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Review

Scalability of biomass-derived graphene derivative materials as viable anode electrode for a commercialized microbial fuel cell: A systematic review

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ABSTRACT

Microbial fuel cell (MFC) is an advanced bioelectrochemical technique that can utilize biomass materials in the process of simultaneously generating electricity and biodegrading or bio transforming toxic pollutants from wastewater. The overall performance of the system is largely dependent on the efficiency of the anode electrode to enhance electron transportation. Furthermore, the anode electrode has a significant impact on the overall cost of MFC setup. Hence, the need to explore research focused towards developing cost-effective material as anode in MFC. This material must also have favourable properties for electron transportation. Graphene oxide (GO) derivatives and its modification with nanomaterials have been identified as a viable anode material. Herein, we discussed an economically effective strategy for the synthesis of graphene derivatives from waste biomass materials and its subsequent fabrication into anode electrode for MFC applications. This review article offers a promising approach towards replacing commercial graphene materials with biomass-derived graphene derivatives in a view to achieve a sustainable and commercialized MFC.

1. Introduction

The world expanding industrialisation has resulted in a sharp increase in energy consumption. Sustained access to some energy sources, such as petroleum–based fuels, has contributed significantly to environmental pollution, resulting in adverse human health issues and negative impacts on terrestrial ecosystems. Some of the consequences of the unintentional release of petroleum hydrocarbons into the environment include air pollution, which may contribute to global climate change causing major setbacks in sustainable development [1–3]. Therefore, the necessity to look for an alternative source of energy that can be found in every country in the world has geopolitical, economic, and environmental benefits. Microbial fuel cell (MFC) represents a viable alternative with promising technology to counter the above-mentioned challenges. In MFC, bio-energy is generated from organic matter through the metabolic activities of microbes such as bacteria and can simultaneously decontaminate toxic pollutants in the system [4]. The fundamental introduction to MFC in terms of components and mechanisms has been extensively defined in previous works [5]. Despite all of the advancements in MFC, the power output performance is still very low for commercial application. Efforts are being made to improve the performance of MFC while lowering their set-up and operating costs. According to a review of the literature, the transfer of electrons from anode to cathode is critical in improving MFC performance. Electron transportation is hampered as a result of the utilization of a poor material as an anode. For example, metal-based anode electrodes can transfer electrons more effectively, but after a while, they create corrosion, which inhibits bacterial growth and activity. Similarly, other common carbon materials such as graphite, carbon rods, and so on, have failed to transport the electrons, despite the fact that carbon, with

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the exception of carbon nanotubes (CNTS), is not hazardous to bacterial species. According to recent research, carbon derivatives can be a beneficial strategy to address such a problem [6,7]. Yaqoob *et al*. [8] comprehensively researched the graphene oxide-based anode in MFC and achieved considerable good results with no hazards. Commercial graphene is not an ideal solution due to economic feasibility. As a result, Yaqoob *et al*. [8] proposed that the biomass-derived graphene derivatives material can fulfil the economic feasibility criteria. Graphene-derived biomass materials for anode fabrication are currently receiving careful attention from researchers in MFC because of the material's requisite property stipulations, which can contribute massively to the high-performance process rate of an MFC [9]. Graphene derivatives are the purest grade carbon-based compounds that may be produced from bio-waste [10,11]. Biomass has recently received a lot of attention due to its sustainability and ability to be transformed into functional carbon-based materials. The precise composition of biomass materials varies depending on the biomass resources used. However, they are mostly made up of lignin, hemicellulose, and cellulose. Certainly, a variety of process conditions, such as feedstock type, temperature, residence time, heating rate, and pressure, would influence the properties of the resulting biomass-based carbonaceous materials; different combinations would lead to a variety of characteristics, such as surface area, surface functional groups, porosity, and so on. As a result, a better understanding of such combinations is required for various applications of biomass-based carbonaceous materials. Raw biomass, on the other hand, is typically composed of organic substances such as saccharides, vitamins, and fatty acids. Many organic substances will be decomposed into H_2O and CO_2 during the thermal carbonization process, eventually escaping through pores [12]. To achieve high-quality biomass-based carbonaceous materials, researchers have worked to optimize the pore structure, modify the surface property, and adjust the degree of graphitization during the preparation process.

Previous research indicates that when graphene derivatives such as graphene oxide (GO) or reduced graphene oxide (rGO) were prepared from bio-waste material, the process produced relatively poor quality when compared to commercial graphene derivatives. The material conductivity may be changed owing to quality assurance. Therefore, several studies show that the utilization of nanomaterial (metal oxide) as a modifier with graphene derivatives can bring a significant breakthrough in MFC as an anode. Recently, Yaqoob *et al*. [8] conducted a brief study on GO-metal oxide composite-based anode for MFC. Up to date, the utilization of nanomaterials such as zinc oxide, titanium oxide, and others as modifiers with rGO has shown to be a beneficial step toward improving the energy performance. According to a review of the literature, nanomaterials are a promising emerging modifier due to their high thermo-chemical stability, good elasticity, biocompatibility, good tensile strength, large surface, high loading capability, excellent penetrability, best electro-catalytic activity, and ability to support remarkable electron-transfer [13–15]. Furthermore, the usage of green synthesized metal oxide nanomaterial as a modifier is the best option, since green synthesis material poses no active threat to bacterial species. Metal oxides are typically thought to be anti-bacterial. To avoid this problem, a conductive polymer such as polysulfone must be used as a binder during the synthesis of the rGO-metal oxide nanocomposite anode [16]. The conductive polymer used acts as a barrier between bacterial species and the rGO-metal oxide nanocomposite composition [17]. Polysulfone is the most important material for successfully transporting electrons to the rGO-metal oxide nanocomposite anode for further transport to the cathode. These features provide a suitable approach for wastewater treatment and energy generation enhancement with increasing the electron transfer rate in electrochemical reactions [18].

However, challenges abound in achieving this at industrial or commercial scale. The production costs of graphene-derived anodes and their sustainability for industrial MFC application have not been adequately harnessed. Fabricating anodes through biomass waste has provided a promising alternative for cost-effectiveness. Insight on the synthesis routes and modification can provide wider knowledge on its large-scale application for MFC. In this review study, we have highlighted our discussion on the various synthesis routes and fabrication of anode electrodes from biomass material for a viable graphene derivative nanocomposite applicable for enhanced MFC with cost-effectiveness. The review article also discusses the economic feasibilities of biomass-rGO derived nanocomposite anode electrodes and their prospects in MFC. The principle of MFC and the biochemical reactions carried out on the anode in MFC, which have not been adequately explored in recent literature have been elaborated herein. This paper also highlighted the waste/biomass-derived materials used as anode electrodes in previous MFC research studies.

2. Fundamental Principle of MFC

MFC structurally consists of two chambers, the anode chamber, and the cathode chamber. In the anode chamber, oxidation occurs while reduction occurs in the chamber of the cathode. The bacterium in the anode compartment decomposes the organic matter during the oxidation process to produce electron charges (e^-) and proton ions (H^+) [19]. These electrons are moved to the cathode with the help of an external circuit that provides the current; the protons are transferred *via* the salt bridge or pass directly through the proton exchange membrane (PEM) [20]. Fig. 1 shows the schematic diagram of the MFC. The two halves of the chemical reactions that occur in an MFC are the anodic reaction and the cathodic reaction. In the absence of oxygen as a direct electron acceptor, the inoculated microbes are maintained in an anaerobic environment adjacent to the substrate, and these inoculated bacteria attach to an electrode to donate electrons from the substrate consumption. The potential difference between the cathode and the anode is generated by the electron charges in the anode. These electrons are transferred from bacteria to the anode by membrane-bounded quinones and by cytochromes in electrogenic bacteria which do not require any mediator for electron transfer or by mediators. The mediators may be either endogenous or exogenous in nature. Endogenous mediators are redox mediators produced by microorganisms. Exogenous mediators are redox mediators that can be supplied from outside the body. Endogenous mediators produced by cells include phenazines, flavin mononucleotides, favins, ribofavins, quinones, pyocyanins, and hydrogen sulphide. Thionine, methylene blue, Fe (III) EDTA, various quinone derivatives, and neutral red are examples of exogenous mediators [21]. These electrons are transferred from the anode chamber to the cathode chamber by an external circuit to which the current is provided, whereas the protons are transferred through the PEM [22]. The electrons are then transferred to the cathode immediately after the circuit gets completed with a resistor, as a result, the oxygen in the air, which is the terminal electron acceptor, is reduced. The oxygen reacts with the protons produced in the chemical reaction in the anode, and H_2O is formed on the cathode side [23].

