Chapter

Emerging Trends in Wastewater Treatment Technologies: The Current Perspective

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Abstract

The quality of freshwater and its supply, particularly for domestic and industrial purposes are waning due to urbanization and inefficient conventional wastewater treatment (WWT) processes. For decades, conventional WWT processes have succeeded to some extent in treating effluents to meet standard discharge requirements. However, improvements in WWT are necessary to render treated wastewater for re-use in the industrial, agricultural, and domestic sectors. Three emerging technologies including membrane technology, microbial fuel cells and microalgae, as well as WWT strategies are discussed in this chapter. These applications are a promising alternative for manifold WWT processes and distribution systems in mitigating contaminants to meet acceptable limitations. The basic principles, types and applications, merits, and demerits of the aforementioned technologies are addressed in relation to their current limitations and future research needs. The development in WWT blueprints will augment the application of these emerging technologies for sustainable management and water conservation, with re-use strategies.

Keywords: contaminants, membrane technology, microalgae, microbial fuel cell, wastewater treatment

1. Introduction

The modern-day world has seen a boom in industrial activities. Due to extensive manufacturing activities taking place, large volumes of waste are produced, including wastewaters which are of major interest for re-use due to the scarcity of potable water in most countries. The wastewater produced poses serious environmental problems in its disposal. Because of new products that are emerging and being manufactured, so are new and recalcitrant wastes produced in production lines. Convectional wastewater technologies may be limited to process these contaminants, further exacerbating the problems the world is already facing with respect to potable water. Hence, there is a dire need to develop new methods to mitigate wastewater's effect on the already degrading environment. On the other hand, clean, fresh potable water has become scarce especially in most African countries due to contamination by intensive industrial activities. To date over one hundred technologies for the treatment of organic and inorganic wastewater streams have been documented; several of these technologies have been emerging and these range from chemical and physical to biological methods. This book chapter focuses on the emerging trends of wastewater treatment technologies, with respect to membrane and biological methods.

Exhibiting high levels of novelty in purification technologies, membranes have been widely used and serve a crucial role in various fields, such as fatty and oily industrial water treatment [1–3].

Microalgae-based technologies are autotrophic in nature and microalgae is a highly potential atmospheric carbon fixation technology. After upstream treatment processes, microalgae technology is usually employed as secondary or tertiary treatment process for effluents that are laden with inorganic components such as nitrogen and phosphorus which cause eutrophication and more long term challenges that are caused by organic material and heavy metals in disposed of wastewater. Microalgal processes then chip in to offer at attractive dimension for the treatment of wastewater coupled with the generation of possibly biomass of high value which can further used for various purposes. Microalgae has minimal risk of production of secondary pollution because of its ability to use inorganic nitrogen and phosphorus for their growth; and their ability to remove heavy metals and toxic organics [4–6].

Another powerful, emerging treatment methodology is the Microbial fuel cells (MFCs) technology which capitalizes on the bioelectrical catalytic activity of microorganisms to generate electric power by oxidizing the organic matter and sometimes inorganic material in wastewater. MFC technology offers a dual goal as it allows for energy recovery and wastewater treatment in a single configuration [7, 8].

2. Wastewater contaminants

The term wastewater is said to be water containing contaminants mainly due to human use. It emanates from diverse sources such as domestic, commercial, agricultural, or infiltration and storm run-off, with most wastewater being 99.9% water and the rest solids [9]. The characteristics of wastewater are usually determined by the chemical components and flow conditions, as this is used in the design of each wastewater treatment plant [10]. The flow conditions of wastewater are based on the seasons and it is mainly the wet season which will result in an inflow of storm run-offs. The organic and inorganic constituents of wastewater are used as an indicator of the chemical quality of wastewater. The following parameters are usually considered when measuring the chemical characteristics of wastewater; biochemical oxygen demand (BOD), chemical oxygen demand (COD), total solids (TS), volatile solids (VS), total nitrogen (TN), total phosphorus (TP), pH and alkalinity [11]; among others.

2.1 Chemical oxygen demand (COD)

This is usually a representative of the contaminants in wastewater as the higher the COD content in wastewater, the higher the degree of contamination. The COD content in industrial wastewater is usually higher when compared to that of domestic/municipal wastewater as presented in **Table 1**. It gives an indication of the degree of biodegradation in wastewater when compared with BOD as the ratio of BOD to COD higher than 0.5 makes the wastewater biologically treatable [16]. It is

Parameters	Brewery	Abattoir	Cane Sugar	Oil refinery	Coke Oven	Tannery	Textile
BOD_5, mg/L	1609.34-3980.61	476-3850	350-2750	100-500	510-1360	1000-2000	50-500
COD, mg/L	1096.41-8926.08	935-6600	1000-4340	150-800	930-3120	2000-4000	250-8000
TSS	530.67-3728.02	750-4400	760-800	130-600	19-3330	2000-3000	100-700
pH	4.6-7.3	6.85-8.19	5-6.5	2-6	6.8-8.2	11-12	5.6-9

Table 1.
Characteristics of raw industrial wastewater [12–15].

measured as the quantity of oxygen required to stabilize the carbonaceous organic matter chemically. It is used to quantify the organic matter, nitrite, sulphide and ferrous salts present in wastewater [17].

COD in wastewater could either be readily biodegradable matter, active autotrophic and heterotrophic biomass, soluble inert organic matter, inert inorganic matter [18]. Generally, the COD content in wastewater is either soluble or particulate (suspended). Classification of domestic wastewater based on COD include low (300-500 mg/L), medium (500-750 mg/L) and high (700 – 1200 mg/L) strength wastewater [19]. According to Henze and Comeau [19], the degradable COD content of a typical medium strength is 90% for soluble COD, 66% for particulate COD and 76% for total COD while the remaining percent are the inert component. The use of membrane technology only is very effective for low-strength wastewater [20] but the efficiency can be increased when combined with other technologies for treatment of high strength wastewater such as seen in the study by Matheus et al. [21] where microfiltration and nanofiltration was preceded by coagulation and flocculation to achieve a 96% COD removal (from 4610 mg/L to 184 mg/L) for dairy wastewater. Wastewater with high COD content usually causes fouling for the membrane [21], therefore, the use of biological treatment techniques such as microalgae and microbial fuel cell are more appropriate for high strength wastewater [22, 23].

2.2 Biochemical oxygen demand (BOD)

This is the quantity of oxygen required by microorganisms for the decomposition of organic matter under aerobic conditions. As stated for COD, BOD is also an indication of the degree of contamination, it affects the amount of dissolved oxygen required by aquatic organisms, and if lower than 6 mg/L could lead to their death. The typical BOD value of domestic wastewater with minor industrial wastewater in it ranges from 100 – 200 mg/L, 200 – 300 mg/L and 300 – 560 mg/L for low, medium and high strength wastewater [19]. The relationship between BOD and dissolved oxygen is inversely proportional, as a low dissolved oxygen indicates a high BOD content in wastewater [24]. However, as the organic biodegradable content of water increases, the BOD increases also [25]. Since increase in biodegradable organic pollutants is an increase in the BOD, therefore, most biological treatment processes such as microalgae or microbial fuel cell technique can remove the BOD content in wastewater. Zhang et al. [26], indicated a 98.6% BOD removal using MFC while Marassi et al. [27] reported a 96-97% efficiency using a tubular MFC. The use of microalgae has also been reported to have effectively reduce the BOD content of wastewater by generation of O_2 during photosynthesis [28] and 87% removal efficiency [29].

2.3 Total solid (TS)

This is the organic and inorganic matter; suspended and dissolved solids; settleable and volatile solid content of wastewater. Though physical separation techniques easily remove most suspended solids, some still find their way into the environment. The dissolved and volatile solid (VS) contents are a representative of the degradable content in wastewater; therefore, some treatment techniques do account for the number of volatile solids removed. The VS content of wastewater, likewise, indicate its strength as higher VS indicate high strength wastewater and vice versa. The more the VS content of wastewater, the greater the impact on the treatment plant as it is an indication of the organic solid content. Total dissolved solids (TDS) are composed of inorganic salts and small quantities of organic matter dissolved in water. TDS in wastewater increases due to chemicals either from washing, cleaning, and production processes [30].

