



Review

Agricultural Waste and Wastewater as Feedstock for Bioelectricity Generation Using Microbial Fuel Cells: Recent Advances

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Abstract: In recent years, there has been a significant accumulation of waste in the environment, and it is expected that this accumulation may increase in the years to come. Waste disposal has massive effects on the environment and can cause serious environmental problems. Thus, the development of a waste treatment system is of major importance. Agro-industrial wastewater and waste residues are mainly rich in organic substances, lignocellulose, hemicellulose, lignin, and they have a relatively high amount of energy. As a result, an effective agro-waste treatment system has several benefits, including energy recovery and waste stabilization. To reduce the impact of the consumption of fossil energy sources on our planet, the exploitation of renewable sources has been relaunched. All over the world, efforts have been made to recover energy from agricultural waste, considering global energy security as the final goal. To attain this objective, several technologies and recovery methods have been developed in recent years. The microbial fuel cell (MFC) is one of them. This review describes the power generation using various types of agro-industrial wastewaters and agricultural residues utilizing MFC. It also highlights the techno-economics and lifecycle assessment of MFC, its commercialization, along with challenges.

Keywords: agricultural waste; wastewater; microbial fuel cell; techno-economic; commercialization

1. Introduction

Today, several challenges are besieging the environment, and as such, an equal measure to address such challenges must be in place to counter environmental and ecological degradation [1]. For example, in maintaining a clean and safe environment, waste reduction and recovery of valuable products [2] and/or their repurposing is a must [3]. Nutrient-rich agro-waste is usually produced from agro-processing industries [4]. Similarly, one of the major wastes is agro-based wastewater containing many carbon-based compounds [5], which in turn affects the receiving water bodies when released untreated [5]. Agricultural residues are also considered one of the most prominent substrates in energy and

carbon source content. Their sugars are obtained either via treatment with dilute acids or enzymes [6].

An example of an important agricultural residue is wheat straw containing about 34–40% cellulose organic carbon content, hemicellulose containing about 21–26% of organic carbon, and lignin-containing about 11–23% of organic carbon. All of these can undergo hydrolysis yielding wheat straw hydrolysate, generating a substantial amount of electricity in a microbial fuel cell (MFC) [7]. Similarly, raw corn stover is another important agricultural waste that contributes immensely to the production of electricity when a single-chamber MFC is used. However, the treatment thereof was effective, but the power output was much lower compared to MFC in which glucose is used as a substrate [8].

Agricultural waste, even in agro-industrial wastewater, is produced during agriculture produce pre-harvesting, harvesting, and processing activities. Agricultural processing activities and industrial food processing operations contribute to agro/food-waste and wastewater generation. Agricultural waste can easily undergo biodegradation as it contains a high level of organic matter and many other different macro-and micro-nutrients suitable for microbial growth. Many agro-industrial wastewaters also contain a high concentration of organic pollutants, including a large amount of waste effluent produced from livestock and agro-products processing [9]. However, these agricultural residues and wastewater can be considered new alternative sources of renewable energy that can be converted into biofuels, biogas, bioelectricity, bio-bricks, fertilizer, and biochar [9] suitable technology such as MFCs, among others.

1.1. The Availability of Various Agricultural Waste

Various types of agro-waste can be found in the environment, which depends upon the source and availability. They can be derived from many different sources such as municipal solid waste works, livestock excrements, lignocellulosic and agro-wastes, food crops, etc. Thus, such waste can be classified into four main generations based on their ability to produce different types of products [6]:

First-generation: This comprises various classes of food crops such as wheat, corn, rice, and sorghum. The direct utilization of these crops as a primary feedstock of interest is often associated with energy generation and the production of various products. However, one of the major challenges associated with this generation is the competition between its utilization in fuel and food production. Fuel production is viewed to be of a higher return on investment than food production.

Second-generation: This generation generally consists of lignocellulosic wastes like sugarcane bagasse, wood chips, crop residues, and organic waste that can be employed to generate bioenergy using different waste beneficiation techniques. This type of waste is associated with the overcoming of major limitations identified with the first-generation biomass.

Third generation: Microalgal biomass, which is used in engineered energy source production systems as a feedstock. Hence, its cultivation can easily be achieved in lagoons and open ponds using a high nitrogenous compound containing agro-waste containing wastewater.

Fourth generation: This type of biomass is from metabolically engineered species such as bacteria, including algae generated from cleaner disposal, or emissions control processes such as CO₂ capture systems. This increases the value of this generation as it can be used in high-value product production associated with higher polymeric hydrocarbon content requirements or any other bioenergy products.

1.2. Current Status of Agricultural Wastes

A majority of agro-wastes are usually derived from oilseed crops, wheat, rice, fruits, and vegetable processing. This usually causes several health-related problems to the human population, animals, and the environment, particularly whereby their means of disposal is through landfilling. Even though most of the chosen techniques are cheap and easy to implement, there is a harmful impact on downstream agro-systems and environmental outcomes due to toxic leachate production. This further contributes to

adverse climatic conditions as other unwanted gaseous by-products are also produced. Additionally, combustion also generates different types of disturbances to the environment, including smoke that simultaneously causes air pollution by releasing greenhouse gases contributing to global warming. Furthermore, smog is also produced and does mobilize particulate matter into the atmosphere, with the residual as haltering the soil's physical, chemical, and biological structure, including microbial community. Therefore, a necessary major intervention is needed for the sustainable disposal of agro-waste. This can take the form of sustainable energy technology development and generation in renewable energy technology.

1.3. Characteristics of Agricultural Wastes and Wastewaters

Today, agro-wastes are known as the best alternative source for renewable energy production. This depends upon their classification and physicochemical properties, as they consist of different proportions of lignocellulosic hemicellulosic, including lignin in some complex and hardy agro-waste materials. These play an important role in converting the agro-waste to hydrolysate used in bioenergy production processes. The properties conferred to agro-waste depends upon its sources' location, climatic conditions, characteristics, etc. Thus, the physical and chemical properties of such agro-waste are discussed in the following sub-sections. Carbohydrates (2300–3500 mg/L), sugars (0.65–1.18 percent), proteins (0.12–0.15 percent), and starch (65–75 percent) are discharged in starch processing wastewater (SPW), which is an important energy-rich feedstock that may be converted to a wide variety of useful products [10]. Worldwide, the varied structure of lipids, proteins, fibers, excessive organic matter, parasites, meat processing effluents, and veterinary medicines is recognized as hazardous [11]. Due to the broad range of slaughterhouse wastewater (SWW) and pollutant concentrations, SWW is often evaluated using bulk criteria. SWW contains substantial amounts of biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) [12]. Substrates such as cellulose and chitin are readily available and cheap biopolymeric resources that may be used to generate electricity. These green materials also account for a significant percentage of organic compounds in industrial and municipal wastewaters [13]. There have been just a few reports on the use of these particle substrates in MFCs.

1.3.1. Physical Properties

The size of the agro-waste particles is usually irregular in shape and size, with some being needle, leave shaped, etc., with different surface areas. This influences the feeding rate along with fluidizing and mixing parameters during processing and pre-treatment. Additionally, the storage conditions of the agro-waste may also affect these processes. The efficiency of the conversion and energy requirements for these processes is associated with the beneficiation of the agro-waste, which can be affected by the variation in shape and size of the initial agro-waste, and the preceding processes generating it. Another characteristic is the length/diameter of the particulate matter constituting the agro-waste is an aspect ratio tending to unity, even when the finely granulated, i.e., converging to a spherical shape [14]. Such an aspect ratio was determined to be suitable for further processing of the agro-waste in bioenergy generating processes.

Other characteristic considerations include particle and averaged bulk density to determine the grindability of the waste, a known energy-consuming process, which is influenced by quality characteristic parameters of the waste such as moisture content, surface properties, shape, and size [15]. For instance, some agro-waste containing a high lignocellulosic content are difficult to grind due to the presence of fibrous cellulose and lignin. Applying the "Hard grove grindability index method" is usually performed to assess the grindability of such agro-waste. Generally, a particle size of 0.6–1.2 mm for the agro-waste is required to have a suitable grindability index. Similarly, fluid ability must also be considered as it seems to impact the operations associated with waste move-

ment from one point to another during beneficiation and/or processing. Fluid ability is influenced by the biomass particle angle repose, cohesion coefficient, flow index, and compressibility index.

1.3.2. Chemical Properties

Proximate Analysis

Several analyses are performed for proximate analysis. This includes the internal and external amount of water content present in the waste sample, and it is expressed as a weight percent of the agro-waste. It is calculated by subjecting the agro-waste to thermal pre-treatment in a furnace usually operated at $>105\text{ }^{\circ}\text{C}$ for at least 3 h until a constant weight is reached to get the exact amount of moisture within the initial un-pretreated agro-waste. The ash content can be obtained after the complete combustion of the waste when there is a specific amount of leftover residue in a process operated at $>575\text{ }^{\circ}\text{C}$ for 3 h. The ash content can be determined by comparing the ash residue to the total amount of the feed agro-waste sample. For volatile matter, except for moisture, it is released when biomass is incinerated at high temperature ($950\text{ }^{\circ}\text{C}$ for 7 min) in anaerobic conditions. The presence of a high amount of volatile matter indicates a high amount of liquids and gaseous by-products, which can be useful products. The total weight loss of the waste during such a thermal operation is estimated to be equivalent to the amount of volatile matter. After accounting for moisture, ash, and volatile matter, the amount of explosive residue, i.e., fixed carbon, can be determined.

Ultimate Analysis

For ultimate analysis, the total carbon and hydrogen in agro-wastes usually vary from 40–50% (w/w) and 4–6% (w/w). Overall, this analysis involves determining total carbon, hydrogen, nitrogen, and sulphur content in the agro-waste sample. The total oxygen can be calculated by subtracting the total amount of nitrogen, hydrogen, carbon, and sulphur from the known weight of the sample. Hence, this analysis can be carried out using a CHNS analyzer on a dry basis.

Similarly, compositional analysis can be performed using the “Van Soest” method, classified as the National renewable energy or Technical Association of pulp and paper industry method. Most agro-wastes are composed of cellulose, hemicellulose, and lignin; albeit, with a varying degree of composition in different waste samples. The degradation temperature of cellulose is around $240\text{--}360\text{ }^{\circ}\text{C}$, leading to the production of liquid products after conversion. Hemicellulose, which surrounds the cellulose, comprises a short and heterogeneous branched chain of polymers. It also links cellulose with lignin. Lignin is the most complex and aromatic compound of higher molecular weight polymer with the cross-link made up of phenolic groups [16]. Other inorganic elements present in the biomass include Na, K, Mg, Cl, etc., and some components such as proteins, resins, gums, etc.

1.4. Pretreatment of Agricultural Wastes

The breakdown of complex molecular structures of agro-waste into simpler monomers is generally considered essential during the pretreatment process. Thus, it contributes to a high output after the conversion process [17]. Different technological approaches can be employed for biomass treatment; this includes physical (grinding, milling), thermal (e.g., steam explosion), biological (e.g., enzymatic), chemical (e.g., use of acids, alkalis) methods, and a combination of treatments such as thermochemical treatments [18]. These methods provide ease of accessibility to enzymes for hydrolysis, increasing the surface area while minimizing operational costs. For instance, the physical treatment of the waste enhances the surface area as it provides easy accessibility for microbial populations and enzymes during hydrolysis. On the other hand, the thermochemical method of pretreatment increases the rate of heat and mass transfer and facilitates the rate of uniform temperature distribution within the agro-waste particles, thus high efficiency for hydrolysate constituents' recovery during liquefaction. Similarly, thermochemical conversion involves two essential methods:

drying and torrefaction [19]. The former involves moisture removal from the waste, which increases the efficiency of the process, while the latter involves the thermal treatment of waste at a temperature of 200–300 °C, where sufficient oxygen is removed from the waste, including water.