3. Significance of Anode Electrode

Among the electrodes, the anode is established as a very significant part of the MFC, both functionally and structurally, due to the

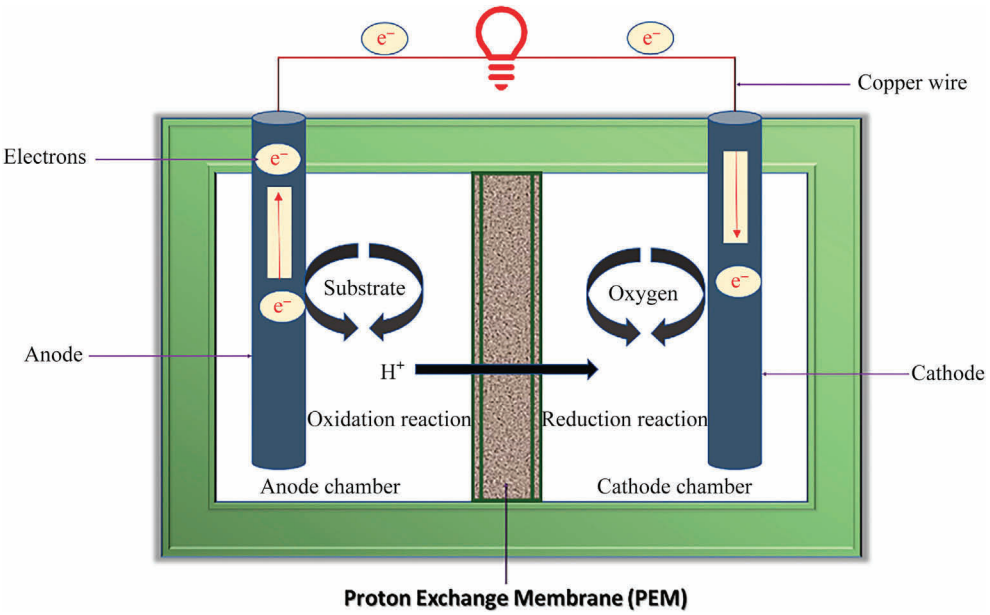

Fig. 1. Systematic presentation of MFC.

major role that it plays in improving the performance of the MFC. The materials mostly used for anode fabrication are from carbon-based origin, such as graphite felt, graphite fiber brush, graphite rod, carbon cloth, carbon felt, carbon paper, and reticulated vitreous carbon (RVC), graphite granules (GGs), or granular activated carbon (GAC). They have also been widely used for the anode due to the certain favourable properties they possess, ranging from stability in bacterial cultures, high conductivity, and a good surface area [24,25]. Modifying the material surfaces before fabricating the anode is one way to improve the performance of MFC. In this way, adhesion to bacteria cells, the potentiality of the cell, and extracellular electron transfer are improved [26]. Recently, MFC scientists have begun to modify the anode material using various modification techniques to improve the electron transfer [27]. Griškonis *et al.* [26] studied the voltage dependence of MFC that utilizes different anodes and observed that MFC with an anode modified with ethylenediamine produced a slightly larger voltage than the MFC with the anode prepared from ordinary GF (graphite felt), whereas the MFC with an anode made of GF, which was treated with paraphenylenediamine, produced about 32% higher voltage than the control MFC when the circuits of the studied MFC were connected with resistors of 659 Ω. The power density of the latter MFC was about 1.75-fold higher than in the control. Fig. 2 shows the temperature and duration effect on the voltage generated by MFC with different anodes at an electrical load of 659 Ω [26]. Another feasible way to enhance MFC output power is using modified carbon such as graphene derivatives and metal-based anodes with conductive polymers. The structure of the anode and its materials are capable of affecting the oxidation process as well as the bacteria adhesion [28]. Materials used for anode fabrication in MFC usually encompass the following essential factors, the compatibility of the material is influenced by a few several reasons, including low price and high biocompatibility, chemical stability, and electrical conductivity. However, compatibility issues can occur even if the anode material selection and design are superficially correct. This is a major reason for the low efficiency of some prototype MFC and remains a significant barrier to their practical application [29].

In the biochemical and electrochemical aspects of the anode surface, the oxidation reaction in MFC takes place at the anode, thereby electrons are released. The bacterial species rely on the energy produced by fuel oxidation. For energy conversion, microbes use two metabolic pathways: respiration and fermentation. Bacterial species use Gibbs free energy for respiration *via* the respiratory or oxidative pathway, in which electrons circulate through a respiratory chain before leaving the microbial cell *via* membrane-bound electron acceptors [30]. The bacterium produces CO_2 and H_2O in the presence of oxygen during the decomposition of the substrate. However, the presence of oxygen is inhibitory and as such, anode chambers are made anaerobic. In these anaerobic conditions, the bacteria decompose the organic matter into only CO_2 [31]. The reactions that utilize organic carbon source such as acetate or glucose as a substrate are oxidized to produce electrons as shown below.

$$CH_3COO^- + 2H_2O \rightarrow 2CO_2 + 7H^+ + 8e^- \quad (\text{anodic reaction})$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (\text{cathodic reaction})$$

$$CH_3COOH + 2O_2 \rightarrow 2CO_2 + 2H_2O + \text{electricity} \quad (\text{overall reaction})$$

Thus, the emf produced can be calculated as:

$$E_{emf} = E_{cathode} - E_{anode} - \eta \quad (1)$$

where $E_{cathode}$, E_{anode} and η are the potential of the half-cell cathode, the anode's half-cell potential and the loss term respectively [32]. The electrochemical system's feasible energy can be calculated using the Gibbs free energy (DG) equation, which is given as:

$$DG = -nFE_{cell} \quad (2)$$

where n is amount of electrons; F is Faraday's constant and E_{cell} is voltage of the cell [33]. Electricity is generated in the MFC according to Gibb's free energy Eq. (2) when the overall reaction is thermodynamically favored.

4. Biomass Waste Material as an Anode

In previous years, biomass derived materials have been receiving more and more attention as high-performance and low-cost materials for the fabrication of anode in fuel cells. With the increasing demand for green energy, anode electrodes have been fabricated from recyclable and renewable materials, especially with waste materials rather than high-cost precursors to obtain more high-performance anode materials. Therefore, due to their

