al. 2024; Haydar et al. 2024). Excessive application of fertilizers can result in runoff, carrying these nutrients into water bodies, where they promote eutrophication; a process characterized by the overgrowth of algae, depletion of oxygen, and subsequent ecological imbalance (Nadarajan and Sukumaran 2021). Additionally, pesticides and herbicides used to control pests and weeds in agricultural fields can leach into groundwater or runoff into surface water, posing risks to aquatic life and human health (Kaur and Sinha 2019; Odewale et al. 2023; Rad et al. 2022). Effective management of agricultural wastewater is essential for mitigating its environmental impacts and safeguarding water resources. Various strategies and technologies are employed to treat, recycle, or safely dispose of agricultural wastewater, tailored to specific contaminants and local conditions. As the global population grows and freshwater resources become increasingly scarce, the need for sustainable solutions to agricultural wastewater management becomes more urgent. Sustainable approaches focus not only on treating wastewater but also on reducing its generation, optimizing resource recovery, and promoting circular economy principles. Amongst the promising approach are the biological treatment methods including constructed wetlands, MFCs, and algae based systems.

### Composition of agricultural wastewater

Agricultural wastewater is a complex mixture that varies in composition depending on farming activities, the types of crops or livestock involved, and local environmental factors. Understanding the general composition of this wastewater is essential to evaluating the effectiveness of various treatment methods, such as constructed wetlands, microbial fuel cells (MFCs), and algae-based systems. The most common pollutants in agricultural wastewater include organic matter, nutrients like nitrates and phosphates (Khan et al. 2022), pesticides (Srivastav et al. 2024), and pathogens (Kupa et al. 2024). Organic matter is predominantly derived from plant residues, animal manure, and food processing byproducts (Moinard et al. 2021; Ogbu and Okey 2023). This organic load, when introduced into water bodies, undergoes microbial degradation, which consumes dissolved oxygen (Mathew et al. 2022; Singh et al. 2019). This process, if unmanaged, can lead to oxygen depletion, or hypoxia, severely affecting aquatic ecosystems by threatening aquatic life. Furthermore, the breakdown of organic matter contributes to increased biological oxygen demand (BOD), a critical indicator of water quality (Lemessa et al. 2023). Nutrients, particularly nitrogen and phosphorus, are key contributors to agricultural runoff (Haque 2021). Nitrates and phosphates typically originate from the overapplication of chemical fertilizers and the use of manure as organic fertilizers (Nadarajan and Sukumaran 2021; Pahalvi et al. 2021). Once in the water, these nutrients can promote eutrophication, a process where nutrient overloading causes excessive algae growth. Eutrophication not only depletes oxygen in water but also leads to toxic algal blooms, which are harmful to aquatic organisms and can disrupt the balance of freshwater ecosystems. Pesticides and herbicides, used widely to control pests and weeds, are another significant class of pollutants in agricultural wastewater (AbuQamar et al. 2024; Verasoundarapandian et al. 2022). These synthetic chemicals, often persistent in the environment, pose severe risks to water quality. They can leach into groundwater or run off into surface water, potentially contaminating drinking water sources. The toxicity of these chemicals endangers both aquatic organisms and human health, as many pesticides are linked to long-term adverse effects (Ali et al. 2021; Khan et al. 2023).

In addition to these pollutants, agricultural wastewater may also contain pathogens from livestock operations, including bacteria, viruses, and parasites, which pose risks to human and animal health (Lin et al. 2022; Wu et al. 2024). Addressing these diverse contaminants requires tailored treatment solutions. Biological methods like constructed wetlands, algae-based systems, and MFCs offer sustainable approaches by removing organic matter, nutrients, and, in some cases, pesticides, while simultaneously promoting resource recovery and energy generation.

## Novel agricultural wastewater treatment techniques

### Constructed wetlands

In the pursuit of sustainable water management and environmental restoration, constructed wetlands (Fig. 1) have emerged as innovative ecosystems that mimic the natural processes of wetlands to treat a wide range of pollutants. These engineered systems harness the innate capacity of wetland plants, microorganisms, and soil matrices to remediate contaminants, reduce nutrient loads, and enhance water quality. Constructed wetlands operate on principles reminiscent of natural wetland ecosystems. As water flows through the system, vegetation, and soil matrices work in synergy to remove contaminants. Plants

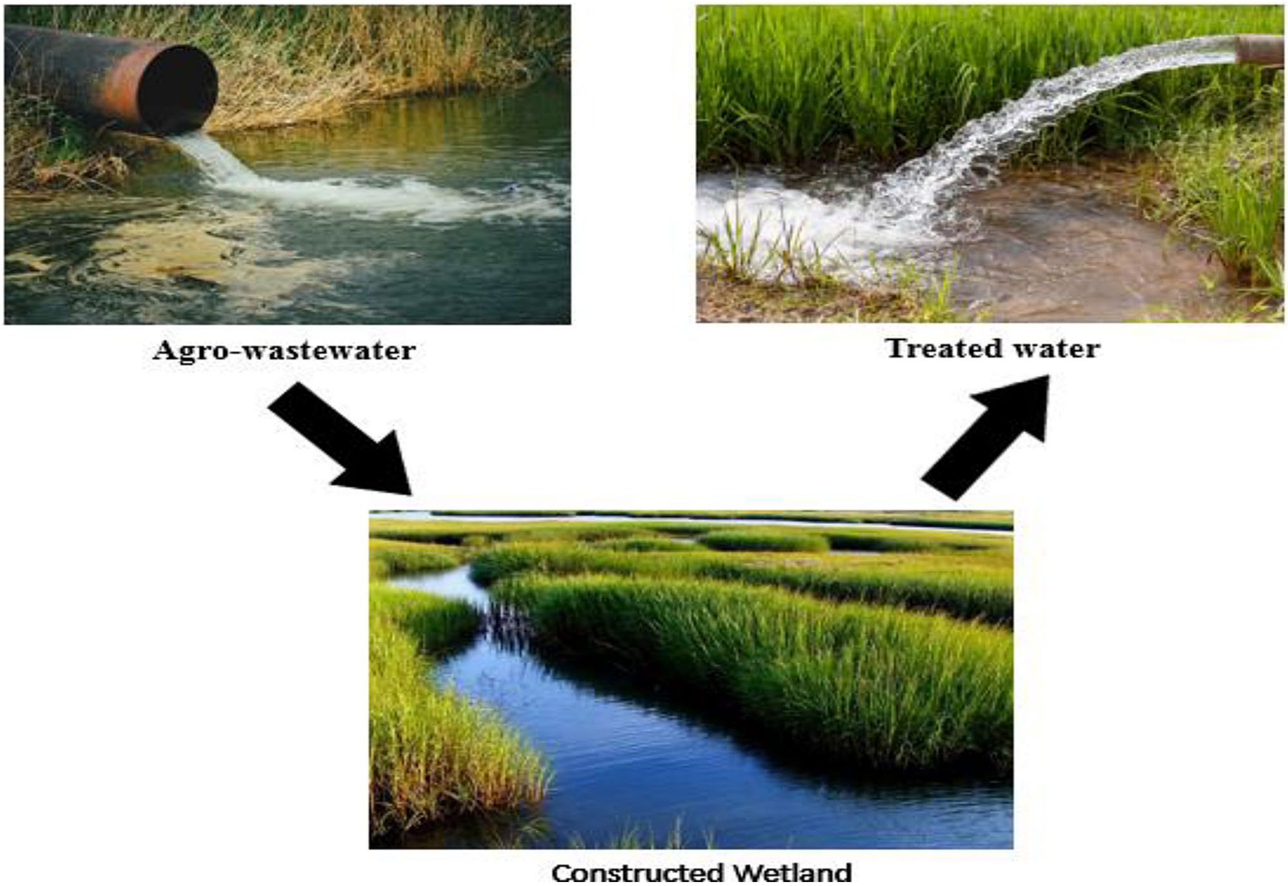


**Fig. 1** Constructed wetland for wastewater treatment

play a pivotal role in phytoextraction, phytoaccumulation, and rhizodegradation, facilitating the uptake and breakdown of pollutants. Microbial communities within the wetland media, fueled by organic matter, engage in biodegradation and microbial transformation of contaminants (Borgulat et al. 2022; Hassan et al. 2021; Yarwood 2018).

Constructed wetlands find wide-range applications in wastewater treatment, addressing challenges in both urban and agricultural contexts. In subsurface flow wetlands, the wastewater percolates through a porous medium, undergoing biological and physicochemical processes that remove pollutants and pathogens. Free water surface wetlands, on the other hand, mimic the surface area and hydrology of natural wetlands, providing habitat for diverse microorganisms that contribute to pollutant removal (Dawen and Nabi 2024). The nutrient removal capabilities of constructed wetlands make them potent tools for addressing eutrophication, a common consequence of excessive nutrient loads in water bodies. Nitrogen and phosphorus compounds are absorbed by wetland vegetation, incorporated into biomass, or transformed into less harmful forms through microbial processes. This nutrient attenuation not only improves water quality but also supports the preservation of aquatic ecosystems (Overton et al. 2024; Stutter et al. 2019).

