Bioelectrochemical system-mediated waste valorization

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Abstract

Bioelectrochemical systems (BESs) are a new and emerging technology in the field of fermentation technology. Electrical energy was provided externally to the microbial electrolysis cells (MECs) to generate hydrogen or value-added chemicals, including caustic, formic acid, acetic acid, and peroxide. Also, BES was designed to recover nutrients, metals or remove recalcitrant compounds. The variety of naturally existing microorganisms and enzymes act as a biocatalyst to induce potential differences amid the electrodes. BESs can be performed with non-catalyzed electrodes (both anode and cathode) under favorable circumstances, unlike conventional fuel cells. In recent years, value-added chemical producing microbial electrosynthesis (MES) technology has intensely broadened the prospect for BES. An additional strategy includes the introduction of innovative technologies that help with the manufacturing of alternative materials for electrode preparation, ion-exchange membranes, and pioneering designs. Because of this, BES is emerging as a promising technology. This article deliberates recent signs of progress in BESs so far, focusing on their diverse applications beyond electricity generation and resulting performance.

Keywords Microbial fuel cells · Waste valorization · Microbial electrolysis cell · Waste-to-energy · Biofuels

Introduction

Fossil fuel-based energy resources are the highest standard energy bases worldwide, which are accounted for 85.5%. However, the fossil-fuel-based energy economy leads to environmental issues, such as greenhouse gas emissions, raising the atmospheric temperature, and causing severe health-related issues to human beings [1–4]. Further, there were limited reserves of fossil fuel; hence, there is a serious search for other alternative fuel sources [5, 6]. In this scenario, worldwide researchers are investigating environmentally friendly and renewable energy resources [1, 3, 7]. In recent times, for reasons, such as rapidly increasing global population, urbanization, industrialization, and unexpected climate change, water scarcity has increased [8]. Industries create a massive demand for water, and it is increasing day

to day due to rapid industrialization[7, 9]; hence, wastewater collection, treatment, and reuse are the best options for overcoming the problem mentioned above [10]. Wastewater resource recovery is not a novel approach; it was successfully applied in several European countries before establishing wastewater treatment facilities [11]. Several studies have successfully established physical, mechanical, biological, and hybrid physical and chemical treatment methods to valorize the waste water's high nutrient account [12]. The biological nutrient removal approach is cost-effective and versatile compared to other treatment methods [13]. Electrochemical energy processing has been under severe thought as alternate energy. This energy use will be considered to become more productive and much more environmentally safe. Anaerobic digestion was widely employed for biogas production from carbon-rich wastewater sources for over a century [7, 14]. There are many inherent advantages of methane fermentation versus aerobic biological treatment, such as renewable energy production (methane), decreased energy prices by aeration removal, and lowered sludge processing and disposal prices [15]. As a result of interest in renewable energy production using hydrogen fuel cells, biological roots for hydrogen production from carbon-rich waste and wastewater have also attracted significant interest in recent years

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[16–18]. Sadly, existing fermentation methods can yield a total of only 2–3 mol H_2 /mol glucose, considering a molar ratio capacity of 12 mol H_2 /mol glucose, while most organic matter stays as volatile fatty acids and alcohols [19]. Therefore, the method is constrained to feedstocks with appropriate fermentation substrates, such that many are carbon-rich and highly biodegradable [5]. Although some bacteria's ability to engender electric current was first described over 100 years ago, this phenomenon did not begin to attract serious attention from scientists and engineers until the beginning of the present century [11, 20, 21]. The progress made over the last decade in the areas of bio-electrochemistry and BES has significantly led to the shift from the bench scale (laboratory) to the pilot-scale studies [22]. So, commercial expansion gives the impression to be getting closer [20].

Preliminary investigative efforts centered on exploring opportunities presented by BES for the treatment and valuation of different waste streams by electricity [23, 24]. So far, the spectrum of uses has increased significantly, spreading to various areas, for instance, bio-electro remediation, desalination of xenobiotic substances, biodegradation of polluted soil and wastewater, nutrient retrieval, metal recovery, or the bio-electro-synthesis of essential and value-added products, amid a lot of others applications [25, 26]. Further, BES has the flexibility together with a multi-layered design which paves the way for multiple uses than traditional fermentation industrial routes. Indeed, when BES is operated with the aim of biofuels and value-added chemical production, the external power supply is required to cross the thermodynamic barrier, and the provided electrical energy will be

transformed into chemical energy and stored in the form of value-added products, such as acetic acid, Formic acid, hydrogen, and methane, etc. (Fig. 1) [27, 28].

