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Review

Waste-to-Energy Pipeline through Consolidated Fermentation–Microbial Fuel Cell (MFC) System

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Abstract: The rise in population, urbanization, and industrial developments have led to a substantial increase in waste generation and energy demand, posing significant challenges for waste management as well as energy conservation and production. Bioenergy conversions have been merged as advanced, sustainable, and integrated solutions for these issues, encompassing energy generation and waste upcycling of different types of organic waste. Municipal solid waste (MSW) and agricultural residues (AR) are two main resources for bioenergy conversions. Bioenergy production involves feedstock deconstruction and the conversion of platform chemicals to energy products. This review provides a detailed overview of waste sources, biofuel, and bioelectricity production from fermentation and microbial fuel cell (MFC) technology, and their economic and environmental perspectives. Fermentation plays a critical role in liquid biofuel production, while MFCs demonstrate promising potential for simultaneous production of electricity and hydrogen. Fermentation and MFCs hold a significant potential to be integrated into a single pipeline, enabling the conversion of organic matter, including a variety of waste material and effluent, into diverse forms of bioenergy via microbial cultures under mild conditions. Furthermore, MFCs are deemed a promising technology for pollutant remediation, reducing COD levels while producing bioenergy. Importantly, the consolidated fermentation–MFC system is projected to produce approximately 7.17 trillion L of bioethanol and 6.12×10^4 MW/m^2 of bioelectricity from MSW and AR annually, contributing over USD 465 billion to the global energy market. Such an integrated system has the potential to initiate a circular economy, foster waste reduction, and improve waste management practices. This advancement could play a crucial role in promoting sustainability across the environmental and energy sectors.

Keywords: bioenergy; municipal solid waste (MSW); agriculture residues (AR); fermentation; microbial fuel cell (MFC)

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1. Introduction

Technological advancement, population growth, and urbanization are increasing waste production and raising challenges to secure resource sustainability, which directly or indirectly constrained economic growth [1]. The World Bank estimates that waste generation will increase as much as 70% by 2050 and estimated that one-third of waste generated is not properly managed worldwide [2]. Due to the wide variation in waste composition and characteristics, solid waste can be classified into municipal solid waste (MSW), industrial waste (IW), agricultural waste (AW), construction and demolition waste (CDW), hazardous waste (HW), medical waste and electronic waste (e-waste) [3]. To overcome resource security and fulfill the intense demands of the increasing population, there has been a significant rise in crop production and livestock which is significantly contributing to the waste generation from agriculture [4,5]. The total solid waste comprises

23% of municipal solid waste with 50% of organic waste and 18% of agricultural waste [6]. It is estimated that 75–80% of the total MSW is collected; however, only 22–28% is processed and treated. Solid waste generation and its adverse impacts on both people and the environment when improperly managed or treated are unavoidable in today's world [7]. The organic fraction of solid waste is generally derived from lignocellulose-based feedstock and is a promising source for the production of renewable energy [8,9].

The production of biofuels using lignocellulosic-based feedstock plays a significant role in fulfilling the global energy demand, accounting for approximately one-tenth of the world's energy consumption [10]. As per a 2019 report on renewables, biofuel production increased by 10% in 2018, with projections indicating a further 25% increase by 2024 [11]. Among various biofuels, bioethanol stands out as the primary fuel derived from organic feedstock, contributing to 65% of total biofuel production, with advanced biofuels making up an additional 5% [12]. In the pursuit of a circular economy and resource sustainability, the establishment of biorefineries for biofuel production becomes crucial. However, to produce biofuels and overcome the recalcitrant nature of lignocellulosic biomass, various pretreatment technologies, including physical, chemical, biological, or physicochemical methods, are employed to disrupt the lignocellulosic structure, often involving lignin removal or cellulose crystallinity reduction (Figure 1).

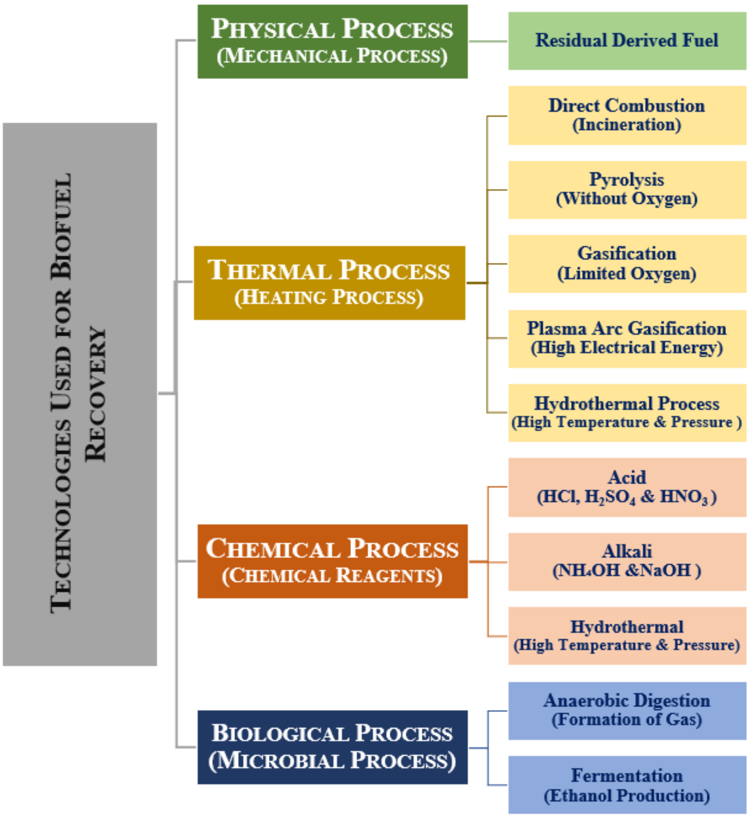

Figure 1. Technologies used for biorefineries.

Physical processes involve the utilization of mechanical techniques to disrupt biomass structure, especially to reduce particle size and increase biomass surface area and accessibility [13]. For the thermal process, extreme temperature (>500 °C) is used directly to break down the biomass into biogas, hydrogen, and hydrocarbons [14]. In biomass pretreatment, a hydrothermal process is applied to open up the biomass structure under high temperatures (200–400 °C) [15]. This process is deemed a physiochemical process since the water acts as an acid under high temperatures to partially solubilize structural carbohydrates [16]. Chemical processes play a crucial role in recovering chemical building blocks from feedstock. For this purpose, chemical pretreatment methods like acid, alkali, and hydrothermal processes are commonly applied [17]. However, these chemical processes pose significant environmental risks and hazards due to the use of acids and alkali solutions. To mitigate or minimize these risks, biological processes are adopted for pretreatment. Biological processes harness the power of microorganisms, such as white-rot, soft-rot, or brown-rot fungi, to alter the lignocellulosic structure by decomposing cellulose and lignin. This treatment facilitates the conversion of biomass feedstock into chemical building blocks or liquid biofuels. The biological conversion of lignocellulosic biomass involves multi-stage processes, including hydrolysis and fermentation, to yield value-added products [18]. After pretreatment, the chemical building blocks can be further upgraded or synthesized into high-value products or biofuels using various technologies. These technologies include anaerobic digestion, fermentation, microbial fuel cells (MFCs), microbial electrolysis cells (MECs), incineration, etc. [19–21].