Constructed wetlands exhibit efficacy in remediating heavy metal-contaminated waters. The sorption potential of wetland plants and the binding capacity of wetland sediments aid in immobilizing heavy metals, preventing their entry into the food chain. Coupled with careful plant selection and management, constructed wetlands offer a sustainable approach to mitigating heavy metal pollution (Hassan et al. 2021; Wibowo et al. 2023). Despite their potential, constructed wetlands are not without challenges. Factors such as hydraulic loading, plant selection, seasonal variations, and maintenance requirements can impact their performance. Adaptive management strategies, such as adjusting hydraulic regimes, incorporating diverse vegetation, and optimizing organic matter supply, are crucial to ensuring consistent and effective contaminant removal (Xu et al. 2024).

Constructed wetlands contribute to biodiversity conservation by providing habitat for a range of plant and animal species. These ecosystems attract avian populations, insects, and amphibians, creating pockets of biodiversity in urban and industrial landscapes. As refuges for native flora and fauna, constructed wetlands contribute to ecological restoration and support overall ecosystem health (Stefanakis 2019). The evolution of constructed wetland technology continues through innovation and integration. In a hybrid systems, combining constructed wetlands with other treatment processes, enhance their versatility and treatment efficiency. Integration with renewable energy sources, such as solar panels or microbial fuel cells, paves the way for self-sustaining treatment systems.

#### *Roles of diverse plant species in constructed wetlands*

Constructed wetlands have garnered attention as sustainable solutions for wastewater treatment, stormwater management, and habitat restoration (de Campos and Soto 2024; Mostafa et al. 2022; Paul and Finlayson 2023). The selection of plant species plays a pivotal role in shaping the functionality and performance of these engineered ecosystems. There are diverse plant species used in constructed wetlands. These plant species have their multifaceted roles in pollutant removal, hydraulic enhancement, habitat creation, and ecosystem resilience. An example of such a plant is the emergent plant. Emergent plants, characterized by their ability to grow above the water's surface, are commonly found in the shallow zones of constructed wetlands. Species like cattails (*Typha spp.)*, bulrushes (*Schoenoplectus spp*.), and reeds (*Phragmites spp*.) possess extensive root systems that create intricate networks. These root systems enhance pollutant removal through physical filtration, sediment trapping, and nutrient uptake. The aboveground biomass provides a habitat for insects, birds, and small mammals, enhancing biodiversity (Ben Salem et al. 2022). However, species like Phragmites can become invasive, outcompeting native plants and requiring ongoing management to prevent overgrowth.

Other very important plants used in constructed wetlands are the oxygenators and microbial hubs often called submerged plants. Submerged plants, such as pondweeds (*Potamogeton spp*.), coontails (*Ceratophyllum spp*.), and water milfoils (*Myriophyllum spp*.), reside beneath the water's surface. They are exceptional oxygenators, releasing oxygen into the water during photosynthesis. Submerged plants offer surfaces for microbial colonization, promoting diverse biofilm communities that contribute to nutrient cycling and pollutant degradation. They enhance water clarity by reducing suspended solids and promoting habitat complexity (Caputo 2022). Despite these advantages, submerged plants are vulnerable to water quality fluctuations. Excessive nutrient levels can promote algal blooms that block sunlight, limiting their growth and effectiveness.

There are also groups of plants known as Riparian plants often used as stabilizers and buffer strips. Riparian plants are strategically positioned along the water's edge, where terrestrial and aquatic ecosystems intersect. Species like willows (*Salix spp*.), sedges (*Carex spp*.), and rushes (*Juncus spp*.) stabilize the shoreline, preventing erosion and sediment runoff. Their root systems bind the soil, reducing the transport of pollutants into the water body. Riparian plants serve as buffer strips, mitigating the impact of pollutants from adjacent areas and promoting vegetative connectivity (Nasiri et al. 2024). The incorporation of a variety of plant species enhances both the aesthetic and ecological diversity of constructed wetlands. However, riparian plants may be less effective in areas with rapidly fluctuating water levels or harsh environmental conditions, and they require adequate space for root development to function optimally. Diversity promotes ecosystem resilience, as different plant species possess varying tolerance to environmental conditions and pollutant types. A mix of emergent, floating, submerged, and riparian plants creates a variety of microhabitats, supporting a wide range of aquatic and terrestrial organisms (Reddy et al. 2018).

#### *Types of constructed wetlands*

The versatility of constructed wetlands lies in their various types, each tailored to specific treatment goals, site conditions, and pollutant characteristics. By harnessing the natural processes inherent in wetland ecosystems, these engineered systems offer sustainable solutions for water treatment, habitat creation, and environmental stewardship. Whether it is enhancing water quality, restoring aquatic ecosystems, or addressing urban runoff, constructed wetlands stand as a testament to the synergy between engineering innovation and ecological restoration. Depending on their design, hydrology, and intended purpose, constructed wetlands can be categorized into several types.

i. **Free water surface (FWS) wetlands**.

Free-water surface wetlands, also known as surface flow wetlands, are characterized by shallow, open-water surfaces where wetland plants thrive. Wastewater or stormwater flows through these systems in a controlled manner, allowing physical, chemical, and biological processes to remove pollutants. Emergent and floating plants, along with microbes, play a crucial role in pollutant uptake, sediment trapping, and nutrient cycling. FWS wetlands are suitable for nutrient removal, suspended solids reduction, and providing habitat for wildlife (Guo and Cui 2022; Wan et al. 2024).

ii. **Subsurface flow (SSF) wetlands**.

Subsurface flow wetlands, also called horizontal flow wetlands, involve the passage of water through a porous substrate where plant roots are submerged. This design promotes interactions between the water, substrate, and plant roots, enhancing pollutant removal. SSF wetlands are particularly effective for reducing nutrients, such as nitrogen and phosphorus, as well as removing organic matter. The substrate provides surface area for microbial activity, contributing to the breakdown of pollutants (Alfa et al. 2024; Goel, Abhishek, & Gupta, 2021).

iii. **Vertical flow (VF) wetlands**.

Vertical flow wetlands utilize a vertical arrangement of layers containing substrate through which water flows from top to bottom. The roots of emergent plants establish a presence in the upper layers, while the lower layers host microbial communities. The VF wetlands excel in removing suspended solids, nutrients, and organic compounds. The vertical flow design optimizes hydraulic distribution and enhances contact between the water and plant roots, facilitating effective treatment (Dąbrowski et al. 2019; Younas et al. 2022).

iv. **Aerated wetlands**.

Aerated wetlands incorporate mechanical or natural aeration to enhance oxygen transfer, promoting aerobic microbial processes. Aeration supports the breakdown of organic matter and increases the microbial degradation of pollutants. These systems are effective in treating wastewater with high organic loads, promoting nitrification and denitrification processes. Aerated wetlands are particularly suitable for achieving stringent effluent quality standards (Nivala et al. 2020).

v. **Floating treatment wetlands**.

Floating treatment wetlands employ floating platforms planted with wetland vegetation. These platforms enhance the surface area available for plant growth and pollutant interaction. The root systems extend into the water column, where they contribute to nutrient uptake and pollutant removal. Floating treatment wetlands are often used for improving water quality in stormwater retention ponds, small water bodies, and urban environments (Landaverde et al. 2024; White 2021).

### *Application of constructed wetlands in agro-wastewater treatment*

Due to the significance of wetlands in wastewater treatment, numerous research endeavours have been conducted to evaluate the potential reuse of wetland effluent for various applications, with a primary focus on agricultural purposes. As an illustration, Cui et al. (2003) conducted a study in China that examined the application of vertical-flow treatment wetlands for treating septic tank effluent. The outcomes of their investigation revealed notable removal efficiencies, such as 60%, 80%, 74%, 49%, and 79% for chemical oxygen demand, biochemical oxygen demand, suspended solids, total nitrogen, and total phosphorus, respectively. Furthermore, the elimination rate of total coliform ranged from 85 to 96%. The treated effluent was subsequently repurposed for cultivating romaine lettuce and water spinach. It was observed that the utilization of the treated effluent led to increased nitrate levels in the cultivated vegetables, as reported by the authors.

In their study, Shelef et al. (2012) investigated the use of *Bassia indica* for salt phytoremediation in constructed wetlands. Constructed wetlands offer an eco-friendly, cost-effective approach for wastewater treatment and reuse, yet salinity elevation in treated water poses a risk, especially in arid regions, potentially harming irrigated crops. The research indicated that halophyte plants, like *Bassia indica*, can mitigate salinity by storing salts. Through three experiments, including hydroponic and wetland setups, *B. indica* demonstrated successful salt reduction of 20–60% compared to unplanted or other-planted systems. Salinity decrease was linked to Na and K accumulation in leaves. This study proposes *B. indica* as a viable option for "green desalination" in constructed wetlands, offering a novel solution for salt phytoremediation in the desert and similar ecosystems.

