processes

MDPI

Review

Advancements in Bioelectrochemical Systems for Solid Organic Waste Valorization: A Comprehensive Review

Shivani Maddirala [1,†], Sudipa Bhadra [1,†], Md. Salatul Islam Mozumder [2], Vijay Kumar Garlapati [3] and Surajbhan Sevda [1,*]

[1] Department of Biotechnology, National Institute of Technology Warangal, Warangal 506004, India; msbt21115@student.nitw.ac.in (S.M.); sb721094@student.nitw.ac.in (S.B.)
[2] Department of Chemical Engineering & Polymer Science, Shahjalal University of Science and Technology, Sylhet 3114, Bangladesh; salatul-cep@sust.edu
[3] Department of Biotechnology and Bioinformatics, Jaypee University of Information Technology, Solan 173234, Himachal Pradesh, India; shanepati@gmail.com
* Correspondence: sevdasuraj@gmail.com or sevdasuraj@nitw.ac.in; Tel.: +91-992-9565697; Fax: +91-870-2459547
† These authors contributed equally to this work.

Abstract: Environmental pollution and energy scarcity are the two significant issues that could substantially impede the sustainable growth of our civilization. Microbial fuel cells (MFCs) are an emerging technique for converting the chemical energy of organic wastes directly into electric energy, allowing for both energy recovery and environmental rehabilitation. Solid organic waste decomposition is generally more challenging compared to organic wastewater due to several factors, including the nature of the waste, the decomposition process, and the associated environmental and logistical considerations. With rapid population expansion and acceleration of urbanization, waste generation continues to rise globally, causing complicated environmental, socioeconomic, and energy problems and a growing demand for public health globally. Bioelectrochemical systems (BES) are promising solid waste management options. However, BES may not be the most effective solution on its own for certain types of waste or may be incapable of treating all waste components. In many circumstances, combining BES with other solid treatment technologies can increase overall treatment efficiency and waste management. Combining BES with other solid treatment methods can have synergistic effects, boosting waste treatment efficiency, resource recovery, and environmental sustainability. However, to guarantee the successful integration and optimization of these combined approaches, site-specific factors, waste characteristics, and system compatibility must be considered.

Keywords: solid waste; solid waste management; bioelectrochemical systems; sludge; solid food waste

Citation: Maddirala, S.; Bhadra, S.; Mozumder, M.S.I.; Garlapati, V.K.; Sevda, S. Advancements in Bioelectrochemical Systems for Solid Organic Waste Valorization: A Comprehensive Review. *Processes* **2024**, *12*, 805. https://doi.org/10.3390/pr12040805

Academic Editor: Aldo Muntoni

Received: 22 August 2023
Revised: 12 September 2023
Accepted: 15 September 2023
Published: 17 April 2024

1. Introduction

Due to its effects on public health, environmental sustainability, and resource conservation, solid waste management is an important worldwide and national concern. Because of the Industrial Revolution and subsequent economic growth, people's spending habits have undergone a complete transformation. However, it has also made solid waste management (SWM) extremely difficult. Because of this modified way of life, the amount of waste has increased dramatically, adversely affecting solid waste management and making it a current global issue [1,2]. Nearly all nations in the world are fighting tooth and nail to manage garbage properly and effectively, but they have not yet succeeded. However, a few industrialized nations, including Germany, Italy, Canada, and Australia, have successfully dealt with this problem. However, much of the remainder of the world, including many developing and underdeveloped nations, is still building out its foundational infrastructure, let alone handling solid waste [3–5]. Energy recovery from solid organic waste, often referred to as waste-to-energy (WtE) or bioenergy, is a process that converts organic materials, such as food waste, agricultural residues, and other biodegradable materials, into energy. This approach helps manage waste, reduce landfilling, and produce renewable energy.

Waste-related pollution is one of the biggest concerns facing the globe today. Due to the rising population, the Industrial Revolution, and following economic expansion, waste output has greatly expanded. Increased garbage generation and poor waste management are to blame for a number of issues, including water pollution, soil erosion, loss of soil fertility, and a variety of human and animal diseases. The ecology and natural resources must be protected; hence, there is a need for proper waste management technologies. Solid waste management is a significant international and national concern because of its effects on public health, environmental sustainability, and resource conservation [1,2].

Conventional solid waste treatments consume a lot of energy, which has led to growing concerns about the serious global energy crisis. In comparison to recently developed techniques and concepts that place a focus on cost-effectiveness and performance efficiency, the conventional approaches for the treatment of solid wastes are currently encountering difficulties. As a viable resource utilization method, the utilization of BES for solid waste stabilization and concurrent electrical energy recovery has been emphasized [6–9]. By utilizing the ability of microbes to transform organic waste into useful goods and produce electricity in the process, BES offers potential options for solid waste management. These systems waste treatment and energy recovery simultaneously, using the concepts of microbial electrochemistry. It is possible to balance the energy required for the treatment plant's functioning by recovering the abundant energy found in the trash. BES may now manage solid waste in addition to micro-molecular organics, wastewater, sludge, and other pollutants because of recent advancements in the field of substrates. Simultaneous waste treatment and energy recovery, reduced environmental impact, versatile waste treatment, and potential for resource recovery are a few benefits of BES over other methods. Although BES has a lot of potential, further study and development are required to maximize its effectiveness, scalability, and affordability for widespread deployment in solid waste treatment [10–13]. However, these systems have a lot of potential for long-term energy recovery and waste treatment. However, for certain types of garbage, BES may not be the most effective solution on its own, or it may be incapable of treating all waste components. Combining BES with other solid treatment technologies can improve overall treatment efficiency and waste management in many cases. Combining BES with other solid waste treatment procedures can have synergistic benefits that improve waste treatment efficiency, resource recovery, and environmental sustainability [14–19].

2. Characteristics of Solid Waste

Solid biological wastes are biodegradable because they are rich in organic matter and nutrients. These wastes include yard garbage, food waste, agricultural waste, and other organic waste that can decompose. However, biological solid waste may also contain infections, toxic metals, and other dangerous substances. Anaerobic digestion and composting offer greater environmental and financial advantages over landfilling and incineration and can produce extremely valuable products like methane. Solid waste is any non-liquid waste produced by human activities, such as domestic, commercial, agricultural, and industrial ones, or animal products, such as dung, referred to as solid waste [19–24]. The characteristics of solid waste can vary significantly depending on the source, composition, and location. Table 1 provides a concise overview of the key characteristics of solid waste.

The composition of solid waste can comprise organic waste (such as food scraps and yard garbage) along with paper, plastics, metals, glass, and other things [25]. The non-biodegradable substances that can be found in solid waste have to be removed before their use in BES. The biodegradable part of the solid waste can be pre-treated as per requirement. The moisture content of solid wastes can be either dry or wet, depending on their type and origin [22]. However, as per various research, it is found that some amount of water is required for the proper flow of electrons and substrate degradation in the BES.

Table 1. Concise overview of the key characteristics of solid waste.

Characteristic	Description
Composition	Can include organic and inorganic materials
Physical State	Neither liquid nor gas, exists in a solid form
Volume	Takes up physical space and has volume
Density	Varies depending on the types of materials present
Biodegradability	Organic waste is biodegradable; inorganic waste is not
Odor	Organic waste can produce unpleasant odors as it decomposes
Pest Attraction	Organic waste can attract pests like rodents and insects
Flammability	Some materials are highly flammable
Volume Reduction	Can be reduced using methods like compaction or shredding
Aesthetic Impact	Improperly managed waste can cause visual pollution
Landfill Potential	Materials that cannot be recycled may end up in landfills
Health and Environmental Risk	Presence of hazardous materials poses risks
Recyclability	Many components can be recycled and reused

The biodegradability of solid waste is defined as decomposing organically over time, such as paper and food scraps [5,26,27]. In contrast, non-biodegradable materials like plastic and metal can linger in the environment for hundreds of years or longer. The chemical composition of solid waste can contain a variety of compounds, including heavy metals, pesticides, and other dangerous substances, which, if improperly managed, can cause threats to human health and the environment. Understanding the characteristics of solid waste is crucial for designing effective waste management systems, promoting recycling and waste reduction, and addressing environmental and health concerns associated with waste disposal. Sustainable waste management practices aim to minimize the negative impacts of solid waste while maximizing resource recovery and energy generation from these materials.

The odor of solid trash can emit unpleasant odors, especially if it comprises organic waste that is in the process of degrading [28]. Managing and disposing of waste properly can reduce odor issues. Infectious substances, such as viruses, bacteria, and parasites, can also be found in solid waste and, if not managed and disposed of appropriately, pose a risk to human health. The choice of technology depends on factors such as the composition of the waste stream, local regulations, available infrastructure, and the desired end-products. Energy recovery from solid organic waste can contribute to reducing greenhouse gas emissions, minimizing landfill usage, and providing a sustainable source of renewable energy. However, it is essential to manage these processes carefully to minimize environmental and health impacts, such as air emissions and the disposal of residues.