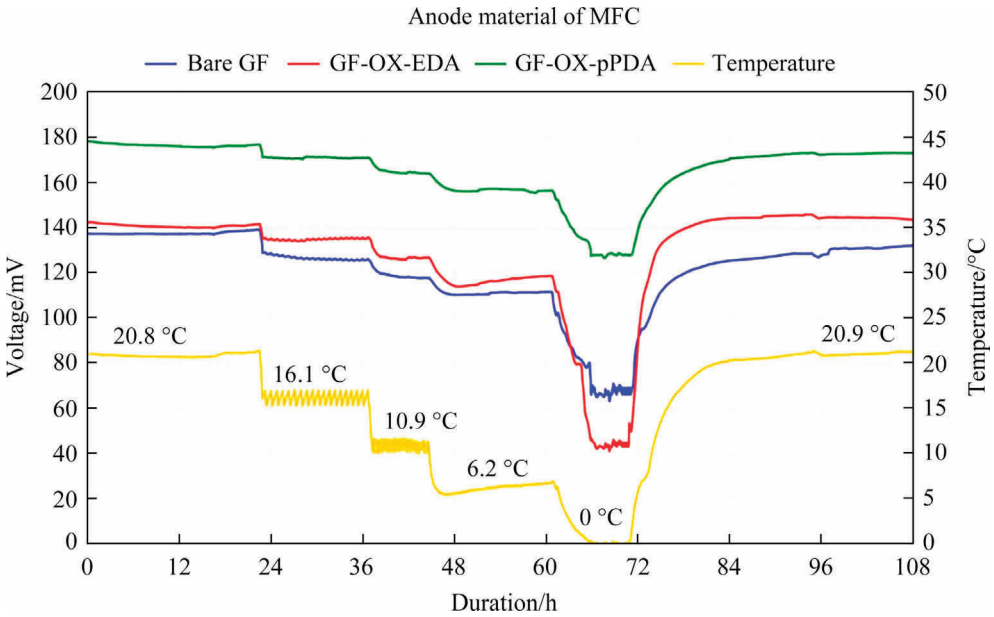

Fig. 2. Temperature and duration dependence effects on voltage generated by MFC with different anode samples at an electric load of 659 Ω (reprinted from Ref. [26] with permission from MDPI).

low-cost and recyclable characteristics, waste-derived carbon derivatives from available bio-waste are considered a very promising alternative to conventional anodes [34–37]. Recently, researchers are introducing this concept of waste materials for anode fabrication in MFC application as summarized in Table 1. For example, Yaqoob *et al.* [8] studied the use of lignin-graphene derived anode (L-GO) obtained from bio-waste (oil palm) in an MFC to generate energy. The authors improved the electron transportation rate of the anode by introducing a zinc oxide composite-based anode (L-GO/ZnO). MFC system featured with L-GO/ZnO anode displayed a higher removal efficiency (91.07%) of the toxic metal (Pb^{2+}), whereas a removal efficiency of 85% was observed when L-GO anode was used. Also, the lignin-based anode (L-GO/ZnO) supported a higher maximum current density (1.350 $mW{\cdot}m^{-2}$) with a corresponding current density (142.98 $mA{\cdot}m^{-2}$) compared to the values exhibited by the anode (L-GO), which displayed a power density of 0.020 $mW{\cdot}m^{-2}$ with a current density of 17.54 $mA{\cdot}m^{-2}$. The authors agreed that oil palm material can be used as a promising and cost-effective waste to improve the anode properties for enhanced performance of MFC. Similarly, Hung *et al.* [38] showed that coffee waste-activated carbons (CWAC) can be used as material to form anode in a *Escherichia coli* based MFC. The pore size of CWAC was modified to achieve a power density of 3927 $mW{\cdot}m^{-2}$, which was greater than that of commercial activated carbon (975 $mW{\cdot}m^{-2}$). The authors attributed the increased power density of CWAC to its high conductivity and appropriate pore size distribution, which resulted in a rapid electron transfer and bacterial attachment. Furthermore, Chen *et al.* [39] directly used carbonized waste tyres as pepped-up anode material in MFC. The current density of the anode electrode made from waste tyres carbonized at 800 °C was of 23.1 $A{\cdot}m^{-2}$, which is significantly higher than the current density of conventional graphite felt anodes (5.5 $A{\cdot}m^{-2}$). They suggested that the outcome of the study provides useful information on the utilization of carbonized waste tyres for optimized anodes in MFC performances improvement with the alleviation of environmental disorders caused by waste

Table 1
Summary of recently used biomass materials for anode electrodes fabrication in MFC

Biomass Material	Surface area/cm^2	Electrode size/cm^2	Strain/Inoculum source	Power density/$mW{\cdot}m^{-2}$	Ref.
Oil palm	76.0	8.0 × 1.3	Pb^{2+}supplemented wastewater	1350×10^{-3} 20×10^{-3}	[8]
Coffee waste	1	–	*Escherichia coli*	3927	[38]
Waste tires	1	–	–	–	[39]
Oil palm	76.0	8.0 × 1.3	Synthetic wastewater	–	[40]
Cellulose waste	0.71	7.5 × 1.2	Synthetic wastewater	–	[41]
Palm kernel shell AC	0.5	–	Fecal sludge	1730	[42]
Corn stem	–	–	Anaerobic sewage	–	[43]
Sludge mixed with fly ash	12	1.8 × 0.8	Sodium acetate	–	[44]
Municipal sludge	–	3.0 × 2.0	*Shewanella oneidensis*	568.5	[45]
Municipal sludge	0.5	3.0 × 3.0	Artificial wastewater	615.2	[46]
Mango wood	75.3	2.0 × 3.0	Inoculum bacteria	589.8	[47]
Onion peels	7	10 × 2.0	Mixed sludge	742	[48]
Compressed mill residue	10.99	0. 5 × 3.0	Anaerobic sludge	532	[49]
Barbed chestnut shell	91	2.7 × 2.7	Mixed sludge	759	[50]
Loofah sponge	11	0.5 × 3.0	Anaerobic sludge	701	[51]
Silk cocoon	7	–	Mixed sludge	5	[52]
Coconut shell/ sewage sludge	10.99	0.5 × 3.0	Mixed sludge	1069	[53]
Bamboo charcoal	59.21	2.4 × 1.57	Anaerobic mix sludge	1652 ± 18	[54]

tyres. Bamboo charcoal was prepared by Zhang *et al.* [54], which was discovered to present better electrode characteristics than that of a conventional graphite rod. The SEM image derived from the carbonized bamboo charcoal is shown in Fig. 3. The observed benefits of this electrode material include low internal resistance, improved biocompatibility, and a rougher surface that promotes biofilm adhesion. According to the findings, the addition of C═N bonds facilitated electron transfer from the bacteria through the anode. As a result, the anode made of bamboo charcoal was 50% more efficient than the anode made of graphite tube [54]. The reachability of bacterial species to the large surface area of the anode improves kinetics and performance significantly. It can be observed from the SEM image that the surface was exceedingly rough with many obvious cracks. Fig. 4 displays some biomass materials that have been used as anode in MFC. According to scanning electron microscopy, these materials as displayed possess high porosity and high surface area/roughness [43].

There are vast numbers of available waste materials useful for anode fabrication, few among them include palm kernel shells, coconut shells, almond shells, chestnut shells, cashew nut shells, wooden wastes, waste papers, corn straw, *etc*. The availability of these materials is based on locations and geographical regions. Most countries around the world are introducing several green policies to save the ecosystem and to attenuate the complicating effects of environmental pollution. For instance, Malaysian government has demonstrated its intention to develop the palm biomass industry since 2001 as a measure of supporting the country's green policy. The small renewable energy program (SREP), introduced in Malaysia in 2001, promotes the use of renewable energy sources [58]. Palm tree-based biomass waste is a major bio-waste source that is readily and abundantly available in Malaysia [59]. Hence, this can serve as a source of raw material to researchers in Malaysia for utilization as biomass-derived anode for MFC system. Yaqoob *et al.* [40] developed a self-assembled and modified anode electrode. Local waste material (oil palm biomass) was used to produce GO anodes. The bioinspired modified GO anodes exhibited more than eight times larger energy output (135.96 $mA{\cdot}m^{-2}$) than unmodified GO anodes (15.65 $mA{\cdot}m^{-2}$). It shows that the waste material converted to an anode delivered a great support for transporting electrons. Furthermore, the modified GO anode supported a higher utilization of waste-derived organic waste (oil palm trunk sap) as the carbon source substrate in the removal of Cd^{2+} from synthetic wastewater. Also, graphene/polyaniline nanocomposite anode derived from cellulosic biomass was utilized for the removal of toxic metals with electricity production *via* benthic microbial fuel cell (BMFC) as studied by Yaqoob *et al.* [41]. In the experiment, 87.71 $mA{\cdot}m^{-2}$ was observed to be the maximum current density. This demonstrated that the altered graphene anode performed four times better than the unmodified one. The remediation efficiency was also higher for the modified graphene anode than for the unmodified graphene anode.