For the biological conversion process, the waste can be treated at a temperature of 50–250 °C. This provides an efficient treatment process in terms of pathogen removal and biodegradability. However, in the biological pretreatment method, different types of enzymes and fungi are utilized; hence, it is considered the less energy-consuming method as it can be operated at both milder and economical temperature. However, it seems to be a very slow process as several days are required for the process to be completed. Therefore, various fungi are required for delignification of the agro-waste. It is carried out by inoculating the agro-waste with fungal spores or hydrolysis by a cocktail of enzymes [20]. In essence, ligninolytic enzymes play a role in the hydrolysis of the recalcitrant lignin. Simultaneously, the fungi (white-rot fungi) participate in lignin degradation with minimal holocellulose consumption [21].

The chemical pretreatment method involves using various chemicals such as acids and alkalis that contribute to the breakdown of organic components present in the agro-waste. This pretreatment method will break down the lignin-carbohydrate bond and crystalline cellulosic structure (Figure 1). Examples of the acid used during pretreatment include H_3PO_4 , H_2SO_4 , HNO_3 , HCl , etc., and alkalis such as $NaOH$ and KOH . Many researchers have considered the use of liquid-ammonia-water mixture to treat the recalcitrant lignocellulosic constituents in the agro-waste.

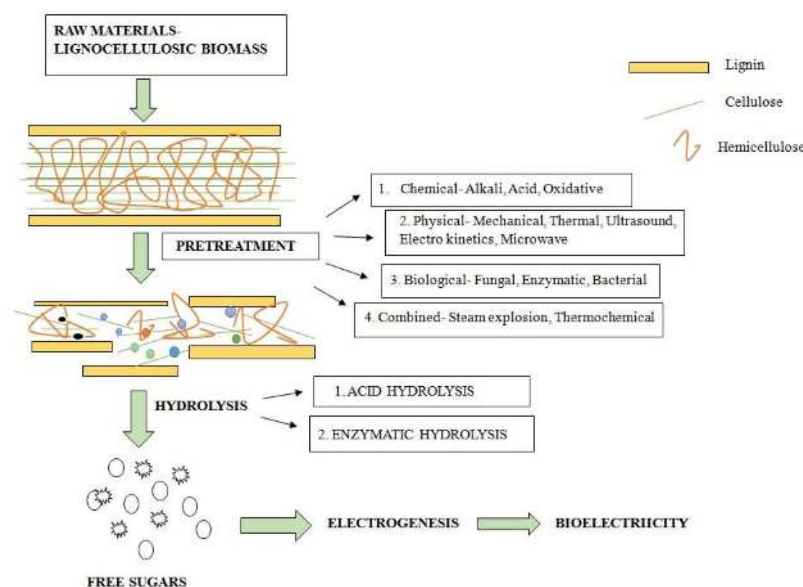


Figure 1. Effect of pretreatment on the biomass component.

1.4.1. Physical Pretreatment

Physical pretreatment techniques requiring mechanical processes such as chipping, milling, and grinding may decrease particle size, break down crystallinity, and increase the degree of polymerization, both of which significantly enhance the biodegradability of biomass in MFCs. Using a fermentation medium containing solid substrate resulted in a low PD attributable to the sluggish hydrolysis of the biodegradable materials, suggesting that particle size is a significant factor for optimum bioenergy production. Additional particle size reduction under 40 mesh has been reported to impact hydrolysis rates and yields, resulting in a significant amount of usable material in the biodegradation phase in MFCs [22]. Furthermore, various irradiation methods (such as ultrasonication, electron beams, X-rays, or gamma rays) may be used to pretreat biomass physically. Shen et al. (2018) studied the effects of ultrasonic pretreatment on electricity production in a dairy

manure microbial fuel cell (DMMFC). At 600 W ultrasonic power, the pretreated DMMFC had a maximum PD of 102 mW/m², which was 241 percent higher than the untreated substrate [23]. According to Tao et al. (2013), ultrasonication may be an effective pretreatment technique for vegetable or grass wastes [24].

1.4.2. Acid Pretreatment

Of the numerous chemical pretreatment procedures, acid pretreatment is among the most widely utilized. Acid hydrolysis will boost enzymatic hydrolysis performance and increase the energy conversion efficiency of lignocellulosic biomass in MFCs. Concentrated mineral acid (CA), dilute mineral acid (DA), and dicarboxylic acid has been utilized to pretreat agro wastes. CAs like H₂SO₄ (Figure 2) and HCl are especially useful for agro wastes. These acids, however, are acidic, corrosive, and dangerous, necessitating the use of specialized reactors that can withstand corrosion. Meanwhile, lignocellulose hydrolysis of agrowastes displayed a strong reaction rate after pretreatment with dilute sulfuric acid. Initially, high temperature (T > 160 °C) and low temperature (T < 160 °C) dilute acid hydrolysis pretreatment methods were created [21]. In contrast, a high temperature throughout the DA hydrolysis is ideal for cellulose hydrolysis due to sugar decomposition. In an MFC inoculated with pure-culture, Wang et al. (2017) used diluted sulfuric acid pretreated corn straw as the substrate for direct power production. The maximum PD provided by this MFC was 17.2 ± 0.3 mW/m², demonstrating the viability of biomass hydrolysate as a source of power production in MFC. A high PD of 660 mW/m² from the hydrolysate with a pure-culture of *Shewanella oneidensis* MR-1 could also be obtained by integrating electrode alteration and electron shuttle attachment [25]. Ionic liquids have also been stated to be beneficial due to their thermal stability, low hydrophobicity, low toxicity, and increased electrochemical stability [26]. Ionic pretreatment of farm straw biomass substantially solubilizes cellulose and may recover 100% of the utilized liquid with high purity under moderate conditions. Straw biomass is pretreated with 1-ethyl-3-methylimidazolium acetate in an ionic liquid (IL) at 120–140 °C (EmimAC). The materials are then washed with anti-solvent for a certain number of hours, resulting in cellulose regeneration. The cellulose is then separated, the lignin precipitated, and anti-solvent recycle, and IL is developed (Figure 3) [27]. Due to the self-evident intra-structure modifications and the disparity in crystallinity characteristics, the generated cellulose precipitate has a strong enzymatic digestibility compared to the rudimentary cellulose from straw waste [28].

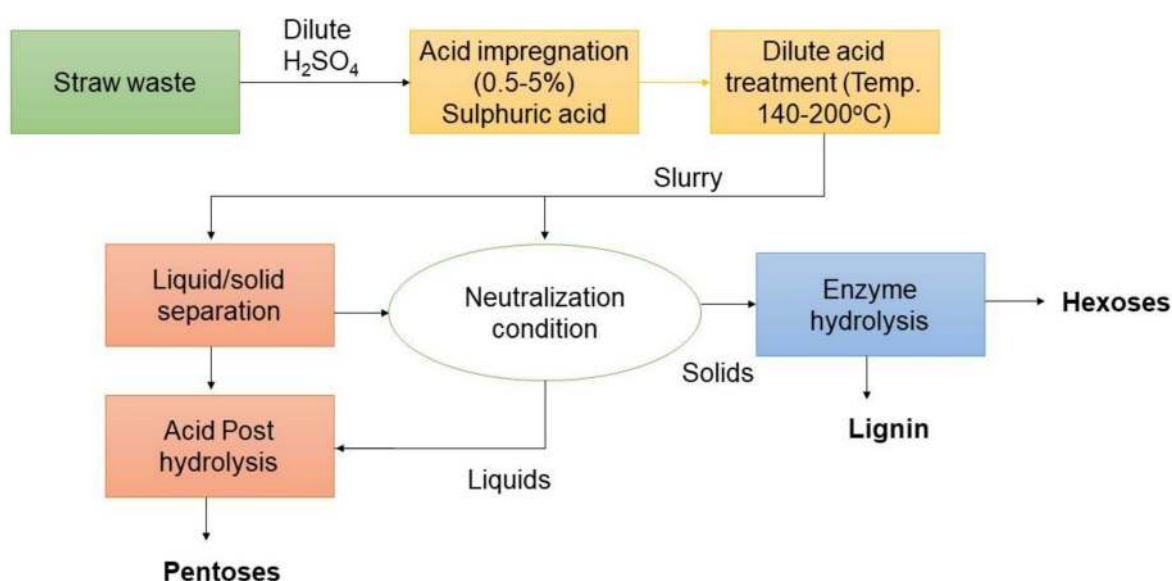


Figure 2. Schematic representation of sulphuric acid pretreatment.

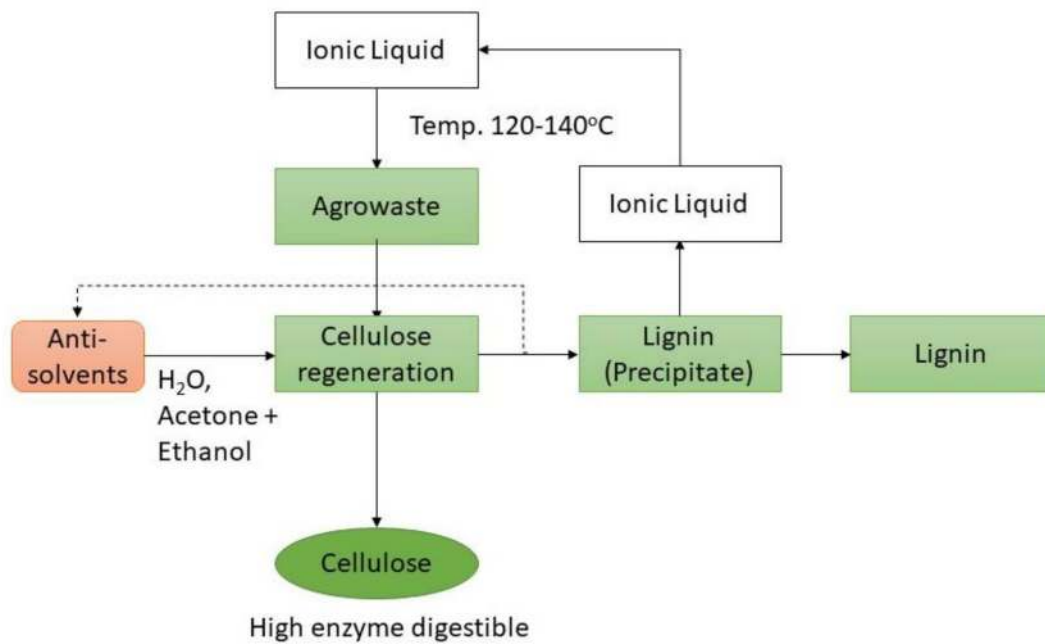


Figure 3. Schematic representation of ionic liquid pretreatment.

1.4.3. Alkali Pretreatment

Basic chemicals such as sodium hydroxide (NaOH), hydrazine, anhydrous ammonia, potassium hydroxide (KOH), or lime (Ca(OH)₂) (Figure 4) are used in alkali pretreatment. Even though this process can be used at room temperature, the reaction period is typically long, ranging from hours to days [29]. Song et al. (2018) showed that rice straw could be pretreated with sodium hydroxide (NaOH) for usage in a solid phase microbial fuel cell (SMFC). The SMFC with NaOH (5%) pretreated rice straw could maintain a maximal PD of 140 mW/m², which was 3.6 times that of the untreated SMFC [30]. The viability of alkaline pretreatment for sludge-fueled MFC was also verified by Xiao et al., which achieved a PD of 46.82–55.88 mW/m² with a quick alkaline procedure using concentrated sodium hydroxide [31].