Fermentation has gained widespread use as a common method for producing biofuels like ethanol and biogas. In this process, bacteria and yeast metabolize sugars to yield ethanol [22]. Meanwhile, microbial fuel cells (MFCs) have garnered attention due to their dual ability to generate energy and facilitate environmental remediation by breaking down organic waste through microbial cultures. MFCs employ electroactive bacteria or proteins as catalysts at an anode electrode, degrading complex biomass as the input substrate under neutral pH conditions and ambient temperatures between 15 °C and 45 °C. These MFCs have evolved into bioelectrochemical systems (BESs), representing emerging concepts and technologies in the realm of energy generation from waste streams [23,24]. This technology not only produces electricity but also generates hydrogen from various organic waste, making it a captivating and advancing research area worldwide.

To address the world's economic and sustainable energy needs, a consolidated biorefinery has been seen as a viable alternative. By integrating fermentation and microbial fuel cell technology, this approach allows it to produce a diverse range of bio-based products, including biofuels, bioelectricity, biogas, etc. The concept of an integrated biorefinery is to optimize the utilization of various biomass resources and biomass deconstruction technologies while enhancing the efficiency and sustainability of bioproducts' productivity. Previous studies have demonstrated the combined approach of fermentation–microbial fuel cell (MFC) by Christwardana et al. in 2021 [25]. In this study, sugarcane bagasse fermentation was integrated with MFC using *Saccharomyces cerevisiae* producing 14.88 mW/m^2 of bioelectricity and resulting in 39.68% of COD (chemical oxygen demand) removal [25]. Additionally, another study reported by Borole et al. in 2009 demonstrated the use of MFC for controlling and removing fermentation inhibitors, enabling the generation of 25% of the total power required by the biorefinery. This approach not only increased the ethanol yield from biomass feedstock in the biorefinery but also contributed to improved water recycling [26].

This review provides an overview of organic waste sources, composition, and different bioconversion processes, including the fermentation process, with a special focus on the microbial fuel cell (MFC) process and design for energy production from biomass.

2. Organic Waste

MSW and agricultural residue are major resources of organic waste, which can be converted into various forms of bioenergy. Organic waste generally includes three main categories: high moisture (food waste, yard waste), low moisture (contaminated fibers, sanitary waste, wet and non-recyclable paper, etc.), and recyclable organics (polyethylene (PET) plastics, wood, dry mixed paper, cardboard, etc.).

2.1. MSW Sources and Composition

MSW is commonly known as solid waste that is discarded within a specific municipal area, irrespective of its source. Globally, a significant 70% of total MSW ends up in landfill, while only 19% is recycled and a mere 11% undergoes treatment for energy generation [27].

MSW can generally be categorized based on its origins into three main groups: urban or city waste (including residential and non-residential waste), rural waste (comprising agricultural residue and livestock waste), and industrial solid waste [4]. Each of these categories can further be divided into different subdivisions, as illustrated in Figure 2.

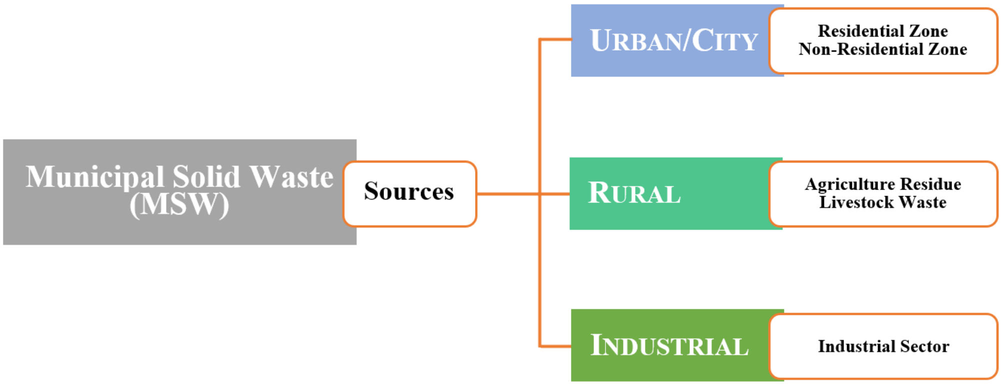

Figure 2. Sources of municipal solid waste (MSW).

The composition (*w/w*) of MSW can be primarily categorized into seven major groups: 46% organics, 17% paper, 10% plastic, 5% glass, 4% metals, 3% textile, and 13% inert materials, with the remaining 2% classified as miscellaneous waste [28]. Figure 3 illustrates a detailed subgroup of global MSW composition, including organics, combustibles, non-combustibles, and other components [29,30]. Based on the origin of MSW, approximately 55% to 80% of it is generated by households, while approximately 10% to 30% of MSW comes from commercial waste [31]. The MSW from the non-residential sector is complex and diverse according to its physiochemical characteristics. Most MSW consists of paper, plastic, fabrics, food waste, demolition or construction waste, leather, etc. [32].

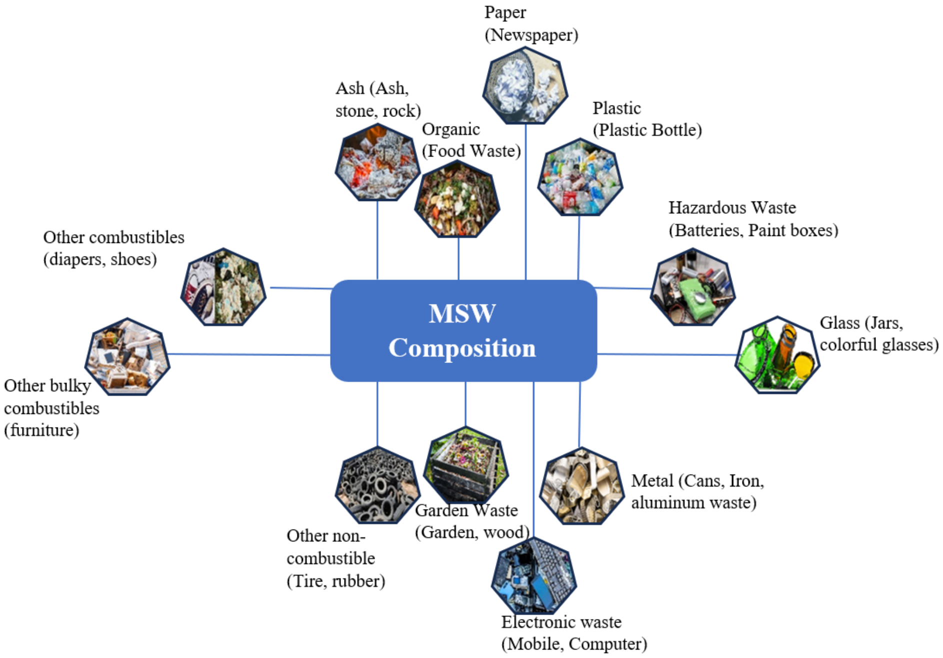

Figure 3. Subgroups of global MSW composition.

2.2. *Agriculture Waste Sources*

The growing population necessitates a corresponding increase in agriculture-related industries. According to the report by Oluseun Adejumo and Adebukola Adebiyi [33], agricultural production has increased more than three times in the last five decades. Along with agricultural production, agriculture-derived waste generation is estimated to increase by 988 million tons annually and contains approximately 790 million tons of organic waste [34]. Agricultural solid residue is the major waste generated from farming activities, crop processing, agrifood production, livestock, etc. (Figure 4). Therefore, agricultural waste generally includes crop residue, aquaculture waste, agro-industrial waste, and animal/livestock waste. Additionally, this waste contributes approximately 21% to total greenhouse gas emissions [33].