The utilization of biochar material for anode electrodes in MFC has been reported in several research articles. Bio-char is an economic material containing high content of carbon with a large specific macro-surface area as well as mesopores, and nanopores [60]. Chakraborty *et al.* [61] reviewed the applications of waste-derived biochar in MFC. It was reported in the review that different raw material sources used to produce biochar can be derived from cellulosic-based biowaste, microalgae, fruit waste like the peel wastes from banana and watermelon fruits. They further stated

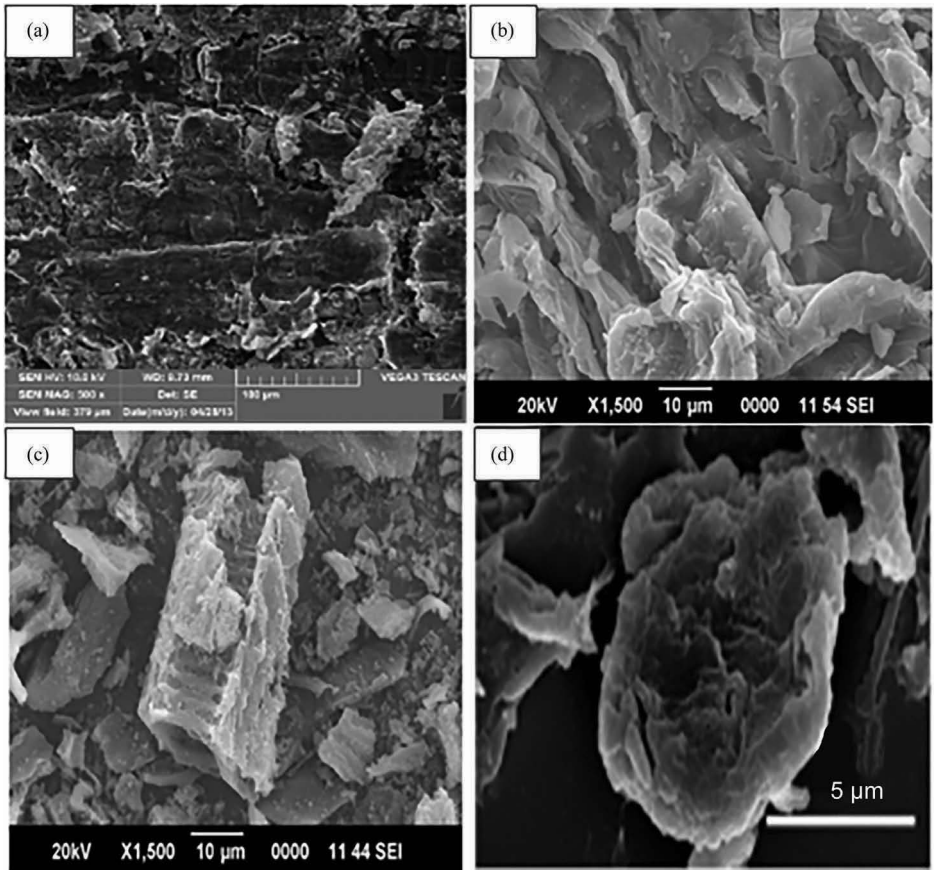

Fig. 3. SEM images of biomass carbon derivative materials: (a) bamboo charcoal tube surface, (b) orange peels biochar, (c) cauliflower leaves biochar, and (d) almond shell carbon (reprinted from Refs. [54–56] with permission from Elsevier and RSC).

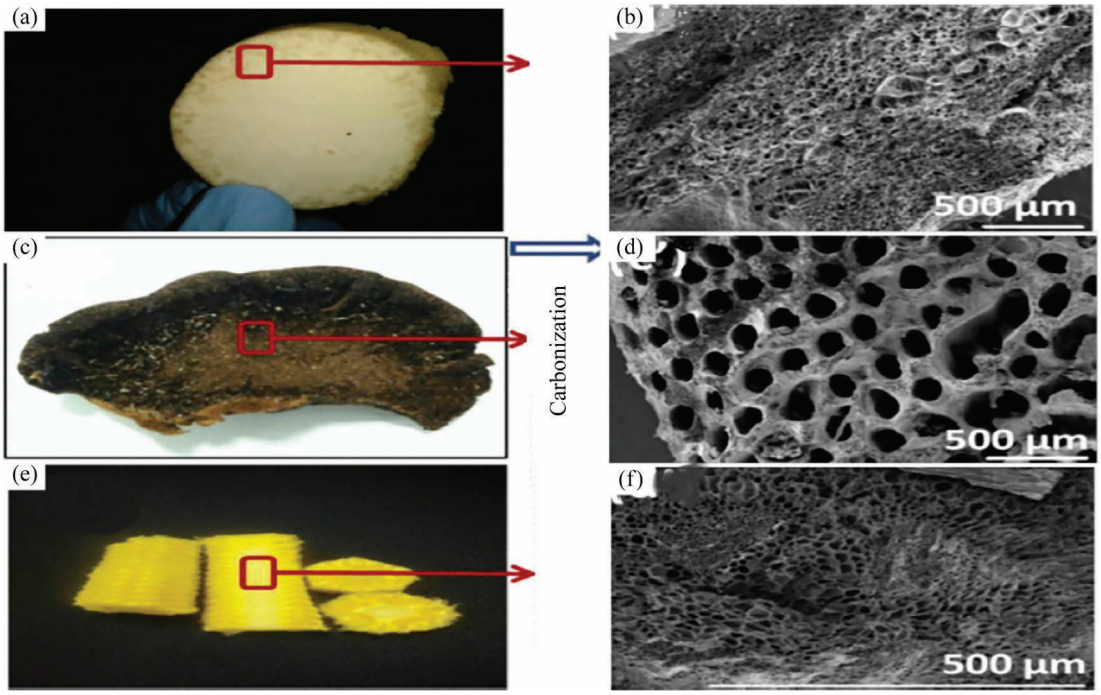

Fig. 4. Samples of biomass that have been recently used for anode fabrication in MFC: (a), (b) king mushroom, FE-SEM micrographs of carbonized king mushroom; (c), (d) wild mushroom, FE-SEM micrographs of carbonized wild mushroom ; and (e), (f) corn stem, FE-SEM micrographs of carbonized corn stem (adapted from Refs. [43,57] with permission from Elsevier).

that the application of sludge derived from sewage and the fraction of organics from landfills have also been investigated as start-up material in making biochar. Huggins *et al.* [49] synthesized biochar from residues obtained from mills and forestry activities at a carbonization temperature of 1000 °C, which was explored as an anode in MFC. MFC performance using biochar as the applied anode was compared to the MFC performance utilizing granular activated carbon (GAC) and graphite granules as an anode. Milling residue and forestry biochar presented the highest power densities of 532 and 457 $mW{\cdot}m^{-2}$, respectively, whereas the outcome of MFC using GAC was the highest, with a value of 674 $mW{\cdot}m^{-2}$. Biochar derived from a variety of biomass/waste materials such as shells, sewage sludge, fruit peels, corncob, food husk, wheat straw, *etc.*, have demonstrated essential anodic properties [62–65]. The production of biochar from waste raw materials and a simple synthesis method makes biochar an economic-effective and alternative to metals and other commercial material for use as electrodes.