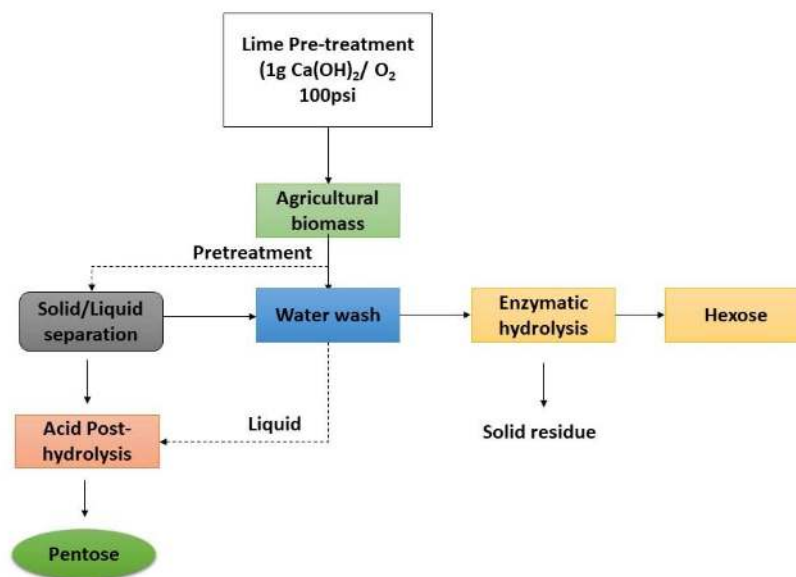


Figure 4. Schematic representation of agricultural biomass pretreatment using lime (Ca(OH)₂).

1.4.4. Biological Pretreatment

Biological pretreatment is a spectacular accomplishment that encourages the generation of minimal to no hazardous material, an environmentally sustainable procedure with low energy usage and moderate operating conditions. Cellulases generated by bacteria and fungi will hydrolyze and degrade the crystalline structure of lignocellulosic biomass, increasing sugar yields and improving MFC efficiency [32]. *Clostridium*, *Cellulomonas*, *Bacillus*, *Termomonospora*, *Ruminococcus*, *Bacteriodes*, *Erwinia*, *Acetovibrio*, *Microbispora*, and *Streptomyces* are among the bacteria that may generate cellulases [33]. The drawbacks of this approach include the need for a longer retention period of 10 to 14 days, close monitoring of growth conditions to prevent contamination, and a significant amount of room for biological pretreatment, both of which render it less economically feasible. Krishnaraj et al. (2015) used a novel three-chamber MFC to produce bioelectricity while simultaneously decaying lignocellulosic biomass (sugarcane bagasse and corncob). In the first compartment of the three-chamber MFCs, *Oscillatoria annae* degraded the LCB. Anodic inoculums of *Oscillatoria annae* and *Gluconobacter roseus* were used to produce electricity in MFCs utilizing decomposed substrates from the first chamber. For sugarcane bagasse and corncob as substrates, the maximum PD was 8.78 W/m³ and 6.73 W/m³, respectively [34].

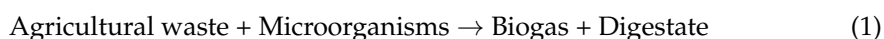
1.5. Route for Conversion

At present, many technologies such as biochemical and thermochemical conversion techniques have been put in place for the proper utilization of agro-waste and beneficiation into valuable products. The biochemical conversion technique employs microbial consortia for the complete degradation of the agro-waste. On the other hand, the thermochemical conversion process usually requires the agro-waste with a minute amount of moisture content, which requires additional energy for drying.

1.5.1. Biochemical Conversion

Today, the biochemical conversion of agro-wastes into energy is a promising and emerging field of technology for sustainable development. Depending on the type and the nature of waste, different microbial consortia can play a crucial part in the conversion processes of such waste for energy generation. Two important processes, i.e., anaerobic digestion (AD) and fermentation, are coupled with biochemical conversion techniques.

AD is usually carried out in an oxygen-free environment where microorganisms help degrade or break down organic waste products into bioenergy. The four (4) main important stages in AD are known. These are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each of the stages above is facilitated by different microbial populations that help convert one complex organic material to another. Most microorganisms associated with agro-waste biodegradation in AD processes include *Pseudomonas*, *Bacillus*, *Streptococcus*, *Clostridium*, *Methanococcus*, and *Methanobacteria* spp. These are mostly employed when handling waste with a high moisture content of about 80–90%. Equation (1) summarizes the stoichiometric relationship between agro-waste biodegradation by microorganisms in AD for biogas production, a renewable energy source.

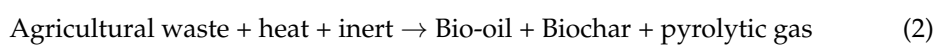


In the fermentation process, which also works in the absence of oxygen, the production of valuable products such as alcohol, organic acids, and a mixture of gases due to microorganisms' action is observed. It is believed that the fermentation of agro-waste is difficult and time-consuming due to the presence of long-chain polymeric molecules and requires acid or enzymatic hydrolysis before fermentation to produce valuable end-products. For instance, bio-butanol production can be achieved with the help of a bacteria called *Clostridium* spp., coupled with sugar production from various types of agro-waste. The process comprises two main steps, i.e., acidogenesis and solventogenesis, which is

referred to as acetone, butanol, and ethanol (ABE) fermentation. Hence, it is a promising technology, but it is costlier and time-consuming.

1.5.2. Thermochemical Conversion

This conversion process consists of pyrolysis, gasification, and combustion. In this process, the treatment of agro-waste into valuable and important products such as biochar, bio-oil, biofuels, etc., usually requires a high temperature. Pyrolysis refers to the thermal depolymerization of agro-waste in an atmosphere with a constant supply of heat. Among the sources of feedstock used for pyrolysis is agro-waste such as rice husk, corn stover, wheat straw, etc., woody biomass (redwood, teak, etc.), and energy crops like bamboo, sorghum, etc., and municipal solid wastes [35]. As a result of the constant and rapid heating of such agro-waste leads to the production of vapor made up of various hydrocarbons coupled with condensation to yield an organic liquid called bio-oil [36]. Moreover, the product obtained from pyrolysis depends primarily upon the composition of the agro-waste used and the interaction between the produced liquefaction products influenced by different parameters such as temperature, heating rate, inert flow rate, and particle size, and conversion time. Due to the influence of these parameters, pyrolysis can be classified as fast, slow, or flash. Pyrolysis is a flash when it operates at a lower temperature, with a lower heating rate and longer vapor formation time. In comparison, fast pyrolysis tends to work at a higher temperature, higher heating rate, and short vapor formation time. Hence, the primary end-products of slow pyrolysis are biochar, bio-oil, and pyrolyzed gas with varying percentages of 35–40% for biochar and 30–35% for pyrolyzed gas. Similarly, flash and fast pyrolysis produce an end-product of biochar (12%) and pyrolyzed gas (13%), while bio-oil is about 75% of the end-product (Equation (2)) [37].



Another vital thermochemical process is the gasification of the agro-waste that works on the principle of a partial oxidative atmosphere at some specific high temperature between 800–1000 °C. It employs a similar feedstock (e.g., agricultural waste) to that which is used in pyrolysis but produces an important end-product, i.e., syngas, made up of 85% of carbon monoxide (CO) and hydrogen gas (H₂), with some proportion of tar (5%) and biochar (10%) [38,39]. The gases produced can also be used in a turbine or engines as fuel as they contain a high calorific value. Studies have shown that, for the gasification to work, it depends on two different modes of processing, i.e., fixed-or fluidized-bed processing. Gases with a lower calorific value of 4–6 MJ/NM³ are seen in the fixed-bed processes. In contrast, fluidized-bed gasification is mostly seen in the provision of uniform temperature distribution, usually in the gasification zone [40]. For combustion, a standardized oxidative-high temperature process is used for the feedstock. As such, it is said to be a heat-based degradation process involving the conversion of chemical energy of biomass to yield heat and power in addition to carbon dioxide and water [41]. The generated energy from combustion can be used in turbines and boilers, among other processes, albeit the moisture content of the waste to be combusted should be below 50%.

1.6. Up-Gradation of End-Products

Recent studies have laid much emphasis on agro-waste-AD systems, in which a mixture of 40–65% of methane (CH₄), 35–55% of carbon dioxide (CO₂), some traces of hydrogen sulphide (H₂S), nitrogen gas (N₂), H₂, water vapor and other components (e.g., volatile hydrocarbons, chlorinated hydrocarbons, etc.) are produced as raw biogas. Similarly, the removal of contaminants, mainly H₂S, CO₂, and water vapor, in addition to some other toxic components from the biogas stream, is termed biogas up-gradation. This is usually performed to obtain a methane-rich gas of >96% CH₄. In the biogas up-gradation process, three main techniques are usually used, i.e., pressure swing adsorption, absorption (physical and chemical), and membrane separation [42]. Pressure swing adsorption is carried out based on the molecular size to adsorb unwanted CO₂, H₂S, N₂, and O₂ from the biogas

stream, and, as such, 96–98% of pure methane is obtained. The most commonly used adsorbent materials during biogas up-gradation techniques are activated carbon and zeolites. Another technique employed in biogas purification is the physical water scrubbing method based on the increased solubility of CO_2 and H_2S in the water compared to CH_4 . Other separation techniques used to remove CO_2 and H_2S from the biogas stream include amine scrubbing, caustic scrubbing, and amino acid salt solution usage. Examples of commonly used amines for chemical absorption are monoethanolamine, aminoethoxy ethanol, etc. On the other hand, the membrane separation technique involves using permeable membranes, which helps in trapping some other biogas constituents. In fermentation, the conventional method used for liquid biofuels up-gradation is distillation, which operates on the principle of the volatile nature of the substances in a mixture. The separation can be carried out primarily based on the less heavy products. Other classes of distillation that can be used for the product up-gradation include extractive, conventional, azeotropic, and molecular distillation. Hence, when an end-product undergoes an up-gradation process using the above processes, it can be utilized efficiently in various technology fields and serve as a promising alternative for renewable energy process development.

2. Agricultural Waste Usage in Microbial Fuel Cell Technology

The technological approach of MFC in electricity generation fulfills numerous requirements. It allows the recovery of electricity from liquefied agro-waste and the removal of pollutants when wastewater is used. Therefore, MFC refers to the system of bioelectrochemical components that aids in converting organic matter to energy from a large source of complex carbon-based compounds. This has been achieved through the action of microorganisms on waste to produce electrical energy (Figure 5) [43].

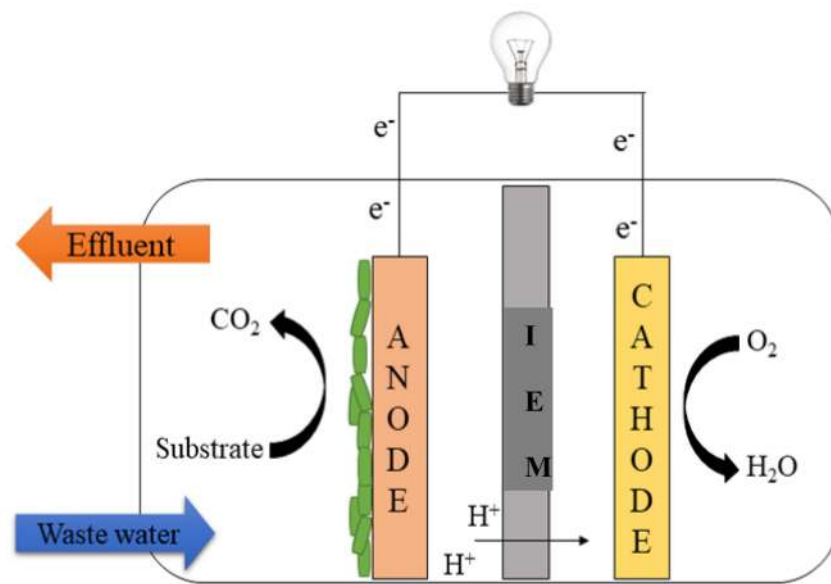


Figure 5. A schematic representation of an experimental set-up of a dual-chambered MFC.