3. Types of Solid Waste Used for Treatment in BES

Solid waste, particularly organic solid waste, can be a valuable resource for BES. BESs are innovative technologies that use microorganisms to convert organic matter into electricity or valuable chemicals using electrochemical processes. Organic solid waste, such as food scraps, agricultural residues, and sewage sludge, contains biodegradable materials. BES can be used to convert this organic matter into electricity directly or indirectly using MFCs or MECs. Microorganisms break down the organic compounds, generating electrons that can be harvested as electrical energy [29–34].

BES can be employed as a sustainable and efficient method for treating solid waste. The microorganisms in these systems help in the decomposition of organic waste, reducing its volume and minimizing the environmental impact. BES can also help in the removal of pollutants and pathogens from solid waste. In addition to electricity and hydrogen production, BES can generate valuable chemicals and bioproducts from solid waste. For example, BES can be designed to produce organic acids, alcohols, or other high-value compounds that have industrial applications. Some solid waste materials, such as organic sludges, can be used as substrates for BES to produce hydrogen gas (H_2). Hydrogen is a clean energy carrier and can be used in various applications, including fuel cells and industrial processes [29–34].

BES can be integrated into waste management systems to recover resources from solid waste streams, aligning with the principles of a circular economy where waste is transformed into valuable resources. BES can contribute to the valorization of solid waste by converting it into useful products, reducing the need for landfilling or incineration, and potentially generating revenue from the sale of electricity or chemicals [29–34]. The use of solid waste in bioelectrochemical systems represents a promising approach for sustainable waste management, renewable energy production, and resource recovery, contributing to more environmentally friendly and economically viable waste treatment practices. There are a few types of solid waste that are commonly used in a bioelectrochemical system [29–34].

1. Municipal solid waste (MSW): It consists of waste produced in towns and cities, including industrial, commercial, and domestic waste. MSW is the perfect substrate for BES since it contains a considerable amount of biodegradable organic materials [2].
2. Agricultural waste: It includes animal dung, crop waste, and other agricultural activity byproducts [35,36]. These wastes are appropriate for BES since they are full of nutrients and organic materials.
3. Food waste: It corresponds to the organic waste produced by restaurants, households, and the food processing industry [2,37]. Food waste is a great substrate for BES since it includes a lot of effortlessly biodegradable organic materials. Food waste is one of the most significant waste components, accounting for 18% of the worldwide waste stream. Every year, more than 1.3 billion tonnes of food waste are generated, with the majority of this trash being disposed of in landfills or incinerated. Food waste contains a high concentration of lipids, carbohydrates, proteins, and other macromolecules, and its composition varies based on cultural routines, geography, climate, economic level, and so on. Due to its high organic content and potential for biodegradation, this waste might serve as a useful substrate for anaerobic digestion. It is possible to use the soluble organic compounds produced by the acidogenesis of carbon-rich food waste as both carbon and energy sources for microorganisms and also in the production of biohydrogen and biodegradable polyhydroxyalkanoates. For biological phosphorus and nitrogen removal, fatty acids produced from food wastes during anaerobic digestion are thought to be superior electron donors.
4. Sewage sludge: It is a byproduct product coming from wastewater treatment facilities that is rich in nutrients and organic substances [19,38,39]. For energy recovery, sewage sludge is frequently employed in BES.
5. Lignocellulosic waste: It consists of lignocellulose-rich plant biomass like wood chips, sawdust, and straw [40,41]. These wastes can be employed in BES for energy recovery even though they can often be difficult to decompose.

Table 2 summarizes different types of solid waste materials that can be used for BES and the potential applications or benefits associated with each type.

The solid wastes that are difficult to undergo biodegradation can be mixed with other substrates to enhance their degradation. This process is called Co-digestion. Co-digestion and co-substrate are further discussed with examples in this article. However, it's important to note that the effectiveness of BES depends on several factors, including the type of solid waste, the composition of organic matter, the design of the BES, and environmental conditions. Successful implementation requires a thorough understanding of both waste characteristics and BES technology.

Table 2. Potential applications in BES using solid waste material.

Solid Waste Material	Potential Applications or Benefits of BES
Food Scraps	- Direct conversion to electricity using MFCs.
	- Waste treatment and reduction.
	Potential for bioproducts or value-added chemicals.
Agricultural Residues	Electricity generation
	Nutrient recovery
	Reduction in waste volume
Organic Sludges	Hydrogen production
	Value-added chemical production
	Waste valorization
Sewage Sludge	Electricity or hydrogen production
	Efficient waste treatment
	Removal of pollutants
Lignocellulosic Waste	Electricity generation
	Biohydrogen or biogas production
	Potential for biofuels
Industrial Waste	Conversion to electricity or valuable chemicals
	Resource recovery
Landfill Leachate	Electricity generation
	Landfill leachate treatment
	Reduction in environmental impact

4. Fundamentals of Bioelectrochemical System (BES)

BES is a technology that can be used to generate eco-friendly electricity from organic waste. BES is based on a bioelectrochemical process, where microorganisms or other bio-based catalysts are used as a catalyst for the oxidation and/or reduction process in the anode and/or cathode, respectively. BES uses the capacity of microorganisms to generate/accept electrons [6,42]. Generally, exoelectrogenic microorganisms perform this job. BESs are capable of converting chemical energy present in the bonds of organic matter into electrical energy or electrical energy into chemical energy by using microorganisms as catalysts (Figure 1). In addition to the production of electrical energy, BES provides a synergistic benefit from its ability to decrease organic contaminant load in the waste/polluted water [34].

In general, a BES consists of an anode and a cathode placed in the anodic and cathodic chamber, respectively, and connected using an external circuit. Electron donors undergo oxidation at the anode. Examples of these electron donors include sulfides and organic waste. An electron acceptor, such as oxygen or nitrate, is reduced at the cathode. An external electrical connection connects the anode with the cathode. The electrical power is invested or harvested from this circuit without the need for combustion [43]. Depending on if the power is being harvested or invested from the circuit and the product of interest, BES is divided into microbial fuel cell (MFC) and microbial electrolysis cell (MEC). MFC has great potential to become a sustainable way to extract energy from waste. Microbial electrolysis cell reverses the process of producing methane or hydrogen from organic waste by applying/investing electric current, and the produced methane or hydrogen can be used to produce current [44].

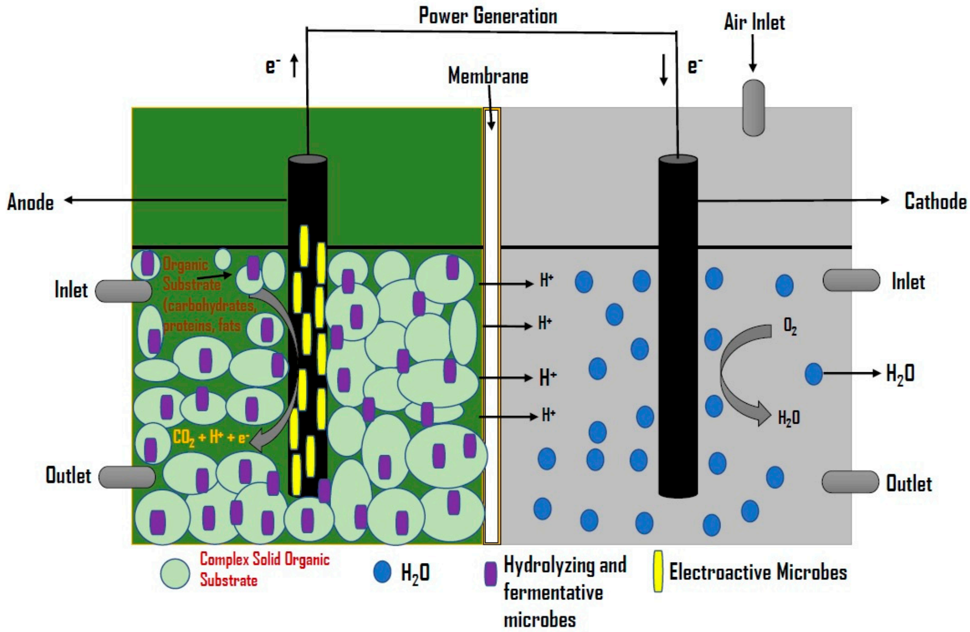

Figure 1. The basic working principle for BES is using solid and liquid waste.

In a microbial fuel cell, waste organics and anaerobic microorganisms are added to the anodic chamber. Acidic water or PBS is added to the cathodic chamber. Microorganisms consume the organic compounds, giving out electrons and protons. Electrons travel through the external circuit via a resistive load and proton through the proton exchange membrane, reaching the cathode and producing electricity. In the cathodic chamber, electrons and protons combine with oxygen to form water. Power generated can be harvested via the external circuit [3].

The cathodic reduction process results in the conversion of organic matter into electrical energy as well as the recovery of nutrients (like ammonia) via migration and ammonium conversion at high pH. BES can also be used to extract or recover metals. Additionally, it was demonstrated that MFCs could generate effluent water suitable for reuse in irrigation [45]. A microbial electrolysis cell is similar to an MFC, except that external voltage is supplied to reduce protons for the production of hydrogen gas. Depending on the microorganisms present in the cathode, an MEC can also produce methane [29].