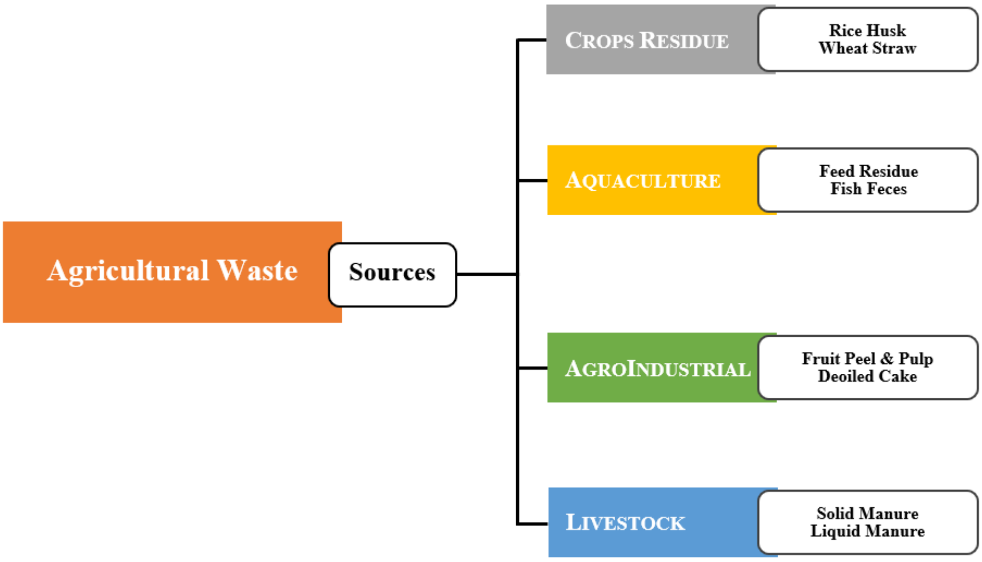

Figure 4. Sources of agricultural waste.

2.2.1. Crop Residue

Crop residue is the feedstock left after harvest and processing, including husk, leaves, stoves, straws, bagasse, etc. Globally, crop residue is projected to be 2802–3758 Mt/year [5]. A very small amount of crop residue, such as corn, wheat, and rice husk, are utilized for animal feeding or bioethanol production [35,36]. However, most of the remaining crop residue is dumped or burned in the fields, which causes environmental pollution and health issues as well as impacts on the sustainability of agriculture [37]. To reduce crop-derived waste, these materials have been seen as a promising source for biofuel conversions, given their abundant organic content, which can be readily utilized in biorefineries [5]. Crop residues typically contain 25–45% cellulose, 18–35% hemicellulose, and 10–25% lignin, classifying them as lignocellulosic biomass (LCB). Efficient biomass deconstruction of these structural hydrocarbons offers a promising resource for subsequent biofuel and bioenergy conversions and syntheses. Additionally, crop residues contain various bioactive compounds like xylooligosaccharides (XOS), polyphenols, pectin, dietary fibers, etc., which can be extracted and utilized [38]. Due to the different chemical compositions of various crop residues, several technologies have been applied to produce value-added bioproducts. For example, hydrothermally treated sorghum was used to produce bioethanol and lipids [39], solid-state fermentation was used to extract lipids from plum fruit [40], anaerobic digestion was employed to produce methane surplus paddy, wheat, maize [41], etc. These innovative approaches help unlock the full potential of crop residues for sustainable and environmentally friendly bioenergy and bioproduct production.

2.2.2. Aquaculture Waste

Aquaculture is another growing industry, and the major products in the market include fish, crustaceans, and mollusks [42]. There is also estimated to be a bulk growth of two-thirds in aquaculture activities around the world by 2030 (FAO, 2016), resulting in a rapid growth of agriculture activities [5]. As per a report from the Food and Agriculture Organization (FAO) in 2018, there was a 5.8% increase per year in global aquaculture production between 2000 and 2016 (FAO 2018). The waste derived from aquaculture can be divided into solid residues and dissolved waste [43].

The solid residues are mainly from aquatic feed, unused feed, and feces. This aquaculture solid waste is highly enriched with nitrogen and phosphorus that harm fishes' health and further damage aquatic life [5,44]. Additionally, aquatic biomass derived from fish processing is another source of aquatic solid waste. The composition of various aquatic biomass such as microalgae, macroalgae, shrimp shells, crab shells, etc., includes chitin, glucosamine-based biopolymer, protein, lipid, and carbohydrates [45–47]. These sources of organic matter are promising feedstocks for value-added bioproduct and bioenergy conversions [48,49]. The upcycling of solid aquaculture waste and its applications in biofuel, biosorbent, hydrochar, etc., production are seen as another value-added process to secure aquaculture sustainability [50].

The fast-growing aquaculture also raises the generation of dissolved waste, including nitrogen (ammonia, nitrite, nitrate, etc.), phosphorous, and organic waste, resulting in water pollution and damage to environmental sustainability [51,52]. Aquaponics was introduced as a remediation strategy to maintain water quality and aquatic life, and produce vegetables at the same time [53,54].

2.2.3. Agro-Industrial Waste

Waste generation from agro-industries is also a major contributor to organic waste and constitutes leftover material from food processing industries. The waste material depends on the type of agriculture crop being processed, such as bagasse from the sugar-producing industry, rice husk, starch residue, animal meat and skin, vegetable and fruit peels (apple, orange, cabbage, tomatoes, etc.), and deoiled cakes (mustard, soybean, sesame, groundnut, cotton, etc.), from their respective industries [55].

The expansion of the agro-industrial sector has played an important role in the accumulation of a huge amount of solid waste. The various waste compositions are found according to different applications in agriculture-related industries. Moreover, packing materials, including paper, cardboard, plastics, etc., used in the market contribute to remarkable amounts of organic waste [5]. The composition of agro-industrial waste mainly consists of cellulose (40–50%), hemicellulose (20–30%), lignin (10–25%), protein, lipids, and other organic matter. Due to its high cellulosic contents, agro-industrial waste is generally treated as LCB [56]. Similarly, to crop residue, agro-industrial waste is a promising bio-based feedstock for bioproducts and bioactive compounds using bioconversion pretreatment approaches. These bioproducts and bioactive compounds include bioethanol, enzymes, biogas, biofertilizers, nutraceuticals, bionanoparticles, etc., [57]. The utilization of agro-industrial waste in these processes promotes sustainable practices and contributes to the development of a circular economy in the agriculture and food processing sectors.

2.2.4. Livestock/Animal Waste

Livestock contributes up to 40% of agriculture products globally, as reported by FOA. Simultaneously, livestock waste is another important source of organic waste from the agriculture sector. This waste includes manure in solids (excreta and feed residue), liquid forms (urine and wastewater consisting of agricultural runoff, leachate, or silage runoff), and semi-liquid mixture (slurry consisting of manure fine particles and water). This manure is enriched with organic matter, pathogens, and nutrients, which cause public health and environmental pollution issues without proper treatment and management [5]. Moreover, animal manure contributes to greenhouse gas emissions by releasing 57% and 18% of methane and carbon dioxide, respectively [58]. Recently, surface water pollution caused by livestock waste and increasing greenhouse gas emissions from livestock have been seen as challenging environmental issues [58].

Additionally, cow, swine and poultry manures are good sources of LCB. Cow manure presents an average of 21.38% cellulose, 20.45% hemicellulose, and 11.48% lignin [59]. On the other hand, swine manure consists of 20.67%, 19.22%, and 8.48%, and poultry manure consists of 24.13%, 18.95%, and 4.17% of cellulose, hemicellulose, and lignin, respectively [60]. These manures hold significant potential for biogas production, and several pretreatment techniques can be applied to maximize methane yield, reaching up to 74% through biological pretreatment [60]. Moreover, several studies have focused on upgrading livestock waste to produce various bioproducts, including biochar as commercial fertilizer, manure-based energy systems for heating farm buildings and equipment, ethanol production, biopolymers, lipids, heart valves, pigments, collagen, etc. [61].