2.4 Total nitrogen and phosphorus

These are plant nutrients that are present in wastewater as either nitrates or ammonia, and fertilizer manufacturing companies usually generate them, agricultural sectors and industries that utilize corrosion inhibitors. Total nitrogen is the combination of both the inorganic and organic nitrogen, and ammonia in wastewater, it exists as either nitrate, nitrite, ammonium, and organic dissolved compounds such amino acids, urea, and organic nitrogen composites. In aquatic ecosystems, phosphorus is also present as phosphates such as orthophosphates, condensed phosphates and phosphates organically bound [25].

Nitrogen and phosphorus in wastewater cause eutrophication in water bodies which can lead to the death of aquatic habitats, if discharged without treatment [31]. High removal rate of nitrogen and phosphorus have been achieved using microalgae treatment process with industrial application of this technique been reported to achieve between 87 and 93% removal [32].

2.5 Metals

Metals are generally found in wastewater, mainly from the manufacturing, mining, and textile industries. Metals such as arsenic, iron, chromium, lead, copper, tin, sodium, potassium, mercury, aluminum, and nickel are common pollutants in industrial wastewaters [33]. Industries such as iron and steel, mining, micro-electronics, and textiles often generate wastewater with heavy metals therein. Metals in wastewater lead to an increase in the treatment costs, and they are known to cause varying environmental problems such as distortion in plant growth, algal bloom, death of aquatic biota, debris formation and sedimentation [34]. Human related health effects include carcinogenicity, chronic asthma, skin related problems, depression, internal organ damage, coughing and nervous system-related diseases [35].

The presence of metal in wastewater in low concentration (1-3 mg/L) is toxic because metals are non-biodegradable and some metals do accumulate overtime [33, 36]. Although some metals which are essential to human, animal and plants may still be tolerated in minimal quantities such as copper, zinc, chromium but above the limit required can be toxic. An example is the reproduction of water flea Daphnia affected by exposure to 0.01 mg hexavalent chromium/L, therefore, the lethal chromium level for several aquatic and terrestrial invertebrates has been reported to be 0.05 mg/L. Some elements, however, such as arsenic, lead, cadmium, mercury is known to be toxic to living beings at any concentration and are not required to be taken into the body even at ultra-trace level [33].

2.6 Viruses and bacteria

The occurrence of human pathogenic viruses in wastewater is a usual occurrence, and newly discovered cases that were not associated with wastewater previously, are now considered as wastewater pollutants. Viral and bacterial infections from waterborne outbreaks are usually connected with environments associated with the discharge of wastewater [37, 38]. Enteric viruses are known to cause gastroenteritis infections, hepatitis, and respiratory tract infections. Enteric viruses such as noroviruses, rotaviruses, enteroviruses, sapoviruses, astroviruses, bocaviruses, hepatitis A virus, hepatitis E virus, Aichi virus, Human polyomaviruses (PyVs), papillomaviruses, a plant virus called pepper mild mottle virus (PMMoV), and enteric bacteria such as bacteriophages, fecal coliforms and *Escherichia coli* are found in wastewater, and the full details of their occurrence and concentration in untreated and treated wastewater by continents can be seen in a review by Farkas et al., [37]. The emergence of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus related to the COVID-19 pandemic has been discovered in wastewater with entry through human feaces into sewer systems as other viruses [39, 40]. Research is on-going on the effect of SARS-CoV-2 on aquatic habitats and its resulting long-term effect.

2.7 Pharmaceutical compounds

These compounds are part of the emerging pollutants in wastewater since their long-term effect on human and aquatic habitats are unknown. Compounds such as analgesics, antibiotics, anticonvulsants, anti-cancer agents, beta-blockers, contrast agents, hormones, lipid-regulators and antidepressants are pharmaceutical compounds that have recently been found in wastewater [41]. This is because human drugs are excreted either in original or metabolized form after administration. Though most pharmaceutical compounds are biologically degradable, but some product is seen in the effluent of wastewater treatment plant [41]. In effluents from a sewage treatment plants about 2 μg/L of tetracycline, ibuprofen, contrast products, caffeine, and codeine were found [42]. Likewise, Clara et al. [43] reported the presence of antibiotics (such as metronidazole, norfloxacin, and dextromethorphan (DMP)) at concentrations below 0.05 μg/L in another effluent. Studies indicate that the removal rate of antibiotic is around 50% and Bisphenol A 71%, that of analgesics, anti-inflammatory drugs, and beta-blockers is within 30–40% because of their resistant to treatment [41].

3. Emerging trends in wastewater treatment technologies

One of the primary reasons that has driven the inception of new or improved wastewater treatment technologies is the legislation and hefty fines that are attracted when the disposal of wastewater does not meet the set discharge limits. This impact on the financial wellbeing of factories and industries has fueled the emergence of new or improved treatment technologies.

Anaerobic and aerobic technologies have been popular lately in the treatment of organic wastewater because of their friendliness to the environment and cost-effectiveness. Anaerobic technologies are, however, a cut above other technologies because of the low energy consumption.

The nature of the wastewater primarily dictates the choice of technology to be adopted, and thus it is crucial to characterize streams to determine key wastewater characteristics, such as COD, TS, VS, and salt content, among others. The main thrust of this chapter is premised on three emerging technologies, that is, membrane, microalgal, and microbial fuel cell (MFC) technologies. These technologies can be employed independently or in series as a treatment mechanism.

3.1 Membrane technology

Membrane technology (MT) encompasses the related engineering and scientific approaches for the transport of components, species, or substances through or by membranes [44]. This technique is generally adopted to explain the mechanical processes for the separation of gas or liquid streams. Membranes are classified as a thin layer barrier for size differential separation, which are usually integrated with chemical and biological treatments, or as a standalone system in secondary treatment of wastewater [44, 45]. For a typical membrane mechanism, there is usually a driving force such as a semi-permeable barrier which controls the rate of movement of components by fractional permeation, and rejection through pores of different sizes as depicted in **Figure 1**. The permeation and selective rejection are a function of the membrane pore size and chemical affinity, allows for a product stream devoid of target components. Some advantages and drawbacks are presented in **Figure 2**.

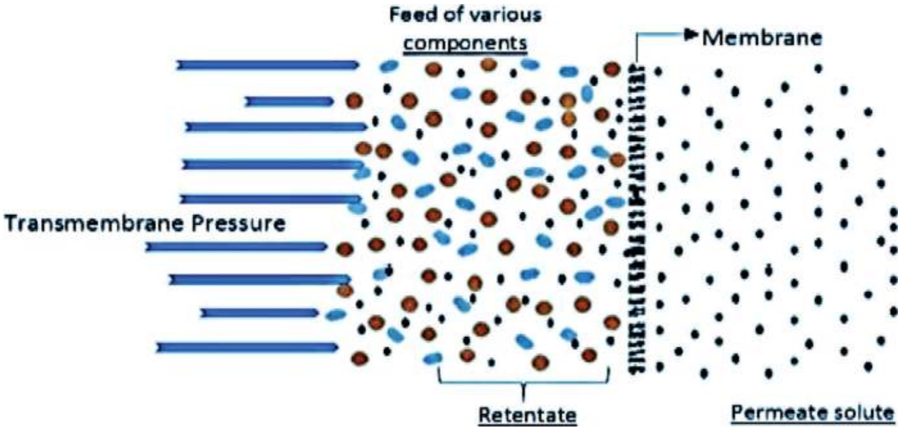

Figure 1.
Membrane selective permeation for various solutes adapted from Tetteh et al., 2019 [45].