BES systems have a wide range of applications, including wastewater treatment, bioenergy production, and environmental sensing. At the heart of BES is the use of microorganisms, such as bacteria or archaea, as electrocatalysts. Some electroactive microorganisms have specialized outer membrane proteins that facilitate direct extracellular electron transfer to electrodes. In BES, microorganisms often form biofilms on the electrode surfaces. These biofilms enhance the stability and efficiency of electron transfer and metabolic processes [3]. An electrolyte solution is used to maintain ionic conductivity between the anode and cathode, allowing ions to move freely while preventing direct electron flow. BES requires an organic substrate, which serves as the energy source for the microorganisms. Common substrates include organic wastewater, sewage, and various organic compounds. BES can be used to treat organic-rich wastewater by harnessing microbial activity to break down pollutants while generating electricity or other valuable products. BES can produce biofuels (e.g., biohydrogen or bioelectricity) from organic feedstocks, providing a renewable and sustainable energy source. BES can be applied to remediate contaminated environments by promoting the degradation of pollutants via microbial activity. BES can be used to develop biosensors for monitoring environmental parameters or detecting specific analytes in real time [3]. BES research faces challenges related to optimizing microbial consortia, improving electron transfer efficiency, scaling up systems for practical applications, and addressing issues such as fouling and biofilm management [3]. BES are considered a sustainable technology because they can simultaneously treat waste and generate renewable energy, contributing to resource recovery and environmental protection [44].

BES has the potential to address both environmental and energy challenges, making them an exciting area of research and development in the fields of biotechnology, environmental science, and sustainable energy production [44].

5. BES Configuration for Solid Waste Treatment

A bioelectrochemical system is made of 2 chambers, with an electrode in each chamber and a membrane separating the chambers. The anode is placed in the anodic chamber. Similarly, the cathode is placed in the cathodic chamber. The two electrodes have a membrane between them and are connected using an external circuit through which the power is harvested or invested [46]. Type of substrate, substrate concentration, size of substrate particles, pH, the material of the electrode, the structure of the electrode, availability of electrons and protons, the flow of electrons and protons, the distance between electrodes, oxidation of the substrate, microorganisms present, concentration and type of electron acceptor are the factors affecting the performance of the bioelectrochemical system [22].

Solid wastes usually have a higher amount of organic matter in comparison to other types of wastes. The organic matter of the solid waste is oxidized in the anodic chamber by the exoelectrogenic microorganisms in anaerobic conditions, with the production of electrons and protons. The proton exchange membrane transfers protons, and the external circuit transports the electrons to the cathode chamber, where oxygen (the electron acceptor), protons, and electrons combine to form water [25].

5.1. Anode Chamber Process

The anodic chamber contains an anode and is maintained in anaerobic condition for the microorganisms to grow and degrade the organic substance added to this chamber. The presence of oxygen inhibits the electricity generation by the microorganisms [29]. The substrate, which is the solid organic waste, is added to the anodic chamber by mixing it with water to maintain moisture content and anolyte conductivity. The water here acts as a medium for the flow of electrons and protons. If the solid organic waste is added directly without water, the flow of electrons and protons will be inhibited. Before being utilized by the microorganisms in the anode chamber, the insoluble macromolecules in solid waste must first be hydrolyzed into simple molecules [47]. Four major steps are involved in this process. Hydrolysis is the initial stage of this procedure. It entails the biological breakdown of organic polymers as well as the solubilization of substrates that are intractable in particle form [48]. Complex organic compounds are hydrolyzed by biofilm that is adhered to the anode. Sugars are produced from carbohydrates, long-chain fatty acids from lipids, and amino acids from proteins. The next step is acidogenesis. In acidogenesis, the soluble molecules from the hydrolysis stage are converted into volatile fatty acids, lactate, alcohol, and carbon dioxide by fermentative bacteria. Acetic acid, propionic acid, and ethanol are the main products here. Inorganic compounds such as CO_2, H_2, H_2S, and NH_3 are also produced. The next step is acetogenesis. In acetogenesis, acetogenic bacteria convert the volatile fatty acids and alcohols produced from the acidogenesis process into acetic acid and hydrogen. The final step is methanogenesis. In methanogenesis, the methanogenic bacteria convert the products of acetogenesis into methane and carbon dioxide [16].

Reactions commonly occurring at the anode are expressed in Equation (1).

$$\text{Biodegradable organic substances} \rightarrow \text{carbon dioxide + proton + electron} \ldots \quad (1)$$

The role of electron donor is played by the carbon fraction/organic fraction of waste. At the anode, chemical energy present in the bonds of the organic molecules is oxidized by the microorganisms, producing electrons, protons, and other products of degradation; the secondary metabolites, such as volatile fatty acids, methane, carbon dioxide, and others, as discussed above. Well-known exoelectrogenic microbes include *Shewanella putrefaciens*, *Geobacteraceae sulfurreducens*, and *Geobacter metallireducens* [49–53]. Substrate concentration, pH, size of substrate particle, material and structure of electrode, oxidation of substrate, microorganisms present, and presence of water for the flow of electrons and protons are the factors affecting the performance in the anodic chamber. Depending on the inoculum type, the inoculum source can have a considerable impact on the creation of the bacteria population in the anode and other bacteria that can be engaged in producing electricity. *Proteobacteria*, *Frimicutes*, and *Bacteroidetes* are dominant species found in MFCs inoculated with anaerobic sludge. *Clostridium* sp., *Lactobacillus* sp., *Flavobacterium* sp., *Methanolinea* sp., *Methanospirillum* sp., *Methanosarcina* sp., *Methanosphaera* sp. are dominant species when inoculum is used in sewage sludge. *Proteobacteria*, *Bacteroidetes*, *Firmicutes*, and *Acidobacteria* are dominant when inoculums used is from food waste. *Clostridium*, *Ochrobactrum*, *Pseudomonas*, *Comamonas*, and *Desulfobulbus* are dominant when inoculums are from dairy manure [54].

5.2. Cathode Chamber Process

The cathodic chamber contains a cathode and is maintained in aerobic conditions. Acidic water and phosphate-buffered saline (PBS) solutions are the widely used cathode chamber solutions. This chamber should be maintained in aerobic conditions for the availability of oxygen for the protons and electrons to combine and form water.

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

In the bioelectrochemical system, electrical energy is continually produced by the cathode and anode chambers [55–57]. The cathode chamber's performance is influenced by the electrode's composition and structure, electron receiver type and concentration, availability of protons, and oxygen availability. Oxygen is a useful electron acceptor for the cathodic chamber due to its great availability, strong oxidation potential, and non-toxic end products [29].

6. Microorganisms Involved in Solid Waste Treatment Using BES

Two groups are involved in a BES. They are exoelectrogenic microorganisms and organic-matter oxidizing microorganisms [58]. Microorganisms called exoelectrogens have the capacity to transmit electrons generated by the oxidation of organic materials from inside their cells to electron acceptors located outside of their cells. Electrical energy is produced as a result of the movement and transmission of electrons. Examples of exoelectrogenic microorganisms are *Geobacter sulfurreducens* (generates high current density and efficiently transfers electrons to the electrode), Shewanella oneidensis (can transfer electrons to solid electron acceptors, such as iron oxides and manganese oxides, as well as electrodes), and *Lactococcus lactis* (can produce electricity from lactate) [59]. Several types of microorganisms are involved in solid waste treatment using microbial fuel cells, with the primary players being bacteria. Electrogenic bacteria are the workhorses of microbial fuel cells. They can transfer electrons to the anode electrode during the oxidation of organic matter. *Shewanella species* are known for their ability to transfer electrons to solid substrates and are often used in MFCs as well.

Acetogenic bacteria are responsible for the production of acetate, which can serve as an electron donor in MFCs. Some acetogens can directly transfer electrons to the anode. *Acetobacterium woodii* is an example of such a bacterium.

Microorganisms that oxidize organic material are in charge of destroying organic material in solid waste (Table 3). They break down complex organic chemicals into simpler molecules that the electrogenic bacteria can employ to produce electricity. Examples of exoelectrogenic microorganisms are bacteria such as *Clostridium*, *Bacteroides* (commonly found in the human gut and can break down complex carbohydrates), and *Proteobacteria*.

In some cases, methanogenic archaea can be involved in the treatment of solid waste using MFCs. Methanogens produce methane (CH_4) as a metabolic byproduct during the degradation of organic matter. However, in MFCs, efforts are made to prevent methane production to maximize electron transfer to the anode [60].

Table 3. Shows the various types of microorganisms used in BES for solid waste treatment.