3. Fermentation and MFC for Biofuel, Bioelectricity Generation

3.1. Fermentation

Fermentation is the most used bioprocessing technology to convert carbohydrates into liquid fuels and value-added biochemicals by microbial cultures [13,62]. The most commonly used microorganisms include yeast (*Saccharomyces cerevisiae*), bacteria (*Escherichia coli, Synechococcus, Clostridium acetobutylicum, Synechocystis*, *Clostridium tyrobutyricum,* etc.), and fungi (*Rhizopus*) [63,64].

Fermentation involves various process designs and configurations for biofuel production. These include separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), co-fermentation of pentoses and hexoses, and consolidated bioprocessing (CBP) [65] (Figure 5). SHF is the process that includes separate biomass saccharification and fermentation in sequence for biofuel conversion. However, the long processing time and high costs are the main obstacles to its commercialization [66]. SSF shortens the overall processing time and reduces costs by combining biomass saccharification and fermentation in a single operation unit [67]. However, optimal operational conditions such as temperature and pH for hydrolysis are incompatible with optimal conditions of fermenting microbes. Therefore, achieving a better yield using SSF requires higher enzyme loads to compensate for the optimal conditions [68]. To overcome this, simultaneous saccharification and co-fermentation (SSCF) and consolidated bioprocessing are viable alternative approaches for biofuel production.

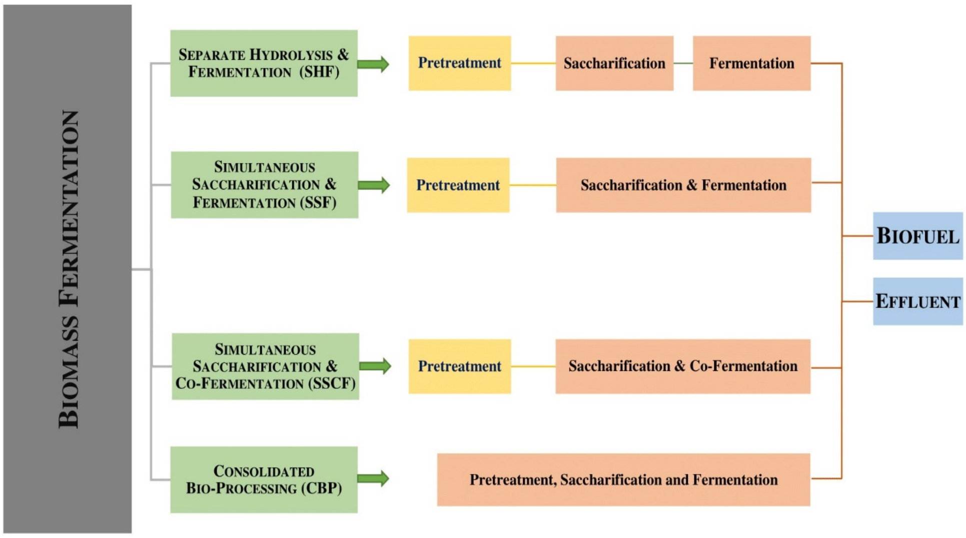

Figure 5. Biomass-to-biofuel pipelines through different fermentation strategies.

Typically, hexose (glucose) is digested in fermentation. To increase the bioproduct titer, genetically modified microorganisms were introduced to convert both hexose and pentose to products [69]. Two different microorganisms, i.e., *Saccharomyces cerevisiae* and *Candida shehatae*, were used in combination for sequential fermentation in SSCF. During sequential fermentation, *Saccharomyces cerevisiae* for hexose utilization in the first phase and *Candida shehatae* for pentose utilization during the second phase were reported. However, the ethanol yield obtained from SSCF is not feasible for commercialization [70]. To enhance the fermentation efficiency and ethanol yield, the other genetically engineered microorganisms (*Saccharomyces cerevisiae*, *Escherichia coli*) have been developed to uptake glucose and xylose simultaneously [71]. Additionally, consolidated bioprocessing (CBP) is a single reaction design which involves cellulase production, biomass hydrolysis, and sugars fermentation into biofuels [72]. This technology uses monoculture or co-culture microorganisms for ethanol production directly from fermentation. *Trametes hirsuta* fungi have been used to integrate various carbon sources, and *Clostridium thermocellum* bacteria is a prospective biocatalyst in CBP for cellulosic ethanol production through direct conversion of biomass-derived material [73]. Overall, the strategy of CBP is to use naturally occurring microorganisms that possess inherent cellulolytic activity [74]. During CBP, 86% of sugars in feedstock are converted into ethanol. Furthermore, value-added products such as biopolymers, propanediol, etc., are produced from unutilized lignocellulosic fraction and organic acids in organic waste effluent from CBP. CBP integration and optimization are needed to increase yield and economic and environmental benefits [74].

In addition to liquid fuel production through fermentation, a biological process is used in biogas production by anaerobic digestion (AD). During anaerobic digestion, bacteria break down organic matter in the absence of oxygen and produce biogas. The AD process occurs in an airtight vessel (vacuum), designed and fabricated in various shapes and sizes depending on the site and type of feedstock. Along with biogas production, it also results in end-product discharge as digestate in solid and liquid form [75]. These digestates can be appropriately treated and used in various applications such as bio-based product foundation material, fertilizer, etc. Furthermore, digestion can be used as feedstock to microbial fuel cells (MFCs) to generate electricity and reduce more than 50% of the concentration of organic, nitrogen, and phosphorus [76].

3.2. Microbial Fuel Cells

Microbial fuel cells (MFCs) are devices that also use microorganisms to convert chemical energy into electrical energy. MFCs are potentially applied to bioenergy recovery from organic waste (biomass) and wastewater [77]. Moreover, many researchers have proven the potential benefits of MFCs over aerobic processes [78]. This technology not only enables the generation of electricity but also facilitates organic waste recycling and serves as a resource recovery option from organic waste. Organic waste, including food, fruit, and agro-industrial residue, is abundant in carbohydrates, making it a valuable source for boosting energy production. The high carbohydrate content in this waste contains various carbon derivatives that enable efficient electron transport from the anode to the cathode [79]. Microorganisms present on the anode participate in the oxidation of the organic substrate, leading to the generation of protons that move across the membrane to the cathode and electrons that flow through an external circuit, resulting in electricity generation. The system's overall efficiency relies entirely on the electron production by the bacteria [80]. An increase in oxygen concentration and flow velocity within the anode or cathode chamber can significantly impact energy production. Furthermore, increasing the system flow can enhance the mass transfer of microorganisms and dissolved oxygen toward the electrode surface. As a result, this phenomenon directly influences the electrochemical behavior of the microbial fuel cell (MFC) and subsequently affects its power output [81]. Bacteria (*Escherichia coli, Paenibacillus lautus, Enterobacter cloacae,* and *Bacillus subtilis*) [82], archaea (*Halobacteria, Methanobacteria, Methanomicrobia,* and *Thermoplasmata*) [83], fungi (*Candida melibiosica, Blastobotrys adeninivorans, Kluyveromyces marxianus, Pichia polymorpha,* and *Pichia anomala*), and yeast (*Saccharomyces cerevisiae*) [84] are the most common microorganisms used in MFCs.