Nowadays, researchers are seriously investigating the viable roots to produce value-added chemicals from BES using cheap and abundantly available carbon sources, such as carbon-rich wastewater (Food waste, agriculture waste, dairy waste, etc.) and carbon dioxide. Here, carbon-rich wastewater can directly be used for this prose or might be exposed to various pretreatment methods to convert complex waste into simple sugars and volatile fatty acids (VFAs) [29]. These simple sugars and VFAs can be used as potential feedstock for the bioelectrochemical synthesis of value-added chemicals in BES. Bioelectrochemical synthesis technology is a process that uses the electrochemical interaction of electrochemically active microorganisms and electrodes [30, 31]. There are several reports available for more than 100 years stating that microorganisms can form electrical connections to devices. Further, microbial electrochemistry has been evolved as a discipline due to extreme interest in the opportunity of using BES for biofuel and alternate energy generation and waste remediation. BES has the capabilities to contribute to a circular economy, where carbon is cycled back into chemicals or electrical energy from renewable sources [20, 31, 32].

The main aim of this review article is to introduce and discuss a few significant and fascinating applications of BES for valuing waste streams for energy. It starts with a brief overview of BES operating concepts and its potential application as a viable treatment device and bioelectricity

Fig. 1 Possible application of bioelectrochemical systems in the direction of waste valorization

generation in wastewater energy valorization. In this direction, the present manuscript majorly focused on microbial fuel cells (MFC) and microbial electrolysis cells (MEC) and their role in waste valorization. BES will also be able to facilitate considerable energy savings for the processing industries of fertilizers, where it can recover nutrients from wastewater.

Bioelectrochemical systems

BES can be considered as a hybrid electrochemical device, whereas a minimum of one of the electrode reactions (anodic and/or cathodic) is carried out by microorganism/biocatalyst, generally under strictly anaerobic conditions [17, 33, 34]. They provide the main feature of being functionally reversible with conventional electrochemical systems, i.e. BES can be controlled as galvanic cells or as electrolytic cells. The first galvanically powered BES systems were known as MFC and were typically called to this as MEC when they were operated under electrolytic mode by applying a small amount of external energy [35]. The actual cell voltage is smaller than the open-circuit voltage whenever the external circuit is closed, and the MFC is associated with the externally applied resistance. The cell voltage reduces when the energy portion of the electrochemical cell is discharged through resistive components, that is, the internal resistance [36]. While the growing number of BES archetypes and designs, some of which have arisen over the last decade, has redefined such language, it remains useful as it represents the two fundamental functionalities in BES. A

graphical view of the theory of action of BES systems is shown in Fig. 2.

Compared to conventional fuel cells and enzymatic fuel cells, BES has many benefits under specific parameters. A wide variety of organic or inorganic matter, such as organic waste (agriculture waste, food waste, industrial waste, dairy waste, forest biomass, domestic waste, vegetable waste, etc.) and soil sediments, can be used as a source of fuel generation with the help of electrochemically active microorganisms [37]. It has been shown that MFCs are the most researched BESs while expanding the application of MFCs to diverse BESs has also received an extensive amount of research [38, 39]. The bioelectrochemical techniques have the ability to gather energy and produce value-added compounds from wastewater treatment. When we refer to the BES systems, it is very much dependent on the type of cathodic processes involved, such as MECs, microbial desalination cells, microbial electrosynthesis cells (MESs), and microbial metal recovery cells [40].

Energy metabolism in bioelectrochemical systems

Bacteria can obtain energy for the following reasons in BES. First, the primary direction of energy production is the indigenous respiration chain. In the BES system, generally, solid electrode materials/metals serve as electron acceptors for electrochemically active microorganisms and engage in the nature of the extracellular electron transport chain [41]. Further, electrochemically active microorganisms (*Pseudomonas Sp.* etc.) will also produce extracellular molecules which serve as electron mediators. *Geobacter* and *Shewanella* will continually obtain energy by decaying carbon-rich organic matter/organic acids for cell growth and metabolism when injected into the MFC system. Moreover, the redox balance has been preserved by releasing electrons into the anode that substitutes for the last acceptor of insoluble metals [42]. The second alternative is also the transport of electrons. The possible process of synthesis of adenosine triphosphate (ATP) is that the emitted proton promotes proton motive force (PMF) production and drives ATP synthesis since electrons are being moved from cathodes into intracellular environments together with proton cotransport phenomena [43]. The energy provided by oxidative phosphorylation relative to aerobic breathing is not adequate for high cell proliferation during anaerobic environments. Due to the availability of reduced intracellular ATP, the key explanation is that levels of oxygen did not accompany the intermediary metabolites as electron acceptors [44]. Due to the direct or single-step transformation of substrate energy to electrical energy, maximum conversion efficacy can be attained with such equipment [45]. MFC can

Fig. 2 Schematic representation of the principle of operation of bioelectrochemical systems

avoid unnecessary gas processing function and no specific energy input is needed for single-compartment MFC; furthermore, it can also be beneficial for broader use in areas without electric power facilities [21, 46].