S.No.	Type of BES	Substrate	Types of Microorganism	References
1	Substrate-enhanced microbial fuel cell (SEMFC)	Secondary clarifier wastewater supplemented with ChitoRemTM SC-20 (Chitin 20)	*Clostridium sticklandii*, *Enterobacter cloacae* strain E717, *Fusibacter paucivorans*, and *Bacillus* sp. *R-31029*	[61]
2	MFC	Cattle manure (livestock organic solid waste)	Hydrogen-generating bacteria (HGB)	[62]
3	MEC	Air-dried corn stalk	Cow dung compost as H_2-producing microflora	[63]
4	MFC	Organic Fraction of Solid Municipal Waste (OFSMW)	Hydrogen-producing mixed consortia	[64]
5	MFC	Organic fraction of municipal solid waste (OFMWS)	*Geobacter*, *Bacteroides*, and *Clostridium*	[65]
6	MFC	Organic fraction of municipal solid waste (OFMSW) (food waste (FW), paper–cardboard waste (PCW), and garden waste (GW)) and their blends	*Bacteroidetes* and *b-proteobacteria*	[66]
7	MFC	Solid potato waste	Anaerobically cultured waste-activated sludge (WAS)	[67]
8	MFC	MFC spent substrate as AD feedstock	*Lactobacillaceae*, *Bacillaceae*, *Clostridia*, *Pseudomonadaceae*, and *Pseudomonas aeruginosa*	[31]
9	Solid-phase microbial fuel cells (SMFC)	Solid waste containing boiled rice (60 ± 5%), cooked vegetables (14 ± 2%), un-cooked vegetables (spoiled) (2 ± 1%), cooking oil (6 ± 2%), and vegetable peelings (3 ± 1%)	Anodophilic bacteria	[33]
10	Solid-phase microbial fuel cells (SPMFCs)	Rice hull, bean residue, ground coffee waste	Native microbial population in individual waste	[32]

Microorganisms in MFCs often form biofilms on the anode electrode's surface. These biofilms consist of various bacterial species that work together to facilitate the electron transfer process. Biofilm formation is crucial for the long-term stability and efficiency of MFCs. The synergy between these various microbes and the optimization of operating conditions, such as pH, temperature, and electrode material, are key factors in the effectiveness of BES for waste treatment. The specific composition of the microbial community in an MFC can vary depending on factors like the type of organic waste being treated, environmental conditions, and the design of the MFC system. Researchers often optimize MFCs by selecting or engineering microorganisms that can efficiently degrade the targeted organic compounds and transfer electrons to the anode, thereby maximizing electricity generation and waste treatment efficiency.

7. Hydrolysis and Degradation Rate Parameters for Solid Waste

Hydrolysis of solid waste is a process that involves breaking down organic materials in solid waste using water and typically an acidic or enzymatic catalyst. This process can be used to convert organic waste into biogas, which is a mixture of methane and carbon dioxide, or into other valuable products such as compost or biofuels. Hydrolysis is a key step in the anaerobic digestion process, which is commonly used for organic waste treatment [68]. The type of waste and the environmental factors to which it is subjected will determine the hydrolysis and degradation rate parameters for solid waste. When it comes to the decomposition of some types of solid waste, the process of hydrolysis, in which water molecules dissolve chemical bonds in a substance, might be a crucial phase [68].

The degradation of solid waste refers to the process by which solid waste materials break down or decompose over time. Solid waste degradation can occur via various natural and human-induced processes, and it is an important aspect of waste management and environmental protection. Biological degradation is one of the primary methods of solid waste degradation is biological decomposition. Organic materials, such as food scraps, yard waste, and paper products, can be broken down by microorganisms like bacteria, fungi, and enzymes. This process typically occurs in landfills, composting facilities, and other environments where organic waste is exposed to moisture and oxygen.

Solid waste is collected and segregated to separate organic waste from inorganic waste. Organic waste includes food scraps, yard waste, and other biodegradable materials. Before hydrolysis, the organic waste may undergo pre-processing to remove contaminants such as plastics, metals, and non-biodegradable materials. This step is crucial to ensure the efficiency of the hydrolysis process. The organic waste is mixed with water and subjected to hydrolysis [68]. Hydrolysis involves the breakdown of complex organic molecules into simpler compounds via the addition of water molecules. This is typically achieved by using enzymes or acids to accelerate the decomposition of organic matter.

Before hydrolysis, the organic waste may undergo pre-processing to remove contaminants such as plastics, metals, and non-biodegradable materials. This step is crucial to ensure the efficiency of the hydrolysis process.

Organic material is broken down into simpler components during degradation. It is necessary to take into account a number of variables, such as the waste's composition, pH, temperature, moisture content, and the presence of microbes, in order to calculate the hydrolysis and degradation rates for solid waste. These elements may have an impact on how quickly hydrolysis and degradation take place [69]. For instance, food waste typically degrades more quickly than paper or plastic garbage.

Hydrolysis and degradation of organic substances are the parameters that determine the power recovery efficiency of the MFC. Measuring the changes in waste over time and using mathematical models is necessary to determine these parameters [25]. This can be described by a first-order sequential model as

$$\frac{dC}{dt} = K_h \times \mathrm{C_a} - \mathrm{K_d} \times \mathrm{C}\frac{dC}{dt} = -K_h \times \mathrm{C_a} \quad (3)$$

where C_a represents the concentration of the hydrolysis products of SPW and WAS, K_h represents the hydrolysis rate parameter, and K_d represents the degradation rate parameter. C represents the SCOD (soluble COD) in the anolyte at time *t*.

Following the initial COD as C_{a0}, the variations in COD concentration in the anolyte can be explained by

$$\mathrm{C} = [(\mathrm{k_h} \times \mathrm{C_{a0}})/(\mathrm{k_d} - \mathrm{k_h})\ (\mathrm{A})\ (\mathrm{e}^{-\mathrm{kh}\times\mathrm{t}} - \mathrm{e}^{-\mathrm{kd}\times\mathrm{t}})] \quad (4)$$

K_h and k_d were found by minimizing the discrepancies between the COD calculated using Equation (4) and the observed COD according to Equation (5).

$$Er = \frac{1}{n}\cdot\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\frac{\mathrm{C_{i(obs)}} - \mathrm{C_{i(cal)}}}{\mathrm{C_{i(obs)}}}\right)^2 \quad (5)$$

where $C_{i(obs)}$ and $C_{i(cal)}$ are the observed and calculated COD concentrations, respectively, and n is the number of samples collected for COD measurement.

After hydrolysis, the resulting mixture, known as slurry or digestate, is transferred to an anaerobic digester. In the digester, microorganisms break down the hydrolyzed organic matter in the absence of oxygen, producing biogas as a byproduct. Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2). Biogas is collected and can be used as an energy source for heating, electricity generation, or as a fuel for vehicles. It can also be upgraded to produce biomethane, a cleaner and more refined form of methane suitable for injection into natural gas pipelines or vehicle use.

Overall, it is crucial for waste management to comprehend how quickly solid waste hydrolyzes and degrades since this information can be used to estimate how long waste will take to degrade and to choose the most effective strategies for handling various waste kinds.

The remaining digestate from the anaerobic digestion process can be further processed into compost or used as a nutrient-rich soil conditioner.

Hydrolysis of solid waste is an environmentally friendly approach to waste management because it reduces the emission of greenhouse gases, minimizes the need for landfill disposal, and generates renewable energy in the form of biogas. Additionally, it can help divert organic waste from landfills, where it would otherwise produce methane, a potent greenhouse gas.

8. Municipal Solid Waste Landfill Mature Leachate and Dairy Wastewater as Co-Substrate in BES

Co-digestion of different types of substrates in anaerobic conditions is advantageous than using a single substrate in BES. This is because of the capability of co-digestion in diluting harmful substances, increasing methane production, adjusting the C/N ratio, and improving the hydrolysis of organic wastes [70–73]. One popular method for biologically treating substrates that are often unsuitable for biological processes and improving process efficiency is the addition of a rapidly biodegradable co-substrate. Combining different types of solid wastes can take advantage of their individual strengths and provide synergistic benefits because they have different qualities, functions, and complexity. This improves the effectiveness of conversion of energy and degradation of organic waste in MFCs. In an MFC, the ability of microbes to break down organic matter and the mechanism of induced electron transfer are what primarily determine how much chemical energy exists in the bonds of organic compounds that may be converted into electrical energy [74,75].

Disposal of municipal solid waste is a big problem without an easy solution. Even though landfill disposal of municipal solid waste is reduced nowadays, leachate generation is still significant. Leachate is generated due to the decomposition of solid municipal waste in the landfilling sites, leading to the closure of sites, groundwater contamination, and the spreading of harmful and toxic pollutants [16,76]. Leachate has organic components that may be broken down by bacteria already present in the waste, but it also has significant amounts of ammonia, heavy metals, and other unresponsive organic and inorganic chemicals that could build up and cause biotoxicity or bioinhibition [77].

Bolognesi et al., 2021, investigated the treatment of two substrates: mature leachate and dairy wastewater in BES [78]. The integrated BES system used municipal solid waste landfill leachate was combined with agro-industrial (dairy) wastewater as co-substrate and fed to two differently structured dual-chamber MFCs at varying dilution ratios in order to evaluate system performance and overcome process barriers related to the poor biodegradability of mature leachate as a substrate for bioenergy production [78].

On-site pre-treatment equipment is made particularly to partially or completely treat waste before it is discharged into municipal sewers; however, this is sometimes not the most economical option. Biological (aerobic or anaerobic) and/or physicochemical techniques are frequently used to treat leachate, depending on the amount of pollutants present. The importance of treatment process sustainability in terms of energy consumption and related environmental emissions is expanding. MFCs have been mentioned as a viable bioelectrochemical method for a range of liquid waste streams, such as contaminated groundwater and domestic or commercial wastewater. They were also recommended as a technique for handling landfill leachate [78].