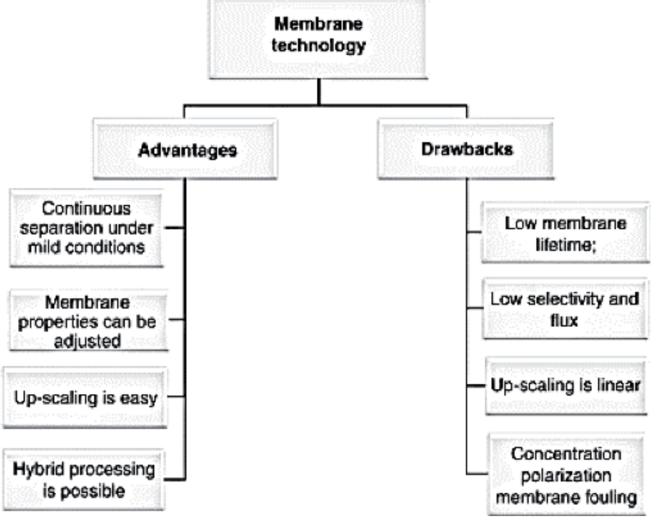

Figure 2.
Some advantages and drawbacks of membrane technology. Adapted from Burggraaf 1996 [46].

3.1.1 Classification of membranes

3.1.1.1 Microfiltration

Microfiltration (MF) employs a sieving mechanism to retain macromolecules or particles larger than 0.1 μm, or more specifically, in the range of 0.1–10 μm [45]. Unlike ultrafiltration (UF), reverse osmosis (RO) and nanofiltration (NF), the transmembrane pressure (TMP) for both sides of the membrane is low as a result of the retention of smaller particles. Thus MF requires a relatively small TMP, that is, lower than 2 bars but it may vary from 0.1 to 2 bar [47]. Larger pore sizes of MF membranes limit the removal of suspended solids, bacteria, viruses, protozoan cysts and on a lesser extent, organic colloids within the region [48].

3.1.1.2 Ultrafiltration

The performance of ultrafiltration (UF) processes are currently receiving increasing recognition as a pretreatment for desalination and membrane bioreactor applications. UF like MF uses physical sieving as a separation mechanism. The pore size, molecular weight cut-off (MWCO) and pressure for a UF membrane filtration ranges from 0.05 μm to 1 nm, 1–500 kDa and an operating pressure of 1–7 bar [47]. In effect, UF with a definite MWCO are impermeable to compounds with molecular weights exceeding the MWCO and have demonstrated a 3–6 log removal of chlorine resistant protozoan cysts, colloids, viruses, and coliform bacteria. The use of MF and UF as pretreatment to reverse osmosis (RO) has progressively arose at an industrial scale. Both could serve as pretreatment strategies for NF and RO processes for the reduction of membrane fouling, which is applied as a post treatment to chemical precipitation of organic chemical removal, pH adjustment, and phosphorus, hardness, and metal removal. Fouling is extremely distinguished in UF applications, due to the high molecular weight of fractions retained in relation with the small osmotic pressure differentials, and liquid phase diffusivity. However, this does not negatively influence the demand for UF's, as any design, configuration and application will be fouled [49, 50]. The configuration for application could be influenced by the mechanical stability, hydrodynamic requirement, and cost implications.

3.1.1.3 Ion exchange membranes

Membranes are classified as anion exchange membrane (AEM) if the polymer matrix is embedded with fixed positive charge groups, and vice versa, for cation exchange membranes (CEM) [51], which involves the permeation of anions/cations, and rejection of cations/anions in the effluent. Electrodialysis (ED), reverse electrodialysis (RED), diffusion dialysis (DD) and the Donnan membrane process (DMP) are examples of such, which usually involves the exchange of ions between solutions across the membrane as shown in **Figure 3**. The application of these processes is usually based on the type of effluent which is usually reported as an energy resourceful mechanism of separation by potential gradient.

3.1.1.4 Reverse and forward osmosis

Reverse osmosis (RO) is often referred to as a tight membrane and has been widely used in brackish and WWT. Its effectiveness in desalination was found to be more effective than conventional thermal multistage flashing [49]. High external pressures of 15 to 150 bars is a result of the hypertonic feed and is usually greater than the osmotic pressure which is applied to retain dissolved solute, and prevent

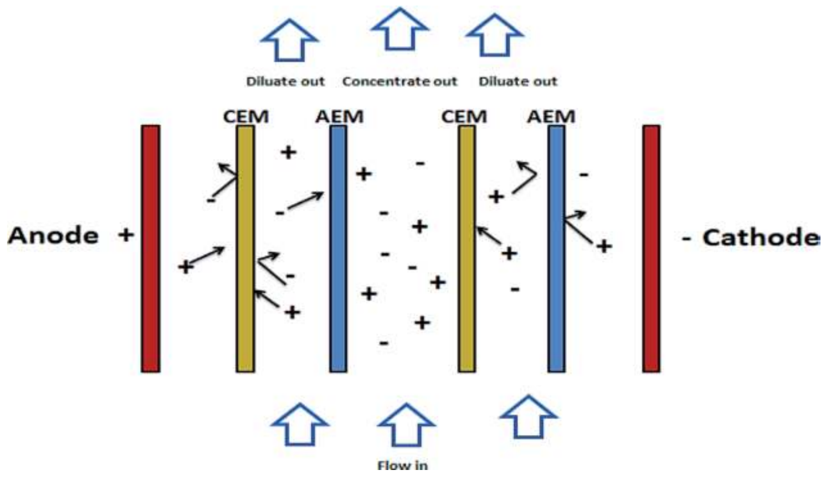

Figure 3.
Schematic diagram of ED adapted from Obotey 2020 [47].

and allow for solvent permeation at a MWCO around 100 Da through diffusion mechanism [47]. Some advantages of the RO system that have been reported in previous studies include low energy consumption, simple configuration and operation, low membrane fouling tendencies and high rejection of a wide range of contaminants. With a concentration gradient as the driving force, the separation and concentration in forward osmosis (FO) occurs as the concentrated solution (e.g. salts such as NaCl) draws water from a less concentrated feed solution. The use of FO operates at ambient conditions, hence irreversible fouling is low. However, to attain the desired process flow and optimum configuration, ROs are arranged in stages and passes. The sequence of the stages has the concentrate stream of the first stage as the feed inlet to the second stage. In addition, the permeate streams from both stages are directed into one discharge channel.

3.1.1.5 Electro-dialysis (ED) and electro-dialysis reversal (EDR)

These processes combine the principles of electricity generation and ion-permeable membranes in the separation of dissolved ions from water [45]. A difference in electric potential leads to a transfer of ions from a dilute solution to a concentrated solution through an ion-permeable membrane. During electro dialysis, two types of ion exchange membrane are used as shown in **Figure 3**. One is permeable to anions and rejects cations, while the other is permeable to cations and rejects anions. There are also two streams which are the concentrate and the diluate (feed). When an electric current is passed through the system, ions from the diluate migrate into the concentrate through oppositely charged membranes (cations migrate to the cathode whiles anions migrate to the anode). The cations are then retained by the positively charged anion-exchange membrane (AEM). Likewise, the anions are retained by the cation-exchange membrane (CEM). The outcome of this is a feed stream depleted of ions, while the concentrate stream becomes rich in ions [44].