A scientometric search is utilizing data accessible in the ISI Web of Knowledge (from 2001) indicating that the total amount of items available on bioelectrochemical systems accounts for 2335 records with a significant amount of citations (59,734), typical citations for each item (25.58), and H-index (101). According to the ISI Web of Knowledge records, literature related to the BES study showed a sharp rise after 2007, touched higher records of 358 in 2018 (total citations: 9878), followed by 2019 (higher records of 339 and overall citations of 12,577) with marginal variations.

Further, from the ISI Web of Knowledge, an average citation per year (from 2001 to 2020) also exposed a growing trend year by year, obviously signifying that quick and encouraging research is underway to make the BES method technologically viable. Available reports in ISI Web of Knowledge indicating that the research related to BES is rapidly increasing year to year. This research might be related to different applications of BES like bioelectricity generation, chemical synthesis, and waste remediation. In recent years, researchers were also focusing on developing a viable technology to utilize atmospheric carbon dioxide for value-added chemical synthesis, such as acetate, ethanol, etc. Few researchers are also aiming to produce bioplastic in the cathodic compartment of BES by providing appropriate conditions to support the growth of bioplastic-producing bacteria. In this case, using VFAs produce from the substrate oxidation in the anodic compartment as a feedstock for bioplastic production in the cathodic compartment might be an economically more viable process [47–49].

BESs and, among these, MFCs reflect a technology principle that enables sustainable biotechnology to utilize the energy stored in low-value biomass (for example, wastewater). The past of MFCs (the prototype BES) is marked by divergence, considering its attractive concept. The experimentation was revived in the 1960s in the NASA space program's context as emerging expertise for wastewater recycling in airships, relying on its first articles by Potter (1910) and Cohen (1931), which discovered hardly constrained significance. Nevertheless, developments in the area of photovoltaic (PV) systems have led to something like a declining concern in MFCs [50]. In recent times, the emerging understanding of both the challenges ahead connected to overwhelming reserves of fossil energy and also the increasing effects of environmental issues such as the greenhouse gasses contributed to both an increased understanding of the need to build methods for sustainable managing of the global ecosystem and an earth's assets [5, 51, 52]. Studies on microbial BESs, in particular MFCs, were revived in this course. In particular, the integration of BES into waste

Fig. 3 Schematic representation of a single-chambered microbial fuel cell

Fig. 4 Schematic representation of double-chambered microbial fuel cell

remediation for concurrent bioelectricity (bioenergy) generation and energy recovery is an excellent feature [53–55]. BESs comprise both an anode (where the mechanisms of biological substrate oxidation occur), and a cathode (where the electrons get reduced with oxygen). Both electrodes (anode and cathode) are connected to form a closed circuit through an external circuit [56]. The metabolic reactions near the anode/in the anode compartment are such as oxidation of a wide range of substrates, such as synthetic substrate

(glucose, acetate, etc.) and carbon-rich organic waste (such as food waste, domestic waste, etc.). The redox reactions at the cathode of MFC may shift towards the reduction reaction-mediated chemical synthesis, like hydrogen or hydrogen peroxide. Besides this chemical synthesis, BES can also be applied to biosensors applications and biosynthesis of nanoparticles. BES contains electrochemically active microbes in the anode compartment, cathode compartment, or both electrodes. Single-chamber BES, do not contain separators (also popular as open-air cathode MFC) (Fig. 3). Whereas in the case of two-chamber systems (also popular as double chamber MFC) (Fig. 4), they contain a separator that separates the microorganisms or chemicals within only one of the two chambers.

This separator is made with cloth, selective membranes, ion-exchange membranes, etc. Whereas in the case of ion-selective membranes, these allow only specific types of ions (anions or cations). The electrode materials will be prepared using different materials, including iron, copper, graphite, etc. Further, these electrodes will be given a coating with a catalyst to enhance the catalytic property. For example, BES operated with a graphite electrode (cathode) will be coated with a platinum catalyst to enhance the cathode compartment's oxygen redox reactions.