5. Synthesis of Biomass Derived Graphene Derivatives and Fabrication of Electrode

Over time, there is a rapid increase in research interest towards the synthesis and use of biomass-derived carbon in energy applications. This perhaps is due to the cost-effectiveness, sustainability, and of course the ease of fabrication from their various bio-precursors [66]. Due to their intrinsic nano porous and hierarchical structures, biomass-derived graphene outperforms the contrived nanostructured carbons such as graphene in terms of capacitance, performance, and stability in supercapacitor applications [67–69]. Long *et al.* [70] synthesized porous layer-stacking graphene-like carbon (PGC) materials from biomass as carbon precursors. The layer-stacking PGC prepared presented a high surface area (1103 $m^2{\cdot}g^{-1}$), high bulk density (about 0.96 $g{\cdot}cm^{-3}$), and hierarchically interconnected porous framework, that provides adequate storage sites with short transport paths for electrolyte ions, and enhances the overall conductivity of the electrode. However, the technicalities of the process to synthesize carbon base from biomass/waste that will present a high yield of carbon content and high energy density remains a challenge for researchers [66]. Biomass wastes or agricultural products are an alternative starting material for preparing graphene and graphene-derived carbons. For instance, recently, researchers have processed corn straw [71], rice husks [72,73], grape seeds [74], sunflower shells [75], cotton stalks [76], and feathers [77] from various synthesis processes to produce graphene-derived carbon as an end product. Similarly, other researchers prepared graphene and graphene-like carbon from biomass materials such as sucrose and gelatine [78], and wheat straw [79]. Recent studies on the synthesis method of biomass-derived graphene derivatives are discussed below.

5.1. Synthesis methods of biomass derived graphene derivatives

The synthesis of biomass-derived graphene derivatives requires concentrating the carbon content of the biomass starting material. Industries have sustained the production of biochar through this process. Biochar is produced by thermal processes such as gasification, carbonization, liquefaction, and pyrolysis [80].

5.1.1. Thermal carbonization and chemical activation

Thermal carbonization is a widely used technique for producing biochar (carbon) from biomass by heating the biomass at a high temperature in a muffle furnace. Light molecular weight compounds are removed during this heating process. The conditions (temperature and time) set for the biomass carbonization are dependent on the nature of the desired char product. For example, a slow heating rate favours the production of more bio-chars [81]. One major reason for most of the researchers to produce graphene using this route is because of the flexibility in choosing the outcome product. The decomposition of the biomass during carbonization generally begins at about 300 °C, depending on the material involved [82]. Different carbonization temperatures have

been used to convert sugarcane bagasse to rGO [83]. Jung *et al.* [84] performed a chemical activation on a biomass-derived carbon to create micropores and mesopores which led to hierarchical porous biomass-derived graphene-based carbons with a high Brunauer-Emmett-Teller specific surface area of 3,657 $m^2 \cdot g^{-1}$. The graphene-based carbon produced was used to construct a supercapacitor. There was an excellent outcome with the highest energy density observed at 74 $kW \cdot kg^{-1}$ resulting in a maximal power density of 408 $kW \cdot kg^{-1}$. Apparently, this approach entails a promising method for graphene synthesis. Fig. 5 displays a simple illustration of how biomass material is converted to biomass-derived carbon.

5.1.2. Chemical exfoliation

Chemical exfoliation has been considered among the best approaching techniques to synthesize graphene. A literature survey showed that researchers have used this method to synthesize highly porous graphene from biomass-derived carbon. Exfoliation methods used to produce graphene from graphite can be used by substituting graphitized biomass for graphite. The graphitized biomass exfoliation method involves peeling the bulk carbon structure by overcoming the van der Waals force, resulting in graphene sheets [86]. For example, Lu *et al.* [87] chemically exfoliated biomass into a graphene-like porous active carbon by oxidising cellulose and hemicellulose to produce rich mesopores, with partial hydrolysis of cellulose and hemicellulose on the surface of biomass for exfoliation. This pre-treatment accompanied by post carbonization pathway yields a carbon with high conductivity and rational pore structure, clutching very considerable potential in supercapacitors with the highest specific capacitance of any carbon-based capacitor material reported to date. The biomass derived graphene-like produced exhibited extremely high specific capacitance (340 $F \cdot g^{-1}$ at 0.5 $A \cdot g^{-1}$) and high specific energy density (23.33 to 16.67 $W \cdot h \cdot kg^{-1}$). Shams *et al.* [88] used sonication to exfoliate biochar from camphor leaves. After 15 min of sonication, the biomass was subjected to 1200 °C treatment, and a few graphene layers were suspended. The graphene's average I_D/I_G was comparable to that of pure graphene. The chemical exfoliation consists of two main stages. Fig. 6 shows the two-step mechanism for producing graphene through chemical exfoliation. The first is the reduction of the interlayer forces to produce graphene-intercalated compounds, then by applying fast heating to exfoliate the graphene into multi-layers [90]. A modified Hummers method is an example of chemical exfoliation. This method for producing biomass-derived graphene derivatives is based on Brodie's oxidation method, which involves chemically treating graphitized biomass with acids and alkali metals to produce GO. Seitzhanova *et al.* [91] produced GO from rice husk using the Hummers method. While being constantly stirred, the biochar was chemically treated with $NaNO_3$ and H_2SO_4. After 30 min of reaction, $KMnO_4$ was gradually added. When this method was compared to Hummers' method of using graphite powder, the oxidation of biochar to GO was noticeably faster. Similarly, an improved hummers method was developed by Chen *et al.* [92] for an eco-friendly synthesis of biomass based GO with the elimination of toxic gases released from the route. They prepared the GO by removing sodium nitrate from the reaction formula after the oxidation process. The researchers concluded that the modified Hummers technique may be used to prepare GO on a wide scale, and it is a viable approach to the ecologically friendly synthesis of graphene and its derivatives.

5.1.3. Chemical vapour deposition

Chemical vapour deposition (CVD) has been identified as a viable method for producing graphene. Because it is inexpensive, CVD has emerged as a promising method for producing large-area graphene. Gas species are fed into the reactor and pass through the hot zone, where biomass precursors decompose to carbon radicals at the surface of the transition metal substrate, forming layers of graphene-like carbons. The most used substrates applied for graphene fabrication are transition metal materials such as Cu and Ni. This method allows graphene films to be transferred to other substrates while retaining their excellent conductivity and permeability [93,94]. The objectives of using CVD to produce graphene are to obtain high-quality graphene or to make a graphene/metal composite. Graphene transferability is a major issue, and CVD is one method for dealing with it [95]. The CVD method for biomass-based graphene derivative synthesis can be achieved by mixing the biomass with transition metal and subjected to pyrolysis. For example, Liu *et al.* [96] developed bio-based GO by combining iron powder and lignin biomass. In the process, the metal melts with lignin biomass, allowing the amorphous carbons to encapsulate the melted metal. The metal is in nanoparticle form during the encapsulation process, while the biomass is in amorphous carbon form. At high temperatures, the amorphous carbon dissolves, and precipitates on the metal surface, arising in metal encapsulated with graphene as the final product. After several washes with de-ionized water, magnetic separation was used to separate the iron particle and graphene structure. Chae *et al.* [97] used an optimized CVD to produce a very crystalline large-area graphene on Ni substrate. In Raman spectroscopy, the D-band with the peak position and intensity of the GO band was applied to observe the quality and thickness of the synthesized

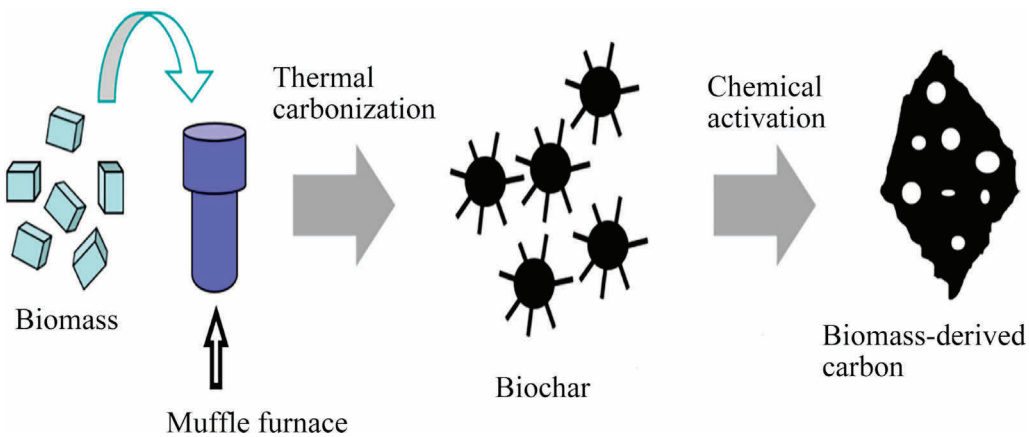

Fig. 5. Conversion of biomass material to carbon derivatives through thermal carbonization and chemical activation (adapted from Ref. [85] with permission from Korea Science Publisher).