MFCs can be classified into two types, mediator-based and non-mediator-based MFCs, based on different mechanisms of electron transfer (Figure 6). Mediator-based MFCs involve indirect electron transfer, as shown in Figure 6a. In this process, conductive biofilms or soluble compounds act as mediators, facilitating the transfer of electrons to the electrodes. The mediator (organic redox species) present in the microbial culture is involved in cellular electron transport chains by accepting electrons and discharging them onto the electrode surface [85]. During electron transport, the mediators reoxidize to their initial state and act as electron shuttles, enabling electron exchange between the electrode and cells [86]. In complex microbial communities within MFCs, these electron shuttles are excreted by one organism and utilized by others, creating a high redox cycle. Furthermore, other metabolic products from fermentation can also be oxidized to generate electric current [87]. Non-mediator based MFCs involve direct electron transfer, as illustrated in Figure 6b, where electrochemically active microorganisms such as *Shewanella* and *Geobacter* play a critical role in the redox reaction. These microorganisms possess redox-active proteins, such as c-type cytochromes, which enable them to contact outer membranes and transfer electrons directly to solid-phase electron acceptors [88]. Some of these microorganisms initiate electron exchange through electrically conductive protein filaments known as nanowires. These direct electron transfer mechanisms enhance the efficiency of MFCs and their ability to generate electricity from organic waste.

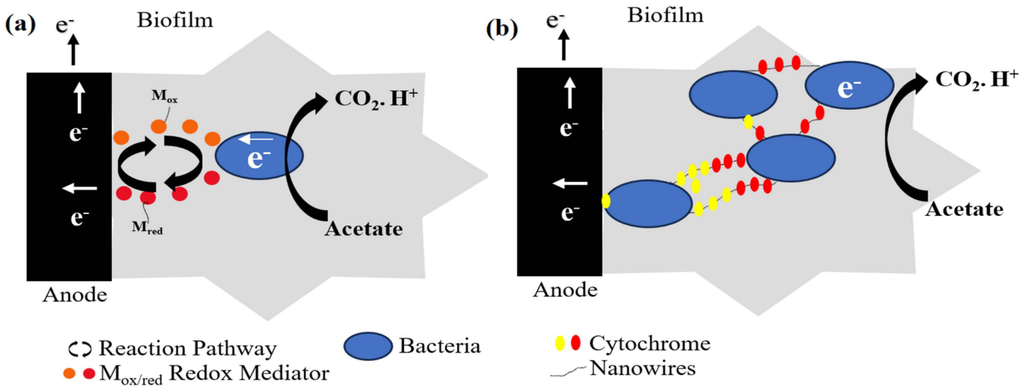

Figure 6. Mechanisms involved in electron transfer: (**a**) Indirect transfer via mediators or fermentation products, (**b**) direct transfer via cytochrome proteins.

Microbial fuel cells (MFCs) have found diverse applications in power generation, wastewater treatment, and biosensors, making them an attractive technology for organic waste treatment, such as food waste, agricultural residue, and wastewater, into electricity [89]. The use of MFCs as biosensors for wastewater streams enhances their prominence in detecting various analytes, including heavy metals and organic pollutants [90]. Additionally, MFCs have been extended to produce hydrogen gas as clean energy fuel and facilitate bioremediation of contaminated waste streams using naturally occurring microorganisms. As a result, MFCs offer the potential to reduce greenhouse gas emissions, minimize carbon footprints, and address the challenges posed by the increasing energy crisis [91].

3.2.1. MFC Configurations

Microbial fuel performance is directly affected by reactor design and configuration. Various configurations are used in MFC designs, including single-chamber MFCs (SC-MFCs), double or dual-chamber MFCs (DC-MFCs), and stacked MFCs (series and parallel) (Figure 7). SC-MFCs have both anode and cathode electrodes positioned within a single chamber, but they are separated by either a proton exchange membrane or an ion selective membrane, as shown in Figure 7a [92]. The colonization of electroactive biofilm on the anode surface, which affects the MFC performance and cathodic reaction, is considered a limiting factor for MFC performance [93]. To address this issue and enhance power output, air-breathing cathodes have been introduced, as they offer advantages such as lower internal resistance and a reduction in energy requirements caused by aeration [93,94].

Air-breathing cathodes are comprised of electrode material, an air diffusion layer, and an oxygen reduction reaction catalyst layer, which allows oxygen from the air to diffuse into the system, eliminating the need for an external oxygen source [95]. The air-breathing cathodes also help in achieving more power output because of their low internal resistance [94]. To overcome the limitations of SC-MFCs (oxygen diffusion, pH control, etc.), the DC-MFC configuration has been used. Figure 7b depicts the DC-MFCs that consist of two separate chambers for the anode and cathode, respectively. Both chambers are connected by an ion selective membrane or salt bridge to avoid electrolyte movement between the chambers [96]. The microorganism in the anode chamber acts as a biocatalyst for organic waste degradation and produces electrons and protons [97]. These electrons are then transferred through an external circuit to the cathode chamber [98]. In previous studies, it has been identified that the MFC configuration critically affects the capacity of electricity generation (Table 1). DC-MFCs have a higher electricity generation capacity (2.27–20.12 mW/m^2) than SC-MFCs (0.009–3.90 mW/m^2) while applying the same substrate and electrodes [99].