The investigation entailed the operation and close examination of two dual-chamber MFCs, each of which featured a cationic exchange membrane between its anodic and cathodic chambers, which were located on either side of a rectangular methacrylate frame [78]. The sole structural difference between the two cells (hence referred to as MFC-1 and MFC-2) was the substance that made up their electrodes. Graphite-coated stainless steel (GCSS) mesh (200 × 200 mm sheets) electrodes were used in both chambers of MFC-1, whereas granular graphite electrodes were used in MFC-2 [78].

The terminal electron acceptor was oxygen, which a porous diffuser attached to a fish tank air pump directly supplied into the cathodic chambers. The two MFCs were inoculated with a mixture of activated sludge and effluent from a parent MFC that only processes dairy wastewater (DW). Bolognesi et al., 2021, used DW and filtered leachate (LL) from a nearby landfill, which were combined and fed to the anodic chambers. Dairy wastewater was the only feed source for both MFCs during phase 0; however, for phases 1 through 10, the feed was a mixture of DW and LL at raising ratios, with a 5% step increase in LL at each succeeding phase [78].

The largest output power peaks for both MFCs were recorded in phase 4 (15% leachate), which indicates that this phase had the most favorable working conditions [78]. Maximum voltages of 151.1 mV and 509.3 mV were attained by MFC-1 and MFC-2, respectively, comparable to current densities of 4.6 and 15.4 A m^{-3} [78]. In the course of the entire investigation, MFC-1 produced much less electrical output than MFC-2, demonstrating how crucial elements like setup design and chosen materials have an impact on this system's performance [78]. MFC-1 generated power quite consistently in phases 3 and 4, but significantly less so in phase 5 (the voltage between the electrodes stabilized at about 10 mV). Up to phase 7, MFC-2 maintained greater and more steady electrical production values, but under all subsequent operating conditions that were tested, the observed voltage fell below 170 mV (equivalent to a current density of 5 A m^{-3}). Both systems initially produced less energy after switching from DW-only feed to the 5% LL-DW mix [78].

This was probably brought on by the anodic biomass of the MFCs continuing to adapt to the altered substrate composition. The quick recovery that was observed serves as proof of this adaptation. In the days that followed, exoelectrogenic biomass activity immediately recovered, sustaining and improving high current output even with increasing leachate ratios in the feed through phases 2 and 3 for MFC-1 and up to phase 7 for MFC-2 [78,79].

Vegetable waste contains a high amount of biodegradable organic fraction. Potato waste, especially, is a rich source of organic carbon content. It is generated in large quantities in each stage of the cycle, from cultivation to consumption. Even though solid potato waste contains high carbohydrate content, which makes it beneficial to use as a substrate for electrical power generation in MFC1, it was found that the rate of hydrolysis is a limiting factor for energy recovery from solid potato waste [25]. Hence, improving the rate of hydrolysis of solid potato waste is essential to improve the recovery of energy in MFC.

Zhang et al., 2015, demonstrated a liter scale BES for leachate treatment using a biocathode electrode and was able to achieve more than 90% COD and ammonia-nitrogen removal [80]. The introduction of dairy waste as a co-substrate in leachate substrate provides the electrochemically active bacteria extra nutrients and leads to enhanced bioelectrochemical breakdown of organics [78]. Landfill type, age, and wastes collected all have a significant impact on how well a bioelectrochemical system performs when using landfill leachate as a substrate. Additionally, pre-treatment, for instance, by performing fermentation, enhancing energy production, and improving substrate conversion, might increase the bioavailability of organic compounds in leachate [25,78,80,81].

Waste-activated sludge (WAS) has ample heterotrophic bacteria. Du and Shao, 2022 predicted that mixing SPW with WAS may enhance the hydrolysis and solubilization of SPW [25]. Additionally, it has the ability to change the C/N ratio, which has a significant impact on the biodegradation of organic waste and energy recovery in MFC. Here, it's important to consider the anaerobic co-digestion of food waste with other organic solid waste and wastewater [25]. The harmful effects of Na^{+} could be minimized by combining SPW with the proper quantity of WAS. The synergistic interactions between WAS and SPW may have a beneficial effect on the efficient decomposition of organic waste and energy recovery. Du and Shao, 2022, investigated the effect of seven different mixing ratios of SPW and WAS on Principal component analysis to fully comprehend how mixing ratios affected the hydrolysis, degradation, and energy recovery of SPW and WAS [25]. Appropriate mixing of WAS with SPW not only enhances hydrolysis and degradation it also promotes shuttle electrons, improves long-term stability, shortens the start-up time of the MFCs, and increases the power recovery efficiency [25].

The electrodes, one of the elements restricting the general applicability of these systems, are important to the performance of MFCs in terms of power output and durability with solid and semisolid substrates in BES [12,78,82,83]. The pre-treatment of solid substrates used in BES is required so that it lessens the presence of any lingering non-biodegradable particles or inhibiting waste components, which may hold the key to operating at larger concentrations in the influent solution.

9. Synergy of BES-Solid Waste Treatment with Other Solid Treatment Technology

To improve overall waste management procedures, BES can be efficiently integrated with existing solid waste treatment technologies. BES and other solid treatment technologies can work together more effectively to improve energy output, resource recovery, and waste degradation. This enhances their efficiency and sustainability. Anaerobic digestion, a popular method for treating organic waste, can be combined with BES. Before entering the anaerobic digester, organic waste might go through microbial electrochemical reactions in the BES as a pre-treatment step. BES can improve the production of biogas as a whole, the decomposition of complex organic molecules, and the effectiveness of AD systems [14].

BES is compatible with thermal treatment procedures like gasification and pyrolysis. Before undergoing thermal conversion procedures, the solid waste might undergo BES pre-treatment. BES can increase the generation of biochar or syngas, improve the biodegradability of the waste, and boost the efficiency of the pyrolysis and gasification system's overall energy recovery [73].

Composting, a natural process for transforming organic waste into nutrient-rich compost, can be combined with BES. During the composting process, BES can be used to speed up the breakdown of resistant organic components. BES can speed up the process of composting and increase the quality of the compost by stimulating the activity of the microorganisms responsible for decomposing organic materials [1].

BES can be used in solid waste landfills to improve trash stabilization and lower greenhouse gas emissions. High levels of organic materials, heavy metals, and other contaminants can be found in the landfill leachate. BES is a post-treatment technique that can be used for landfill leachate. In addition to treating the leachate, microorganisms in the BES can oxidize organic contaminants and salvage electrical energy. The generated electricity can be used to drive the treatment process and remove pollutants more effectively [1]. BES can enhance mechanical or biological treatment processes like sorting, shredding, or screening by further processing the waste's organic component. In order to improve resource recovery and waste management, BES can accelerate the breakdown of complex organic substances that are difficult to access using only mechanical techniques [73].

BES can be used in conjunction with technologies like waste-to-energy (WtE) systems or the creation of value-added chemicals that attempt to valorize solid waste [84–87]. The WtE plant may be powered by the electricity produced by BES, minimizing the need for outside electricity sources. BES can aid in enhancing the quality of waste streams so that they are better suited for further conversion into useful products or energy, maximizing the use of resources. With the speed of urbanization and rapid population expansion, food waste generation continues to rise globally, causing complicated socioeconomic, environmental, and energy problems. According to the United Nations Food and Agriculture Organisation (FAO), over 33% of food goes to waste globally at different phases of food production, including storage, transportation, and distribution. A sustainable method of dealing with food waste is required. The usage of a microbial fuel cell could be a sustainable solution. MFCs facilitate the direct conversion of chemical energy present in the bonds of organic matter into electric power. This results in simultaneous remediation of waste and recovery of electric power.

The BES can have synergistic effects when combined with other solid waste treatment methods [88–90]. Their combination has the ability to promote resource recovery, enhance waste management procedures, and boost the effectiveness of energy production. The properties of the solid waste and the system's overarching goals will determine the precise combination and design.

10. Conclusions

In conclusion, BES is a great way to treat solid wastes. Either individually or in synergy with other conventional methods, the effectiveness of BES for the treatment of solid waste depends on the cooperation of the many microorganisms and the optimization of operational factors like pH, temperature, and electrode material. The use of BES in synergy with other methods improves their sustainability and efficiency. Anaerobic digestion + BES, composting + BES, pyrolysis and gasification + BES, landfill leachate + BES, mechanical or biological treatments + BES, and solid waste volarization + BES are a few methods discussed in this article. While the synergic integration of BES with other conventional methods has shown promising results, there are still some gaps that need further investigation. System optimization, long-term performance and stability, scale-up and techno-economic analysis, integration in different waste streams, environmental impacts, and resource recovery are a few areas that need to be addressed. This will enable the development of more effective and sustainable waste management strategies by advancing our understanding of and application of BES in conjunction with current waste treatment techniques.

Author Contributions: Conceptualization, S.S.; Literature survey, S.M. and S.B.; formal analysis, M.S. and S.B.; investigation, S.M. and S.B.; writing—original draft preparation, S.M. and S.B.; writing—review & editing, S.M., S.B., M.S.I.M. and V.K.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was supported by the Science and Engineering Research Board (SERB), India, Grant No. SRG/2021/001460. (Dr. Surajbhan Sevda); Bangladesh Bureau of Educational Information and Statistics (BANBEIS), Project ID: SD20211542 (Dr. Md. Salatul Islam Mozumder).