The study by Zohar et al. (2020) investigated phosphorus pools in aluminium (Al) and iron (Fe)-based water treatment residuals (WTRs) following their mixing with agricultural wastewater. Constructed wetlands (CW) incorporating clinoptilolite zeolite and five halophyte species were tested with treated dairy farm effluent over two years, with retention times from 2 to 7 days. Plant selection did not affect the Sodium Adsorption Ratio (SAR). It reduced from 4.85 to 2.59 $(mmol/L)^{0.5}$ due to zeolite ion exchange. Halophytes increased evapotranspiration to 30 mm/day, offsetting sodium removal. *Sesuvium portulacastrum* planted with zeolite exhibited 15% lower sodium and 5% higher calcium, indicating zeolite reconditioning. Batch experiments demonstrated enhanced SAR removal by zeolite from *Sesuvium*-planted CW, particularly reducing SAR to $3.33 \pm 0.3$ $(mmol/L)^{0.5}$ compared to $3.68 \pm 0.12$ by non-planted zeolite ($p < 0.05$). This biological reconditioning of the CW matrix by tailored macrophytes presents a promising strategy for pollutant remediation.

The study by Borges and Tavares (2017) aimed to assess a constructed wetland's efficiency in treating wastewater from bullfrog farming, specifically during the fattening growth phase. Notably, water detention time was uncontrolled due to varying wastewater input linked to animal biomass. The research was conducted in two phases, differing in bullfrog biomass. Phase I demonstrated superior removal of nitrite, BOD, and thermotolerant coliforms. Conversely, phase II excelled in removing turbidity, nitrate, total phosphorus, total suspended solids, total dissolved solids, and chlorophyll. The findings highlighted the need for extended water retention times for constructed wetlands dealing with high organic loads.

A study by Gikas et al. (2018) investigated the efficacy of horizontal subsurface flow (HSSF) constructed wetland (CW) systems over a prolonged duration of one year in eliminating pesticides. The study utilized CWs containing either *Phragmites australis* or *Typha latifolia*, showcasing their capability to eliminate up to 73.7% and 58.4% of pesticides in the system, respectively. Notably, significant concentrations of terbuthylazine were found in the roots, leaves, and shoots of both plant species within the CWs. In a distinct study by (Parlakidis et al. 2021), three HSSF CWs were employed for treating fluopyram from rinsing water generated during the cleansing of pesticide application equipment. These CWs, planted with *Phragmites australis* in fine gravel layers, demonstrated a remarkable fluopyram removal efficiency exceeding 96%. The removal mechanisms involved microbial biodegradation, adsorption on porous media, and bioaccumulation processes.

Numerous research investigations have provided evidence that wetlands represent a highly efficient and cost-effective solution for the removal of multiple water pollutants. These studies provide valuable insights into the diverse applications and effectiveness of constructed wetlands in agricultural wastewater treatment. While each study focuses on different aspects of pollutant removal and water reuse, they collectively highlight the versatility and efficacy of constructed wetlands as a sustainable solution for addressing agricultural wastewater challenges. Interactive comparisons between these studies reveal the importance of considering factors such as plant species selection, substrate amendments, hydraulic retention times, and pollutant characteristics in designing and optimizing constructed wetland systems for agricultural wastewater treatment. Table 1 highlights recent global studies that substantiate the superior efficacy of this technology in achieving up to a 99% reduction in pollutant levels.

### Algae-based systems

Algae-based systems harness the photosynthetic prowess of microalgae to tackle agricultural wastewater pollution. These microorganisms thrive on nutrients present in wastewater, effectively absorbing nitrogen and phosphorus compounds. This dual-function approach not only purifies water but also results in biomass growth that holds potential for various applications, including biofuel production. Algae's ability to sequester carbon dioxide during photosynthesis further emphasize their environmental benefits. Algae-based systems exemplify

**Table 1** Removal percentage of pollutants by wetlands

| S/*N* | Type | TSS(%) | TDS(%) | TP(%) | COD(%) | $BOD_5$(%) | TN(%) | Ref. |
|---|---|---|---|---|---|---|---|---|
| 1 | SFCW | – | – | 90±6 | 91±7 | 95±5 | 70±10 | (Yin et al. 2016) |
| 2 | HSSF | 86.5 | – | 64.85 | 68.1 | – | – | (Zhao et al. 2016) |
| 3 | VSSFs | – | – | – | 65–69 | 75–85 | 60–66 | (Tuttolomondo et al. 2020) |
| 4 | FWSCW | – | 87.36 | – | 86.6 | 83.7 | – | (Midhun et al. 2016) |
| 5 | HSSF | 77 | – | 25 | 63 | 62 | 48 | (Russo et al. 2019) |
| 6 | VSSF | 83 | – | 64 | – | 81 | – | (Rozema et al. 2016) |
| 7 | WCCW | – | – | – | 86 | 83 | – | (Dal Ferro et al. 2021) |
| 8 | HFCW | 86.1 | 67.27 | – | 87.81 | – | – | (Upadhyay et al. 2017) |
| 9 | SSFW & SFW | – | – | 55 | 75 | – | 75 | (Sartori et al. 2016) |
| 10 | HSSF | 32.82±22.14 | – | 0.67±1.08 | – | – | 8.49±4.49 | (Grinberga and Lagzdins 2017) |
| 11 | HSSF | 30 | 50 | – | 53 | 59 | – | (Shukla et al. 2021) |
| 12 | HSSF | 32 | 52 | – | 58 | 61 | – | (Shukla et al. 2021) |
| 13 | HSSF | 53 | 54 | – | 79 | 77 | – | (Shukla et al. 2021) |
| 14 | HSSF | 95.8±1.4 | – | 26.7±11.2 | 92.7±6.8 | 93.2±3.6 | 55.1±7.1 | (Russo et al. 2019) |
| 15 | MSCW | 89 | – | 43 | – | – | 60 | (Masi et al. 2013) |
| 16 | HSSF | 73.72 | – | 41.11 | 66.21 | 67 | 50.33 | (Licata et al. 2021) |
| 17 | V-SSF and H-SSF | – | – | 27 | 92 | – | 71 | (Mietto and Borin 2013) |
| 18 | MSCW | 69 | – | – | 81 | 78 | 56 | (Milani et al. 2020) |
| 19 | In-VCW | 89-94.9 | – | – | 78.7–85.7 | – | 86.1–93.2 | (Cocozza et al. 2023) |
| 20 | HSSF | 79.6–76.1 | – | 35.6–39 | 51.5–53.1 | 61.8–61.4 | 45.2–41.7 | (Licata et al. 2022) |

Where, TSS: Total suspended solids, TDS: Total dissolved solids, TP: Total Phosphorus, COD: Chemical Oxygen demands, $BOD_5$: biological oxygen demands, TN: Total Nitrogen, HSSF: horizontal sub-surface flow constructed wetland, SFCW: Sub-surface constructed wetlands, VSSFs: vertical subsurface flow system, FWSCW: Free water surface constructed wetland, WCCW: wall cascaded constructed wetland, HFCW: Horinzotal flow constructed wetland, SSFW: sub-surface flow wetland, SFW: Surface flow wetland, MSCW: Multi-stage constructed wetland, In-VCW: in vessel contructed wetlands.

a circular economy model that aligns with sustainable resource utilization through convertion of wastewater nutrients into valuable biomass and mitigating greenhouse gas emissions. The pursuit of sustainable agricultural practices has intensified the search for innovative wastewater treatment methods that can simultaneously address water pollution and resource depletion. Algae-based systems have emerged as a formidable contender in this quest, utilizing the innate nutrient-removal capabilities of microalgae to purify wastewater while offering a platform for biomass production with diverse applications. This section discusses mechanisms of nutrient uptake and water purification within algae-based systems. It highlights their significance in reshaping the landscape of agricultural wastewater treatment. Microalgae, tiny photosynthetic organisms, abundant in aquatic environments, have long captivated the attention of researchers for their remarkable ability to harness nutrients from their surroundings. It has been a versatile source of products across multiple industries, ranging from pharmaceuticals to everyday food items. One of their most significant applications is in wastewater treatment and carbon dioxide reduction, where they play a crucial role in environmental sustainability (Hashmi et al. 2023). In wastewater treatment, their natural propensity to uptake nutrients becomes a powerful tool for remediating nutrient-rich agricultural runoff, a common contributor to water pollution (Goh et al. 2022; Wei et al. 2024; Zhao et al. 2024).