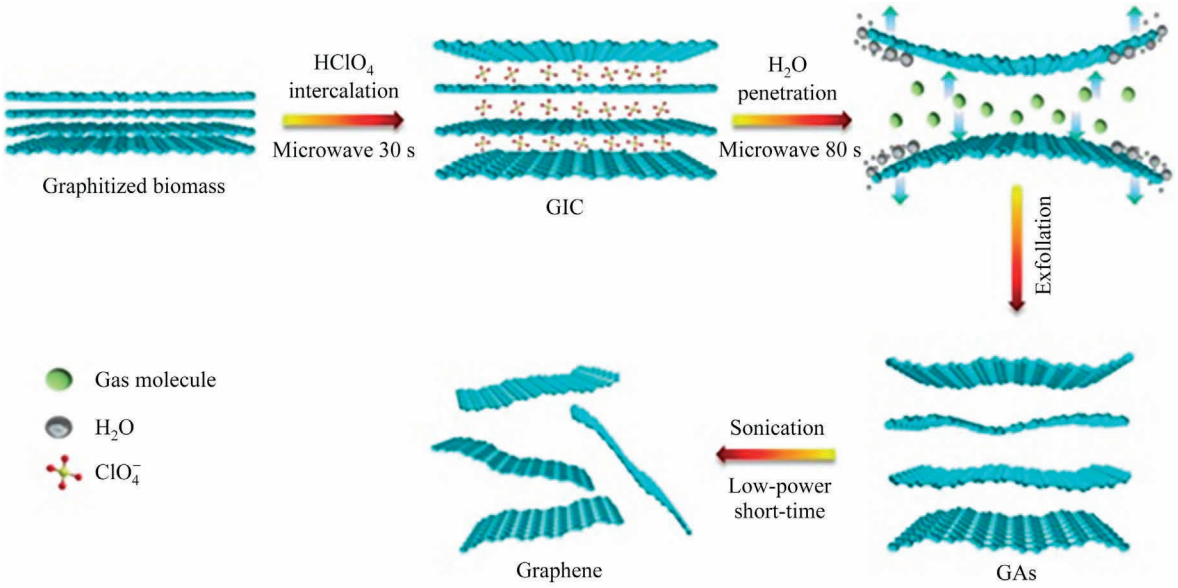

Fig. 6. Chemical exfoliation mechanism for the synthesis of graphene (modified from Ref. [89] with permission from Elsevier).

graphene films. The hydrocarbon gas-hydrogen gas mixing ratio, temperature, and growth time were optimized to produce highly crystalline graphene in a few layers on a poly-Ni substrate. To synthesize highly crystalline graphene in a few layers, high temperature, short growth time, and optimum gas mixing ratio (C_2H_2/H_2 = 2/45) were required. The properties of graphene produced *via* the CVD method suggest their potential for utilization in electrodes fabrication [98].

Other methods can be utilized in synthesizing biomass-derived graphene which may include oxidation and reduction method [99], self-assembled method [42,100], template method [101], the ionophoresis method [102], ferromagnetic/electrostatic interaction [103], and bio-catalysed redox process [104]. To study the advancement of power generation in MFC, a few of the methods can be utilized to fabricate the graphene derivative electrode. Methods of converting biomass material into carbon derivatives are represented in Table 2.

5.2. Fabrication of electrode

The fabrication of suitable electrodes is critical in enhancing the performance of the MFC. Researchers in the last decade have recorded tremendous improvement in the development of highly efficient electrode materials for MFC. For instance, Pareek *et al.* [119] manufactured electrodes from 3-D graphene powder prepared. To prepare a paste, graphene powder was mixed with polytetrafluoroethylene (PTFE). The paste was evenly added to the surface of the carbon cloth and subjected to the oven at 100 °C for 6 h before being used in MFC application as an anode. Similarly, Masoudi *et al.* [120] fabricated activated carbon, carbon black (AC-CB) coated stainless steel mesh (SSM) electrode by mixing and agitating activated carbon, superconductive carbon black, and PTFE in a mass ratio of 60:30:10. Isopropyl alcohol was slowly added to the carbon mixture while the agitation continues until the mixture formed a paste pellet. Then, the paste pellet was coated around the surfaces of the SSM and oven-dried at 60 °C for 3 h to eliminate any excess of alcohol in it. The electrode dimensions were 2.5 cm × 2.5 cm, and the surface density of the air permeable carbon layer was of 38.96 mg·cm^{-2}. 3-D macroporous anodes were built by coating carbon nanoparticles (such as graphene, carbon nanotubes, or activated carbon) on stainless steel fibre felts (SSFFs) that presented an open, solid, and macroporous structure. The SSFFs were earlier cut into 1.8 cm × 1.8 cm pieces and were soaked in acetone for 3 h to dissolve the organic substances adsorbed and then rinsed with the ultrapure water before the experiments. The carbon nanotubes were also treated using a 3:1 mixture of concentrated H_2SO_4/HNO_3 and then rinsed with the ultrapure water continually till a pH value of 7 is obtained, and finally oven-dried at 60 °C before the experiment was conducted [121]. The general fabrication processes are represented in Fig. 7.

6. Biomass Derived Graphene Derivatives-based Composite Anode

Composite-based anodes have gained a lot of consideration recently, owing to their ability to improve biocompatibility, electrical conductivity, bacterial adhesion, and surface area. As research into more cost-effective anodes continues, biomass wastes were introduced to fabricated anodes. In recent years, major advances have been made in the use of graphene derivatives with metal oxide and conductive polymer composites as material for anode electrodes in MFC [122–124]. However, it is a good idea to use biomass wastes to make the graphene-based anode since it appears to be a cost-effective and sustainable material for MFC. It is particularly interesting to fabricate biomass-derived carbon base electrode composites employing metal oxides such as ZnO, TiO_2, or conductive polymers. During the carbonization of biomass waste, carbon-based material is produced which can then be subjected to Hummer's method to produce GO [125]. Due to its high electron movement rate and electrocatalytic activities, biomass-derived GO/metal oxide composite expands the application range of MFC electrodes. Serious consideration needs to be given to improve the biomass-derived GO through a composite combination with other metal oxides or conductive polymers to apply the MFC approach at larger-scale applications and to fulfil the current energy demand, environmental management requirements, and economic challenges. A series of previous studies have shown that an anode modified with graphene derivatives can stimulate bacterial species to release signalling molecules. These could stimulate bacterial growth while serving as intermediate molecules to improve the electron transfer efficiency [126]. Lignin-based biomass carbon was used to produce L-GO and L-GO/TiO_2 composite in a dual-chamber MFC. The L-GO/TiO_2 composite was developed by introducing the convectional solvothermal method. Within 90

Table 2
Some synthesis methods for biomass-derived materials in various energy applications