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author (S.S.).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sridevi, V.; Modi, M.; Lakshmi, M.V.V.C.; Kesavarao, L.; Tech, M. A Review on Integrated Solid Waste Management. *Int. J. Eng. Sci. Adv. Technol.* **2012**, *2*, 1491–1499.
2. Gattrell, M.; Gupta, N.; Co, A.; Cavinato, C.; Giuliano, A.; Bolzonella, D.; Pavan, P.; Cecchi, F.; Liu, Z.; Zhang, C.; et al. Investigation of Microbial Biofilm Structure by Laser Scanning Microscopy. *Bioresour. Technol.* **2018**, *5*, 9391–9410. [CrossRef]
3. Zhao, Q.; Yu, H.; Zhang, W.; Kabutey, F.T.; Jiang, J.; Zhang, Y.; Wang, K.; Ding, J. Microbial Fuel Cell with High Content Solid Wastes as Substrates: A Review. *Front. Environ. Sci. Eng.* **2017**, *11*, 13. [CrossRef]
4. Valdez-vazquez, I.; Sparling, R.; Risbey, D. Hydrogen Generation via Anaerobic Fermentation of Paper Mill Wastes. *Bioresour. Technol.* **2005**, *96*, 1907–1913. [CrossRef] [PubMed]
5. Lee, D.H.; Behera, S.K.; Kim, J.W.; Park, H.S. Methane Production Potential of Leachate Generated from Korean Food Waste Recycling Facilities: A Lab-Scale Study. *Waste Manag.* **2009**, *29*, 876–882. [CrossRef] [PubMed]
6. Sevda, S.; Sreekrishnan, T.R. Removal of Organic Matters and Nitrogenous Pollutants Simultaneously from Two Different Wastewaters Using Biocathode Microbial Fuel Cell. *J. Environ. Sci. Health Part A Toxic/Hazardous Subst. Environ. Eng.* **2014**, *49*, 1265–1275. [CrossRef]
7. Nayak, S.; Sevda, S. Urine Based Bioelectrochemical System: Resources Recovery and Domestic Wastewater Treatment Prospectives. *Bioresour. Technol. Rep.* **2022**, *20*, 101257. [CrossRef]
8. Kuleshova, T.; Rao, A.; Bhadra, S.; Kumar, V.; Sharma, S.; Kaushik, A.; Goswami, P.; Sreekirshnan, T.R.; Sevda, S. Biomass and Bioenergy Plant Microbial Fuel Cells as an Innovative, Versatile Agro-Technology for Green Energy Generation Combined with Wastewater Treatment and Food Production. *Biomass Bioenergy* **2022**, *167*, 106629. [CrossRef]
9. Sevda, S.; Dominguez-Benetton, X.; Graichen, F.H.M.; Vanbroekhoven, K.; De Wever, H.; Sreekrishnan, T.R.; Pant, D. Shift to Continuous Operation of an Air-Cathode Microbial Fuel Cell Long-Running in Fed-Batch Mode Boosts Power Generation. *Int. J. Green Energy* **2016**, *13*, 71–79. [CrossRef]

10. Rodrigo, M.A.; Cañizares, P.; García, H.; Linares, J.J.; Lobato, J. Study of the Acclimation Stage and of the Effect of the Biodegradability on the Performance of a Microbial Fuel Cell. *Bioresour. Technol.* **2009**, *100*, 4704–4710. [CrossRef]
11. Xie, X.; Ye, M.; Hsu, P.C.; Liu, N.; Criddle, C.S.; Cui, Y. Microbial Battery for Efficient Energy Recovery. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 15925–15930. [CrossRef] [PubMed]
12. Wu, Q.; Jiao, S.; Ma, M.; Peng, S. Microbial Fuel Cell System: A Promising Technology for Pollutant Removal and Environmental Remediation. *Environ. Sci. Pollut. Res.* **2020**, *27*, 6749–6764. [CrossRef]
13. Al-Salem, S.M. Thermal Pyrolysis of High Density Polyethylene (HDPE) in a Novel Fixed Bed Reactor System for the Production of High Value Gasoline Range Hydrocarbons (HC). *Process Saf. Environ. Prot.* **2019**, *127*, 171–179. [CrossRef]
14. Ağdağ, O.N.; Sponza, D.T. Co-Digestion of Mixed Industrial Sludge with Municipal Solid Wastes in Anaerobic Simulated Landfilling Bioreactors. *J. Hazard. Mater.* **2007**, *140*, 75–85. [CrossRef]
15. Zhang, C.; Xiao, G.; Peng, L.; Su, H.; Tan, T. Bioresource Technology The Anaerobic Co-Digestion of Food Waste and Cattle Manure. *Bioresour. Technol.* **2013**, *129*, 170–176. [CrossRef] [PubMed]
16. Richard, E.N.; Hilonga, A.; Machunda, R.L.; Njau, K.N. A Review on Strategies to Optimize Metabolic Stages of Anaerobic Digestion of Municipal Solid Wastes towards Enhanced Resources Recovery. *Sustain. Environ. Res.* **2019**, *1*, 36. [CrossRef]
17. Naji, Z.; Hu, Z.; Sun, N.; Xiao, B.; Rajaa, N.; Liu, C. Batch Anaerobic Co-Digestion of OFMSW (Organic Fraction of Municipal Solid Waste), TWAS (Thickened Waste Activated Sludge) and RS (Rice Straw): In Fl Uence of TWAS and RS Pretreatment and Mixing Ratio. *Energy* **2016**, *107*, 131–140. [CrossRef]
18. Ge, X.; Xu, F.; Li, Y. Solid-State Anaerobic Digestion of Lignocellulosic Biomass: Recent Progress and Perspectives. *Bioresour. Technol.* **2016**, *205*, 239–249. [CrossRef]
19. Tyagi, V.K.; Fdez-Güelfo, L.A.; Zhou, Y.; Álvarez-Gallego, C.J.; Garcia, L.I.R.; Ng, W.J. Anaerobic Co-Digestion of Organic Fraction of Municipal Solid Waste (OFMSW): Progress and Challenges. *Renew. Sustain. Energy Rev.* **2018**, *93*, 380–399. [CrossRef]
20. Du, Y.; Ju, T.; Meng, Y.; Lan, T.; Han, S.; Jiang, J. A Review on Municipal Solid Waste Pyrolysis of Different Composition for Gas Production. *Fuel Process. Technol.* **2021**, *224*, 107026. [CrossRef]
21. Uddin, M.N.; Siddiki, S.Y.A.; Mofijur, M.; Djavanroodi, F.; Hazrat, M.A.; Show, P.L.; Ahmed, S.F.; Chu, Y.M. Prospects of Bioenergy Production From Organic Waste Using Anaerobic Digestion Technology: A Mini Review. *Front. Energy Res.* **2021**, *9*, 627093. [CrossRef]
22. Zhu, Y.; Zhang, Y.; Luo, D.; Chong, Z.; Li, E.; Kong, X. A Review of Municipal Solid Waste in China: Characteristics, Compositions, Influential Factors and Treatment Technologies. *Environ. Dev. Sustain.* **2021**, *23*, 6603–6622. [CrossRef]
23. Ding, Y.; Zhao, J.; Liu, J.-W.; Zhou, J.; Cheng, L.; Zhao, J.; Shao, Z.; Iris, Ç.; Pan, B.; Li, X.; et al. A Review of China's Municipal Solid Waste (MSW) and Comparison with International Regions: Management and Technologies in Treatment and Resource Utilization. *J. Clean. Prod.* **2021**, *293*, 126144. [CrossRef]
24. Panigrahi, S.; Dubey, B.K. A Critical Review on Operating Parameters and Strategies to Improve the Biogas Yield from Anaerobic Digestion of Organic Fraction of Municipal Solid Waste. *Renew. Energy* **2019**, *143*, 779–797. [CrossRef]
25. Du, H.; Shao, Z. Synergistic Effects between Solid Potato Waste and Waste Activated Sludge for Waste-to-Power Conversion in Microbial Fuel Cells. *Appl. Energy* **2022**, *314*, 118994. [CrossRef]
26. Zhang, F.; Ahn, Y.; Logan, B.E. Treating Refinery Wastewaters in Microbial Fuel Cells Using Separator Electrode Assembly or Spaced Electrode Configurations. *Bioresour. Technol.* **2014**, *152*, 46–52. [CrossRef]
27. Zeller, M.A.; Hunt, R.; Jones, A.; Sharma, S. Bioplastics and Their Thermoplastic Blends from Spirulina and Chlorella Microalgae. *J. Appl. Polym. Sci.* **2013**, *130*, 3263–3275. [CrossRef]
28. Huang, D.; Du, Y.; Xu, Q.; Ko, J.H. Quantification and Control of Gaseous Emissions from Solid Waste Landfill Surfaces. *J. Environ. Manag.* **2022**, *302*, 114001. [CrossRef]
29. Pant, D.; Singh, A.; Van Bogaert, G.; Irving Olsen, S.; Singh Nigam, P.; Diels, L.; Vanbroekhoven, K. Bioelectrochemical Systems (BES) for Sustainable Energy Production and Product Recovery from Organic Wastes and Industrial Wastewaters. *RSC Adv.* **2012**, *2*, 1248–1263. [CrossRef]
30. Budihardjo, M.A.; Syafrudin; Effendi, A.J.; Hidayat, S.; Purnawan, C.; Lantasi, A.I.D.; Muhammad, F.I.; Ramadan, S.B. Waste Valorization Using Solid-Phase Microbial Fuel Cells (SMFCs): Recent Trends and Status. *J. Environ. Manag.* **2021**, *277*, 111417. [CrossRef]
31. Florio, C.; Nastro, R.A.; Flagiello, F.; Minutillo, M.; Pirozzi, D.; Pasquale, V.; Ausiello, A.; Toscano, G.; Jannelli, E.; Dumontet, S. Biohydrogen Production from Solid Phase-Microbial Fuel Cell Spent Substrate: A Preliminary Study. *J. Clean. Prod.* **2019**, *227*, 506–511. [CrossRef]
32. Wang, C.T.; Liao, F.Y.; Liu, K.S. Electrical Analysis of Compost Solid Phase Microbial Fuel Cell. *Int. J. Hydrogen Energy* **2013**, *38*, 11124–11130. [CrossRef]
33. Mohan, S.V.; Chandrasekhar, K. Bioresource Technology Solid Phase Microbial Fuel Cell (SMFC) for Harnessing Bioelectricity from Composite Food Waste Fermentation: Influence of Electrode Assembly and Buffering Capacity. *Bioresour. Technol.* **2011**, *102*, 7077–7085. [CrossRef] [PubMed]
34. Tommasi, T.; Salvador, G.P.; Quaglio, M. New Insights in Microbial Fuel Cells: Novel Solid Phase Anolyte. *Sci. Rep.* **2016**, *6*, 29091. [CrossRef] [PubMed]