At the heart of algae-based systems lies the process of nutrient assimilation. Microalgae capitalize on the presence of nutrients like nitrogen and phosphorus in wastewater, absorbing them for growth and biomass production. This dual-function approach offers a twofold benefit: it efficiently removes these nutrients from the wastewater, mitigating the risk of eutrophication in receiving water bodies. It simultaneously drives the growth of microalgae biomass, which holds immense potential for various applications. In algae-based systems, microalgae are not the sole players in the nutrient-removal work. The interaction between microalgae and associated microbial communities within the system creates a dynamic ecosystem that thrives on nutrient cycling. Microbes, through processes like denitrification and mineralization, further enhance nutrient removal from the wastewater, resulting to its purification (Gupta et al. 2022; Mathew et al. 2022). The nutrient uptake and biomass accumulation by microalgae have a direct impact on water quality improvement. When excess nitrogen and phosphorus are removed from water bodies, algae-based systems reduce the likelihood of nutrient-driven algal blooms and oxygen depletion in water bodies. This in turn enhances the overall ecological health of aquatic ecosystems and supports biodiversity conservation.

The significance of nutrient uptake and water purification in algae-based systems goes beyond pollution control. The removal of nutrients transforms wastewater from a problem into a solution. The harvested microalgal biomass, enriched with nutrients, can be repurposed as a nutrient-rich substrate for various applications. This biomass can be utilized in animal feed production, as a soil conditioner or even as a substrate for other biotechnological processes (Ahmad and Ashraf 2023). The ability of microalgae to uptake nutrients and purify wastewater within algae-based systems offers a holistic and sustainable approach to agricultural wastewater treatment. The intricate ecological relationships within these systems, combined with technological advancements, position algae-based systems as powerful tools in the pursuit of both pollution control and sustainable resource utilization.

#### *Conditions and parameters for algae-based remediation*

The efficiency of microalgae-based systems for agro-wastewater remediation is influenced by several critical environmental conditions and operational parameters. Optimizing these factors can significantly enhance the performance of microalgae in removing contaminants and recovering valuable byproducts. These conditions include light intensity, $CO_2$ concentration, nutrient availability, Temperature, pH level, hydraulic retention time and aeration.

i. **Light intensity**.

Light is a fundamental requirement for photosynthesis, the process by which microalgae convert light energy into chemical energy, leading to biomass growth and nutrient uptake. Adequate light intensity is essential for maximizing the remediation potential of microalgae. Typically, light intensities ranging from 200 to 400 μmol photons $m^2/s$ are considered optimal for algal growth, although this can vary depending on the species (Metin and Altınbaş 2024). Excessive light can cause photoinhibition, while low light conditions reduce photosynthetic efficiency (La Rocca et al. 2024). Artificial lighting systems or exposure to natural sunlight are commonly used to maintain consistent light intensity in algal cultures.

ii. **$CO_2$concentration**.

Carbon dioxide is another critical factor for microalgae growth and nutrient removal efficiency. In algae-based systems, $CO_2$ serves as a carbon source, supporting photosynthesis and enabling the conversion of inorganic nutrients like nitrates and phosphates into biomass (Saini et al. 2024). Typical $CO_2$ concentrations range from 1 to 5% in culture systems. Supplementing algae cultures with additional $CO_2$ can boost growth rates, enhance nutrient uptake, and increase the rate of carbon sequestration, making the system more effective in wastewater treatment and carbon capture.

iii. **Nutrient availability**.

Nutrient availability, especially nitrogen and phosphorus, is a key parameter that determines the performance of algae-based remediation systems. Microalgae thrive in nutrient-rich environments, such as wastewater, where nitrogen (in the form of ammonium or nitrate) and phosphorus (as phosphate) are abundant (Alavianghavanini et al. 2023; Baldisserotto et al. 2020). A balanced nitrogen-to-phosphorus (N) ratio is crucial for maximizing growth. Excessive nutrients can lead to uncontrolled growth, while nutrient limitation can slow down the remediation process. Optimal nutrient concentrations for most microalgae species are around 10–50 mg/L for nitrogen and 1–5 mg/L for phosphorus.

iv. **Temperature**.

Temperature affects the metabolic activity of microalgae and, consequently, their ability to remove pollutants. Most microalgae species grow efficiently in temperatures ranging from 20 °C to 30 °C. Lower temperatures can reduce metabolic rates and nutrient uptake, while higher temperatures may inhibit growth or lead to cell damage.

v. **pH levels**.

Microalgae metabolic activity is closely influenced by pH, as it plays a key role in regulating ion uptake, enzyme function, and overall growth. Maintaining an optimal pH ensures efficient nutrient absorption and supports the metabolic processes that drive microalgae proliferation (Hashmi et al. 2023). The pH of the culture medium also plays a critical role in determining the effectiveness of algae-based remediation systems. Microalgae generally prefer a slightly alkaline environment, with an optimal pH range of 7.5 to 8.5. Deviations from this range can negatively impact nutrient uptake and photosynthesis. Acidic conditions can hinder $CO_2$ availability, while highly alkaline conditions can reduce the solubility of essential nutrients.

vi. **Hydraulic Retention Time (HRT)**.

Hydraulic Retention Time (HRT) refers to the duration wastewater stays in contact with algal biomass. Longer HRT provides microalgae with more time to absorb nutrients, remove pollutants, and promote growth (Zhang et al. 2020). However, excessively extended retention times can reduce system efficiency, leading to operational challenges. Achieving the right balance in HRT is essential for optimizing the performance of algae-based remediation systems, ensuring both effective nutrient removal and operational efficiency.

vii.**Mixing and aeration**.

Mixing and aeration are critical components in optimizing algae-based remediation systems. Proper mixing ensures the even distribution of light, nutrients, and microalgae cells throughout the culture, preventing cells from settling at the bottom and creating uniform growth conditions. This homogeneity is essential for maximizing photosynthesis, nutrient uptake, and pollutant removal. Aeration, on the other hand, plays a crucial role in promoting gas exchange by supplying oxygen and removing excess carbon dioxide. Oxygen is necessary not only for the respiration of aerobic organisms in the system but also for the degradation of organic matter in the wastewater. Additionally, aeration helps maintain appropriate pH levels, contributing to an optimal environment for microalgal growth (Yusoff et al. 2019). Together, effective mixing and aeration increase the overall efficiency of the system, enhancing the breakdown of pollutants, promoting algal biomass production and improving the sustainability and cost-effectiveness of wastewater treatment.

#### *Application of algae-based systems to agro-waste treatment*

Algae-based systems have emerged as versatile and environmentally friendly solutions for addressing the diverse range of agricultural wastewater challenges. These systems effectively tackle the environmental issues associated with various agricultural activities, spanning piggery wastewater, poultry wastewater, fishery wastewater, dairy wastewater, and other agricultural effluents. Piggery operations, notorious for their wastewater's richness in organic matter and nutrients, find a reliable ally in algae-based systems, with microalgae taking center stage. These microorganisms excel in the treatment of piggery wastewater, efficiently absorbing nutrients such as nitrogen and phosphorus, thus reducing the risk of water pollution. Moreover, their ability to transform organic compounds into biomass contributes to mitigating the environmental impact and odor concerns linked to swine farming. In poultry farming, where wastewater bears a high nutrient and organic load, algae-based systems come to the fore as efficient treatment mechanisms. Here, microalgae and macro-algae swiftly assimilate nutrients and organic pollutants, ultimately enhancing water quality. Furthermore, the harvested algal biomass holds value as a nutrient-rich poultry feed supplement or for alternative applications, promoting resource sustainability.

In fishery industry, algae-based systems offer a natural approach to nutrient removal in fishery wastewater. Algae's capacity to absorb excess nutrients, including ammonia and phosphates, is complemented by their provision of oxygen through photosynthesis, creating a healthier aquatic environment for fish and supporting aquatic ecosystems. Dairy operations grappling with wastewater characterized by high organic loads and nutrient content also benefit from algae-based systems. These systems efficiently remove nitrogen, phosphorus, and organic matter, thereby reducing the risk of eutrophication in receiving waters. Additionally, the harvested algal biomass can be repurposed as a nutrient-rich supplement for dairy cattle feed, boosting the circular economy. Beyond these specific agricultural sectors, algae-based systems adapt seamlessly to various agricultural wastewater types, ranging from crop runoff to agro-industrial effluents. Their effectiveness in removing nutrients, pesticides, heavy metals, and contaminants from diverse agricultural effluents highlights their holistic and sustainable approach to wastewater treatment across different agricultural areas. These systems not only mitigate environmental risks but also provide opportunities for biomass utilization, enhancing the overall sustainability of agricultural practices. Thus, the versatility and efficacy of algae-based systems position them as invaluable assets in responsible agricultural water management. Numerous researchers have employed algae-based systems for the treatment of agricultural wastewater, and their findings are summarized in Table 2.

#### Microbial fuel cells (MFCs)

In the pursuit of sustainable waste management and renewable energy generation, MFCs have emerged as a groundbreaking technology that seamlessly combines wastewater treatment with electricity generation. These bioelectrochemical systems harness the metabolic activities of microorganisms to oxidize organic matter in wastewater while simultaneously generating electrical energy. Organic matter, present in wastewater, serves as a substrate for the microorganisms, facilitating a process known as microbial oxidation. During microbial oxidation, microorganisms break down organic molecules, releasing electrons in the process. These electrons are then harnessed through an external circuit to generate electrical current. This bioelectrochemical interaction not only treats wastewater by removing organic pollutants but also produces valuable electrical energy (Elhenawy et al. 2022; Kesarwani et al. 2022; Roy et al. 2023).