Bioelectrochemical systems for wastewater valorization

BES for wastewater treatment and power production

Early-stage BES research focused primarily on knowing how functional factors (such as electrode material, biocatalyst, pH, temperature, etc.) influence their efficiency and develop new system designs and novel techniques to improve their overall process efficiency [21, 27, 57, 58]. Most of these investigations were conducted as electrolytes with synthetic media to allow investigators to maintain control over the substrate's composition [21]. Industrial effluents typically carry an immense amount of organic and inorganic pollutants, with organic compounds not just occurring at high

concentrations and exhibiting an extensive range of organic molecules [54, 55, 59]. Several researchers carried out their research throughout the world to increase the power density level of BES and make the entire process economically viable to bring it to a large scale. Subsequent laboratory experiments with carbon-rich real wastewater were used to gain awareness of the ability of BES in the real world (Table. 1). These experiments have helped to measure the degree to which a natural substrate's existence influences reactors' efficiency. For example, BES operated with real field wastewater produced power densities in the range of several tens of mW/m^2 , which contrasts with the hundreds and even thousands of mW/m^2 that can be achieved with synthetic effluents [60, 61]. Regardless of modern developments in electrode materials [27] and device configurations, BES power generation has not been dramatically enhanced. Problems, for instance, low conductivity and low power of the buffer, are often cited as the key aspects explaining the low output detected [21]. The MEC would certainly face similar obstacles, although economic viability conditions seem to be less stringent [62, 63]. Besides, the disparity in architecture among the MFC and the MEC presents additional scaling problems. Aeration to the cathode invites complicated problems with a pilot-scale BES, as either the cathode chamber essentially be exposed to the atmospheric air or there is an additional aeration cost. Nonetheless, with a MEC, the cathode is anaerobic, simplifying the construction of a more massive structure, all of which outlines a more desirable MEC scenario.

Due to their low energy requirement, BESs are attracting interest because of their capacity to recover nutrients by means of ion migration across membranes. This project examines the potential for the use of nutrient bio-electroconcentration, an ionic nutrient form that is typically harvested from domestic wastewater and then concentrated and processed in centralized wastewater treatment plants, by further exploring the economic viability of the process [64].

Bacteria known as “electroactive bacteria” (electrogenic bacteria) were added to the anode, which is capable of oxidizing soluble organic substrates and generating electrons. These electrons are subsequently utilized in the reduction of water at the cathode, and that leads to an elevation in pH that

Table 1 Energy recovery from numerous wastewater as potential substrates in MFCs

Substrate type	Reactor type	Bioelectricity	COD removal	References
Brewery industrial wastewater	Double chamber MFC	0.35 W/m^3	79–83%	[66]
Agro-food industry wastewater	Double chamber MFC	27 W/m^3	83 ± 11%	[67]
Vegetable oil industrial wastewater	Double chamber MFC	2166 mW/m^2	80–90%	[68]
Seafood wastewater	Air cathode MFC	570 mW/m^2	58 ± 1.2%	[69]
Landfill leachate	Single-chamber MFC	344 mW/m^3	90%	[70]
Silver laden artificial wastewater	Double chamber MFC	3006 mW/m^3	82.7%	[71]
Fish market wastewater	Air cathode MFC	420 mW/m^2	90%	[72]

Fig. 5 Bioelectrochemical systems mediated recalcitrant removal during anodic (substrate/wastewater oxidation) reactions and cathodic (substrate/pollutants reduction) reactions

is quite near to the cathode (Fig. 5). As a result, phosphate may be eliminated by releasing calcium ions into the aqueous solution next to the cathode, resulting in the removal of calcium phosphate on the cathode's surface [65].

BES for biohydrogen and biomethane production

In recent years, BES is widely using as a potential biohydrogen producing system from a wide range of substrates, including wastewater [73, 74]. BES can produce biofuels, such as hydrogen and methane, by providing external electrical energy, as discussed in the above sections. For this purpose, MEC needed a very low electrical supply under optimum conditions [75, 76]. The rise in MEC should be due to the ongoing development of energy and resource recovery from zero value wastewater, particularly concerning the research related to hydrogen production from the dark-fermentation process and bioelectricity generation from MFCs [77, 78]. MEC offers a “one stone two birds” solution for energy generation (in the form of hydrogen/methane) and waste remediation at the same time [79, 80]. MEC is an efficient approach for biohydrogen production; it can also utilize wastewater to produce hydrogen, methane, or other chemical compounds [77]. In MECs, electrochemically active microbes utilize carbon-rich organic substances near the anode and need significantly low energy compared to the electrolysis process [81]. Hence, these MECs can be directly used in the existing wastewater treatment plants with few sustainable energy modifications with concurrent waste treatment. This approach will make the waste treatment process economically viable process [77].