Biomass material	Synthesis method	BET surface area /$m^2 \cdot g^{-1}$	Pore volume /$cm^3 \cdot g^{-1}$	Material application	Ref.
Lignin-based biomass	Carbonization (1100 °C, 20 °C·min^{-1} rate, argon gas flow) and Hummer's method	280	0.22	Anode electrode in MFC	[105]
Argan seed shells	Carbonization (500 °C, 3 h, N_2 gas flow)	1279	0.47	Supercapacitor electrodes	[106]
Pinecone hull	Carbonization (450 °C, 3 h, N_2 gas flow) and activation (800 °C, 30 min, CO_2 atmosphere)	380	0.20	Lithium secondary battery anode	[107]
Sewage sludge	Carbonization (900 °C, 2 h, N_2 atmosphere)	44	0.08	ORR catalyst in MFC	[108]
Coffee shells	Pyrolysis (900 °C with $ZnCl_2$ and KOH as pore-forming chemicals)	842	0.40	Lithium battery anode	[109]
Peanut skin	Autoclave heating (180 °C, 24 h) and activation with KOH (800 °C, 1 h, Ar flow)	1930	0.64	Sodium ion battery anode	[110]
Forest residue	HHT carbonization (1000 °C, 1 h, ramp rate of 16 °C·min^{-1})	4.70	–	Anode electrode in MFC	[49]
Pine wood	Carbonization (1000 °C, 1 h)	152.3	–	Wastewater treatment	[53]
Walnut shells	Carbonization (800 °C, rising rate 10 °C·min^{-1}. N_2 atmosphere	1197	0.60	Supercapacitor electrode	[111]
Spongy pomelo peels	Carbonization (900 °C, argon flow, 3 h, 2 °C·min^{-1} ramp rate)	114	0.03	Lithium-ion batteries	[112]
Sorghum pith	Carbonization (300, 400 and 500 °C, 3 h in an isolated atmosphere)	35, 27, 17	–	Electrode for electric double layer	[113]
Rubber tree sawdust	Pyrolysis (500 °C, 2 h)	88.26	–	Anode electrode in MFC	[114]
Basswood slice	Stabilization (150 °C, 3 h) and carbonization (950 °C, 2 h, N_2 flow, 3 °C·min^{-1} ramp rate)	200	0.22	ORR and supercapacitor application	[115]
Watermelon rind	Pyrolysis (400, 500, 600 and 700 °C, 2 h, N_2 as protection, 5 °C·min^{-1} rate)	658.90, 476.83, 156.05, 78.03	–	Oxygen reduction catalyst in MFC	[116]
Sunflower seed shell	Carbonization (800 °C, N_2 gas flow, 5 °C·min^{-1} rate, 1 h) and chemical activation (KOH)	619	0.33	Nonporous carbon electrode capacitor	[117]
Banana peels	Pyrolysis (600 °C, N_2 atmosphere, 2 h)	70	–	Proton exchange membrane in MFC	[118]

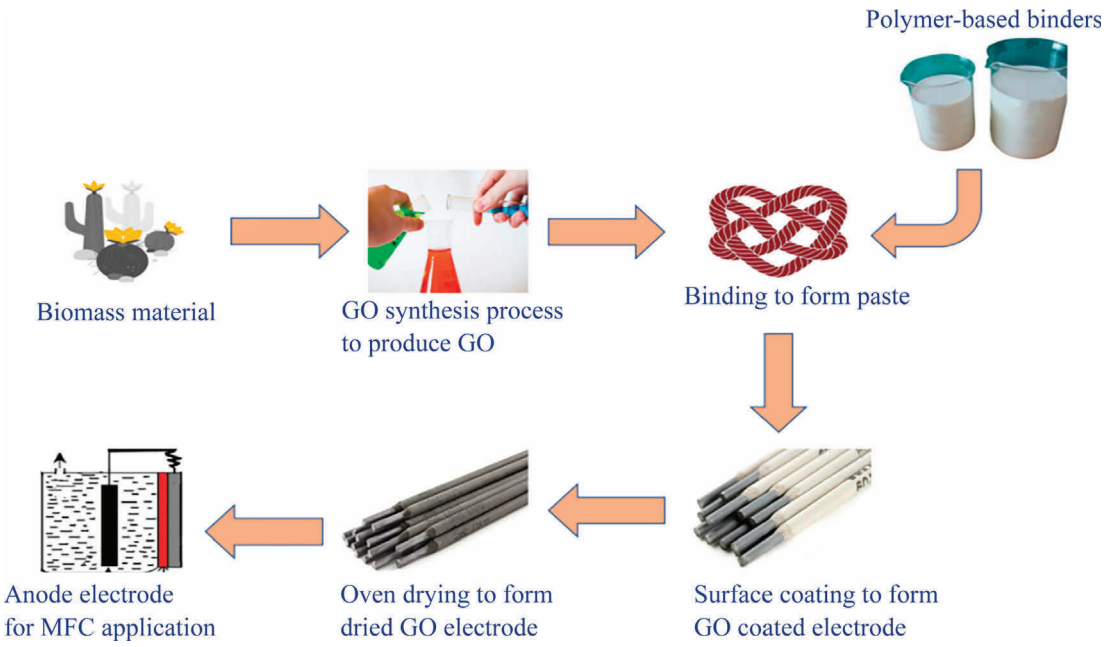

Fig. 7. General process flow diagram for the fabrication of graphene-derived anode electrode.

experimental days of the MFC operation, the L-GO and L-GO/TiO_2 provided a current density of 57.01 mA·m^{-2} and 70.17 mA·m^{-2}, respectively, and 85% and 90% removal of Pb (II) ions from the Pb^0 enriched wastewater. The maximum power density measured at the L-GO anode was of 0.44 mW·m^{-2}, on the same vein, the maximum power density measured at the L-GO/TiO_2 anode was of 0.78 mW·m^{-2}. The bioinspired GO lignin-based anodes showed excellent efficiency in removing toxic metals from synthetic wastewater [16]. Yuan *et al.* [127] published a comprehensive study on the ability of graphene-modified anodes to improve the remediation and power generation performance of MFC systems. Graphene-based anodes have shown their great influence on microbial metabolism in a way that promotes extracellular electron transfer (EET). When using a graphene-coated carbon fabric anode, Liu *et al.* [102] achieved a high peak current and a lower peak separation. Their findings support the view that graphene-based anode applications can improve EET. When the peak current was plotted against the scan rate, which represents direct electron transfer, the worthwhile effect of the graphene anode was found to be more remarkable. This discovery, along with the loads of biomass observed on the anode surface, may indicate that exoelectrogens have incorporated graphene materials into their EET

pathways. An intriguing phenomenon proportionately corresponded to both EET and GO is on the fact that GO can be reduced *in situ* by microbes like *Shewanella* spp. [128], which are a group of predominant facultative exoelectrogens in MFC [129]. Electron transfer as a result of microbial reduction on graphene has been linked to the cytochromes MtrA, MtrB, and MtrC/OmcA, all of which play important roles in EET [130]. Over the years, tremendous progress has been made in the use of biowaste-derived graphene-based materials as electrodes in other energy storage devices and supercapacitors. This may offer a promising opportunity for improving its application for MFC performance. For example, Guardia *et al.* [131] presented a biomass-derived graphene derivative as a low-cost material for improved supercapacitor performance. The combination of biomass waste-derived carbon with rGO significantly improves the operation of microporous carbons for supercapacitor application. Literatures revealed that the fabricated bio-based graphene derivative composites exhibit excellent electrochemical properties that make it an ideal candidate for electrochemical energy storage applications. Based on these characteristics, researchers hypothesised that these materials used in energy storage applications could be useful in related systems such as fuel cells. Aside from being used as anode electrodes in MFC, graphene-based materials derived from biomass waste have been found to be useful in a variety of applications, including improved energy storage, power generation (solar cells), sensing, and even as an advanced membrane material for separations as well documented in Table 3.