MFCs (described in Fig. 2) offer an innovative approach to wastewater treatment by promoting biodegradation of organic matter. In anaerobic conditions at the anode, microorganisms metabolize organic compounds, leading to the production of electrons and protons. The electrons are transferred to the anode electrode, and the protons migrate to the cathode through the surrounding electrolyte. Oxygen reduction occurs at the cathode, completing the electrochemical circuit. This synergistic interaction between microbial metabolism and electrochemistry results in the removal of organic pollutants from wastewater (Garbini, Barra Caracciolo, & Grenni, 2023). MFCs capitalize on the metabolic processes of microorganisms to generate electricity. The harvested electrons from microbial oxidation travel through an external circuit to the cathode, where they combine with protons and oxygen to form water. This redox process at the cathode generates electrical energy that can be harnessed for various applications. MFCs have the potential to provide sustainable power sources for remote areas, sensor networks, and low-power electronic devices (Jayaraj et al. 2024; Kurniawan et al. 2022).

MFCs also hold promise for nutrient recovery from wastewater. MFCs facilitate the accumulation of nutrients such as phosphorus and ammonium at the anode through driving microbial metabolism. These accumulated nutrients can be harvested and repurposed as valuable fertilizers, thereby closing the nutrient loop and reducing the environmental impact of nutrient pollution. Furthermore, the use of MFCs as a pre-treatment step for anaerobic digestion can enhance biogas production and

**Table 2** Treatment efficiencies of the algae-based system on agro-wastewater

| S/*N* | Wastewater | Algae strain | Efficiency | Ref. |
|---|---|---|---|---|
| | Paddy-soaked rice mill wastewater | *Scenedesmus obliquus* | 96% ammonical nitrogen removal, 97.58% phosphates, biochemical composition of lipids 12%, protein 40%, and carbohydrates 20% | (Umamaheswari and Shanthakumar 2019) |
| 2 | Agro-Industry | *Microalgal consortia* | Removal efficiency of 49% TN, and 70% TP | (Singh et al. 2011) |
| 4 | Palm oil mill effluent (POME | *Scenedesmus sp. and Chlorella sp.* | 86% TN removal, 85% Reactive Phosphate ($PO_4$-3), 77% TOC and 48% COD. | (Hariz et al. 2019) |
| 7 | Aquaculture wastewater | *Chlorella vulgaris* | Removal efficiency of 86.1% TN, 82.7% TP | (Gao et al. 2016) |
| 8 | Dairy Wastewater | *Mixed microalgae* | Removal of 90% organic carbon, biochemical composition of 38% carbohydrates, 15% proteins and 22% lipids. | (Hemalatha et al. 2019) |
| 9 | Aquaculture wastewater | *algal-bacterial flocs* | Removal efficiency of 58% TN, 89% TP and 71% TOC | (Michels et al. 2014) |
| 10 | Aquaculture wastewater | *Tetraselmis suecica* | Removal efficiency of 49.4% TN, 99% TP | (Michels et al. 2014) |


**Fig. 2** Application of MFCs in agro-wastewater treatment

methane yields (Ghangrekar et al. 2022; Kaur et al. 2024; Singh et al. 2023a; Sivamani et al. 2021).

While MFCs present a revolutionary approach to wastewater treatment and energy generation, challenges such as low energy conversion efficiency, microbial diversity, and scaling up remain areas of active research. Recent advancements in electrode materials, microbial enrichment strategies, and system design have led to significant improvements in MFC performance and overall feasibility (Kurniawan et al. 2022; Malik et al. 2023). The integration of MFCs with other technologies, such as constructed wetlands, membrane bioreactors, and anaerobic digestion, enhances treatment efficiency and resource recovery. The concept of wastewater-to-energy becomes increasingly attractive as MFC technology matures and gains wider acceptance. As the world seeks sustainable solutions for energy generation and waste management, microbial fuel cells stand as a pioneering concept that exemplifies the intersection of environmental stewardship and technological innovation.

#### *Microbial fuel cell processes*

At the core of MFCs lie three indispensable components: the anode chamber, the cathode chamber, and a selectively ion-conductive membrane demarcating the two compartments (Jalili et al. 2024; Xu et al. 2024). This physical separation ensures distinct electrode environments while permitting ion migration to maintain ionic equilibrium (Daud et al. 2024). Within the anode chamber, microorganisms, primarily electroactive bacteria, catalyze oxidation reactions of organic substrates sourced from wastewater or substrates. This microbial metabolism yields electrons, protons, and other metabolic byproducts, forming the cornerstone of electron generation. Electroactive bacteria, such as *Geobacter* and *Shewanella* species, typify the catalysts of MFCs' microbial oxidation processes (Garbini et al. 2023). These bacteria are adept at extracellular electron transfer, releasing electrons through a process known as exoelectrogenesis (Jayathilake et al. 2024). The released electrons originate from microbial respiration pathways and flow to the anode electrode, constituting the anodic current (Amanze et al. 2024). Simultaneously, protons are expelled into the anode chamber, creating a proton gradient that acts as the driving force for proton migration across the ion-conductive membrane. MFCs' electron transfer mechanisms involve a complex interplay of electrochemical and biological processes (Roy et al. 2022; Umar et al. 2020). The anodic electrons, delivered by the microorganisms, traverse the external circuit towards the cathode. Within the circuit, the electrons generate electrical current, which can be harnessed for various applications (Liu et al. 2024). Meanwhile, the protons accumulated in the anode chamber diffuse through the ion-conductive membrane to the cathode chamber, generating a pH gradient (Jalilnejad et al. 2024). This gradient plays a vital role in the cathodic reactions, further facilitating electron transfer at the cathode (Yang et al. 2021).

**Anodic reaction** At the heart of MFCs' energy conversion process lies the oxidation of organic compounds, facilitated by microorganisms such as Geobacter and *Shewanella* species (Garbini et al. 2023). This intricate process of metabolic reactions converts organic matter into electrical energy, revealing the intriguing dynamics of electron release and proton generation. Organic matter, the diverse reservoir of carbon-based compounds, serves as the primary fuel source for MFCs' anodic reactions. For instance, consider glucose, an abundant organic compound found in large quantity in various substrates. Within the anode chamber of MFCs, specialized microorganisms, notably *Geobacter* and *Shewanella* species, initiate the oxidation of glucose through their unique metabolic pathways (Garbini et al. 2023). This process extracts energy from glucose and facilitates the production of electron-rich byproducts. The oxidation of glucose is a multistep process resulting in the release of electrons, protons, and carbon dioxide. When glucose undergoes microbial metabolism, it undergoes a sequence of reactions, yielding electrons and protons. The overarching equation summarizing this transformation is shown in Eq. (1).

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (1)$$

Notably, Eq. (1) illustrates the conversion of glucose and water into carbon dioxide, accompanied by the liberation of 24 protons and 24 electrons. The release of these electrons and protons marks the initial phase of the energy generation process within MFCs. The liberated electrons from the glucose oxidation process are not released into the surroundings. Instead, microorganisms, equipped with specialized extracellular electron transfer mechanisms, facilitate the transport of these electrons to the surface of the anode electrode. This electron transfer is essential for establishing an electric current that can be harvested for various applications.

While electrons embark on their journey toward the anode electrode, the protons generated during glucose oxidation follow a different path. They are released into the solution surrounding the microorganisms. This proton release causes a localized increase in proton concentration within the anode chamber. Simultaneously, it triggers the formation of a concentration gradient, prompting protons to migrate towards regions of lower proton concentration. The ion-selective membrane that demarcates the anode and cathode chambers plays a critical role in facilitating proton migration. Protons, driven by the established concentration gradient, cross this membrane and migrate towards the cathode chamber. This proton migration process parallels a symphonic movement, where protons flow in response to the gradient, setting the stage for subsequent cathodic reactions. The primary anodic reactions in MFCs reveal a interesting account of organic compound oxidation, electron liberation, and proton release. Through a designed series of biochemical transformations, coordinated by microorganisms like *Geobacter* and *Shewanella* species, organic matter is transformed into a flow of electrons and protons. While electrons migrate to the anode electrode, protons create concentration gradients, setting in motion their migration toward the cathode chamber. This coordinated interplay showcases the sophistication and complexity of MFCs, where microbial metabolism and electrochemical processes merge to generate sustainable energy.