However, within the MFC, the bacteria facilitate oxidation processes that oxidize the organic substrates, leading to the production of electrons transferred by several different enzymes within some essential cells. At the terminal section, electrons are released in the cathode compartment leading to a reduction in oxygen. Today, MFCs have developed two emerging solutions, which are of significance, contributing to environmental concerns' mitigation, i.e., the production of an abundance of pollutant-free and hygienic water while generating the required power at some stage of wastewater treatment in the MFC. In essence, MFC is a promising technology that can achieve the simultaneous production of energy and the treatment of wastewater [6].

The COD removal efficiency was reported in MFC technology for wastewater treatment using such technology being associated with an emergence of a need for renewable energy sources. Although MFC technology still needs further improvement that can make them economically viable and attractive on the international market, it can be another system of organic matter removal from the effluent of different industries. The organic matter removal rate of the MFC compared to the other wastewater treatment systems was estimated, with the result indicating that the removal rate was up to 7 kg COD/m³·day. In comparison, a range of 0.5–2 kg COD/m³·day was determined for generic wastewater treatment systems, with studies reporting 8–20 kg COD/m³·day removal being directly associated with AD [44,45].

The inadequate production of power and current cannot be the sole measure of MFC's practical application and implementation on an industrial scale for electricity generation. For example, in comparison with AD, the gain in electricity generation in using MFCs was seen to be very low with reduced capital investment and operational costs, respectively [46].

In previous studies, the use of MFC has played a vital role in wastewater treatment. It provided various alternatives as a secondary means of energy production and a promising way for technological upscaling in wastewater treatment, particularly whereby agro-waste is to be oxidized [47]. Therefore, the use of wastewater from agro-based industries, in particular, seems to be promising, as such wastewater is constituted by a high content of oxidizable organic matter with its biodegradability, i.e., BOD/COD ratio, being greater than 60% [48–50].

Overall, a typical MFC consists of two chambers, an anode and cathode for oxidation-reduction reactions, respectively, with the chambers usually separated by an anion exchange membrane (IEM) (Figure 4). Electrons are usually produced after an anodic oxidation reaction which leads to the production of electric current. In contrast, protons, on the other hand, travel through an IEM as they are utilized for cathodic reduction reactions to generate water [51]. Other studies have shown that the oxidation-reduction reactions from both anodic and cathodic sides from organic matter-containing wastewater using electron acceptors can be attached bio-electrochemically in an MFC [52].

In a typical mediator-less MFC, the extracellular electrons are transferred via electroactive bacteria (EAB). These microbes are dissimilatory metal or sulphate-reducing bacteria. In the presence of an anode, they donate extracellular electrons to the anode to continue anaerobic respiration. These EABs capture electrons released by the oxidized organic matter and transport it directly to the anode. This form of direct electron transfer is further divided into three pathways: Cytochrome mediated, nanowire, and electron shuttle or soluble mediators. In electron transport, cytochrome C (CTC) plays a critical function. It is a heme-containing protein that is found in both archaeobacteria and eubacteria. Electricity harvesting is aided by Cytochrome C. CymA, whose N-terminal is connected to the inner membrane. At the same time, the C-terminal is exposed to the periplasm, is a good example of CTC. Because it links the inner membrane to the periplasmic region, CymA is an essential electron route. It is important in anaerobic respiration and interacts with a variety of terminal reductases, including nitrate and fumarate reductases. Microbial nanowires are one of the most recent methods for transporting electrons. These nanowires are the bacterium's pilus, which are electrically conductive and were found by reducing iron oxide using *G. sulfurreducens* bacteria. Other bacteria also have an electrically conducting pilus, indicating the presence of bacterial appendages in the environment. The electron shuttles, also known as electron mediators, are gram-negative bacteria secretions that assist power generation in MFCs. Ideally, these mediators should be soluble, stable, reusable, and environmentally benign, with a redox potential between the bacterial membrane protein and anodic substance. Endogenously generated flavins by *Shewanella* species are a well-known electron shuttle in MFCs. Riboflavin (RF) and flavin mononucleotide (FMN) are the most common, as described in Savla et al. [53]. As previously stated, MFC uses two types of bacteria: mediator-dependent and mediator-independent. *Actinobacillus succinogenes*, *Proteus mirabilis* and *Pseudomonas fluorescens* are among the bacteria that need mediators, according

to the National Institutes of Health. There is a growing interest in bacteria that do not need mediators, such *Shewanella putrefaciens* [54], *Rhodospirillum rubrum*, and *D. desulfuricans* [55]. Various materials utilized in the MFC components have been illustrated in Table 1.

Liquefied agro-waste is considered one of the most promising substrates for microbial oxidation in the anodic chamber of the MFC. It contains a high amount of carbohydrates, organic matter, and other nutrients [56].

Table 1. Various materials utilized in MFC configuration and construction.

MFC Configuration	MFC vol. (L)	Type of Operation	Anode Material	Cathode Material	Power Output	References
Single chamber	20	Continuous	Activated Carbon	Carbon cloth	0.35–0.9 W/m ³	[57]
	250	Continuous	Carbon brush	Carbon mesh	0.47 W/m ³	[58]
Two chamber	40	Continuous		Carbon cloth	0.44 W/m ³	[59]
	50	Batch		Activated semicoke	43.1 W/m ³	[60]
Stack	10	Continuous	Carbon felt	MEA	6 W/m ³	[61]
	60		Granular graphite		4 W/m ³	[62]
	72		Activated carbon		50.9 W/m ³	[63]
	94		Stainless steel mesh		2 W/m ³	[62]
	200		Carbon brush	Carbon cloth	0.009 W/m ³	[64]
	1000		Activated carbon		7–60 W/m ³	[65]

Microbial Fuel Cells Used in Laboratory Studies for Scale-Up Purposes

Several MFCs have been used in the laboratory for scale-up studies. These include single or dual-chambered cylindrical and cubic MFCs. Similarly, tubular or flat-plate designs have been employed for most scale-up studies. The MFC configuration mostly used in scale-up studies includes a tubular anode surrounded by a separator to isolate the anode from the cathode [66] electrically. Moreover, the MFCs, usually tubular or a product of cylindrical construction materials, can easily be upscaled. Most of the materials that are used as support materials to scale-up reactors include polyvinyl chloride, cylindrical glass, polypropylene, measuring cylinders, cation exchange membranes produced in a tubular shape, and nylon tubing. Most recent studies have shown the mechanism of operation of tubular designs in a continuous flow mode. This resulted in further opportunities for scale-up because of the tube length extension. As such, this culminated in the extension and additional tubular MFC modules to form an MFC stack. However, when considering the flat-plate and tubular designs, multiple MFCs configured this way can only be hydraulically controlled in parallel or series. In another arrangement in series, the effluent flow goes through each of the MFC modules sequentially; on the other hand, each MFC module obtains the same influent when a parallel connection is used. Overall, this means modules of MFCs can be connected in parallel or series to increase voltage and current generation, respectively [53].

3. Agro-Industrial Wastewater as a Substrate for Microbial Fuel Cells

Generally, agro-food processing waste is comprised of a large number of organic constituents, which can be either in a solid, liquid, or gaseous state. For example, carbohydrates, fat, etc., present in wastewater, indicate the need for the maximum oxygen demand for biodegradation [67]. Various solids in the wastewater are known to halt or reduce the MFCs efficiency. Severe pollution challenges can occur to the environment when there is an absolute lack of proper treatment or management of such agro-industrial wastewater [66,68]. Conventionally, agricultural activities lead to the production of different amounts of food debris and wastes from either man or animal due to various activities

derived directly from the human or animal population, which contribute significantly to effluent discharged into receiving streams [69]. The agricultural production streams that usually produce agricultural residues and wastewater require several treatments to avoid water pollution, which enormously varies in pollutant composition and concentration. Some effluent from various agro-industries and their suitability for use in MFCs is discussed in subsequent subsections.

3.1. Palm Oil Mill Effluent

Palm oil is a digestible and high nutritive oil manufactured in some regions globally, mainly for food and energy production in some countries. The palm oil industry usually produces two main products, crude palm oil and solid palm kernels [70]. Moreover, residual waste of different types is usually produced from palm oil-agro industrial processes [71]. Many waste types, including palm oil mill effluent (POME), are normally obtained from different extraction processes. The treatment of such waste can confer advantageous attributes to MFC processes, resulting in high energy generation [72,73]. POME inoculated with an anaerobic sludge has been treated as reported by some researchers with the aid of a simple two-chambered MFC. This process demonstrated a higher power output (Pd_{max}) of 45 mW/m^2 to 304 mW/m^2 ; albeit, achieving a considerably lower coulombic efficiency (CE) percentage of 0.8% and 45% COD removal [72].

3.2. Mustard Tuber and Molasses Wastewater

Mustard tuber processing is often known to generate a large volume of effluent, with the wastewater being of high strength and salinity. A case study was observed when a two-chambered MFC was employed to treat mustard tuber wastewater, recording a Pd_{max} of about 246 mW/m^2 , including 67% and 85% of CE and COD removal [74]. On the other hand, molasses are broadly employed in many research fields and are usually derived from sugarcane mills. It is usually considered a rich source of sugar and minerals such as Ca, including vitamins. It contains a high COD concentration, which varies from 60–100 g/L and thus acts as a major pollutant from the sugarcane processing factories. When the diluted molasses wastewater is used in MFCs, a 62 mW/m^2 power density was recorded, whereas 81% of COD was removed using a mixed inoculum [75]. A generated bioelectricity of 0.18 W/m^2 was recorded from an MFC treating sugarcane molasses whereby *Brevibacillus borstelensis* STRII was used [76]; additionally, there was an increase in power density when the sugarcane molasses concentration was increased. This demonstrates a promising way to manage the substrates in wastewater and energy generation whereby MFC integration in dark fermentation processes can result in positive environmental outcomes [77]. Table 2 summarizes some of the agricultural product processing wastewater used in MFC technology for its treatment and CE.

Table 2. MFC types and performance using different agricultural product processing wastewater.

Wastewater Type	MFC Type	Feeding Mode	Volume (mL)	COD Removal (%)	CE (%)	Reference
Cassava mill wastewater	Two-chamber MFC	Continuous	1500	72	20	[78]
Cereal processing wastewater	Dual-chamber MFC	Batch	310	95	40.5	[79]
Mustard tuber wastewater	Dual-chamber MFC	Batch	150	57.1	67.7	[74]
Olive mill wastewater mixed with domestic wastewater (1:14)	Air-cathode single-chamber MFC	Batch	28	60	29	[80]
Starch extract (potatoes)	Mediator-less two-chamber MFC	Batch	100	61	18.5	[81]
Raw corn stover	Bottle-type air cathode MFC	Batch	250	42 ± 8 (cellulose) $17\% \pm 7$ (hemicellulose)	3.6	[8]
Rice milling	Earthen pot MFC	Batch	400	96.5	21	[82]
Steam exploded corn stover	Batch	Batch	250	60 ± 4 (cellulose) 15 ± 4 (hemicellulose)	1.6	[8]
Rice straw hydrolysate	Air-cathode single-chambered	Batch	220	49–72	8.5–17	[83]
Steam exploded corn stover	Single-chambered air-cathode MFC	Batch	28	60–70	20–30	[84]

3.3. Brewery Wastewater

Brewery wastewater is another high-strength wastewater that can be used in energy generation. It is generated in large volumes during beer production, whereby several processing steps, such as fermentation, saccharification, etc., are undertaken [59]. It has been studied that the MFCs can carry out brewery wastewater treatment [85,86]. A 20 L MFC was tested for one year [59], with the MFC being operated in different modes and/or phases, with phase A producing an external resistance (R_{ext}) of 10 ohms and phase B producing R_{ext} of 3.7 ohms, and up to R_{ext} of 5.3 ohms in other phases, with the overall COD removal efficiency of up to 94.6% being achieved; albeit, the energy obtained seemed to be low, i.e., 1.61 mW/m² [59].