35. Pathy, A.; Ray, J.; Paramasivan, B. Challenges and Opportunities of Nutrient Recovery from Human Urine Using Biochar for Fertilizer Applications. *J. Clean. Prod.* **2021**, *304*, 127019. [CrossRef]
36. Sonawane, J.M.; Mahadevan, R.; Pandey, A.; Greener, J. Recent Progress in Microbial Fuel Cells Using Substrates from Diverse Sources. *Heliyon* **2022**, *8*, e12353. [CrossRef]
37. Sundberg, C.; Smårs, S.; Jönsson, H. Low PH as an Inhibiting Factor in the Transition from Mesophilic to Thermophilic Phase in Composting. *Bioresour. Technol.* **2004**, *95*, 145–150. [CrossRef]
38. Lin, C.; Hung, C.; Chen, C.; Chung, W.; Cheng, L. Effects of Initial Cultivation PH on Fermentative Hydrogen Production from Xylose Using Natural Mixed Cultures. *Process Biochem.* **2006**, *41*, 1383–1390. [CrossRef]
39. Lin, C.; Cheng, C. Fermentative Hydrogen Production from Xylose Using Anaerobic Mixed Microflora. *Int. J. Hydrogen Energy* **2006**, *31*, 832–840. [CrossRef]
40. Bello, S.; Galán-Martín, Á.; Feijoo, G.; Moreira, M.T.; Guillén-Gosálbez, G. BECCS Based on Bioethanol from Wood Residues: Potential towards a Carbon-Negative Transport and Side-Effects. *Appl. Energy* **2020**, *279*, 115884. [CrossRef]
41. Prasad, S.; Singh, A.; Joshi, H.C. Ethanol as an Alternative Fuel from Agricultural, Industrial and Urban Residues. *Resour. Conserv. Recycl.* **2007**, *50*, 1–39. [CrossRef]
42. Sevda, S.; Sreekishnan, T.R.; Pous, N.; Puig, S.; Pant, D. Bioelectroremediation of Perchlorate and Nitrate Contaminated Water: A Review. *Bioresour. Technol.* **2018**, *255*, 331–339. [CrossRef] [PubMed]
43. Dominguez-Benetton, X.; Sevda, S.; Vanbroekhoven, K.; Pant, D. The Accurate Use of Impedance Analysis for the Study of Microbial Electrochemical Systems. *Chem. Soc. Rev.* **2012**, *41*, 7228–7246. [CrossRef] [PubMed]
44. Yu, H.; Jiang, J.; Zhao, Q.; Wang, K.; Zhang, Y.; Zheng, Z.; Hao, X. Bioelectrochemically-Assisted Anaerobic Composting Process Enhancing Compost Maturity of Dewatered Sludge with Synchronous Electricity Generation. *Bioresour. Technol.* **2015**, *193*, 1–7. [CrossRef] [PubMed]
45. Fantozzi, F.; Buratti, C. Biogas Production from Different Substrates in an Experimental Continuously Stirred Tank Reactor Anaerobic Digester. *Bioresour. Technol.* **2009**, *100*, 5783–5789. [CrossRef] [PubMed]
46. Abu-Reesh, I.M.; Kunju, A.; Sevda, S. Performance of Microbial Fuel Cells in Treating Petroleum Refinery Wastewater. *J. Water Process Eng.* **2022**, *49*, 103029. [CrossRef]
47. Callegari, A.; Bolognesi, S.; Cecconet, D. Operation of a 2-Stage Bioelectrochemical System for Groundwater Denitrification. *Water* **2019**, *11*, 959. [CrossRef]
48. Li, Z.; Yao, L.; Kong, L.; Liu, H. Electricity Generation Using a Baffled Microbial Fuel Cell Convenient for Stacking. *Bioresour. Technol.* **2008**, *99*, 1650–1655. [CrossRef]
49. Kim, M.; Hyun, S.M.; Gadd, G.M.; Kim, G.T.; Lee, S.-J.; Kim, H.J. Membrane-Electrode Assembly Enhances Performance of a Microbial Fuel Cell Type Biological Oxygen Demand Sensor. *Environ. Technol.* **2009**, *30*, 329–336. [CrossRef]
50. Hou, H.; Li, L.; Cho, Y.; de Figueiredo, P.; Han, A. Microfabricated Microbial Fuel Cell Arrays Reveal Electrochemically Active Microbes. *PLoS ONE* **2009**, *4*, e6570. [CrossRef]
51. Park, D.-H.; Kim, B.-H. Growth Properties of the Iron-Reducing Bacteria, Shewanella Putrefaciens IR-1 and MR-1 Coupling to Reduction of Fe (III) to Fe (II). *J. Microbiol.* **2001**, *39*, 273–278.
52. Pons, L.; Délia, M.; Basséguy, R.; Bergel, A. Electrochimica Acta Effect of the Semi-Conductive Properties of the Passive Layer on the Current Provided by Stainless Steel Microbial Cathodes. *Electrochim. Acta* **2011**, *56*, 2682–2688. [CrossRef]
53. Liu, Z.; Li, H.; Liu, J.; Su, Z. Effects of Inoculation Strategy and Cultivation Approach on the Performance of Microbial Fuel Cell Using Marine Sediment as Bio-Matrix. *J. Appl. Microbiol.* **2008**, *104*, 1163–1170. [CrossRef] [PubMed]
54. Ward, A.J.; Hobbs, P.J.; Holliman, P.J.; Jones, D.L. Optimisation of the Anaerobic Digestion of Agricultural Resources. *Bioresour. Technol.* **2008**, *99*, 7928–7940. [CrossRef] [PubMed]
55. Rossi, R.; Fedrigucci, A.; Setti, L. Characterization of Electron Mediated Microbial Fuel Cell by *Saccharomyces cerevisiae*. *Chem. Eng. Trans.* **2015**, *43*, 337–342. [CrossRef]
56. Ai, C.; Hou, S.; Yan, Z.; Zheng, X.; Amanze, C.; Chai, L.; Qiu, G.; Zeng, W. Recovery of Metals from Acid Mine Drainage by Bioelectrochemical System Inoculated with a Novel Exoelectrogen, *Pseudomonas* sp. E8. *Microorganisms* **2020**, *8*, 41. [CrossRef]
57. Rahimnejad, M.; Adhami, A.; Darvari, S.; Zirepour, A.; Oh, S.E. Microbial Fuel Cell as New Technol Ogy for Bioelectricity Generation: A Review. *Alex. Eng. J.* **2015**, *54*, 745–756. [CrossRef]
58. Khalid, A.; Arshad, M.; Anjum, M.; Mahmood, T.; Dawson, L. The Anaerobic Digestion of Solid Organic Waste. *Waste Manag.* **2011**, *31*, 1737–1744. [CrossRef]
59. Sun, R.; Xing, D.; Jia, J.; Liu, Q.; Zhou, A.; Bai, S.; Ren, N. Optimization of High-Solid Waste Activated Sludge Concentration for Hydrogen Production in Microbial Electrolysis Cells and Microbial Community Diversity Analysis. *Int. J. Hydrogen Energy* **2014**, *39*, 19912–19920. [CrossRef]
60. Rojas-Flores, S.; De La Cruz-Noriega, M.; Benites, S.M.; Delfín-Narciso, D.; Luis, A.S.; Díaz, F.; Luis, C.C.; Moises, G.C. Electric Current Generation by Increasing Sucrose in Papaya Waste in Microbial Fuel Cells. *Molecules* **2022**, *27*, 5198. [CrossRef]
61. Rezaei, F.; Richard, T.L.; Logan, B.E. Analysis of Chitin Particle Size on Maximum Power Generation, Power Longevity, and Coulombic Efficiency in Solid–Substrate Microbial Fuel Cells. *J. Power Sources* **2009**, *192*, 304–309. [CrossRef]