**Cathodic reactions** The cathode chamber is where oxygen reduction reactions occur, culminating in the final step of MFCs' energy generation cycle (Daud et al. 2024). Oxygen, typically supplied as dissolved oxygen in aqueous solutions or as ambient air, serves as the terminal electron acceptor (PİŞKİN and Nevim 2022; Umar et al. 2021). At the cathode, protons combine with electrons, coupled with oxygen reduction, to form water (Arun et al. 2024; Savla et al. 2020). This reduction reaction liberates energy, manifested as a voltage difference across the cathode and anode (Zhang et al. 2024). The energy generated through this redox reaction can be harvested as electrical power (Umar et al. 2021). Within the cathode chamber, oxygen reduction stands as the central cathodic reaction, supporting the entire energy generation cycle of MFCs. This reaction involves the incorporation of oxygen molecules into the system, activating a transformation that terminates in the formation of water molecules. The reduction of oxygen is a process that not only generates electricity but also holds immense potential for environmental remediation and green technology (Arun et al. 2024; Sonawane et al. 2024). The cathodic reaction equation briefly summarizes the transformation that takes place in the cathode chamber as seen in Eq. (2)

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (2)$$

In this equation, oxygen molecules ($O_2$) engage in a fascinating reaction with protons ($H^+$) and electrons (e−) to create the invaluable end product of water molecules ($H_2O$). This process not only drives the generation of electricity but also highlights the inherent capacity of MFCs to contribute to water treatment by facilitating the conversion of oxygen into water, thereby mitigating the presence of dissolved oxygen (DO) in wastewater (Arun et al. 2024). As electrons travel from the anode to the cathode through the wire, they join in the process happening at the cathode. These electrons were set free when organic matter was broken down at the anode. They move towards the cathode because of the electric pull between the two ends. When these electrons reach the cathode, they help in a reaction that changes oxygen and protons into water. This process of turning oxygen into water is aided by the electrons and is called reduction. So, the journey of electrons connects with the cathode's work, leading to the formation of water. The culmination of the cathodic reaction results in the formation of water molecules, a testament to the potential energy stored within organic matter that is harnessed through microbial metabolism and electron transfer processes. The flow of electrons from the anode to the cathode during oxygen reduction generates an electric current that can be harnessed for practical applications. This electric current holds the promise of powering devices, and sensors, as well as contributing to larger energy grids. This transforms organic matter's intrinsic energy into a tangible and usable form (Jayaraj et al. 2024). Beyond its role in energy generation, the cathodic reaction in MFCs contributes to environmental sustainability. The reduction of oxygen in water aligns with the principles of green technology and helps to offer a path to cleaner and more efficient energy generation (Thirugnanasambandan 2019; Zhang et al. 2024). Additionally, the catalytic capabilities of MFCs hold potential for applications in wastewater treatment, where the reduction of oxygen can play a role in reducing the dissolved oxygen levels and enhancing water quality (Malik et al. 2023; Thapa et al. 2022).

#### *Applications of MFCs in environmental remediation and agro-wastewater treatment*

MFCs have significant applications in agricultural wastewater treatment. They facilitate the degradation of organic pollutants in wastewater through microbial oxidation processes at the anode chamber, transforming them into simpler and less harmful compounds. Additionally, MFCs offer exciting prospects for bioremediation in agricultural wastewater by enhancing the degradation of various contaminants, including organic pollutants and heavy metals. Microorganisms in MFCs contribute to removing and immobilizing these contaminants through microbial metabolism and electrochemical processes. This emphasizes MFCs' potential as versatile tools for addressing agricultural wastewater pollution and promoting environmental restoration. Beyond energy generation, MFCs play a pivotal role in environmental remediation and wastewater treatment (Arun et al. 2024; Rani et al. 2023; Roy et al. 2023; Zhao et al. 2022). The microbial oxidation processes occurring at the anode chamber facilitate the degradation of organic pollutants present in wastewater (Roy et al. 2023). As microorganisms break down complex organic compounds, pollutants are transformed into simpler and less harmful compounds (Krithika et al. 2022). These systems can be engineered to enhance the degradation of various contaminants, including organic pollutants and heavy metals (Luo et al. 2017). Microorganisms thriving in MFCs can contribute to the removal and immobilization of these contaminants through a combination of microbial metabolism and electrochemical processes (Luo et al. 2017). This capability highlights MFCs' potential as versatile tools for environmental restoration.

#### *Comparison of related works on MFCs with agro-wastewater*

The comparison of MFCs (Table 3) across various agro-wastewater highlights a significant diversity in performance metrics, substrate types, and MFC configurations. This diversity underlines the versatility of MFC technology and emphasizes the importance of tailored configurations to optimize performance based on specific application requirements. Different substrates used in MFC studies contribute to variations in performance outcomes. Studies employing substrates like composite vegetable waste, swine waste, domestic and olive mill wastewater, and dairy waste demonstrate varying power densities (PD) and efficiencies (Table 3). The choice of substrate impacts nutrient availability and organic content, directly affecting microbial activity and MFC performance. Additionally, the type of MFC configuration, whether Single Chamber (SC-MFC) or Double Chamber (DC-MFC), influences performance outcomes. SC-MFCs, known for their simplicity, often exhibit lower power densities compared to DC-MFCs but achieve higher efficiency due to better control over reaction conditions and substrate utilization. Anode and cathode materials also play a crucial role in determining MFC performance. Materials like graphite plates, carbon paper, carbon cloth, stainless steel fiber felt, titanium rods, and platinum catalysts impact electron transfer efficiency, microbial attachment surface area, and corrosion resistance. Moreover, the presence or absence of mediators and catalysts further affects MFC performance as observed in Table 3. Mediator-less MFCs relying solely on microbial electron transfer often demonstrate competitive efficiencies. However, the choice of mediator or

**Table 3** MFCs performance with Agricultural Wastewater

| Substrate | MFC Type | Anode | Cathode | PD(mW/m$^2$) | Eff. (%) | Ref. |
|---|---|---|---|---|---|---|
| Composite vegetable waste | Mediator-less SC-MFC | Graphite plate | Graphite Plate | 57.4 | 62.9 | (Mohan et al. 2010) |
| Swine waste | DC-MFC | Carbon paper | Carbon cloth | 13.0 | 83.0 | (Ma et al. 2016) |
| Olive mill wastewater | SC-Air cathode | Graphite fibre brush | carbon | 124.6 | 65.0 | (Sciarria et al. 2013) |
| Dairy waste | Mediator-less, DC-MFC | Graphite plate | Graphite plate | 621.13 | 90.5 | (Mansoorian et al. 2016) |
| Dairy waste | SC-MFC | Carbon cloth | Carbon cloth with Pt | 0.5 W/ m$^3$ | 95.5 | (Marassi et al. 2020) |
| Yogurt wastewater | SC-MFC | stainless steel fibre felt | Activated carbon | 1043.0 | 88.0 | (Luo et al. 2017) |
| Orange peel waste | DC-MFC | Graphite felt | Pt + graphite cloth | 358.8 | 80.0 | (Miran et al. 2016) |
| Soyabean oil refinery wastewater | SC-MFC | Graphite brush + titanium | Stainless steel mesh + activated C | 746.0 | 93.6 | (Yu et al. 2017) |
| Molasses wastewater | Waterfall-type MFC + polyvinyl alcohol-hydrogel as membrane | Carbon felt | Carbon cloth | 16.1 | 90.1 | (C.-H. Wu et al. 2017) |
| Vegetable oil waste | DC-MFC | Titanium Rod | Carbon cloth | 6119.0 | 90.0 | (Firdous et al. 2018) |
| Sugarcane molasses | DC-MFC | NA | NA | 188.5 | 81.7 | (Hassan et al. 2019) |
| Citrus waste | SC-MFC | Plantain Graphite plate | Plantain Graphite plate | 71.1 | 63.8 | (Kondaveeti et al. 2019) |
| Labanah Whey wastewaters | Cylindrical membrane-less MFC | Graphite | Graphite | 23.23 W/m$^3$ | NA | (Mohanakrishna et al. 2018) |
| Winery wastewater | DC-MFC | Carbon felt | Carbon felt | 890.0 | 600 mg/ld | (Penteado et al. 2016) |
| Lemon peel waste | DC-MFC | Carbon felt | Carbon cloth | 371 | 75.8 | (Miran et al. 2016) |

Where, DC: double chamber, MFC: microbial fuel cell, SC: single chamber, Pt: platinum

catalyst can enhance electron transfer rates and overall MFC performance under specific conditions.

Understanding the complex interplay between substrate composition, MFC configuration, and water quality parameters is essential for optimizing MFC design and operation. Further research and innovation are needed to explore new substrates, electrode materials, and microbial communities to advance MFC technology for applications in wastewater treatment and renewable energy generation. Physical factors such as the type of electrode materials, surface area, electrode-spacing, and catholyte characteristics significantly affect MFC performance (Pandit et al. 2021). Biological factors, including biocatalyst proliferation and activity, biofilm-forming ability, and complex organic matter degradation efficiency, also play a crucial role. Additionally, operational factors like pH conditions, anolyte nature and type, and load configuration influence MFC power generation. Integrating these factors into MFC design and operation is essential for optimizing performance and achieving desired outcomes.