3.4. Winery Wastewater

Winery wastewater with different compositions was tested using MFCs made up of two single-chamber air cathodes [80]. A wire made up of titanium along with carbon fiber was put in place of generic anodes, while on the other hand, cathodes were made up of platinum-coated carbon cloth of 0.4 mg Pt/cm². The white wine wastewater resulted in less promising results with an energy generation capacity of 263 mW/m²; albeit a significant quantity of COD (90%) and BOD (95%) removal was achieved with a CE of 15%. Comparatively, red wine wastewater had 111 W/m², with a recorded 27% COD removal, whereas a maximum BOD removal of 83% was achieved; hence, a lower CE of 9% was observed. These experiments indicated that different wastewater, even from the same industry, can have different usable substrates with differentiated compositional characteristics, which determines the MFC's power output. This was facilitated by diverse and different microbial populations found in the anode; besides, the negative influence on MFC performance was due to a high concentration of polyphenolic compounds in some winery wastewater.

3.5. Other Agricultural Activity Effluents and Waste

Most agro-industrial activities in the food, plant, and animal processing industries generate a high quantity of wastewater. Most agricultural wastewater has been demonstrated as suitable for use in MFCs, i.e., either used in a minute and/or large quantities [87]. One of the recent studies has shown that sugar beet processing wastewater at a concentration of 2.56 g COD/L was able to generate a power of 1.41 W/m² which in turn contributed to the complete removal of suspended solids up to 97% of organic matter [87]. However, the hydraulic retention time was up to 40 days. Similarly, up to 93% can be removed from coconut husk retting wastewater containing phenols (potent toxicants) with a concentration of up to 320 mg/m³, with 91% COD removal being achieved in a dual-chamber MFC [88]. Similarly, the use of crude starch extracts from potato processing has shown promising results when used in a dual-chamber mediator less MFC, culminating in 18.5% CE and a COD removal of 61% [81]. Furthermore, olive mill wastewater (OMW) is usually produced during the processing of olives and is considered the most pollutant containing wastewater constituted by up to 100,000 mg/L COD. This type of wastewater is characterized by a strong, intensive black color, acidic pH, a strong odor, and toxicant concentration in the range of 200–800 mg/L in the form of polyphenols [89] while possessing differentiated values of electro-conductivity [90].

It has been reported that an MFC made up of a 12 mL inner volume and a single-chambered air-cathode can be used with diluted OMW in a ratio of 1:10 with OMW acting as a sole source of carbon for bioenergy generation. A COD of 65% was removed for this type of set-up, and a total phenolic content of up to 49% was removed while reaching a maximum voltage generation of 381 mV. In a similar study, an MFC made up of a single-chambered air cathode was used; albeit, with a cathode equipped with platinum-coating (0.5 mg Pt/cm²) enveloped with a carbon cloth; a configuration which was demonstrated as being efficient for OMW treatment [91]. However, OMW is not a promising substrate for energy production and as such, is not usually considered as an alternative source of

substrates in MFC technology development. However, a mixture of any other wastewater combined with OMW generated high-power density results whereby COD was removed with a low yield in CE [56]. This combination was determined to produce a virtuous power output and has shown promising results, particularly for OMW treatment [91].

4. Agricultural Residues

Agricultural residues are considered one of the most prominent substrates in renewable energy production and carbon source content due to their availability as a cheap renewable energy feedstock.

Moreover, any microbial community cannot directly utilize the agricultural residues in MFC to produce electricity. To generate fermentable sugar hydrolysates easily, either acidic or enzymatic pre-treatments is required [6]. Some of the important agricultural residues that contribute to bioelectricity generation include wheat straw, corn stover, rice straw, cassava mill effluent, plant and flower waste, vegetable waste, etc.

4.1. Wheat Straw and Corn Stover

Wheat straw is a known agricultural residue containing cellulose of about 34–40% of the total organic carbon of the waste. Hemicellulose is 21–26% of the organic carbon, while lignin is 11–23% of the total organic carbon content. Due to hydrolysis, the formation of a hydrolysate rich in carbohydrates can be achieved [7]. Some studies have shown wheat straw as an alternative means of carbon source provisioning in MFCs to generate electricity. The hydrolysate is formed after converting the solid residue into a carbohydrate-rich liquid, which can be used as a substrate in MFC to obtain a maximum power density of up to 123 mW/m² when the initial concentration of the substrate was 1 g/L. However, the reported energy output seemed to be on the lower side. Overall, wheat straw showed a high efficiency as a substrate in MFC. However, corn stover, another agricultural residue containing 70% cellulose and hemicellulose, can undergo conversion processes through cellulosic enzymatic treatment or steam explosion into sugar hydrolysates containing a similar profile of sugar content to other agricultural residue hydrolysates obtained [6]. In another experimental setup, the substrate as a hydrolysate from “raw corn stover” employed in the production of electricity in an MFC, generated a considerable amount of low power output, unlike in control MFC whereby glucose was employed [8]. This means an improvement is required in producing a hydrolysate from wheat straw and corn stover that is suitable for use in MFC technology development.

4.2. Rice Straw

Rice straw consists of mainly lignocellulosic biomass with varying compositions of organic carbon. The electricity production can be carried out using this agricultural residue, with its hydrolysate being observed to be suitable to serve as a substrate. Comparatively, industrial wastewater has been recorded to generate maximum energy of 2.3 mW/m³, while achieving a 96.5% COD reduction; albeit, a pot MFC was used [82]. However, in the case of a carbohydrate-rich hydrolysate from rice straw in which 400 mg COD/L removal was observed, the recorded maximum energy output of 137 mW/m² was obtained. Still, when the conductivity of the solution was increased to about 17 mS/cm, about 293 mW/m² power density was reported [83]. In a two-chambered MFC to produce electricity without a pretreatment process, the powdered rice was applied directly to the anode side of the MFC in the presence of a mixed culture containing bacteria capable of breaking down the cellulose in the straw, culminating in a 54.3% increase in energy generation [76]. In other studies, the highest generated power was 190 W/m³ when the utilized substrate underwent no pretreatment process; a mixed culture containing bacteria capable of breaking down cellulose in the MFC was used [92]. In this regard, MFC has shown a promising and convenient channel of treatment of wastewaters containing rice straw for the effective management of the wastewater to minimize pollution in the environment, which will simultaneously generate electricity.

4.3. Cassava Mill Effluents

In the processing of cassava to produce starch, a large number of effluents rich in COD and total solids with high acidic pH, including a minute concentration of cyanide, are released to freshwater streams can be alternatively redirected for energy generation in MFC technology. The starch processing industry effluent is rich in carbohydrates. It usually consists of a high organic content, which ranges from 10–16 g/L, thus making it suitable for use in MFCs. Some studies have demonstrated the feasibility and biodegradability of such effluent in MFCs for the treatment of cassava mill effluent, with a high percentage (88%) of COD being removed, while 1.7 W/m² of power was generated [78,93]. An increase in energy recovery of 22.19 W/m³ in a single-chambered MFC was also recorded after adding a buffer solution for pH correction to within the range 5–9 [68]. Many microbial species such as *Pseudomonas aeruginosa*, *Bacillus cereus*, *Bacillus subtilis*, *Escherichia coli*, *Saccharomyces cerevisiae*, *Aspergillus niger*, *Aspergillus flavus*, and *Rhizopus* sp., were all found to be in the anodic biofilms in the MFC treating cassava mill effluent [94].

4.4. Vegetable Waste

Vegetable waste can be regarded as another promising substrate that can generate energy from various MFC designs. It is usually generated during the washing and cutting of vegetables from various vegetable markets, restaurants, and some vegetable packaging industries. The electrogenic population in vegetable waste MFC tended to utilize the slurry form of the waste better during hydrolysis. In other studies, when the proportion of cooked and uncooked potato substrate was used in an MFC, increasing the coulombic yield culminated in 86.3% of COD removal (Du 2017; Du et al., 2018). An average current density of about 72.2–100.2 mA/m² was recorded, and 15.6–17.3% COD removal was achieved using vegetable waste containing effluent in combination with MFC; however, a diverse microbial consortium was needed, with some organisms such as *Firmicutes*, *Proteobacteria*, and *Geobacter* sp. proliferating in the anodic solution of the MFC. These organisms were the most dominant when using potato wastewater as a substrate, conferring the characteristics of suitable electrogens for electron transfer (Du, 2017). Moreover, a U-shaped MFC generated a current density of 314 mA/m² at a resistance of 123 ohms when a vegetable waste extract was applied as a substrate, demonstrating a higher power density output than the dual-chambered MFCs [95].

4.5. Fruit Waste

To date, the biodegradation of fruit waste effluent is a challenge due to monosaccharides, disaccharides, and polysaccharides which can facilitate an exponential proliferation of disease-causing organisms when such effluent is released into rivers untreated. As observed in different MFCs configurations, a proportion of fruit wastes can generate about 330 mV during conversion, as observed in some biotransformation of effluent from fruit processing (Table 2) [96]. In another study, a voltage of 0.563 V and 0.492 V in MFC was generated when an orange and banana peel effluent was used with no chemical pretreatment. The residual total reducible sugars were a source of carbon for the microbial consortium [97]. Different fruit processing effluent containing residues and soluble components from orange, lemon, grape, and mixed fruit processing were observed for their performance in MFCs to assess the generation of power output compared to conventional MFCs. Improved performance resulting from highly fermentable carbohydrates was observed; albeit, the concentration of organic acids such as citric acid from lemon fruit processing, might have been detrimental for the MFC performance [98]. Lemon processing effluent was considered a source of energy in which the electrogenic population in the dual-chambered MFC led to an electron recovery of 0.99 A/m² with 32.3% CE [99]. Therefore, fruit waste and peel extract containing effluent can be considered an alternative source of energy-rich support for electrochemical oxidation in MFCs and possibly can invigorate an emerging renewable energy technology development field.

4.6. Plant and Yard Waste

Plant and yard waste residue contain a relatively high concentration of cellulose, hemicellulose, and lignin. This can undergo hydrolysis by providing a pretreatment step to make it easily biodegradable during microbial oxidation in MFCs. When a hydrolysate was generated from plant and yard waste, an energy output of 1.02 W/m^2 with COD removal efficiency of 76% and CE of 69% was recorded using an air cathode MFC [100]. Some aquatic plants have been demonstrated to have similar attributes to those observed for generic plant and yard waste hydrolysates with *Canna indica* (Canna)—rich in cellulose and hemicellulose. Lignin is observed to be suitable to generate a hydrolysate with a consortium maintenance capability. For the use of hydrolysates from these plant- and yard-based hydrolysates using an air cathode MFC, about 0.45 W/m^3 of volumetric power density can be generated [101].

5. Treatment of Animal Debris Waste and Wastewater in Microbial Fuel Cells

5.1. Slaughterhouse and Animal Debris Containing Waste

Generally, slaughterhouses and animal manure are usually derived from the livestock industry, which generates a large amount of wastewater containing suspended solids and high organic matter content. The release of such wastewater into municipal wastewater treatment works can cause major environmental odor problems if released untreated. The wastewater produced from slaughterhouses consists of different substances that the action of microorganisms can break down. The wastewater also has many suspended nutrients such as proteins, carbohydrates, minerals, and fat, all of which are also present in animal blood [102]. Wastewaters derived from abattoirs are usually discharged in several different channels due to a lack of monitoring for such discharges.