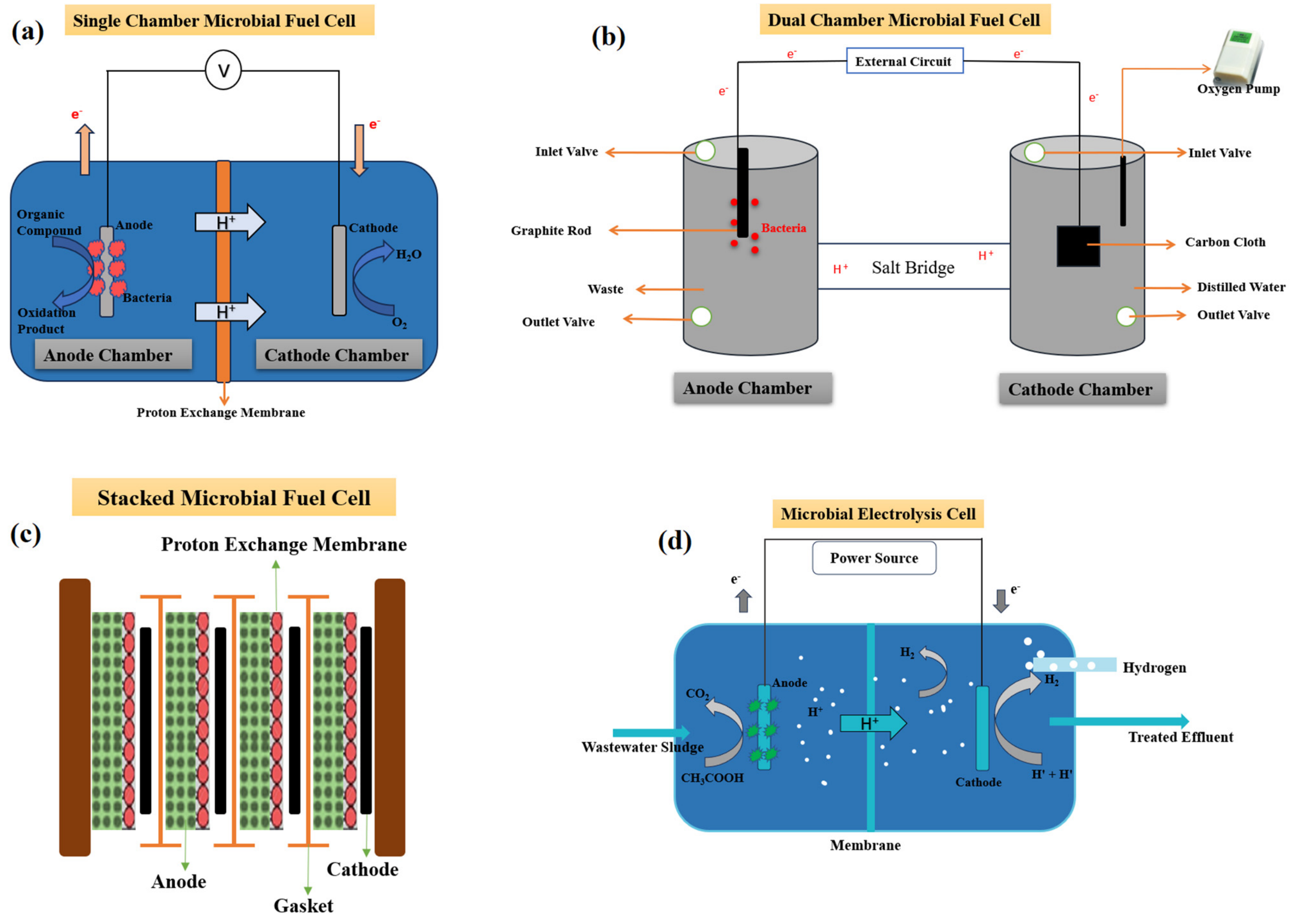

Figure 7. Schematic diagram of (**a**) single chamber MFC with proton exchange membrane, (**b**) double chamber MFC connected with a salt bridge, (**c**) stacked MFC with proton exchange membrane, and (**d**) MEC for treating wastewater to produce H_2.

Stacked MFCs have been employed to enhance power output. This improvement involves configuring multiple MFCs that are connected in series or parallel. Stacked MFCs increase the overall performance, power output, and scalability (Figure 7c) [100]. Similarly, power output was measured for DC-MFC and stacked MFC in series and parallel for rice straw substrate. Stacked MFC in series provided a higher power output of 2.17 V, compared to 0.723 V and 0.345 V from stacked MFC in parallel and DC-MFC, respectively [101]. Moreover, microbial electrolysis cells (MEC) are developed based on MFCs, which require external current or voltage to initiate the microbial electrochemical reaction to produce hydrogen (H_2), as shown in Figure 7d [102]. MECs are widely applied in wastewater treatment and hydrogen production.

Both cell volumes and electrode materials play an important role in power output efficiency. In a study by Chiu et al. (2016) [99], different volume capacities (1.5 L and 4 L) of DC-MFCs and SC-MFCs employing similar substrates and electrodes were investigated. Higher power output efficiency was obtained from higher volume capacities. There was a 50% and three-fold increase in power output for DC-MFC and SC-MFC, respectively. However, opposite results were observed from the MFC equipped with different electrode materials. Lower energy outputs were obtained from larger DC-MFC capacities equipped with a combination of carbon felt with stainless steel and carbon plate with a carbon plate. Further research is needed to investigate the impact of the electrode material on the power output, especially regarding the factor of MFC volumes.

The electrode material and surface area are other critical factors affecting MFC performance, because they are directly related to the kinetics of the electrode in the system [103]. For example, the electrode material has an impact on the energy loss in the MFC by the high internal resistance, while the extended operational lifespan and cost of electrodes are other crucial concerns for industrial applications [81]. Carbon-based and carbon composite electrodes have been extensively used in MFCs to improve energy output [104]. Carbon-based materials, including carbon cloth, graphite rod, carbon felt, etc., have been deemed promising materials due to their biocompatibility, chemical stability, higher electrical conductivity, and low cost [105]. Additionally, composite material, such as carbon nanotube polyaniline, also helps enhance the adhesion and electrocatalytic property of bacteria cells [106].

Metal-based electrodes, such as copper, stainless steel, etc., have been studied and resulted in an increase in power output due to an increase in corrosion employing galvanic (abiotic) current production [107]. The effect of Cu-based electrodes was reflected in a study performed by Masud et al. (2021) [108]. The food waste solution was prepared and used as the substrate for DC-MFC with various combinations of anode and cathode, including Cu–Cu, Zn–Cu, and graphite–Cu. Due to the better conductivity of Cu, the combination of Cu–Cu showed the highest efficiency of 0.936 V, compared to 0.86 V and 0.50 V by Cu-Zn and Cu-graphite (Cu stands for anode electrode whereas Zn and graphite stand for cathode), respectively [108].

Table 1. Different configurations of MFC using agriculture residue and MSW. (* Power output units are retrieved from the literature and are only modified wherever available).

MFC Configuration	Additional Configuration (Volume, PEM)	Microorganism	Anode/Cathode Material	Organic Waste	Power Output/Voltage Obtained *	Organic Waste Degradation	Reference
Single-chamber MFC	25 mL	*Geobacter, Dysgonomonas*, and polysaccharide-degrading bacteria	Anode: Graphite brush Cathode: Carbon cloth with Pt catalyst	Potato pulps waste	32,100 mW/m^3	COD Removal = 68.40%	[109]
	120 mL Air cathode	Anaerobic sludge	Anode: Carbon cloth Cathode: Carbon Cloth with 10% Platinum and three diffusion layers	Food waste	0.51 V		[110]

Table 1. *Cont.*

MFC Configuration	Additional Configuration (Volume, PEM)	Microorganism	Anode/Cathode Material	Organic Waste	Power Output/Voltage Obtained *	Organic Waste Degradation	Reference
	1.5 L and 4 L	Anaerobic sludge seeding	Combination of electrodes: a. carbon felt + carbon felt, b. carbon felt + stainless steel, c. carbon felt + carbon paper, d. carbon felt + carbon plate, e. carbon plate + carbon plate.	Organic fraction of MSW (OFMSW)	1.5 L (mW/m^2) a. 0.009 b. 0.33 c. 0.13 d. 3.90 e. 1.91 4 L (mW/m^2) a. 0.03 b. 0.42 c. 0.007 d. 1.06 e. 0.32		[99]
Dual-chamber MFC	Proton exchange membrane	Coupled with anaerobic digestion	Graphite	Banana waste	41.3 mW/m^2	COD removal = 85.4 ± 1.0%	[111]
	500 mL Connected with salt bridge		Anode: Stainless steel mesh with carbon cloth Cathode: Stainless steel mesh (air cathode)	Raw food waste	0.0005 V 14,010 mW/m^3	COD removal = 69.78%	[112]
	1 L Proton exchange membrane	*Saccharomyces cerevisiae yeast*	Graphite electrodes	Molasses substrate with electrolyte solution	$KMnO_4$ = 0.48 V $K_3Fe(CN)_6$ = 0.36 V		[113]
	4000 mL Connected with salt bridge		Combination of electrodes Cu–Cu, Zn–Cu, Graphite–Cu	Food waste solution	Cu–Cu = 0.936 V Zn–Cu = 0.855 V Graphite–Cu = 0.501 V		[108]
	150 mL Connected with salt bridge	Cathode: *Phlebia floridensis* and *Phlebia brevispora* Anode: *Pichia fermentans*	Anode: Carbon fibers (100 Cm L, 7 µm) Cathode: Stainless steel (100 cm, 0.05 mm diameter)	Wheat straw	331.9 mW/m^2	35% to 38%	[114]
	Nafion proton exchange membrane (PEM)	Yeast	Carbon fiber electrode tissue	Inner layer of sugarcane	5.5 V		[115]
				Outer layer of sugarcane	6 V		
				Banana peels	6 V		
	H-type Proton exchange membrane	Anaerobic sludge	Anode: Carbon fiber paper Cathode: Carbon cloth coated with a Pt catalyst	Food residue biomass	29.6 mW/m^2	COD removal efficiency = 71–91%	[116]