### *Challenges of MFCs*

While the potential of MFCs is fascinating, challenges persist that necessitate further research and innovation. Enhancing electron transfer efficiency between microorganisms and electrodes, optimizing electrode materials, exploring novel electroactive bacteria, and addressing the scalability of MFC systems are ongoing activities (Tiruye 2021). Additionally, understanding the complex interplay between microbial communities, operational conditions, and performance outcomes remains an essential area of investigation.

A dominant challenge in MFCs is to enhance the efficiency of electron transfer between microorganisms and electrodes. While microorganisms release electrons during metabolic processes, the efficient transfer of these electrons to the anode is crucial for optimal electricity generation (Roy et al. 2022). Overcoming the resistance at the microbe-electrode interface requires ingenuity in electrode design, biofilm formation, and tailored electron mediator integration. This challenge is a wake up call to researchers to design electrodes that foster seamless electron flow, thus maximizing the potential of MFCs as energy generators. Also, the selection of electrode materials plays a pivotal role in dictating MFC performance. While various materials have been explored, identifying electrode materials that exhibit robust electrocatalytic activity, stability, and cost-effectiveness remains a quest. Research is directed toward developing novel electrode materials that foster efficient electron transfer, mitigate fouling, and promote sustainable energy conversion processes. In the small-scale version of MFCs, the quest for novel electroactive bacteria takes center stage. These microorganisms, capable of facilitating electron transfer, are key players in driving MFC performance. Exploring the vast biodiversity of microorganisms to uncover novel strains with exceptional electron transfer capabilities is a growing field of research. As MFC technology strides towards real-world applications, the challenge of scalability emerges. While laboratory-scale MFCs demonstrate potential, transitioning to larger systems that can cater to practical energy needs necessitates tackling issues such as power density optimization, system stability, and cost-effectiveness. Overcoming the challenges of scale requires engineering solutions that preserve MFC efficiency while adapting to real-world constraints. Furthermore, the MFC performance is intricately interweaved with microbial communities inhabiting the system. Understanding the dynamic interplay between operational conditions, microbial diversity, and performance outcomes remains a scientific frontier. This challenge emphasizes the need for comprehensive investigations that will unravel the complex relationships between microbial communities and MFC functionality.

## Economic analysis of biological treatment methods

Constructed wetlands, MFCs, and algae-based systems are economically favourable for biological wastewater treatment as they offer low to moderate costs and high efficiency with added environmental benefits. Constructed wetlands (Table 4) have low to moderate initial costs ($420–$1,730), high efficiency (80–96% COD), minimal operational costs, and environmental sustainability (Abdelhay and Abunaser 2021). Although initial setup costs for constructed wetlands may vary due to factors like land availability, site preparation, and plant selection, their long-term operational expenses are relatively low. Constructed wetlands require minimal maintenance and leverage natural processes, reducing the need for costly chemicals and energy inputs. Their multifunctional benefits, such as habitat provision, biodiversity enhancement, and flood mitigation, contribute to their overall economic feasibility. Using locally available materials and native plant species can further reduce costs and improve resilience. Revenue generation from wetland byproducts, like bioenergy and animal fodder, offsets operational expenses, enhancing economic viability. MFCs provide low/moderate initial costs ($6,064), renewable energy production, moderate operational costs, and sustainability, despite requiring technical expertise for maintenance and having moderate efficiency for soluble COD (76.8% Total COD and 55.5% Soluble COD) (Ge and He 2016).

Microbial Fuel Cells (MFCs) demonstrate effectiveness in organic matter degradation and energy generation but

**Table 4** Cost analysis of biological methods of wastewater treatment

| Methods | Capacity | Cost ($) | Efficiency | Ref. |
|---|---|---|---|---|
| Constructed wetlands | | 420–1730 | 80–96% COD | (Abdelhay and Abunaser 2021) |
| MFCs | 10,000 gpd | 6064 | 76.8% Total COD & 55.5% Soluble COD | (Ge and He 2016) |
| Algae Based System | 1 tonne | 510.65 | | (Hoffman 2016) |
| Anaerobic digestion | | € 28,357,709 | 1,090,800 $m^3$ of $CH_4$ yield annually | (Chowdhury 2021) |
| Bioremediation | 1820/$m^3$ | 1,822,159 | | (Orellana et al. 2022) |
| Tricking filter | 200,000 $M^3$/day | 23,663,119.96 | 20 mg/day BOD | (Zahid 2007) |
| Complex mix Activated sludge | 200,000 $M^3$/day | 38,414,386 | | (Zahid 2007) |
| Oxidative ditch-activated system | 200,000 $M^3$/day | 36,242,200 | | (Zahid 2007) |
| Circular microalgal culturing | 7377 $M^3$/day | € 6,554,960 | | (Nobre et al. 2024) |

involve significant initial setup costs, including materials and infrastructure. Despite these challenges, MFCs offer economic advantages by generating electricity from organic waste, providing decentralized energy solutions for remote areas. They can offset treatment costs by harnessing wastewater energy, with potential economic value from treated water and residual sludge for irrigation or fertilizers. The economic feasibility of MFCs depends on factors such as local energy prices, access to financing, and government incentives. While upfront costs may be high, long-term benefits like energy independence and resource recovery make MFCs a promising sustainable wastewater treatment option.

Algae-based systems offer very low initial costs ($510.65 per ton), potential revenue from biomass, and environmental benefits, though they have moderate operational costs and efficiency dependent on conditions, making them suitable for different scales and contexts based on specific needs and resources (Hoffman 2016). Algae-based systems, despite high upfront investments, offer economic benefits through the production of algal biomass for biofuels and fertilizers, creating additional income streams. These systems can boost farm profitability by reducing the need for chemical fertilizers and improving water quality. However, challenges like algae harvesting and processing require optimization to enhance economic efficiency. The feasibility of algae-based systems depends on operational efficiency, resource availability, and market demand, necessitating further research to reduce costs.

In contrast, traditional methods like anaerobic digestion, bioremediation, trickling filters, complex mix-activated sludge, and oxidative ditch-activated systems are economically disadvantageous and less favourable. Anaerobic digestion has extremely high initial and operational costs ($28,357,709) despite high efficiency and significant methane production (Chowdhury 2021). It requires substantial space for reactors and associated infrastructure, has complex operation and maintenance needs that require specialized knowledge and technical expertise, and their efficiency can be significantly affected by the variability in the composition of the feedstock, making consistent performance a challenge. In the same way, bioremediation is prohibitively expensive ($1,822,159 per m$^3$) and only effective for specific contaminants (Orellana et al. 2022). It is suitable only for specific contaminants, particularly organic pollutants, which limits its applicability. It is a time-consuming process that can be slow in achieving desired levels of contaminant reduction, and its effectiveness can vary widely depending on environmental conditions and the specific contaminants present.

Further more, trickling filters incur very high initial costs ($23,663,119.96) and are only moderately efficient (20 mg/day BOD) for large-scale treatment (200,000 m$^3$/day capacity) (Zahid 2007). Trickling filters, while effective at reducing BOD, are less efficient for larger volumes. It faces operational challenges such as the need to maintain the biological film on the filter media and prevent clogging, and requires continuous energy input to maintain appropriate conditions for microbial activity. Complex mix-activated sludge systems have extremely high initial and operational costs ($38,414,386) and, while they are efficient, are suitable only for very large-scale operations (200,000 m$^3$/day capacity) (Zahid 2007). Complex mix-activated sludge systems have high energy consumption due to the need for continuous aeration and generate large volumes of sludge that must be treated and disposed of, adding to operational complexities. They also require skilled personnel for operation and maintenance, which can be a limiting factor in less developed regions. Oxidative ditch-activated systems also suffer from very high initial and operational costs ($36,242,200) despite their high efficiency and flexible operation for large-scale applications (200,000 m$^3$/day capacity) (Zahid 2007). The oxidative ditch-activated system requires a high level of technical expertise for operation, often needs large areas, which can be a limitation in urban or densely populated areas, and necessitates regular maintenance to prevent issues such as clogging and to ensure consistent performance, adding to the operational burden.

## Other biological methods of agro-wastewater treatment

Various other biological methods for treating agro-wastewater have been documented in the literature, including anaerobic digestion, aerobic digestion, and trickling filter systems. Anaerobic digestion stands out as a highly effective and sustainable method for treating agro-wastewater, addressing the challenges posed by the organic matter and nutrients inherent in agricultural effluents. This biological process harnesses the power of microorganisms in an oxygen-deprived environment to break down complex organic materials, yielding a range of compelling environmental and economic advantages. At the core of anaerobic digestion lies its ability to significantly reduce the organic content of agro-wastewater. In diverse agricultural activities such as dairy farming, poultry production, and crop cultivation, organic matter is a prevalent component of wastewater. In anaerobic bacteria, the key players in the digestion process, undertake the crucial task of converting this organic material into biogas, primarily composed of methane and carbon dioxide. This microbial transformation not only results in improved water quality but also addresses the environmental concerns associated with the discharge of organic waste. A study by Cruz-Salomón et al. (2017) investigated the potential of using anaerobic expanded granular sludge bed (EGSB) bioreactors to treat three significant agro-industrial wastewaters (cheese whey, vinasse, and coffee-processing wastewater) in Chiapas, Mexico. The bioreactors were operated under stable conditions for 60 days and demonstrated high chemical oxygen demand (COD) removal efficiencies, ranging from 74 to 96%, along with substantial methane production. These findings suggest that EGSB bioreactors could offer a sustainable solution for both wastewater treatment and bioenergy production, addressing environmental concerns in the process.