Previously for bioelectricity generation, both the slaughterhouse and animal carcass cleaning wastewater were employed in MFC technology, with a generated power of 578 mW/m^2 being recorded [103]. Similarly, the generation of bioelectricity using animal debris containing wastewater as a substrate achieved a maximum power density of 2.19 W/m^3 in an up-flow tubular MFC made up of an air-cathode, recording a COD removal of 50.66%. In contrast, a low CE (0.25%) was recorded elsewhere [104].

5.2. Livestock Compost Wastewater

Livestock compost wastewater is also one of the effluents most produced in the livestock industry. Livestock compost is described as an important source of some organic and inorganic components [105]. Some of these components can be easily broken down into simpler molecules, which in turn can provide a source of easily fermentable constituents for consortium support in MFCs [106]. Overall, a complex organic substrate may assist in the propagation of different species of microorganisms. Generally, exoelectrogenic bacteria possess a limited ability to utilize complex substrates. Many different microbial populations are needed for the wastewater to undergo the required oxidation processes and with microbial species undergoing directed evolution to decompose semi-biodegradable carbon-based compounds [107]. For example, when wastewater treatment was carried out in an air-cathode MFC using cattle manure sludge as a substrate with and without any mediators, increases in power density up to 200% were observed when methylene blue was used as a mediator [108]. In another study, a maximum power density of 16.3 W/m^3 was recorded using suspended cattle manure as a substrate. This was achieved when a cassette-electrode MFC configuration operating in a batch mode was used, with 41.9% COD removal being reported in the first ten days of the MFC operation [106]. Some studies have demonstrated that using a small number of substances derived from livestock waste via fractionation in combination with compost wastewater as a substrate showed promising results when fed into an MFC. Generally, $67\text{--}215 \text{ mW/m}^2$ power density was generated by livestock waste and compost wastewater which was greater than when supplied as a liquefied feedstock in MFCs. When livestock compost was employed and the substrate is halted in MFC, only 15.1 W/m^3 of power density was produced [109].

5.3. Swine Wastewater

A greater emphasis on the use of swine wastewater treatment is currently being advocated for, with some studies showing that a 110 L capacity MFC can achieve a maximum of 5 kg COD/m³.day reduction, representing a 65% efficiency in terms of COD removal while generating 110 Wh/kg COD net energy [110]. In another case study, about 85.6%, 70.2% and 93.9% of ammonium nitrogen, total nitrogen, and total organic compounds were removed using *Chlorella vulgaris* algal-biocathode photosynthetic MFC, achieving a maximum power density of 3.7 W/m³ with carbon dioxide sequestration. Others reported swine wastewater treatment while generating a maximum power density of 45 mW/m² in MFC made up of two-chambered aqueous cathodes [111]. In a further experiment of similar wastewater, a maximum power density of 261 mW/m² was generated in an MFC made up of a single-chambered air-cathode [112], whereas 382 mW/m² was recorded elsewhere [113].

5.4. Poultry Slaughterhouse Wastewater

Disposed poultry slaughterhouse waste and effluents containing excreta from birds, feed, feathers, hatchery waste, urine, feces, sawdust, etc., were determined to be suitable to generate an engineered biofilm in the anode of an MFC. The biofilm was constituted by *Escherichia coli*, *Enterobacter*, *Citrobacter*, *Geobacter*, *Klebsiella*, *Lactobacillus*, and *Pseudomonas* spp. [114]. Using MFC with rice husk charcoal as an electrode in combination with effluent from poultry slaughterhouses generated a volumetric power output of 6.9 W/m³ while achieving a 40% dissolved organic carbon reduction [115]. Similarly, an energy generation harvesting rate of 278 mW/m² was observed with an effective 82% BOD removal efficiency in a continuous horizontal flow MFC [116].

5.5. Dairy Industry Wastewater

The most prominent characterization of dairy industrial wastewater is associated with its unique constituents attributed to differentially complex organics, including proteins, lipids, and polysaccharides. The hydrolysis of such wastewater can transform the wastewater components into organic acids, fatty acids, and sugars, respectively. The properties attributed to dairy industrial wastewater were seen as effective and efficient in an anolyte in MFC [117]. However, another important product rich in nutritional constituents from the dairy industry is cheese whey (CW) classified as milk casein obtained after the separation of milk constituents; hence, the dairy industrial wastewater containing CW treatment using MFC was evaluated by many researchers and reported in several investigations regarding the bioelectrochemical recovery of electricity from such MFC operations. CW contains high organic carbon-based compounds that can be broken down into simpler constituents that are readily available to microorganisms [118]. Results indicated electron transfer variability using different materials in MFC with different designs, i.e., single, dual, and tubular chambered MFCs, and different anodic materials, e.g., carbon graphite, stainless steel, composites, etc. The highest CE of 37.2% was recorded using a catalyst-free and mediator-less MFC treating wastewater from the dairy industry [119]. The electrical performances of the MFC increased with an increase in organic matter loading rates (OLRs) [120]; albeit, it was noticed that a high anolyte's COD concentration of up to 2800 mg/L could lead to a reduction in electrical energy, and the flow rate of substances in the MFC IEM may be lowered. Overall, CW containing wastewater has shown a promising result with an MFC made up of an H-type-two-chambered system connected to a carbon paper anode and a platinum-coated (0.5 mg/cm²) cathode, achieving the highest energy generation of up to 18.4 mW/m² with 94% of COD removal being recorded with the said MFC; albeit, operated in a fed-batch mode [121]. A CE of 11.3% was also reported, further showing CW containing wastewater as a promising substrate in MFCs [122]. Another system of an MFC operated in a four-fed batch mode using a cylindrical cathode made from carbon brushes, and carbon powder was determined to serve as an example of a suitable electrode and catalyst configuration for dairy wastewater treatment in MFCs. A comparative account of the substrate used in MFCs and their performance is given in Table 3.

Table 3. MFC efficiency is based on various substrates.

Substrate	MFC Configuration	Volume (mL)	Power Density	CE (%)	COD (%)	References
For types of food industry wastewaters						
Brewery wastewater diluted with domestic wastewater	Single chambered MFC	100	30 mW/m ²	—	90.4	[123]
Dairy wastewater	Single chambered MFC	480	1.1 W/m ³ (~36 mW/m ²)	7.5	95.49	[120]
Dairy wastewater	Annular single chamber MFC	90	20.2 W/m ²	26.87	91	[124]
Dairy wastewater	Dual Chambered MFC	300	161 mW/m ²	NA	90	[125]
Cheese whey	Dual chambered Tubular MFC	500	1.3 ± 0.5 W/m ²	3.9 ± 1.7	59.0 ± 9.3	[126]
Chocolate industry wastewater	Dual Chambered MFC	400	1500 mW/m ²	—	74.77	[127]
Molasses wastewater	Single chambered cuboid MFC	650	1410 mW/m ²	−1	53.2	[128]
Distillery wastewater (Molasses based)	Single chambered MFC	400	124.35 mW/m ²	Ft	72.84	[129]
Molasses wastewater mixed with sewage	Single chambered MFC	800	382 mW/m ²	—	59	[130]
Palm oil mill effluent	Cylindrical MFC	2360	41.8 mW/m ²	—	−60	[72,73]
			44.6 mW/m ²	—	−90	
Vegetable waste	Single chambered MFC	400	57.38 mW/m ²	—	62.86	[131]
Fermented vegetable waste	Single chambered MFC	400	111.76 mW/m ²	—	80	[132]
Cereal-processing wastewater	Dual Chambered MFC	310	81 ± 7 mW/m ²	40.5	95	[79]
For types of agricultural wastes						
Dairy cow waste slurry	Air cathode Double chamber MFC	—	0.34 mW/m ²	0.22	84 (BOD)	[133]
Manure	Air cathode single chamber	—	67 mW/m ²	1.3–5.2	—	[134]
Manure wash water	Air cathode single chamber	—	215 mW/m ²	—	—	[134]
Soil organic matter	Solid-phase Soil MFC	—	0.72 mW/m ²	—	—	[135]
Bean residue, ground coffee waste and rice hull	Solid-phase Compost MFC	—	264 mW/m ²	—	—	[136]
Powdered rice straw	H type MFC	—	145 mW/m ²	54.3% to 45.3%	—	[137]
Cattle manure slurry	Air cathode Cassette-electrode microbial fuel cell	—	765 mW/m ²	28.8	41.9–56.7	[106]
Cow manure	Single chamber Compost MFC (Pt in cathode)	—	349 ± 39 mW/m ²	—	~50 (carbon)	[138]
Wheat straw hydrolysate	H-type double chamber MFC	—	123 mW/m ²	15.5–37.1	—	[139]
Diluted wheat straw hydrolysate	Double chamber MFC	—	148 mW/m ²	17 ± 2	95% (xylan and glucan)	[140]
Steam exploded corn stover hydrolysate	Air cathode Single chamber MFC (Pt/C cathode)	—	371 ± 13 mW/m ² (neutral)	20–30	93 ± 2 (Neutral pH)	[84]
			367 ± 13 mW/m ² (acid)		94 ± 1 (Acidic pH)	

6. Comparison of Related Works

In comparison to related studies, the quantity of various important factors, including CE, COD removal, and maximum energy generated, was recorded using different agricultural residues, agro-industrial wastewater, and other by-products generated from the agricultural industry. These wastes can be used as substrates in MFC technology development. Among the agricultural waste that contributes to the highest power generation in MFC includes wheat straw effluent, rice straw hydrolysate (without pretreatment), and corn stover along with the application of glucose as a substrate; although, the percentage rate of COD removal was seen to be very effective in MFCs when rice straw was used. Similarly, the use of vegetable waste extract produces a high-power output in U-shaped MFCs than dual-chambered MFCs. Overall, some convincing results were obtained regarding power generation using slaughterhouse and animal carcass debris containing

wastewater. In particular, cattle manure and manure wash wastewater were considered good substrates for bioelectricity production, with a high percentage of COD removal achieved. Other substrates such as disposed of poultry waste and swine wastewater can be used in MFCs, indicating a 65% COD removal, with plant, fruit, and cassava processing effluent achieving COD removal of up to 88%; although with low power production. A substantial amount of power density was observed with swine wastewater using an MFC made up of an air cathode in a single-chambered cell than in an algal bio-cathode in a photosynthetic MFC. Considering chicken manure treatment, 82% of BOD can be successfully removed with high energy production using a horizontal flow continuous MFC. Similarly, the treatment of mustard tuber wastewater in the dual-MFC has shown a good result with high energy recovery and a high percentage of COD removal. Other agro-industrial wastewaters containing agricultural activity by-products showed a poor performance in terms of power generation; this includes POME, brewery, and dairy wastewater, though it has proven that a high percentage of COD can be removed from these wastewaters with a moderate quantity of CE. For winery wastewater, only white wine wastewater with the less organic matter has shown a good result during power production with a high reduction of BOD and CE. Thus, the application of agricultural waste and its effluents to generate bioelectricity was demonstrated, with some adequate energy recovery. This can thus be considered as an alternative source of renewable energy technology, supported by different microbial communities largely found in the anodic solution of most MFCs; as these types of microbial communities confer characteristics of electrogens for efficient electron transfer, most especially to support redox reactions; therefore, this ultimately characterizes the ability of these organisms to support AD.