3.1.2 Applications of membrane technology (MT)

A wider scope of industrial and environmental applications of MT are based on its advantages such as (1) clean technology, (2) energy saving (in most cases) and (3) ability to replace conventional processes; such as filtration, distillation, ion exchange, and chemical treatment systems [52]. A schematic representation of the applications of MT is depicted in **Figure 4**. Other advantages are (4) its ability

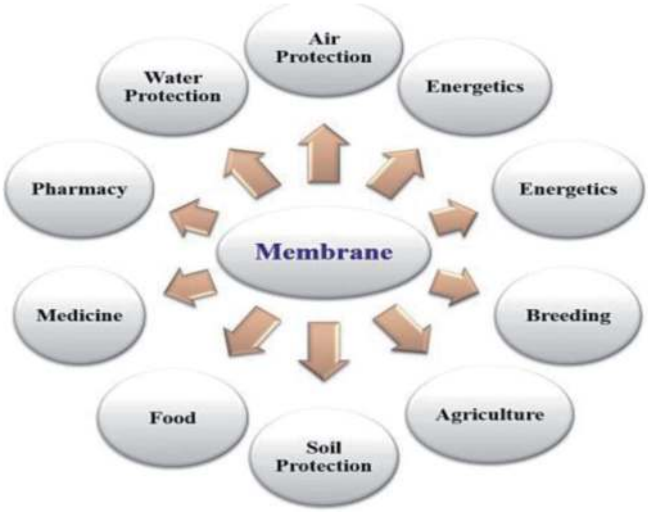

Figure 4.
Application of membrane processes adapted from Obotey 2020 [47].

to produce high-quality products and (5) its flexibility in system design. Because of its multidisciplinary application, this technique is applied in several industries, including water treatment for domestic and industrial water supply, chemical, pharmaceutical, biotechnological, beverages, food, metallurgy, and various separation processes.

3.2 Microalgal wastewater treatment (MWWT)

Water-security is a perspective which defines the reliable availability of an acceptable quality and quantity of water for health, livelihoods and production; coupled with an acceptable level of water-related risks [53, 54]. However, population dynamics and the proliferation of industrial set-ups have induced an imbalance in the water-resource equation. Domestic use of water and the demand for water in the production sector of the economy, coupled with commercial services and the agricultural sector, have surpassed the supply capacity of potable water sources [54]. The unethical discharge of wastewater from some of these sources results in serious social, health, and environmental problems. In addition, freshwater-scarce nations have the growing need to encourage strategies for water reuse, because of inadequate precipitation and lack of capacity to harvest rainwater,, which in turn aims to reduce effluent wastewater disposal. Functional wastewater treatment plants (WWTP) for municipalities across the globe have proven to be highly demanding to run in terms of chemical input and energy. Although the basic stages of treatment are primary, secondary, and tertiary, the effluent from these plants contribute to secondary pollution as they are unable to meet the green-drop guidelines [54]. Phytoremediation is a green strategy that sequesters residual pollutants from wastewater and renders it potent for re-injection into the water supply system. The use of microalgae-based WWT systems has received serious scrutiny in the research community; and in synergy with industry, various wastewater technologies and strategies have been developed to address specific needs in the sector [55].

3.2.1 Microalgal intervention

Standard culture media have been optimized for specific microalgae strains and are subsequently modified to cultivate many other strains. These are then used as templates to define wastewater characteristics and to select the microalgal strain or microalgae consortium that would best be able to treat a given wastewater source. The microalgae intervention protocol (MAIP) is mainly designed to rid the effluent wastewater from WWTP of the residual pollutants and concurrently produce high value products, thereby meeting the green-drop requirements [2, 3]. MAIP is therefore integrated into regular WWTP and upgrades it to advanced WWTPs (AWWTPs). This in turn confers the ability to sequester nitrates and orthophosphates, which, if unsuccessful will result in eutrophication to be induced and propagated in the receiving waters [3]. The need to regulate nitrogen and phosphorus discharge to the environment is born out of the following: (i) as free ammonia, ammonia-nitrogen is harmful to fish and other aquatic biota, (ii) ammonia consumes dissolved oxygen (DO) and therefore presents the potential of DO depletion, (iii) both phosphorus and nitrogen are plant nutrients and therefore contribute to eutrophication, (iv) is the NO_3- ion, nitrate-nitrogen reacts and combines with hemoglobin, which contributes to infant mortality. In addition, nitrate-nitrogen can be reduced to mutagenic nitrosamines in the gastrointestinal tract thereby posing more hazards to infants [56]. Various research teams [57–60] reported the presence of emerging pollutants (EP) in WW and the possible undesirable effects many of them can have on the environment and living organisms. These EP include, among others, pesticides, pharmaceuticals, and personal care products; and some technologies have been proposed for their removal; such as physico-chemical and biological treatment strategies. EP removal using pure microalgae strains has been proven to be effective. However, microalgae-based EP removal technologies have not received appreciable attention in the global research community.

The advocacy for employing microalgae to sequester wastewater nutrients, as a treatment option has attracted global acceptance. However, there are skepticisms in employing wastewaters for microalgal cultivation to produce biomass and bio-products. This is primarily due to the reality that wastewaters are of a wide variety of sources and therefore have a wide range of properties whose stability is in question. Pre-treatment is therefore a necessary stage for microalgal WWT, which imposes on the economy of the process. This brings to bear the necessity to adopt the integrated microalgal WWT protocol [61–64].

3.2.2 Microalgal WWT strategies

Aside from the ability of microalgae to sequester NH3-N, NO3- -N and PO43-, microalgae also removes heavy metals as well as organic carbon from wastewater, while preventing secondary pollution. However, previous research has indicated that microalgae can rarely grow in undiluted wastewater due to high concentrations of ammonium and other compounds frequently present in wastewater. Different microalgae species present different growth indices in each wastewater treatment application. It is therefore paramount to select a suitable microalgal strain to treat a given wastewater source. Ungureanu and co-workers [63, 65] reported that the microalga *C. mexicana* recorded the highest removal of N, P and C from piggery wastewater compared with five other species (*C. vulgaris*, *M. reisseri*, *Nitzschia cf. pusilla*, *O. multisporus* and *S. obliquus*). On cultivation of the microalga C. zofingiensis with piggery wastewater using different dilution ratios, 79.84% of COD, 82.70% of total N and 98.17% of total P were removed [63]. In another study with *V. vulgaris*, 60–70% of COD and 40–90% of NH_4^+ -N were removed from diluted piggery wastewater [65]. The highest removal percentage was obtained with 20-fold diluted wastewater. Whilst tertiary treatment of municipal wastewater effluent and remediation of animal waste streams are an additional technological and economic pressure on municipalities and farms that threatens their economic sustainability, but at the same time it also presents an opportunity [63]. However, there are several challenges with current microalgae growth systems. For example, algae grown in an open pond or raceway system are suspended in the water in the presence of soluble and suspended waste and can be extremely difficult to harvest because oilagenous microalgae are approximately 5–10 micrometers in diameter. Many of the highly productive microalgae cannot be easily filtered and harvested through centrifugation which is an expensive unit operation. Algae can be harvested by sedimentation; however, this is a slow process and requires considerable floor space. Metal salts can be used as flocculants to facilitate sedimentation; however, this results in water contamination. Algal pond systems are also susceptible to washout, where algae leaves the system and enters surface waters [63, 65]. Integrated microalgal WWT systems are examples of green technology, which incorporates both the conventional WWTP and the microalgal WWT protocol which is primarily considered to address imperative issues such as global warming and climate change. The microalgal biomass generated during wastewater treatment, represents a carbon sink, and thus mitigates the negative effect of CO_2 by photosynthetic sequestration of this greenhouse gas [66].

3.2.2.1 Open ponds

Open ponds are grouped into natural systems, artificial ponds, and containers. Natural systems include the lakes and lagoons; artificial ponds which are either unmixed open ponds, circular open ponds mixed with a center pivot mixer, or raceway ponds; and containers. The commonly used forms include raceway ponds, circular ponds, and tanks, of which raceway ponds have received the most attention [64].

Waste stabilization ponds are used for wastewater treatment by tens of thousands of small communities around the world. These ponds are low cost, simple to operate and provide effective wastewater treatment in terms of organic carbon and pathogen removal. However, phosphorus removal in waste stabilization ponds is often low, generally between 15 and 50% [62, 64]. Because of this, there is increasing pressure from regulators to upgrade pond systems to prevent eutrophication of receiving water bodies. The problem is that current upgrade options often involve the use of chemical dosing which contributes to secondary pollution that makes recovery and reuse of the phosphorus very difficult, and in some cases almost impossible. What is needed is a sustainable low-cost solution to remove phosphorus from the wastewater and ideally allow the phosphorus to be recovered and reused. A potentially emerging environmental process technology has been identified whereby microalgae in waste stabilization pond systems may be triggered to excessively accumulate phosphorus within their cells. While microalgae in lakes can store polyphosphate there is the potential of using this natural phenomenon to optimize for phosphorus removal in algal wastewater treatment ponds [62, 63].