On the other hand, aerobic digestion is a widely employed biological method for treating agro-wastewater, offering an effective and sustainable approach to managing the organic matter and contaminants present in agricultural effluents. Unlike anaerobic digestion, which occurs in the absence of oxygen, aerobic digestion relies on the presence of oxygen to facilitate the breakdown of organic materials. It represents a valuable and sustainable method for agro-wastewater treatment. It effectively addresses organic matter decomposition, nutrient removal, pathogen inactivation, odour control, and sludge reduction. This contributes to improved water quality and environmental protection in agricultural settings. The method's versatility and compatibility with a wide spectrum of agricultural sectors make it a pragmatic and eco-conscious choice for the responsible management of agricultural wastewater, aligning seamlessly with the primary goals of sustainability and environmental stewardship. Numerous examples exist where aerobic biological treatment methods have been employed to treat agro-industrial effluents. Moore et al. (2016) conducted a study involving the treatment of wastewater generated from blends of fruits and vegetables using an aerobic pilot-scale ultrafiltration membrane bioreactor (MBR) with the intention of potential water reuse. The first mixture of wastewater was derived from processing lettuce, beets, carrots, and cassava; exhibiting COD and total Kjeldahl nitrogen (TKN) concentrations of 1.5 g/L and 0.01 g/L, respectively. The second mixture, originating from potatoes, carrots, apples, onions, lettuce, beets, and bananas, had higher COD and TKN concentrations of 7.1 g/L and 0.23 g/L, respectively. The study involved varying hydraulic retention times (HRT) from 24 to 52 h and organic loading rates (OLR) ranging from 0.82 to 2.7 kg COD/$m^3$·d for the first mixture and 2.9 to 6.5 kg COD/$m^3$·d for the second mixture. Both fruit- and vegetable-based effluents showed remarkable COD removal efficiencies of 97–98% and TKN removal efficiencies exceeding 91% when treated in the MBR. Combining an activated sludge system with UV disinfection and activated carbon for colour removal led to the production of high-quality effluent suitable for use in the agro-food sector. Roveroto, Teles, Vuitik, Batista, and Barana (2021) conducted a study involving the treatment of brewery wastewater using a fixed-bed batch reactor with an intermittent aeration cycle of 3 hours of aeration followed by 4 h of rest, resulting in a hydraulic retention time (HRT) of 0.83 days. The raw brewery wastewater had COD levels ranging from 2 to 10 g/L, BOD levels between 1.2 and 3.6 g/L, and total nitrogen concentrations of up to 0.08 g/L. The highest removal efficiency, reaching 92%, was achieved in the bioreactor when the influent COD was 2.7 g/L, and the COD/N ratio was 107. Under these specific conditions, nitrification efficiency reached 88%, and total nitrogen (TN) removal was at 85%.

Furthermore, the trickling filter system is a widely employed biological wastewater treatment method known for its efficiency in removing organic matter and nutrients from various types of wastewater, including agro-wastewater. This system utilizes naturally occurring microorganisms to break down organic pollutants, making it a valuable asset in agricultural wastewater treatment. The trickling filter system consists of a bed or container filled with a porous medium, such as rocks, gravel, or synthetic media, which provides a surface for biofilm formation. Wastewater is evenly distributed over the surface of the medium and allowed to trickle through it. As the wastewater trickles downward, a layer of microorganisms, known as biofilm, forms on the surface of the medium. These microorganisms, including bacteria, fungi, and protozoa, metabolize and degrade organic pollutants present in the wastewater. The trickling filter system serves as a robust and versatile biological method for agro-wastewater treatment. Its proficiency in organic matter and nutrient removal, pathogen inactivation, odour control, and adaptability to diverse agricultural activities make it a valuable tool for improving water quality and mitigating the environmental impact of agricultural wastewater discharges. When integrated into agricultural wastewater management practices, trickling filters contribute to more sustainable and responsible water treatment in the agricultural sector. The use of a trickling filter for the removal of residual organic matter in the dairy industry was studied by Pilco et al. (2023). This study focused on the treatment of residual organic matter in the dairy industry, specifically examining the use of trickling filters as a sanitation technology. Trickling filters employ microorganisms that adhere to a medium with a large surface area to primarily remove soluble organic matter, such as BOD and COD, as the wastewater flows through the medium. It is important to note that all trickling filters require preliminary treatment of suspended solids to prevent filter clogging. While trickling filters excel at removing soluble organic matter, they are not particularly effective at removing pathogens. In this study, the achieved removal efficiency for BOD ranged from 69 to 78%, and for COD, it ranged from 65 to 80%. Suspended solids removal varied from 38 to 56%, while total dissolved solids removal ranged from 20 to 36%. The system also exhibits moderate removal rates for other components such as turbidity (32 to 54%) and color (25 to 42%). The trickling filter system is a promising option due to its simplicity, reliability, and space/time efficiency in BOD removal. From both a technical and economic perspective, this dairy wastewater treatment approach offers an attractive alternative.

## Integration and future outlook

This work highlights the importance of developing hybrid models that integrate MFCs, constructed wetlands, and algae-based systems. These integrated approaches offer greater treatment efficiency, resource recovery, and ecological protection. Integrating the strengths of each technology; MFCs generating power from organic matter, constructed wetlands utilizing natural purification processes, and algae-based systems absorbing nutrients while producing biomass. This can provide a comprehensive solution to farm effluent management. This integration could result in more efficient and sustainable wastewater treatment, reducing both costs and environmental impact.The future of integrating constructed wetlands, algae-based systems, and MFCs in wastewater treatment is promising. Constructed wetlands can serve as a pre-treatment stage for algae-based systems, filtering solids before wastewater enters algal ponds. For large-scale adoption, it's essential to develop cost-effective algae harvesting methods and systems to utilize the nutrient-rich algal biomass as fertilizer or other agricultural products. Future research should focus on increasing MFCs' power output and developing cost-effective materials for MFC construction to enhance scalability. To strengthen these systems, advancements in materials science and biotechnology are essential. Developing new electrode materials for MFCs could boost power generation, while optimizing plant species selection in constructed wetlands could improve pollutant removal and resilience. Genetic engineering can enhance microorganism performance in algae-based systems, increasing biomass production through better nutrient absorption.

These innovations promise more effective treatment, lower costs, and easier large-scale implementation. Digital technologies like sensors and data analytics ois needed t optimize agricultural wastewater treatment through real-time decision-making and continuous monitoring. However, challenges remain in scaling algae harvesting, optimizing MFC power output, and assessing long-term impacts. Collaboration among researchers, policymakers, and industry is essential to accelerate innovation, scale these systems, and ensure sustainable farming practices that protect ecosystems and community health. This collective effort will drive the shift towards environmentally sound farming, safeguarding both natural resources and community well-being.

## Conclusion

The review reveals the transforming potential of advanced biological methods in the sustainable management of agro-wastewater, with each system presenting unique strengths. The review showed that Constructed wetlands offer an eco-friendly, cost-effective solution with robust capabilities for high COD removal, biodiversity enhancement, and flood control. Although, the initial costs are substantial, long-term economic benefits are realized through reduced operational expenses and revenue from byproducts. Although challenges such as electron transfer efficiency and scalability exist in MFCs, it has proven to provide a better viable option for remote areas with their dual role of waste treatment and energy production. Furthermore, algae-based systems stand out for their low-cost operation and environmental benefits, including biomass production for biofuels and fertilizers, supporting diverse agricultural settings.

Traditional methods like anaerobic digestion, bioremediation, and trickling filters, though effective, face significant economic and operational limitations. Integrating constructed wetlands, MFCs, and algae-based systems offers a synergistic approach to overcoming these limitations. This integration can reduce carbon emissions, enhance renewable energy production, and improve resource recovery. Future research should focus on optimizing these hybrid systems, developing cost-effective algae harvesting techniques, enhancing MFC power output, and advancing material science for better system efficiency and scalability. Combining these advanced biological methods enables the creation of a more sustainable and resilient framework for managing agro-wastewater. This integrated approach promises not only to address current challenges but also to pave the way for innovative solutions, driving progress in wastewater treatment and promoting environmental stewardship.

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M.N, C.C and C.O, wrote the original draft. while J.T supervised and proof read the manuscript.

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**Data availability**

No datasets were generated or analysed during the current study.

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**Competing interests**

The authors declare no competing interests.

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