The process must occur for this to happen, and it will only happen if you provide at least -0.414 V of voltage to the

cathode. Compared to the usual fermentation biomethane synthesis, MEC technology takes far less energy input. It drives virtually all stoichiometric conversion of the feedstock to hydrogen. In contrast, dark fermentation has only been able to produce 33% of this potential. The efficiency of electrohydrogenesis depends on a number of factors, including the kind of electrodes used, the potential range, the kind of microorganisms, the design of the MEC reactors, and notably influenced by the feedstock type [82–84]. A hydrogen production and energy efficiency as high as possible was obtained using readily biodegradable substrates. Hydrogen synthesis in MECs using acetate as an electron donor is proven in Eqs. (1), (2) when temperature, pH, and pressure are 25°C , 7.0, and 1 atm, respectively [85].

To enable biohydrogen promotion, the process known as electrohydrogenesis has been shown to have the capability of eliminating the endothermic barrier. Also, in this process, the small external energy as well as that produced by naturally occurring anode respiring bacteria work together to assist in the transfer of the electrons created through the respiration of the anode to the cathode, where they combine with protons and subsequently generate additional biohydrogen gas.

BES for carbon dioxide valorization

Raise in atmospheric carbon dioxide concentration is commonly considered one of the primary causes of global climate change [86]. Capturing carbon dioxide at significant sources of emissions and eventual sequester has been

suggested as an effective method to reduce the deposition of carbon dioxide in the atmosphere, although this solution is of considerable public concern [87–89]. Some other options that are more appealing to public sentiment and might help alleviate the expense of reducing carbon dioxide emissions into the environment are the use of this gas as a raw material for manufacturing applications [88, 90]. One of several options, in this case, is the transformation of carbon dioxide into chemical precursors or products [87, 91, 92].

The use of carbon dioxide as a green carbon feedstock for chemicals benefits this low-cost and plentiful carbon fuel. It successfully mitigates carbon pollution with immense environmental and social benefits [93]. To use carbon dioxide as feedstock, the condensed or atmospheric carbon dioxide source must first be collected and solubilized, whether by biotic or abiotic processes, for subsequent reduction reactions. Microbial electrosynthesis is a modern combination of biochemical and electro-chemical approaches to microbial cells for the transformation of dissolved carbon dioxide, especially multi-carbon precursor compounds, into value-added organic compounds [94]. The specific benefit of BES for the recovery of carbon dioxide, while the availability of these electron sources can be sporadic, is that electrons are used to reduce electricity from coal, biogas or solar and wind sources. Because microbes can reap solar power at a pace 100 times higher than chemical output dependent on biomass, BES can help tackle the pressing problems of storage and delivery of renewable energies [95]. In BES, methanogens and acetogens were used as pure cultures or have been enriched in mixed cultures among certain autotrophic microorganisms. We outlined and evaluated quantitatively in this segment how MES was used for carbon dioxide use, which goods were produced, and the system's performance under different conditions. Furthermore, the BES's economic and environmental effects were examined and addressed for the recovery of carbon dioxide. BES for organic waste or carbon dioxide recovery is a possible method that enables harvesting electrons from solar energy, wind energy, biomass [94]. Excellent reports have been made on the working concepts and mechanisms for microbial electron transfer, rational evidence and structures, the economic viability of BES, and the BES principles and industrial capacity. The critical problem here is that carbon dioxide is the low energy-efficient form of carbon. Therefore, a considerable amount of energy is needed to turn it into usable reduced products [96]. In this regard, BES could provide a practical approach via a bioprocess described as bio-electrosynthesis, that needs even relatively mild conditions. BEC is a well-established technology that turns carbon dioxide into useful products and biofuels. BEC meets all the criteria of green synthesis techniques. It utilizes microbes since low-cost and sustainable catalysts may work under atmospheric conditions and,

therefore, be fed with carbon dioxide for atmospheric remediation [97].

Methane, which is stronger than most other typical organismic chemicals like acetate, butyrate, or ethanol, is electrochemically generated under biologically applicable conditions (pH 7 and 25 °C) (Eq. (3)), and is the most thermodynamically effective substance in the reduction of carbon footprint. More detrimental capacity for jobs has, in fact, been used to mitigate overpotential losses and to increase output rates [98]. The job capacity in this analysis is standardized to the typical hydrogen electrode (SHE).