Figure 5(A) Is the raceway pond that uses a motorized paddle wheel (PW) to initiate and sustain movement and mixing of the microalgal cell (MCs,) thereby preventing them from settling to the reactor bed. It enhances exposure of the MC to light and nutrients and promotes interphase mass transfer. However, while the mixing energy requirement of a PW is relatively low, efficiency of gas transfer is also low. In some instances, aerators are used to supplement CO_2 to improve microalgae growth, and hence promote nutrient sequestration from the broth. The pond operates at the prevailing temperature and light intensity depends on the incoming solar insolation [68]. **Figure 5(B)** is a rectangular open unmixed pond (ROP). The MCs here do not have the privilege of equal exposure to light. The MCs that are near the bottom are shielded from light by those above, thereby creating blind zones to photosynthetic activities resulting in reduction in cell density (CD)

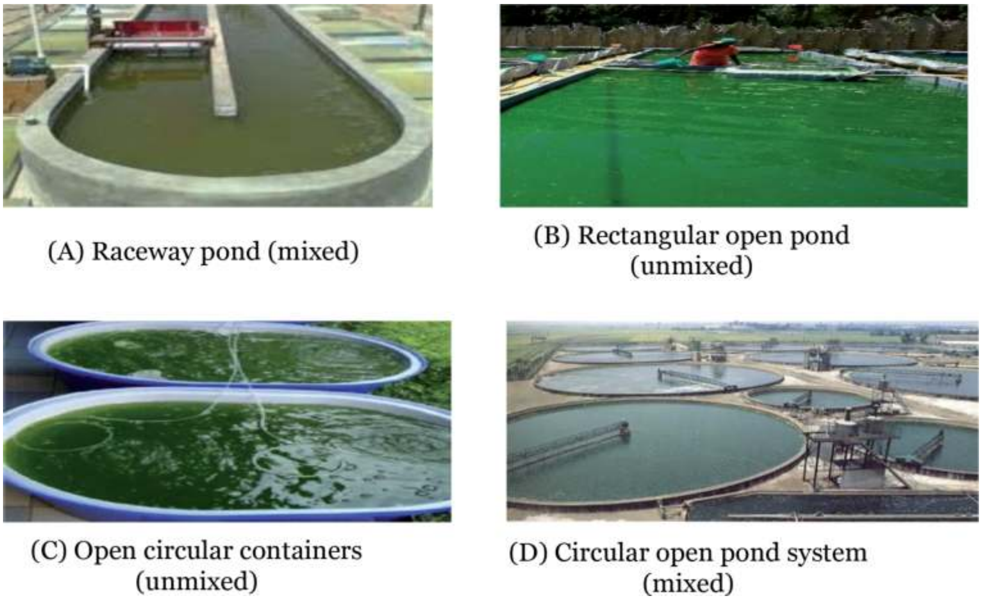

Figure 5.
Microalgal open pond systems [66–68].

and productivity. **Figure 5(C)** shows open circular containers (OCC) which are unmixed. **Figure 5(D)** shows circular open pond systems (COPS) equipped with mixers [15, 16].

3.2.2.2 Closed bioreactor (CBR) systems

Closed photobioreactor systems are characterized by (i) efficient photosynthetic activities associated with adequate control of the operational variables, (ii) lower risk of contamination and (iii) minimization of water loss by evaporation, which is a serious concern in open systems. However, closed systems are more expensive, since they must be constructed with transparent materials, and are more complicated to operate and challenging to scale up. Closed photobioreactors vary in configuration, and the main types are bubble columns, airlift reactors, tubular (loop) and stirred tank reactors. Photobioreactors employing microalgae to treat wastewater and produce biomolecules have (i) elevated efficiency in the use of light energy, (ii) an adequate mixing system, (iii) ease of control of the reaction conditions, (iv) reduced hydrodynamic stress on the cells [69–71].

Figure 6 gives a pictorial view of photobioreactor scenarios for bubble column, airlift, and annular configurations. A bubble column reactor is basically a cylindrical vessel with a gas distributor at the bottom. The gas is sparged in the form of bubbles into either a liquid phase or a liquid–solid suspension without mechanical agitation. During operation, mixing and CO_2 mass transfer are carried out through the action of the spargers with an external light supply. The configuration of a gas sparger is important since it determines the properties of bubbles; such as bubble size, which in turn affects gas hold-up and other hydrodynamic parameters associated with bubble columns. Photosynthetic efficiency depends on the gas flow rate, which further depends on the photoperiod as the liquid is circulated regularly from central dark zones to external photic zones. This exposes more MCs to the nutrients in the medium, which in the context of this chapter, is wastewater. Photosynthetic efficiency can be increased by increasing the gas flow rate (≥ 0.05 m/s), which in turn leads to shorter photoperiods [69, 70]. This type of reactor has advantages of higher mass transfer rates; and low operational and maintenance costs due to

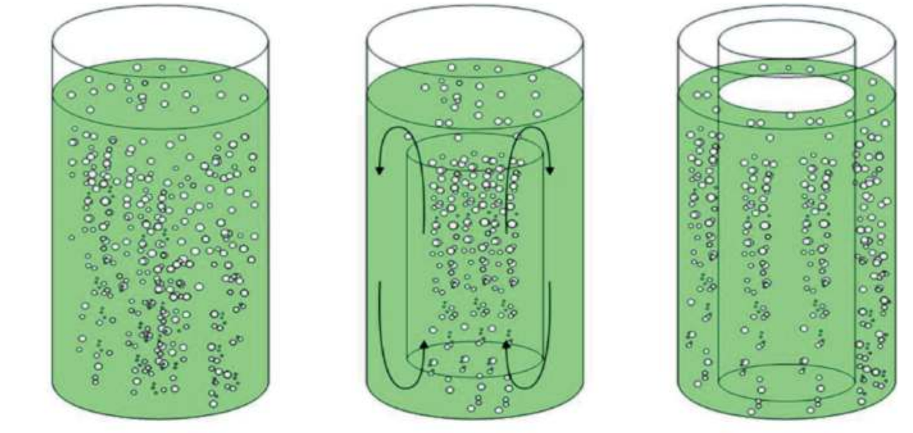

Figure 6.
Bubble column reactors Płaczek et al., 2017 [47].

fewer moving parts. However, back-mixing and coalescence have been identified as major challenges for these reactors. There is an upper limit for increasing the flow rate, beyond which the heterogeneous flow formed will eventually cause the back-mixing of gas components. Scalability and economics of microalgae cultivation using photobioreactors remain the challenges that have to be overcome for large-scale microalgae production.

Hom-Diaz and co-workers [57], in an outdoor pilot 1200 L microalgal photobioreactor (PBR) used toilet wastewater (WW) and evaluated the PBR's ability to remove pharmaceutically active compounds (PhACs). Nutrients (ammonia-nitrogen, nitrate-nitrogen and total phosphorous) were removed and chemical oxygen demand (COD) was efficiently reduced to the extent of 80%, whilst as much as 48% of the pharmaceutical residues were removed, thereby satisfying the green-drop requirement.

Airlift photobioreactors comprise of two interconnecting zones, called the riser and the down-comer, in an annular setup. Generally, there are two types of airlift photobioreactor: (i) the internal-loop and (ii) the external-loop [19]. For the internal-loop airlift reactor, the two regions are separated by either a draft tube or a split cylinder, whilst for an external-loop airlift reactor, the riser and down-comer are separated physically by two different tubes. Mixing is done by bubbling the gas through a sparger in the riser tube, with no mechanical agitation. A riser is synonymous with bubble column, where sparged gas moves upward randomly and haphazardly, and decreases the density of the riser making the liquid move upward. Gas hold up in the down-comer significantly influences the fluid dynamics of the airlift reactor thus forcing the liquid downwards The external-loop which is a draft tube confers certain advantages to the airlift bioreactor, namely, preventing bubble coalescence by directing them in one direction; distributing shear stresses more evenly throughout the reactor. This exposes more MCs to the nutrients, minerals, volatile organic compounds and a host of other pollutants for sequestration and for cell growth; enhancing the cyclical movement of fluid, thus increasing mass and heat transfer rates [71–73].