62. Lee, Y.; Nirmalakhandan, N. Electricity Production in Membrane-Less Microbial Fuel Cell Fed with Livestock Organic Solid Waste. *Bioresour. Technol.* **2011**, *102*, 5831–5835. [CrossRef] [PubMed]
63. Li, X.H.; Liang, D.W.; Bai, Y.X.; Fan, Y.T.; Hou, H.W. Enhanced H2 Production from Corn Stalk by Integrating Dark Fermentation and Single Chamber Microbial Electrolysis Cells with Double Anode Arrangement. *Int. J. Hydrogen Energy* **2014**, *39*, 8977–8982. [CrossRef]
64. Sekoai, P.T.; Gueguim Kana, E.B. Semi-Pilot Scale Production of Hydrogen from Organic Fraction of Solid Municipal Waste and Electricity Generation from Process Effluents. *Biomass Bioenergy* **2014**, *60*, 156–163. [CrossRef]
65. Karluvali, A.; Köroğlu, E.O.; Manav, N.; Çetinkaya, A.Y.; Özkaya, B. Electricity Generation from Organic Fraction of Municipal Solid Wastes in Tubular Microbial Fuel Cell. *Sep. Purif. Technol.* **2015**, *156*, 502–511. [CrossRef]
66. Pendyala, B.; Chaganti, S.R.; Lalman, J.A.; Heath, D.D. Optimizing the Performance of Microbial Fuel Cells Fed a Combination of Different Synthetic Organic Fractions in Municipal Solid Waste. *Waste Manag.* **2016**, *49*, 73–82. [CrossRef]
67. Du, H.; Li, F. Enhancement of Solid Potato Waste Treatment by Microbial Fuel Cell with Mixed Feeding of Waste Activated Sludge. *J. Clean. Prod.* **2017**, *143*, 336–344. [CrossRef]
68. Ren, N.; Wang, A.; Cao, G.; Xu, J.; Gao, L. Bioconversion of Lignocellulosic Biomass to Hydrogen: Potential and Challenges. *Biotechnol. Adv.* **2009**, *27*, 1051–1060. [CrossRef]
69. Haghpanah, T.; Sobati, M.A.; Pishvaee. Multi-Objective Superstructure Optimization of a Microalgae Biorefinery Considering Economic and Environmental Aspects. *Comput. Chem. Eng.* **2022**, *164*, 107894. [CrossRef]
70. Xu, D.; Tree, D.R.; Lewis, R.S. The Effects of Syngas Impurities on Syngas Fermentation to Liquid Fuels. *Biomass Bioenergy* **2011**, *35*, 2690–2696. [CrossRef]
71. Liew, F.M.; Martin, M.E.; Tappel, R.C.; Heijstra, B.D.; Mihalcea, C.; Köpke, M. Gas Fermentation-A Flexible Platform for Commercial Scale Production of Low-Carbon-Fuels and Chemicals from Waste and Renewable Feedstocks. *Front. Microbiol.* **2016**, *7*, 694. [CrossRef]
72. Silva, F.C.; Serafim, L.S.; Nadais, H.; Arroja, L.; Capela, I. Acidogenic Fermentation towards Valorisation of Organic Waste Streams into Volatile Fatty Acids. *Chem. Biochem. Eng. Q.* **2013**, *27*, 467–476.
73. Abdeljaber, A.; Zannerni, R.; Masoud, W.; Abdallah, M.; Rocha-Meneses, L. Eco-Efficiency Analysis of Integrated Waste Management Strategies Based on Gasification and Mechanical Biological Treatment. *Sustainability* **2022**, *14*, 3899. [CrossRef]
74. Guermoud, N.; Ouadjnia, F.; Abdelmalek, F.; Taleb, F.; Addou, A. Municipal Solid Waste in Mostaganem City (Western Algeria). *Waste Manag.* **2009**, *29*, 896–902. [CrossRef] [PubMed]
75. Bolzonella, D.; Mıcoluccı, F.; Battısta, F.; Cavınato, C.; Gottardo, M.; Pıovesan, S.; Pavan, P. Producing Biohythane from Urban Organic Wastes. *Waste Biomass Valorization* **2020**, *11*, 2367–2374. [CrossRef]
76. De Gisi, S.; Gadaleta, G.; Gorrasi, G.; La Mantia, F.P.; Notarnicola, M.; Sorrentino, A. The Role of (Bio)Degradability on the Management of Petrochemical and Bio-Based Plastic Waste. *J. Environ. Manag.* **2022**, *310*, 114769. [CrossRef]
77. Maiti, D.; Ansari, I.; Rather, M.A.; Deepa, A. Comprehensive Review on Wastewater Discharged from the Coal-Related Industries—Characteristics and Treatment Strategies. *Water Sci. Technol.* **2019**, *79*, 2023–2035. [CrossRef]
78. Bolognesi, S.; Cecconet, D.; Callegari, A.; Capodaglio, A.G. Bioelectrochemical Treatment of Municipal Solid Waste Landfill Mature Leachate and Dairy Wastewater as Co-Substrates. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24639–24649. [CrossRef]
79. Cheng, S.; Xing, D.; Call, D.F.; Logan, B.E. Direct Biological Conversion of Electrical Current into Methane by Electromethanogenesis. *Environ. Sci. Technol.* **2009**, *43*, 3953–3958. [CrossRef]
80. Zhang, G.; Jiao, Y.; Lee, D.-J. A Lab-Scale Anoxic/Oxic-Bioelectrochemical Reactor for Leachate Treatments. *Bioresour. Technol.* **2015**, *186*, 97–105. [CrossRef]
81. Zhang, G.; Jiao, Y.; Lee, D.J. Transformation of Dissolved Organic Matters in Landfill Leachate-Bioelectrochemical System. *Bioresour. Technol.* **2015**, *191*, 350–354. [CrossRef] [PubMed]
82. Santoro, C.; Arbizzani, C.; Erable, B.; Ieropoulos, I. Microbial Fuel Cells: From Fundamentals to Applications. A Review. *J. Power Sources* **2017**, *356*, 225–244. [CrossRef] [PubMed]
83. Prajapati, K.B.; Singh, R. Bio-Electrochemically Hydrogen and Methane Production from Co-Digestion of Wastes. *Energy* **2020**, *198*, 117259. [CrossRef]
84. Luo, H.; Jenkins, P.E.; Ren, Z. Concurrent Desalination and Hydrogen Generation Using Microbial Electrolysis and Desalination Cells. *Environ. Sci. Technol.* **2011**, *45*, 340–344. [CrossRef]
85. Ma, L.; Chen, N.; Feng, C.; Yao, Y.; Wang, S.; Wang, G.; Su, Y.; Zhang, Y. Enhanced Cr(VI) Reduction in Biocathode Microbial Electrolysis Cell Using Fenton-Derived Ferric Sludge. *Water Res.* **2022**, *212*, 118144. [CrossRef] [PubMed]
86. FP7 | CORDIS | European Commission. Final Report Summary—PLANTPOWER (PlantPower—Living Plants in Microbial Fuel Cells for Clean, Renewable, Sustainable, Efficient, in situ Bioenergy Production). Available online: https://cordis.europa.eu/project/id/226532/reporting (accessed on 2 August 2023).
87. Durruty, I.; Bonanni, P.S.; González, J.F.; Busalmen, J.P. Evaluation of Potato-Processing Wastewater Treatment in a Microbial Fuel Cell. *Bioresour. Technol.* **2012**, *105*, 81–87. [CrossRef]
88. Sevda, S.; Jyoti Sarma, P.; Mohanty, K.; Sreekrishnan, T.R.; Pant, D. Microbial Fuel Cell Technology for Bioelectricity Generation from Wastewaters. In *Waste to Wealth*; Energy, Environment, and Sustainability; Springer: Berlin/Heidelberg, Germany, 2018; pp. 237–258. [CrossRef]

89. Hamelers, H.V.M.; Ter Heijne, A.; Sleutels, T.H.J.A.; Jeremiasse, A.W.; Strik, D.P.B.T.B.; Buisman, C.J.N. New Applications and Performance of Bioelectrochemical Systems. *Appl. Microbiol. Biotechnol.* **2010**, *85*, 1673–1685. [CrossRef]
90. Bolognesi, S.; Bañeras, L.; Perona-Vico, E.; Capodaglio, A.G.; Balaguer, M.D.; Puig, S. Carbon Dioxide to Bio-Oil in a Bioelectrochemical System-Assisted Microalgae Biorefinery Process. *Sustain. Energy Fuels* **2022**, *6*, 150–161. [CrossRef]