Table 1. *Cont.*

MFC Configuration	Additional Configuration (Volume, PEM)	Microorganism	Anode/Cathode Material	Organic Waste	Power Output/Voltage Obtained *	Organic Waste Degradation	Reference
	1.5 L and 4 L	Anaerobic sludge seeding	Combination of electrodes a. carbon felt + carbon felt, b. carbon felt + stainless steel, c. carbon felt + carbon paper, d. carbon felt + carbon plate, e. carbon plate + carbon plate.	MSW (organic fraction of MSW)	1.5 L (mW/m^2) a. 20.12 b. 2.63 c. 2.27 d. 7.59 e. 7.92 4 L (mW/m^2) a. 30.47 b. 0.21 c. 7.03 d. 10.48 e. 3.40		[99]
	0.24 L Cation exchange membrane	Anaerobic consortia	Carbon felts	Potato waste	1.4–6.8 mW/m^2	COD removal = 90%	[117]
	U-shaped Cation exchange membrane	Mix microbial culture (composed of anaerobic bacteria)	Graphite rods	Household vegetable waste	88,990 mW/m^2		[118]
	Proton exchange membrane	Cellulose-degrading bacteria	Non-wet-proof carbon paper	Powdered rice straw	0.345 V		[101]
Stacked MFC (Series and Parallel)	3 MFCs connected	Cellulose-degrading bacteria	Non-wet-proof carbon paper	Powdered rice straw	Series = 2.17 V Parallel = 0.723 V		[101]
			Thin felt disc	Food waste (mango, banana and orange leftover and peels)	Series = 1.185 V Parallel = 2.05 V		[119]

3.2.2. Feedstock Used in MFCs

When using MFCs for power generation and waste treatment, different types of organic waste, such as agriculture residue (AR) and organic fractions of municipal solid waste, have been used as feedstock, as shown in Table 1.

DC-MFCs are the most used for power generation from organic waste because of their various advantages over SC-MFCs. These advantages include the ability to enhance cathode performance through pH control, increased flow rate, reduced oxygen diffusion, and the addition of a mediator to the cathode [120]. The power output (0.007–hundreds of mW/m^2; 0.5–6 V) varies with organic waste degradation efficiency from 65% to 91%. Potato peels and pulp waste were used as substrates for SC-MFC and DC-MFC [108,116]. A power output of 32,100 mW/m^3 was obtained from SC-MFC equipped with a graphite brush anode and carbon cloth–Pt catalyst cathode. In this study, the combination of *Geobacter, Dysgonomonas*, and polysaccharide-degrading bacteria was used to degrade organic waste, and they helped in removing 68.04% of COD [109]. A power output between 1.4 and 6.8 mW/m^2 with 90% COD removal was obtained using anaerobic consortia with carbon felts as the electrode material in DC-MFC connected with a cation exchange membrane [116].

To increase process sustainability and reduce operation costs [121], SC-MFC with air cathode has also been employed for food waste treatment by using anaerobic sludge. The configuration with a carbon cloth anode and carbon cloth with 10% platinum and three diffusion layers as the cathode resulted in 0.51 V power output [109]. Moreover, in a recent study, molasses was used as the substrate for DC-MFC along with a proton exchange membrane (PEM) [113]. This study included comparative energy output by using two different electrolyte solutions, $KMnO_4$ and $K_3(Fe(CN))_6$. These electrolyte solutions act as oxidants instead of air to improve the energy output by enhancing the electrochemical reactions. *Saccharomyces cerevisiae* and graphite as electrode materials were used in DC-MFC. It was observed that the maximum energy yield of 0.48 V was achieved by using a $KMnO_4$ solution and 0.36 V energy output was obtained from using a $K_3(Fe(CN))_6$ solution with a molasses substrate [113].

Wheat straw was also used as the substrate for DC-MFC, as summarized in Table 1, where *Pichia fermentans* was used in the anode chamber with carbon fiber as the electrode. The study also applied *Phlebia floridensis* and *Phlebia brevispora* in a cathode chamber with a stainless steel cathode electrode. This study resulted in 331.9 mW/m^2 of energy output and 35–38% of organic degradation [114]. Comparative studies among different AR, including sugarcane bagasse and banana peels, were carried out with DC-MFCs coupled with a carbon fiber tissue electrode [115]. In this study, both chambers were connected with Nafion PEM. Based on the results, the energy outputs from different layers of sugarcane bagasse and banana peel were similar (5.5–6 V) [115]. These results refer to the similarity of the cellulose-based composition of sugarcane bagasse and banana peel. In another study [111], banana waste was used as the substrate in DC-MFC with a graphite electrode coupled with anaerobic digestion, which resulted in 41.3 mW/m^2 of energy output and 85% COD removal [111]. The study conducted by Rincón-Catalán et al. (2022) showed that food waste generated an electricity output of 0.0005 V using a stainless steel mesh with a carbon cloth anode and stainless steel mesh cathode. This also helped in 69.7% of COD removal [112]. Rice straw was also used for DC-MFC and stacked-MFC in series and parallel with cellulose-degrading bacteria, along with non-wet-proof carbon paper as the electrode material. This study resulted in a maximum electricity output of 2.17 V from series stacked-MFC, whereas a minimum electricity output of 0.345 V was observed from DC-MFC [102]. The parallel connected stacked-MFC resulted in an electricity output of 2.05 V using food waste with a lower electricity output of 1.185 V from the series-connected stacked-MFC [119]. Additionally, two different designed DC-MFCs, namely, H-type and U-shaped, were used for food residues and household vegetable waste, respectively [116,118]. Both studies used anaerobic bacteria as a microbial culture. The H-type DC-MFC resulted in 26.9 mW/m^2 of power output and COD removal between 71 and 91% using a carbon fiber paper anode and a carbon cloth Pt catalyst-coated cathode [116]. In a U-shaped MFC, the power output obtained was 88,990 mW/m^2 using a graphite electrode [118].

From these studies, no evidence directly reflected the feedstock effects on energy output. Carbohydrates are the major composition of AR and food waste [79]. Nitrogen and other organic matter may affect the electron transfer between microorganisms and electrodes, impacting bioelectricity generations [80]. Furthermore, the different power measurements used in the literature have resulted in diverse power output units (V, mW/m^3, mW/m^2). Consequently, additional normalization works are necessitated to make comprehensive comparisons of energy generation efficiency among various feedstock and MFC configurations. Based on the literature, the interactions and synergistic effects of the MFC configuration and feedstock resources are yet to be explored.

3.3. Consolidated Fermentation–MFC System

Recently, the integration of MFC with fermentation and anaerobic digestion has been investigated to maximize the benefits of organic waste treatment by increasing bioenergy recovery, reducing pollutants, and enhancing the yield of value-added products. Several studies have focused on the integration of anaerobic systems (anaerobic digestors) with bioelectrochemical systems (MFC and MEC). The effluent, including solids and liquids, from AD is enriched with high organic nutrients and contaminants, which can be further utilized as resources in bioelectrochemical systems to produce bioenergy and value-added bioproducts. Furthermore, this system acts as a biosensor to monitor AD process stability, facilitating in situ electro methanogenesis [122].