Fully closed tubular photobioreactors are potentially attractive for large-scale axenic culture of microalgae and is one of the more suitable types for outdoor mass culture. Tubular photobioreactors consist of an array of straight, coiled, or looped transparent tubes that are usually made of transparent plastic or glass. Algae are circulated through the tubes by a pump, or airlift technology [21].

Many factors contribute to the inability of microalgae to remove nutrients and produce biomass. Some minerals, such as calcium, iron, silica, magnesium, manganese, potassium, copper, sulfur, cobalt, and zinc, also influence microalgae development in wastewater, along with pH, temperature, light, mixing, and dissolved oxygen, which influence development rates and chemical composition of microalgae in wastewater treatment systems [74, 75].

3.2.3 Benefits of microalgal WWT

Molinuevo-Salces and co-workers [76] pointed out the benefits of microalgal-based WWT systems to include:

1. treating diverse kinds of wastewater including domestic, commercial, agricultural, and industrial wastewater

2. reducing pollutants and pathogens

3. recovering nutrients as biomass

4. mitigating CO_2 gas emissions

5. recovery of metabolites and

6. energy savings

Starch-based textile de-sizing wastewater (TDW) was treated with the microalgae, *Scenedesmus sp*. to remove organic carbon with lab-scale reactors, which achieved 92.4% color removal, reduction in chemical oxygen demand (COD) by 89.5%, carbohydrates by 97.4% and organic acids by 94.7% [22]. Phasey and co-workers [23] averred that cultivation of microalgae using municipal and agricultural wastewater in high rate algal ponds (HRAP) partitions nutrients into microalgal biomass, which can be recovered and reused.

3.2.4 Microalgal WWT challenges

In spite of all the advantages, some challenges have to be surmounted before the microalgal WWT protocol can be applied. The challenges include (1) land requirement, (2) effect of wastewater characteristics, (3) environmental and operational condition influence and (4) biomass harvesting and valorization [14]. However, limitations such as algae biomass separation from water, process efficiency in cold climates and limited ability of the algae biomass to reduce micropollutant content in wastewater discourages full-scale use [77].

3.3 Microbial fuel cells for wastewater treatment

In order to build a sustainable platform for the future society needs to substantially reduce its reliance on fossil fuels. This reduction can then minimize the global scale of pollution. As has been discussed in this chapter, these two global challenges could be concurrently addressed through the application of wastewater treatment technologies which reduce pollution and provide the starting blocks for biofuels. In recent years, a paradigm shift has occurred where wastewater, which can also be referred to as waste matter, is being used by industries generate electricity. In particular, studies have illustrated that a number of biological processing methods can be used to produce bioenergy or bio-chemicals while treating industrial wastewater. Specifically, brewery wastewater treatment has been highlighted for the application of microbial fuel cells (MFCs) [78]. One such instance of this method is using MFCs to simultaneously treat wastewater and produce bioenergy which is most referred to as bioelectricity. Production of these bio-products happens from simply converting the organic and chemical energy contained in wastewater to electrical energy. To further explore these possibilities, this section first describes an MFC, second it discusses applications of MFCs in wastewater treatment, and thirdly it reviews the different techniques and operations that use MFCs to treat wastewater while concurrently producing electricity. In addition, it also describes other applications and bioenergy products of this technique, its advantages and disadvantages, further promising applications of the MFC technology in wastewater treatment. An MFC is a device that converts organic matter to electricity using microorganisms as the biocatalyst. Typical MFCs have three major components: electrodes, separator, and electrogens. All MFCs contain two electrodes, which, depending on the design, can either be separated into one or two chambers. These chambers operate as completely mixed reactors. As illustrated in **Figure 7** below, each electrode is placed on each side of the membrane, which can either be a proton exchange membrane (PEM) or a cation exchange membrane (CEM). The anode faces the chamber that contains the liquid phase, and the cathode faces the chamber that only contains air [79].

Aforementioned literature proposed the use of carbon, graphite, and metal-based materials as electrodes. For example, materials made from carbon cloth, carbon paper, carbon felt [80], graphite granules, carbon mesh [81], platinum, platinum black and activated carbon with single or tubular or multi-electrode configurations are suitable as electrodes [82]. These electrodes should have properties which render them biocompatible and stable In addition high electrical conductivity, and large surface area is recommended [83, 84]. The cathode can be exposed to air or other additional electron acceptors like permanganate, chromium hexacyanoferrate and azo dye, etc. [85]. The separator is either a cation exchange membrane [86] or a salt bridge [87] which is used to keep the chamber. The potential difference generated between the two chambers drives the electrons to move through the circuit while microbial degradation of wastewater acts as the substrate to generate bioelectricity [88]. MFCs were first considered to be used to treat wastewater as early as 1991 [89]. Municipal wastewater contains a multitude of organic compounds that can fuel MFCs. The amount of power generated by MFCs in the wastewater treatment process can potentially halve the electricity demand in a conventional treatment process which consumes a significant amount of electric power

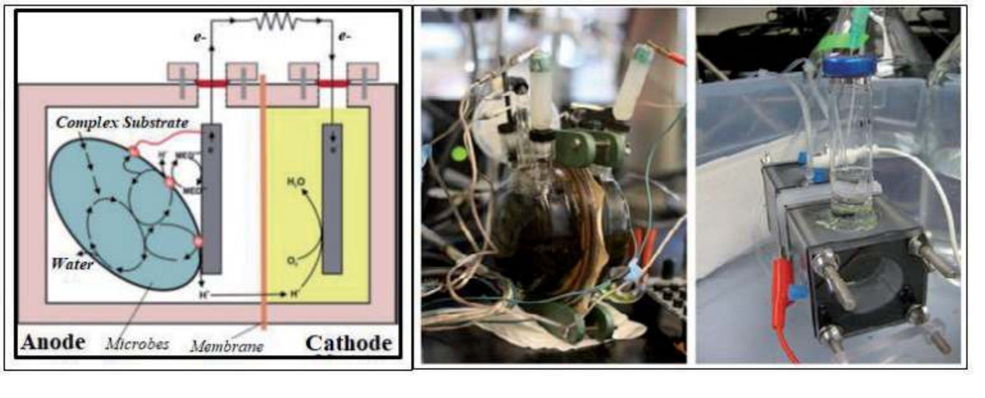

Figure 7.
Schematic diagram and pictures of a typical double-chamber microbial fuel cell (MFC), sourced from Logan et., 2006 [78].

for aerating the activated sludge. MFCs yield 50–90% less solids to be disposed of than conventional activated sludge treatment methods. Anaerobic digesters, are sometimes integrated with aerobic sequencing batch reactors to overcome the challenges of sludge disposal [90]. Furthermore, organic molecules such as acetate, propionate and butyrate can be thoroughly broken down to CO2 and H2O. A hybrid MFC incorporating both electrophiles and anodophiles are especially suitable for wastewater treatment because more organics can be biodegraded by a variety of organics. MFCs using certain microbes display a special ability to remove sulphide as necessary in wastewater treatment [91]. MFCs can enhance the growth of bio electrochemically active microbes during wastewater treatment, thus enabling operational stabilities. Continuous flow, single-compartment MFCs and membrane-less MFCs are favored for wastewater treatment amidst concerns in scale-up of other technologies [92–94]. Sanitary waste, food processing wastewater, swine wastewater and corn stover are all favorable biomass sources for MFCs because they are rich in organic matters [95–97]. Up to 80% of the Chemical Oxygen Demand (COD) can be reduced in some cases [96, 98] and a columbic efficiency as high as 80% was obtained by Kim et al. [99].