It has further been shown that sugar beet processing wastewater at a concentration of 256 g COD/L could generate a power of 1.41 W/m². Even for coconut husk retting wastewater containing phenol, 91% of COD was successfully removed when employed a dual-chamber MFC. Similarly, the use of crude starch extract from potato processing wastewater has shown promising results when used in a dual-chambered MFC, with a substantial amount of energy recovered. In another comparative analysis, it has been observed that OMW is not usually considered a promising substrate for MFCs compared to sugar beet processing wastewater and coconut husk retting wastewater in terms of energy production. Thus, it is not usually considered an alternative substrate source in MFC technology unless combined with another substrate source. Conclusively, when various comparative analyses of related MFC-substrate studies were conducted, it is clear that substrates such as wheat straw effluent, rice straw hydrolysate, and corn stover are good substrate sources that can be utilized in MFCs for energy generation. Others include slaughterhouse and animal carcass debris containing wastewater, which provides a large quantity of energy. In contrast, substrates such as POME, brewery, plant and yard waste, and dairy wastewaters showed a poor performance in energy recovery using MFCs. To this end, other studies have shown better applicability of some substrates such as swine wastewater, livestock compost wastewater, fruit waste, vegetable waste, and cassava mill effluent to facilitate the generation of electricity using MFCs. However, all these studies have elucidated the fundamental MFC design approach in increasing power generation quantity.

However, among the physical factors affecting the performance of MFC include the type of electrode materials used (graphite rod, graphite fiber brush, carbon cloth, carbon mesh, carbon paper), the surface area of the electrode, and electrode-spacing, and characteristics of the catholyte. On the other hand, biological factors are considered as another key component that governs the overall MFC performance, which includes biocatalyst (mixed culture, monoculture) proliferation and activity, including their biofilm-forming ability and the complex organic matter degradation efficiency, whereas the operational factors affecting the working principle of MFC in terms of power generation include pH conditions, the nature and the type of anolyte and load configuration.

7. Factors Affecting the Performance of MFC Utilizing Food Waste

7.1. pH

For ideal microbial growth, MFCs are usually controlled at pH nearby neutral environments. However, due to reduced ionic concentration at neutral pH, the internal resistance of MFCs is strong in comparison to chemical fuel cells that are using alkaline or acid as electrolytes. Unintended pH shift reduces the power generating potential of MFCs. Ghangrekar et al. [141] analyzed the pH-change effect on the overall efficiency of a two-chambered MFC. When the pH gap between the two chambers was high, they measured optimum current and voltage. Cathode alkalization and anode acidification have been documented to affect the efficiency of MFCs [142]. During the short- or long-term activity, the pH gradient is created at the membrane. Because the electrons aggregate at the anode, an equal amount of H⁺ is released into the electrolyte and eventually travels into the cathode, where they are absorbed in cathodic reactions. However, the pH of the anodic compartment reduces because of inadequate or slow migration and diffusion of H⁺ via the membrane. On the other side, as a consequence of proton intake, the pH of the cathodic compartment decreases for the oxygen reduction reaction (ORR). The presence of H⁺ is the main element in evaluating the ORR efficiency of electrochemical water splitting devices [143] in the cathode chamber. In the anodic container, the performance of electron transfer and the function of neutrophilic biofilm microbes are decreased if pH is dropped too suddenly. Although alkaline pH decreases power production in the cathode chamber markedly. Zhang et al. [144] analyzed the role of initial pH on the anodic bacteria, biofilm, and MFC's efficiency in power generation. At acidic conditions, they achieved voltage output of 232–284 mV vs. 311–339 mV along with a power density of 95–116 mW/m² vs. 182–237 mW/m². Reduced and cracked biofilm at pH 5. Around pH 4, the MFCs were unable to obtain the optimum power around neutral pH. The findings indicated that the power supply corresponds to the output voltage and time-speed pH variance of the cathodic and anodic chambers of the MFCs. MFC's poor performance at pH 4 remained for a long time and could be irreversible; therefore, low pH conditions in MFCs should be avoided.

7.2. Substrate Concentration

The impact of substrate concentration on electricity output was explored by the dual chamber MFC (DCMFC) to treat domestic wastewater [145]. The performance of DCMFC in the removal of COD was analyzed at various organic loading levels varying from 435 to 870 mg COD/L·d. It can be said that the COD removal efficiency is greater than 90% as the organic loading rate rises from 435 to 720 mg COD/L·d. In contrast, the COD removal efficiency declined to about 70% at a lower loading rate (870 mg COD/L·d).

Various performance evaluation studies about pH and substrate concentration have been illustrated in Table 4.

Table 4. Effect of pH and substrate concentration on MFC performance.

Sr. No.	MFC Configuration	Substrate	Substrate Conc. (COD mg/L)	pH	COD (%)	Power Density	Ref.
1.	Dual Chambered MFC	Dairy wastewater	1600	7	91	2.7 mW/m ²	[125]
2.		Food waste leachate	39,048	6.3–7.6	84.5	5.591 mW/m ²	[146]
3.		Wastewater	1587	6.3	41	461 mW/m ²	[147]
4.	Single Chambered MFC	—	1000	9.5–11.50	91	20.2 mW/m ²	[124]
5.		Lactate	—	8	80	4.8 mW/m ²	[148]
6.	Single Chambered tubular MFC	Fruit and Vegetable slurry	48,320	3.0 ± 0.5	45	55 mW/m ²	[149]
7.	Sediment MFC	Aquaculture wastewater	170–185	8.5	96	4.52 mW/m ²	[150]

7.3. Temperature

The temperature influences the efficacy of MFCs because it affects ORR catalyzed by Pt on the cathode, bacterial kinetics, and the rate of mass transfer of protons through the liquid. MFC experiments are often conducted at about room temperature or somewhat higher (20–35 °C). At low temperatures in the range of 4–30 °C, MFC functionality requires a longer starting time to provide consistent power cycles and performance. MFCs could not generate significant electricity at temperatures below 15 °C, even after a month of operation [151]. Researchers are now focusing their efforts on creating effective MFCs based on thermophilic bacteria as it has an advantage over agri-waste as it also promotes pre-treatment. Thermophilic microorganisms have a high rate of metabolic processes and electron generation, which may be advantageous for their use in MFCs operating at elevated temperatures [152]. Choi et al. (2004) constructed an efficient MFC using thermophilic microorganisms. The authors utilized thermophilic bacteria (*Bacillus licheniformis* and *Bacillus thermoglucosidasius*) to investigate various operational parameters in the MFC system, including redox mediators, temperature, pH, and carbon sources. The authors stated that they produced a significant quantity of power via the use of a redox mediator. Maximum performance was found at 50 °C, and cell productivity remained constant at this temperature [153].

7.4. Salinity

Although approximately 5% of the earth's wastewaters are extremely saline, MFC may be more helpful in treating these wastewaters. Increased salinity improves power generation through increased conductivity. Increased conductivity promotes proton transport and therefore reduces the system's internal resistance. Lefebvre et al. demonstrated that adding up to 20 g/L of NaCl improved the cumulative efficiency of MFCs by decreasing internal resistance by 33% and boosting maximum power output by 30% [154].

8. Strategy to Enhance the Efficiency of MFC Performance

The recent studies conducted by Nadafpour have revealed that to upsurge the current in MFCs that have unique characteristics, including strong electric conductivity stability in microbial cultures. In addition, vast surface area and oxidizing agents such as potassium permanganate have a great ability along with anode that is made up of carbon-containing material such as graphite rod carbon paper carbon cloth; graphite fiber brush carbon cloth reticulated vitreous carbon, and carbon flesh [155]. Along with increasing surface area, Nanoengineering material is being used as anode material instead of conventional material, improving the electronic transfer mechanism [44,45]. As well to improve the output electrical power conductive polymer along with modified carbon and metal-based anode are being used in other suitable matter where during operation of MFC system charged balanced must be maintained for unhindered migration of H, OH ions and attention must be paid to electrode stability [156] and at the same time between electrode compartment any kind of diffusion should be avoided, but significant losses in the performance of the bioelectrical microbial system as always happening due to the crossover process. A study conducted by Miyake et al. (2003) has shown that by using functionalized hydrocarbon polymer in polymer electrolyte fuel cell as proton conductive material an increase in conductivity of fuel cell under the humid and heated condition it is seen that long term stability and higher conductivity than 0.01 cm has been provided by the MFC system along with impermeability to hydrogen methanol and oxygen [157]

In a study conducted by Li et al. (2016) has shown that the characteristic of the substrate in food waste after MFC treatment to perceive information about how the organic material was biodegraded and transform during MFC treatment and the aromatic compound in the hydrophilic fraction in comparison to non-aromatic compound such as aliphatic compound tryptophan were far preferably removed along with average output voltage of 0.51 V and maximum power density of 5.6 W per meter cube was achieved [158]. For the power generation and routine electrical purposes, MFC is not the economical

method; it is incapable of producing as much electricity as is required, nothing less electric current merely [159] and the very first fuel cell produces $1/40 \text{ mW/m}^2$ energy, in addition, a mixed bacterial culture having carbon sources as glucose has been reported to produce power up to 3.6 W/m^2 microbial fuel cell, which is the higher power output of about 5 fold then the very first fuel cell.

For practical application, it's crucial to use cost-effective material for building the system. There has been ample focus to make high surface and low-cost electrode materials for high-performing systems. The surface area of an anode directly impacts power generation. Higher the surface area of anode could lead large accessible surface area for biofilms results in higher charge generation in the system.

9. Techno-Economic Evaluation of Microbial Fuel Cell Technology

Trapero et al. year evaluated the techno-economic status of MFC utilizing juice industry wastewater in an aerobic system [160] through modifications conducted in the parameters like utilization of a dual-chambered reactor with carbon cloth as an anode along with the two types of cathodes; Pt coated carbon cloth and non-Pt coated carbon cloth, both in comparison to the conventional process utilizing activated sludge. This configuration has an effluent flow rate of $54 \text{ m}^3/\text{day}$ with a COD of $15,000 \text{ mg/L}$. The removal of COD ranges from 40–90%, along with the Coulombic efficiency from 2–30% chosen for the techno-economic assessment relying mostly on the power efficiency and wastewater treatment. The initial investment in consideration of MFCs, including electrodes, DC/AC converter, membranes, pumps, and the fan, is much greater than the conventional treatment plant, requiring just pump fans and a biological tank. Various other investments need to be estimated, such as the costs for operating the treatment plant of 100 m^3 of the volume, including the labor cost of 35%, which is around EUR 3248/year, 19% of the investment for management of the sludge costing EUR 1763/year along with 34% of the investment costing EUR 3155/year for electricity, indicating that most of the investment will be carried out for providing labor and electricity for the plant. In comparison to MFCs, the overall cost of the investment can be reduced because of the automation and no necessity for aeration at the wastewater treatment plant. Based on this estimation, the overall operating cost of MFC ranges around EUR 1700–2300/year, which is very low compared to the conventional process. However, this estimation can be considered only if there is no requirement of replacing the electrodes or membranes. Thus, the construction of highly durable MFC parts is essential for making the process economically viable. Therefore, it is a practical implementation because the capital cost is high compared to the operating cost, which is directly in contrast to the conventional treatment system. In a general scenario, at 30% Coulombic Efficiency, there is 90% efficient COD removal creates a relatively better cash flow than the conventional process (EUR 2600–3400/year) [161].