Several capacities of MFC have been utilized to treat supernatant fractions of organic matter. Therefore, the integrated fermentation–MFC system has been introduced to reduce nitrogen content and produce bioelectricity simultaneously [123]. In the previous study [25], MFC was integrated with two different fermentation processes, including liquid fermentation (LF) and semi-solid-state fermentation (S-SSF), for sugarcane bagasse treatment. This integrated system demonstrated that the LC process could approximately double the power output (14.88 mW/m^2) from the S-SSF process (8.70 mW/m^2) [25]. In LF, the substrate was free from fibers, which led to biofilm growth on the anode surface. This biofilm formation facilitated electron transfer, resulting in high current production during the MFC operation. However, the substrate with fibers in S-SSF caused more distance between microorganisms and the electrode surface, which slowed down the electron transfer and generated less energy output [25].

Additionally, the integrated fermentation–MFC affected the pH value of the fermentation slurry. During the LF process, the pH value decreased due to acid formation from microbial metabolism. On the other hand, nitrogen waste was generated during waste degradation in the S-SSF process, which led to a slight increase in the pH value [25]. Furthermore, the LF process had a higher COD removal (39.68%) than the S-SSF process (28.94%) [25]. According to these findings, it was observed that the integrated LF-MFC system has more potential in waste handling and bioenergy conversion efficiency than the S-SSF-MFC system [25]. There are still gaps that need to be addressed in future studies to provide more insights into potential applications using an integrated approach.

4. Waste-to-Energy Role in Circular Economy and Environmental Sustainability

Waste-to-energy (WTE) pipelines play a significant role in promoting the circular economy and securing sustainability across environmental and energy sectors by converting waste streams into clean energy products in various forms. While focusing on the circular economy perspective, waste streams are considered resources that can be recycled and reused to produce value-added products. The energy generation from waste streams through WTE pathways is also seen as a promising strategy for waste management, green energy generation, and GHG reduction.

Techno-economic analyses have been performed based on various types of fermentation processes using AR and OFMSW, as shown in Table 2. In a study performed by Chen et al. (2022) [124], the minimum selling price of food waste-derived ethanol (MESP) was estimated at USD 548.48 t^{-1} (19.36 cents/L), which was approximately half of the fuel ethanol price of USD 1082 t^{-1} in 2022. A higher MESP (52.61–64.3 cents/L) was obtained from the ethanol production from sugarcane bagasse through HSF, SSF, and co-fermentation of pentose and hexose [125]. The different fermentation technologies led to approximately a 10% variation in ethanol yields, resulting in an eight cents range of the MESP [125]. Based on these studies [124,125], the operating costs of lignocellulosic fermentation are higher than non-lignocellulosic fermentation. This difference in costs is attributed to higher energy inputs and the need for more complex processing involved in lignocellulosic feedstock pretreatment and bioconversions. Therefore, the economic feasibility of integrated fermentation–MFC highly relies on feedstock origins, fermentation efficiency, and energy output of the system, whereas the integrated fermentation–MFC system could help increase economic benefits from multiple products, including biofuel and bioelectricity. Moreover, the residue of fermentation is highly enriched with microbes and nutrients, which can be readily used in the MFC to produce bioelectricity and increase the profitability of the integrated fermentation–MFC system. To date, few studies have focused on evaluating the economic benefit when combining fermentation with MFC in a single pipeline.

Table 2. Techno-economic analysis of waste to energy.

Feedstock	Technology	MESP	Final Fuel Products	GHG Emission	Reference
Food Waste	Enzymatic Hydrolysis + Fermentation	19.36 cents/L (USD 548.48 t^{-1})	Ethanol	N/A	[124]
Sugarcane Bagasse	Liquification + Simultaneous Saccharification and Co-fermentation	52.61–64.3 cents/L (USD 627.2 t^{-1})	Ethanol *	N/A	[125]
Food Waste, Microalgae	Fermentation	N/A	H_2, CH_4	15.1 kg CO_2-eq/kg H_2	[126]
Urban Wastewater	MEC	N/A	H_2,	18.8 kg CO_2-eq/kg H_2	[127]

* Co-product: Electricity and Fertilizers.

The ethanol production from global municipal solid waste (MSW) through fermentation can be estimated as follows. The global annual MSW generation is estimated to be 2.01×10^{12} kg (2.01 billion tons) [2], with 55% of the waste being carbohydrates (estimated at 1.1055×10^{12} kg) [128]. Through hydrolysis, the carbohydrate can be converted to 1.227×10^{12} kg of fermentable sugar (1.11 conversion factor from carbohydrate to reducing sugar) [129]. The theoretical ethanol yield from the fermentable sugars in global MSW can be estimated to be 6.258×10^{11} kg (0.51 conversion factor) [130]. Considering that the empirical ethanol yield is typically 90% [131], this results in an estimated ethanol annual production of 5.63×10^{11} kg (7.165×10^{11} L). Based on the 2023 ethanol market price of USD 9.31/L [132], the bioethanol converted from MSW globally could contribute to USD 465.7 billion. Additionally, bioelectricity generated from the consolidated approach can be estimated at 6.124×10^4 MW/m^2 using a DC-MFC setup with a carbon felt anode and cathode [101]. It is important to note that the actual revenue from bioelectricity production will fluctuate depending on the prevailing market price of electricity, which can vary significantly across different grids and providers.

Bioethanol has the potential to reduce 65–77% of GHG emissions from fossil fuels [133]. Considering the GHG emissions of hydrogen production (15–18 kg CO_2 eq/kg H_2) [126,127] from fermentation and the MEC system (Table 2) with biofuel and bioelectricity conversions, the integrated fermentation–MFC/MEC system can be regarded as a promising decarbonization technology for waste management and bioenergy production. However, there is a gap in research focusing on the life cycle assessment of MFC using an organic waste substrate due to the lack of practical data.

Additionally, electroactive biofilm in MFCs demonstrates a remarkable capability of removing more than 90% of chemical oxygen demand (COD). Moreover, MFCs can efficiently monitor biochemical oxygen demand (BOD) in a significantly shorter timeframe, typically around one day, making them valuable and cost-effective devices for environmental monitoring [134]. With these benefits, adopting the consolidated system becomes crucial in reducing and treating organic waste, leading to a substantial reduction in GHG emissions. When fermentation and MFC technologies are integrated cohesively, they can have a synergistic impact on the circular economy and environmental sustainability. The combination of these technologies presents a promising solution for tackling waste management, energy generation, and environmental concerns, contributing to a more sustainable and eco-friendly future.

5. Conclusions and Future Outlook

The integrated biorefining system has attracted considerable attention due to its potential to secure economic and environmental feasibility. An integrated waste-to-energy (WTE) system is designed to produce multiple products from a single pipeline, making it highly adaptable to a wide range of resources. The integrated fermentation–MFC can be realized as a new system to simultaneously produce bioenergy in multiple forms from organic waste.

However, the integrated fermentation–MFC system lacks a sustainable process design that considers viability across technical, economic, and environmental sectors. While the fermentation and MFC technologies have been individually developed, their combination for waste treatment and bioenergy production is still under development. Several topics remain to be determined, especially regarding the optimization of MFCs for compatibility with the fermentation process. These include MFC configuration improvement, electrode selection, microorganisms' performance and screening, the interaction between organic matter and microorganisms, feedstock effects on electron transfer, electrochemical reactions, etc. Additionally, comprehensive sustainability modeling, including economic cost evaluation and life cycle assessment, is yet to be explored. By integrating technology innovation with sustainability modeling, the consolidated WTE pipeline can be designed and established. Through implementing intelligent system design, this WTE pipeline, with the capability of producing multiple products, can become more effective, scalable, and efficient in the future.

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