MFC technologies are a promising yet novel strategy in wastewater treatment, as the treatment process itself becomes a method to capture energy in the form of electricity or hydrogen gas, rather than being a net consumer of electrical energy. In the early 1990s Kim and colleagues illustrated that bacteria could be used in a biofuel cell as an indicator of the lactate concentration in water [80], which in turn supports electricity generation [81]. Although the power generation was low, it was not apparent whether the technology would have much impact on reducing wastewater strength. In 2004 this changed, and the link between electricity generation with MFCs and wastewater treatment was clearly forged when it was proven that domestic wastewater could be treated to practical levels while simultaneously producing electricity [82]. The amount of electricity produced in this study, while low (26 mW/m2), was considerably higher than previously obtained with other wastewater types. Research conducted prior to 2004 had shown that organic and inorganic matter in marine sediments could be used in a novel type MFC design [83], making it apparent that a wide variety of substrates, materials and system architectures could be used to generate electricity from organic content with bacterial biomass. Still, power levels in all these applications were relatively low. The final development that raised the current interest in MFCs was peaked when power densities of two orders of magnitude greater was produced in an MFC with the addition of glucose [84]. This application had no need for exogenous chemical mediators or catalyst thus ensuring this operation was purely biological.

Following these demonstrations, the competition was on to advance a rather practical approach to MFC applications. The first objective being the development of a scalable approach and design of the MFC for various wastewater treatment types [78]. While the energy that could be harnessed from the wastewater may not be enough to power a typical city, it has been reported that a substantial amount of energy can be used to power the WWTPs. As can be observed in the few studies discussed above on MFC technology, the per capital basis of the energy is not particularly substantial and impressive. Also, it can be noted that the most significant energy savings associated with the use of MFC for wastewater treatment, besides generation of electricity and removal of high strengths pollutants form these recalcitrant substrates, is savings in expenses for aeration and solids handling in typical WWTPs. The main operating costs for wastewater treatment are, aeration, sludge treatment and pumping. It has been argued that aeration alone can account for half of the operational costs at a typical WWTP [85]. Reducing this cost can also ensure that WWTPs become net producers of energy if MFCs are integrated with other treatment technologies.

3.3.1 Applications of microbial fuel cells in wastewater treatment

Applications of MFCs in wastewater treatment include a variety of advantages like long-term sustainability, use of renewable resources, degradation of organic and inorganic waste, bio-hydrogen production, and removal of compounds like nitrates, etc. [86]. The electrochemical active microbial community requires an in-depth understanding of its solution chemistry to engage in full-scale implementation and exploitation of MFC technology for electricity generation. [9]. Under ideal laboratory conditions, these systems have produced power densities of 2 to 20 mW/m^2 [87]. However, the amount of biomass-based energy produced by microbial processes is very low. It has yet to reach to its full potential to work in pilot scale units. It has also been noted that the success of specific MFC applications in wastewater treatment will depend on the concentrations and biodegradability of the organic matter in the effluent, the wastewater temperature, and the absence of toxic chemicals [78]. One of the first applications could be the development of a pilot-scale reactor at industrial locations where a high quality and reliable influent is available. Food processing wastewaters and digester effluents are good candidates. Moreover, decreased sludge production could substantially decrease the payback time. In the long term, dilute substrates, such as domestic sewage, could be treated with MFCs, thus decreasing society's need to invest substantial amounts of energy in their treatment. A varied array of alternative applications could also emerge, ranging from biosensor development and sustained energy generation from the seafloor, to bio-batteries operating with various biodegradable fuels. While full scale, and highly effective MFCs are not yet within our reach, the technology holds considerable promise, and major hurdles will undoubtedly be overcome by engineers and scientist in the near future [88]. The growing pressure on our environment, and the call for renewable energy sources will further stimulate development of this technology, to full scale plant operation. As part of the aforementioned applications of MFC in wastewater treatment, potential for application of this technology it as a typical sensor for pollutant strength analysis for in situ process monitoring and control [89]. The proportional correction between the columbic efficacy of MFCs and the strength of the wastewater can propose MFCs to be potential biological oxygen demand (BOD) sensors [80]. An accurate method to measure the BOD value of a liquid is to calculate its Columbic yield. A number of works, namely [80, 90] showed a strong linear relationship between the Columbic yield and the strength of wastewater in BOD concentration range. MFC-type BOD sensors are advantageous because they have excellent operational stability, and good reproducibility and accuracy. An MFC-type BOD sensor constructed with the microbes can be kept operational for over five years without extra maintenance [80]. These biological sensors promise a longer service life than ordinary versions of BOD sensors reported in literature.

3.3.2 Promising techniques of MFCs in wastewater treatment and electricity valorisation

Waste biomass is a cheap and relatively abundant source of electrons for microbes capable of producing electrical current outside the cell [85]. Rapidly developing microbial electrochemical technologies, such as microbial fuel cells, are part of a diverse platform of future substantial energy and chemical production technologies. In this section, we discuss the key advances that will enable the use of exo-electrogenic micro-organisms to generate biofuels, hydrogen gas, methane, and other valuable inorganic and organic chemicals. Moreover, this section will scrutinize the crucial challenges for implementing these systems and compare them to similar renewable energy technologies. Although commercial development is already underway in several different applications, ranging from wastewater treatment to industrial chemical production, further studies are still required regarding efficiency, scalability, system lifetimes and reliability of MFCs in the field of wastewater treatment and bioenergy production [85].

Power generation using domestic wastewater in the flat plate system was developed and found to be capable of continuously generating electricity from the organic matter in the wastewater while undergoing treatment [82]. Following an acclimation period of approximately 1-month, constant power generation from wastewater was obtained with the Flat Plat Microbial Fuel Cell (FPMFC) over a period of five months. For wastewater containing 2463 mg COD/L, an average power density of 560 mW/m^2 was obtained with a hydraulic retention time (HRT) of 2.0 h (0.22 mL/min flow rate; 164 mg/L log mean COD) and an air flow rate of 2 mL/min with a 470 *ohms*' resistor. Under these operating conditions, the COD removal rate was 1.2 mg/L min (58% COD removal), and the maximum power density was achieved at a flow rate of 0.22 mL/min. This power density was about 10% higher than that obtained under typical operating conditions with a 470 *ohms*' resistor.

Continuous wastewater treatment and electricity generation using a Single Chamber Microbial Fuel Cell (SCMFC) was successfully piloted with feasible results [82, 91]. It was found that the system could generate 26 mW/m^2 at the maximum power density while reducing 80% of the COD. In a specially designed, smaller batch system by Liu et al. [92] showed that up to 28 mW/m^2 of power could be generated with domestic wastewater. It was further demonstrated that by removing the proton exchange membrane (PEM), they could generate a maximum of 146 mW/m^2 of power. In these systems, the anode was separated from the PEM/cathode or plain cathode in a large chamber, but the anode chamber was not mixed except by the flow of liquid into the system. In other MFCs, the anode chamber was often mixed in [93–95] . In hydrogen fuel cells, the electrodes are usually combined into a single strip separated by a PEM. This is necessary to keep the two electrodes near to enhance proton conduction between the two electrodes. However, PEMs such as nafion are permeable to oxygen, resulting in the transfer of small amounts of oxygen from the cathode chamber to the anode chamber.

Domestic wastewater treatment was examined under two different temperature gradients, (23 ± 3°C and 30 ± 1°C) and flow modes (fed-batch and continuous) using a single-chamber air–cathode microbial fuel cells (MFCs) in view of the effect of operating parameters which affect the production of electricity [94]. Temperature was an important parameter which influenced efficiency and power generation. The highest power density of 422 mW/m^2 (12.8 W/m^3) was achieved under continuous flow and mesophilic conditions, at an organic loading rate of 54 g COD/L-d with reduction of COD by 25.8%. Energy recovery was found to depend significantly on the operational conditions (flow mode, temperature, organic loading rate, and Hydraulic Retention Time (HRT)) as well as the reactor architecture. The results demonstrate that the main advantages of using temperature gradients, in series MFC configurations for domestic wastewater treatment are power savings, low solids production, and higher treatment efficiencies.