Acetic acid is alternative essential product of BES by carbon dioxide reduction. It was found in apparatuses with single or combination acetogenic microorganisms. Acetic acid formed much lesser than the CH_4 production potential (−0.240 V) from carbon dioxide. It can be generated electrochemically in biologically relevant conditions at −0.280 Volts (Eq. 4):

In reality, the overpotential loss has been minimized, and the output rate increased by utilizing more pessimistic working potentials. Nevin et al. [99], for the first time, reported that the electrosynthesis capabilities displayed by the acetic acid by the biotransformation of carbon dioxide at −0.4 V were demonstrated by six acetogenic microbes *Sporomusa ovata*, *Sporomusa sphaerioides*, *Sporomusa silvacetica*, *Clostridium ljungdahlii* and *Moorrella thermoacetica* [99]. The potential was above the hydrogen development value, with graphite as the cathode, which has been calculated in an earlier study at a value of −0.6 V and an overpotential of 0.2 V.

Besides CH_4 and acetic acid, other organic compounds are also made from the carbon dioxide biotransformation process in BES. It is thought that acetyl-CoA played a significant role in synthetic pathways. It should be remembered that enhanced proton-coupled reactions complicate the forming of several C–C bonds. Furthermore, an equilibrium model has shown that acetic acid development in BES is related stoichiometrically and energetically with the Wood–Jahl pathway's ATP production and why organic synthesis is not favorable. A microbial electrosynthesis-based BES platform is ideal for the production of value-added chemicals and materials from waste and carbon dioxide as a carbon source.

Limitations of BES for waste valorization

The BES-mediated energy generation in the form of bioelectricity and biohydrogen from wastewater as potential substrate is a very complex process governed by many factors that include seed culture, pH, temperature, nutrients availability, hydraulic retention time, hydrogen partial pressure, fermentation end-products, polarization Losses, activation Losses, concentration Polarization, ohmic Losses, microbial interaction with the electrode surface, O₂ reduction by the cathode, and biomass pretreatment-linked inhibitors. It is the fact that there are very few studies conducted on these parameters and intensive research is needed to address these issues to enhance the overall process efficiency and make BES-mediated waste valorization is an economically viable and practically applicable process.

Future directions

Bioelectricity and biohydrogen energy are highly advantageous renewable energy sources in the fight against fossil fuel-based energy. It may be possible to achieve a sustainable carbon neutral operation and be the most cost-effective using renewable, inexpensive feedstock, such as lignocellulosic agricultural leftovers and/or carbon-rich wastewater. While using the technique to produce hydrogen from wastewater has shown some issues, mainly related to the wastewater composition hindering microbial hydrolysis reactions and accumulation of acid-rich by-products, this fermentation technique has a disadvantage in that it produces darker than traditional lactic acid- or alcohol-based fermentation. The bioreactor that MEC has developed can process agricultural waste biomass, VFAs, and other non-degradable organic materials, which speeds up the breakdown of that material, increasing the amount of hydrogen produced. Therefore, connecting MEC/MFC with the dark fermentation system can be an extremely promising approach to optimizing the conversion of pretreated lignocellulosic agricultural wastes and by-products into bio-hydrogen. In this system, dark fermentation predominantly transforms substrates into biohydrogen, carbon dioxide, and VFAs, and the electrohydrogenesis process follows this in MEC for increased biohydrogen conversion efficiency.

Conclusion

BES technology is a group of comparatively emerging innovations that have tremendous opportunities for energy recovery from a wide variety of contaminants. The chemical energy stored in the wastewater can be converted into electrical energy, which is eco-friendly. BES can significantly influence the existing wastewater treatment technology by enhancing energy efficiency and also by making the process economically viable by energy generation with concurrent waste treatment. The organic matter present in the wastewater will convert or biotransform into either biofuels or value-added chemicals. Further, this technology can also address atmospheric pollution by reducing carbon dioxide levels in the atmosphere. Further, possible waste valorization roots of BES have been discussed in the manuscript. Discussed options towards waste valorization, reduce substrate cost and address waste treatment/disposal-related issues. Also, the functional simplicity of BES may provide more outstanding options for wastewater recovery and also the recovery of valuable products and resources, such as ammonium or phosphorus. This will possibly include a low-cost and eco-friendly approach for reducing carbon dioxide emissions to the atmosphere.

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