10. MFC Commercialization

MFC is a well-established and contemplated technology and provides various functional benefits compared to the technologies used to generate energy from organic chemicals [162,163]. It has been exhibited that any compound, which can be used by microorganisms, transformed into electricity using microorganisms [164]. MFCs offer many alluring attractions, e.g., (a) direct conversion of chemical energy to electricity which prompts high transformation effectiveness; (b) the fuel to electricity transformation by MFCs is not constrained by the Carnot cycle since it does not include the change of energy into heat, rather straightforwardly into electricity and, hypothetically it is possible to accomplish higher transformation proficiency (70%) (c) MFC operate at ambient temperature, due to involvement of microbes as a catalyst; (d) MFCs generate sustainable electricity; and (e) calm and safe execution of performance [165] and (f) no off-gas treatment is necessary because MFC usually generate carbon dioxide which has no useful content of energy [166]. It is hypothesized that MFCs can generate about half the power needed for a conventional treatment process involving aeration of the activated sludge [167]. Even if MFCs are still

holding on to be completely commercialized, they are not confined to the laboratories alone. MFCs have ventured into a few smaller-scale applications, which mostly require long-haul, sustainable low power supply, viz. for sensors for small electronic devices, cell phones, robots, and urinals. From the industrial application point of view, several start-up companies have been already established and are trying to commercialize it as illustrated in Table 5. Such recent progress in MFC design highlighted the optimization and economic efficiency of operating conditions. However, practical MFC systems must be demonstrated in a step towards marketing, but they can present new challenges and limitations that must be tackled systematically in the years to come. Table 6 comprises various patents involving lignocellulosic biomass as substrates in MFC for the production of value-added products.

Table 5. Various MFC commercialization.

Sr. No	Head Quarter	Company Name	Website/Information Link	Foundation Year	Services	Specific Product
1.	USA	Cambrian Innovation Inc.,	https://www.cambrianinnovation.com/ (accessed date—13 August 2021)	2006	wastewater treatment technology	EcoVolt; EcoVolt MBR
2.	Israel	Fluence Corporation Limited (earlier Emefcy)	https://www.fluencecorp.com/emefcy-and-rwl-water-merge-to-create-fluence/ (accessed date—13 August 2021)	2008	wastewater treatment	electrogenic bioreactors (EBR)
3.		Zigco LLC,	http://www.zigcollc.com/ (accessed date—13 August 2021)		soil powered battery	-
4.	USA	Magical microbes	https://www.magicalmicrobes.com/ (accessed date—13 August 2021)	2010	educational kit	MudWatt; MudWatt Core Kit; MudWatt DeepDig Kit
5.	Canada	Pron-gineer	http://prongineer.com/ (accessed date—13 August 2021)		water and wastewater treatment technology	-
6.		CASCADE Clean Energy, Inc.	http://www.ccleanenergy.com/ (accessed date—13 August 2021)		clean energy production	Wastewater Works (WWW)

Table 6. Various Patents associated with MFC utilizing Agricultural biomass as substrate.

Patent No.	Description	Reference
US9716287B2	A fuel cell with an anode electrode, a cathode electrode, and a reference electrode that are all electronically connected to each other; a first biocatalyst with a consolidated bioprocessing organism; and a second biocatalyst with a consolidated bioprocessing organism. (e.g., a <i>Cellulomonas clostridium</i> or related strains, like <i>Cellulomonas uda</i> (<i>C. uda</i>), <i>C. lentocellum</i> , <i>A. cellolulyticus</i> , <i>C. cellobioparum</i> , alcohol-tolerant <i>C. cellobioparum</i> , alcohol-tolerant <i>C. uda</i> , <i>Clostridium cellobioparum</i> (<i>C. cellobioparum</i>) and combinations thereof) capable of fermenting biomass (e.g., cellulosic biomass or glycerin-containing biomass) to produce a fermentation byproduct; and a second biocatalyst comprising an electricigen (e.g., <i>Geobacter sulfurreducens</i>) suitable for transferring nearly all the electrons in the fermentation byproduct (e.g., hydrogen, one or more organic acids, or a combination thereof) to the anode electrode to produce electricity is disclosed. A consolidated bioprocessing organism is also disclosed, as well as systems and methods relevant to it.	[168]
EP3071517A1	A plant-derived nanocellulose material that consists of nanocellulose particles or fibers derived from a plant material with a hemicellulose content of 30% or more (<i>w/w</i>) (calculated as a weight percentage of the lignocellulosic components of the material). Aspect ratios of more than 250 are possible for nanocellulose. Plant materials with a C4 leaf morphology could be used to make the nanocellulose. Arid Spinifex is a good source of plant material. Mild processing conditions can be used to create nanocellulose.	[169]

Table 6. Cont.

Patent No.	Description	Reference
US20090017512A1	In other implementations, the invention relates to a method for generating ethanol and electricity or ethanol and hydrogen that involves supplying a microbial catalyst and a fuel source to a fermentation vessel in operable connection with a microbial fuel cell or a BEAMR device, where the microbial catalyst has cellulolytic, ethanogenic, and electricigenic operation, and the microbial catalyst has a cellulolytic, ethanogenic, and electricigenic activity. Compositions and apparatus for carrying out the invention are examples of other embodiments.	[170]
US10686205B2	An electrochemical cell with an anode electrode, a cathode electrode, and a reference electrode that are all electronically connected; the first biocatalyst with a consolidated bioprocessing organism. (e.g., a <i>Cellulomonad</i> or <i>Clostridium</i> or related strains, such as <i>Cellulomonas uda</i> (<i>C. uda</i>), <i>Clostridium lentocellum</i> (<i>C. lentocellum</i>), <i>Acetivibriocellulolyticus</i> (<i>A. cellulolyticus</i>) <i>Clostridium cellobioparum</i> (<i>C. cellobioparum</i>), alcohol-tolerant <i>C. cellobioparum</i> , alcohol-tolerant <i>C. uda</i> , and combinations thereof) capable of fermenting biomass (e.g., cellulosic biomass or glycerin-containing biomass) to produce a fermentation byproduct; and a second biocatalyst comprising an electricigen (e.g., <i>Geobacter sulfurreducens</i>) capable of transferring substantially all the electrons in the fermentation byproduct (e.g., hydrogen, one or more organic acids, or a combination thereof) to the anode electrode to produce electricity is disclosed. A consolidated bioprocessing organism is also revealed by systems and methods relevant to it.	[171]

11. Life Cycle Assessment

Distinguishing the decrease in energy and discharges from bioenergy production and use, an exhaustive assessment from “cradle to grave” is to be deliberately carried out [172]. Life cycle assessment (LCA) is a universally acknowledged way to deal with the climatic impact of a certain product over its whole production cycle. This structured outlook will uncover the genuine capability of the product assessed and recognize the situation dilemma in the product trials in the long run so that prudent advances can be proposed to lessen the cynical climatic impact [173]. However, LCA is a technique to characterize and decrease the ecological weights from a product, procedure, or activity by distinguishing and measuring energy along with usage of materials, in addition to waste releases, surveying the effects of these wastes on nature and opportunity evaluation for ecological refinements over the entire life cycle. LCA is, therefore, important to avoid unplanned outcomes of new technology or alleviation strategy. A cycle assessment study including MES ought to characterize the objective, purview, and practical unit as the essential strides of the investigation. The objective should be to evaluate the energy and financial flows related to the MES systems. There must be well characterized to certify its affinity with the objective. The extent of LCA can be assessed by various MESs and some novel systems for transforming the food waste to straightforwardly produce electricity or other chemical products. The practical unit is setting the correlation scale for at least two or more products giving the reference for which the sources and yields are standardized to establish the inventory. The basic role of the unit in functionality is to cite the information sources and yields connected and important to guarantee the likeness of results [174]. In the waste treatment plan’s LCA, the practical unit is characterized regarding systems input which is waste. Thus, if MES is anticipated as a sewerage treatment apparatus, the operative system will likewise contrast in like manner.

12. Challenges in Using Microbial Fuel Cells

In recent years, the evolution of MFC technology has raised many concerns due to its unrealized potential for simultaneous bioenergy production and wastewater treatment. There is also a rising concern for environmental waste management and the amount of organic matter being released to the environment in the form of untreated effluent, which affects both terrestrial and marine life. However, these effluents and waste can be used

for the production of energy. Some companies have launched MFC-based wastewater treatment systems; although, there are numerous challenges still associated with the use of such technology. One of the paramount shortcomings of MFC technology is the problem of high operating costs and low power output. Other challenges associated with MFC technology are the selection of appropriate and suitable substrate thus wastewater and the complexity of the molecular structure of the agro-waste identified as a suitable substrate for MFCs and its resistance to oxidation, which will, in turn, affect its treatability and organic constituents' removal which will affect the MFC working principle. However, the pH of the substrate and its sudden alteration while performing some remediation activities must be considered for substrate conditioning as the changes in pH may lower the activity of microorganisms if the optimum is altered, which will, in turn, affect the MFC performance and quality of the wastewater being treated.

Another factor affecting the performance of the MFC system is the CE when the MFC is alternatively fed with low strength wastewaters, which will affect electrode performance due to the diversion of electrons into non-exoelectrogenic growth when using both plant and animal waste materials, resulting in the rapid depletion of the substrate along with the process of metabolism, which will lower processes such as methanogenesis thus low electron transfer efficiency. Scaling-up is another challenging factor that needs to be considered, which requires an economic evaluation with appropriate safeguards for a simple wastewater treatment-MFC set-up that can be maintained effectively and easily to generate a high-power output. Considering the capital cost of MFC based on simplified designs and their configuration and agro-waste treatment capability, this technology it is said to be more promising for long energy security than the sole use of conventional wastewater treatment systems for domestic wastewater [117]. Most of the expensive electrode materials used, such as catalyst and membrane materials, may result in the high capital and operational cost implications of MFC [175]. A high potential loss has been observed at the surface of the electrodes, leading to a reduction in current density when the upscaling of the MFC technology from a few milliliters to hectoliters is considered [6]. Furthermore, the inability of the MFC to recover heavy metal ions is a great challenge, also affecting its selection as a preferred technology. Overall, the bio-toxicity of certain heavy metals would negatively affect the performance of MFCs, imparting low energy production rates and limited wastewater remediation efficiencies [176].

13. Conclusions and Future Direction

The use of agricultural waste in MFC has been critical in the renewable energy industry, contributing significantly to the production of bioenergy. Similarly, the development of MFC technology has enabled the use of agricultural waste as a feedstock by various microbial communities in the anode compartment of the fuel cell. Due to the complex structure and crystallinity of agricultural biomass, biodegradation is limited. As a result, the agricultural waste's greater moisture content would assist in overcoming this barrier. By using a variety of wastewater resources, such as agricultural wastewater and fruit wastewater, the bacteria may easily break down the solid biomass. Conclusively, this review has demonstrated the use of various agricultural wastes for bioelectricity generation. Therefore, the use of different agricultural wastes and wastewater containing different industrial-by products for bioelectricity production in MFC seems to be a promising and alternative source of renewable energy generation. Moreover, it has been shown that different varieties of agricultural wastes and wastewater can be utilized using several different MFCs to enhance bioenergy production; thus, the conversion of agro-waste into bioenergy can be carried out by both biochemical and thermochemical MFC routes. Several papers report numerous experimental studies, whereby the use of various substrates from different agri-based industries and with different compositions for application in MFCs, has been demonstrated: most importantly, in terms of simultaneous wastewater treatment and energy recovery. Another attractive and fascinating trait of MFC technology development is the incorporation of wastewater treatment, which provides an alternative

solution to wastewater management, pollutant removal, and the maintenance of a safe and eco-friendly environment in addition to energy production. Overall, it has been noted that MFC technology offers significant advantages such as low input energy cost and a low level of residual biosolid production. In essence, improvement has been made in the total bioenergy production arena in using—concentrated wastewater derived from various agro-waste, indicating that various microbial consortia of different origins play an important role during the oxidation-reduction reactions for bioenergy production using different anodes and cathodes. Overall, an effective pretreatment approach has been made to solve problems associated with agri-waste mitigation even when such waste has a different particle size, calorific value, etc. There is also a need to promote environmental sustainability in agricultural activities and the standard management of agro-wastes that will reduce the volume of wastes released into the environment and provide a channel for bioenergy generation. To this end, local governments and regulatory agencies should explore ways of generating bioelectricity from various agro-waste as there is an urgent need to disabuse the general public's minds that agro-waste is useless.

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