A study on MFCs used to produce electricity from different compounds sources, including acetate, lactate, and glucose has proven its ability in high efficiencies and versatility in applications for wastewater treatment [96]. Clearly, the possibility to produce electricity in a MFC from domestic wastewater, while at the same time accomplishing biological wastewater treatment (reduction of COD) was emphasized. Tests were conducted using SCMFC containing eight graphite electrodes (anodes) and a single air cathode. The system was operated under continuous flow conditions with primary clarifier effluent obtained from a local wastewater treatment plant. The prototype SCMFC reactor generated electrical power (*maximum of 26* mW/m^2) while reducing the COD by about 80%. The power output was proportional to the hydraulic retention time over a range of 3 to 33 h, and to the influent wastewater strength over a range of 50–220 mg/L for COD. Current generation was controlled primarily by the efficiency of the cathode. Optimal cathode performance was obtained by allowing passive air flow rather than forced air flow (4.5–5.5 L/min). The Columbic efficiency of the system, based on COD reduction and current generation, was <12%, indicating that a substantial fraction of the organic matter was not accessible to the microorganisms thus limiting the current generation. Bioreactors based on power generation in MFCs may represent a completely new approach to wastewater treatment. If power generation in these systems can be increased, MFC technology may provide a new method to offset wastewater treatment plant operating costs, whilst making advanced wastewater treatment more affordable for both developing and industrialized nations.

The development of electric power from MFCs was initially investigated for its potential contribution to applications in space research [97]. It was discussed that one of the determining factors in MFC technology was the use of applied microbial cultures, which are responsible for converting electric energy from the chemical bonds in the substrates. In the last decade, despite the intensive development there is a knowledge gap regarding electricity production from microbes and the screening for electricity production. The fast screening method was based on microbial iron (III) – reduction, and do not require any MFC infrastructures. The method is suitable for the evaluation of numerous microbe species or strains simultaneously; and in this way there is possibility to extend the range of potential MFC biocatalysts and be able to predict the electricity generation from the chosen cultures. The knowledge which was generated from this study concerning the growth – iron (III) – reduction, substrate utilization, adhering and biofilm forming properties, extracellular conductive proteins and redox mediator production measurements is essential for the utilization of *G.toluenoxydans* and *S. xiamenensis* species for the different types of MFC applications (wastewater treatment and/or energy production). This information is vital for further strain-improvement and to create an efficient MFC design for electricity production. *S.xiamenensis* DSMZ 22215 species can catalyze *maltose* or *maltodextrine* efficiently. This ability makes the microbes available to be useful in MFC systems for the treatment of starch-based wastewaters *(e.g. Brewery wastewater, starch wastewater and the pulp and paper industry).*

Simultaneous wastewater treatment for biological electricity generation, through the membrane electrode assembly air-cathode MFC in starch processing wastewater (SPW) as substrate, was proven in this study [82]. Over the entire experimentation time, it was perceived that the optimum voltage output of 490.8 mV and power density of 293.4 mW/m^2 was ascertained with a current density of 893.3 mA/m^2. An internal resistance of 120 ohms was also recorded within the third cycle of experiments. Removal efficiencies for COD and $NH_4^+ - N$ increased with time, with a maximum of 98.0% and 90.6%, respectively. This was higher than most reported works on MFC operations. High values of nitrate removal might have been a result of both biological and physiochemical processes. Columbic Efficiency (CE) was not high (maximum 8.0%) and was mainly caused by other electron acceptors in the SPW, and oxygen diffusion during long operation periods. SEM revealed the presence of biofilm on the anode, in which short rod-shaped bacillus might have been the dominating bacteria responsible for MFC operation. This study demonstrated the feasibility of using MFC technology to generate electricity and simultaneously treat SPW with high removals of COD and $NH_4^+ - N$, thus providing an attractive alternative to reduce the cost of wastewater treatment whilst generating electricity from a renewable resource.

3.3.3 Advantages and disadvantages (Limitations) of MFCs in WWT

MFCs present several advantages and disadvantages (**Table 2**), both operational and functional in comparison to currently implemented wastewater treatment technologies for both high organic pollutant removals in the form of CODs and for the valorization of bioenergy in the form of electricity [98]. The generation of bioenergy from wastewater treatment is mostly considered to be the green or blue energy aspect of MFCs [92]. Electricity is generated in a direct way from biomass and organic matter, hence chemical energy is directly converted to electrical energy. The direct conversion of wastewater substrates to bioenergy has also been reported to be a third of the input during the thermal combustion of biogas [85]. Due to the harvesting of electrical energy, the bacterial growth yield in a MFC is considerably lower than the sludge output of an aerobic process [85, 99]. Generally the off-gas of an anaerobic process has a high content of nitrous gases together with the targeted hydrogen and methane [78]. The off-gases of MFCs has less economic viability, since the energy contained in the substrate was previously directed towards the anodic chamber of the MFC during processing [78]. The gas produced in the anodic chamber of the MFC can be literally discharged, considering no large amounts or other odorous compounds are present, and in addition no aerosols with noxious or undesired bacterial contents are liberated into the environment. Power generation from MFCs have improved considerably and reached the level of primary power target, at least in small scale systems, but the scale up is still a big challenge and a major limitation of the application of MFC technologies. The high cost of cation exchange membranes, the potential for biofouling and associated high internal resistance restrain the power generation and limit the practicality and commercial application of this technique [100].

Domestic wastewater is organic matter with embedded energy content of almost 10 times the energy needed for treatment [101]. While emerging techniques are promising, none of the processes available today can yet fully extract all the energy available in wastewater without further investment in their research and development [100]. A major setback of MFC applications is associated with the process start up time, and sequence which may be between 4 to 103 days depending on the inoculum, electrode materials, reactor design and operating conditions (temperature, external loading rates etc.), but it is largely affected by the type of substrate being fed into the MFC system [96]. Another vital impediment in scaling up of MFCs for wastewater treatment is the shortage of buffer capacity of electrolytes. This might require some external mediators, or chemical substance to maintain and stabilize the hydrogen potential of the anodic and cathodic chambers. This has to enhance the wastewater treatment process but still favor the valorization of bioenergy within the MFC system.

Advantages	Disadvantages (Limitations)
• Generation of energy from Wastewater / Biomass	• Low Power Densities
• Direct Conversion of Substrate Energy to Bio Electricity	• High Design and Fabrication Costs
• Minimal Sludge Production	• Electricity Up-Scaling Problems
• Less Gas Emissions / Treatment	• Activation Losses
• Low Aeration Costs	• Ohmic Losses
	• Bacterial Metabolic Losses
	• Concentration Losses

Table 2.
List of advantages and disadvantages of MFCs, sourced from Quach-Cu et al., 2018 [61].

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4. Conclusion

In this chapter, we have reviewed the use of the MT, Microalgae and MFC technology, particularly focusing on their strengths and limitations in treating wastewater while producing bioenergy and other viable products. In the case of membrane distillation, continuous studies are needed to adequately understand the concept of temperature polarization and, accordingly, a suitable membrane should be developed to make the process viable for large scale application. Microalgal WWT achieves a dual purpose of reducing wastewater of their pollutants and producing biomass of value. It also adds the benefit of mitigating global warming as microalgae biofix anthropogenic carbon dioxide. Microalgal WWT by the airlift bioreactor technology application has advantages over other available reactor technologies as it maximizes carbon dioxide and oxygen gas mass transfer with high remediation potentials. Presently, MFC technology is at research stage hence more research and practical attempts are a necessity for its commercial viability and applications practically at large scale. Although some of the basic knowledge has been gained in MFC research, there is still a lot to be learned in the scale-up of MFC for real plant application and commercialization.

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