7. Bacteria-anode Interaction

Basically, the MFC's anode is the main pathway for interaction with bacteria. The anode material must be biocompatible and have a large surface area that allows bacteria to settle around the anode electrode and form a biofilm. The formation of biofilms on the anode surfaces is the cause of the interaction between the anode and bacteria. The main reason for the anode-bacteria interaction is to influence electron transfer from the bacteria to the anode, and then to the cathode electrode. Fig. 8 shows the mode of electron transfer from bacteria to the anode. A variety of chemical, physical, and biological parameters influence the nature and efficiency of electron transfer from bacteria to electrodes [143]. However, it has been shown that especially the application of a certain potential to the bio-anode invigorates the formation of an electroactive biofilm. Thus, Pinto *et al.* [144] investigated the performance of an MFC by examining whether a potential applied to the bioanode stimulated the formation of *S. oneidensis* bacterial complexes on the surfaces of the anode. Using various electrochemical methods, they demonstrated that a potential applied to the anode between −0.3 V and +0.5 V showed a different electrochemical behaviour to favour the biofilm growth. At an applied potential of −0.3 V to the bioanode, it favoured a mediated electron transfer with rapid biofilm formation. However, at +0.3 V, the bioanode was observed to stimulate direct electron transfer with rapid adhesion of bacterial fibres. The result of their research provides a fundamental understanding of the interaction between anode and bacteria in MFC. There are two critical processes that occur before biofilm growth. The first is the attachment of bacteria to the surfaces of the anode and the second is the development of the bacterial layers that lead to the growth of biofilms [145]. Recently, researchers are developing anode materials that can promote bacterial attachment and smooth electron transfer. This is achieved by surface treatment and modification of the anode material. In general, the anode material can be modified to improve its efficiency by mixing materials to form composites, such as metal/metal oxide nanocomposites, composites with conducting polymers, and so on. For example, Wu *et al.* [146] improved the performance of MFC by modifying the carbon cloth anode. The surface of the carbon cloth was modified by adding various nanoparticles and nanotubes. The results showed that the modification significantly improved the energy performance of MFC. However, electrochemical oxidation has been shown to be the most suitable method to improve the rapid growth of bacteria and the electron transfer rate. In this method, both structural morphology and functional groups are associated with the surfaces of the anode material, improving electron transfer between the bacteria and the anode electrode [41]. Our knowledge of the reaction mechanisms that take place on the electrode anode remains limited. With further expedition of the mechanisms, updated approaches to anode modification could be developed. Materials that improve electron transport, for example, can be developed as anodes for MFC applications [147].

8. Economic Feasibility of Biomass-derived Graphene Derivatives Nanocomposite Anode Electrode

Graphene-based nanocomposites materials have been widely used as anode electrodes in MFC and other similar electrochemical systems for years. However, the cost of graphene-based anodes has contributed in no small part to the setbacks in the commercial application of MFC systems. The high cost of conventional graphite and its non-renewable nature makes it unsuitable for industrial operation. It has been reported that the cost of electrode materials in the operation of MFC can account for up to 50% of the total cost [148]. Hence, the synthesis of graphene-based anodes from biomass/waste material [149], has become a welcome development in this regard. When selecting a material for the anode electrode in MFC, although the cost of the material plays an important role, selection must be influenced by the electrochemical efficiency and the ability of the material to enhance electron transport [150,151]. Previously, commercial granulated active carbon (GAC) and graphite particles (GP) were the most commonly used electrode materials in MFC system setup because they both have high catalytic activity and good electrical conductivity [25]. Aside from the current need for a more sustainable and economically viable MFC setup, biomass-based materials used as anodes in MFC have greater biocompatibility with microbes, allowing for better microbial attachments and faster electron transfer processes. There is insufficient data to compare the costs of producing biomass-derived graphene derivatives with those of commercially available electrodes. However, Table 4 addresses some of the limited information available in the literature.

9. Conclusion and Future Prospects

The greatest challenge that must be addressed to achieve a commercialized and sustainable MFC system is the cost of MFC setup and the suitability of the component materials, which determines the economic feasibility. In terms of cost and sustainability, the anode electrode has been identified as the most critical component of MFC. As a result, recent and future research is being directed toward developing an alternative anode electrode that is both cost-effective and meets the necessary property requirements of an anode electrode. Biocompatibility for bacterial adhesion, good surface area to create space for bacterial growth, electrical conductivity, and cost-effectiveness of the material are all essential requirements of a good anode material for MFC application. Carbon derivatives, such as graphene oxide/metal oxide composite anode electrode and other biochar electrodes derived from biomass material, have been reported in recent works to be encouraging and economically viable anode materials for MFC application. However,

Table 3
Summary of synthesis conditions of biomass-derived electrode and the characterization tools in MFC

Biomass-derived carbon-based electrode	Biomass material	Carbonization/thermal treatment conditions	BET surface area /$m^2 \cdot g^{-1}$	Electrode material characterization tool	MFC application	Ref.
SS-derived carbon monolith	Sewage sludge (SS)	1000 °C in a gasifier with top-lit for a period of 1 h	152.3	Elemental analyser, XPS, SEM, BET.	Anode enhanced the performance of the MFC	[53]
L-GO L-GO/ZnO	Oil palm biomass	1050 °C, argon gas flow with 20 $ml \cdot min^{-1}$ rate for 3 h	253.91	UV–Visible, photoluminescence (PL) spectroscopy, FTIR, SEM, EDX, TEM, X-ray diffraction, BET, atomic force microscopy (AFM), TGA, Raman spectroscopy	The anode was fabricated from low-cost material, effective for MFC performance	[8]
Biochar	Pine wood lumber	1000 °C, 1 h in a TLUD gasifier	152	SEM, inductively coupled plasma mass spectrometry (ICP-MS), four-point probe, BET	The biochar attains a high surface area suitable for MFC electrode purpose	[132]
Coconut shell/metal CS-$Si_{0.2}$, CS-$Zn_{0.2}$, and CS-$Cu_{0.2}$	Waste coconut shell	500 °C at rise rate of 10 $°C \cdot min^{-1}$ and residence time of 60 min	0.1825 0.1900 0.2162	X-ray diffraction (XRD), (SEM + EDX), FT-IR spectroscopy, BET	CS-$Cu_{0.2}$ electrode demonstrates higher MFC performance potentials	[133]
Lignin-derived activated carbon (LAC)	Plant lignin	850 °C, ramp rate 5 $°C \cdot min^{-1}$ for a period of 1 h	420	SEM, TEM, Raman spectroscopy, XRD, and nitrogen physisorption analysis	The LAC is usefulness as electrode in MFC	[134]
$Si_{0.4}$/$Zn_{0.4}$/$Cu_{0.4}$/coconut shell mixtures	Waste coconut shells (CS)	600 °C, ramp rate 10 $°C \cdot min^{-1}$ for a residence time of 1 h	0.19 0.20 0.25	FT-IR spectroscopy, BET, XRD, Malvern Panalytical multipurpose diffractometer, SEM + EDX	The CS/metal composite electrode improves the power out of the MFC	[135]
Activated microporous-mesoporous carbon	Chestnut shell	900 °C for 2 h at a rate of $°C \cdot min^{-1}$ under N_2 atmosphere	342 881 468	SEM, FT-IR, XPS and BET	A promising approach for sustainable and cost-effective anode	[136]
Graphene oxide GO/TiO_2	Lignin powder, oil palm trunk sap orange peel	1100 °C, rate of 20 $°C \cdot min^{-1}$ using argon gas	225	FT-IR, BET, UV-spectroscopy, TGA, TEM, energy dispersive X-ray, EDX, SEM, AFM and Raman spectroscopy.	Fabricated GO/TiO_2 anode enhanced the performance of the MFC	[105]
Sugar cane activated carbon	Sugar cane refuse	300 °C, 400 °C and 500 °C with an interval of 1 h	Average particle size: 1.59 μm.	XRD; FTIR, AFM, SEM, particle size analyser.	The biomass-derived AC cathodes were cost-effective and demonstrated superior catalytic performance	[137]
Lignocellulosic-derived GO/ZnO GO/TiO_2	Oil palm, lemon peel	3 h at 20 $°C \cdot min^{-1}$ and argon gas allowed to flow continuously	63 40	FT-IR, XRD, Raman spectroscopy, TGA, BET, UV–Vis's spectroscopy, SEM, EDX, TEM, AFM.	The fabricated anode shows high level of conductivity	[138]
Polydopamine-modified activated carbon	Waste cotton textiles	1000 °C for 1 h with flow of Ar gas	888	FESEM, EDS, XPS, XRD, Raman spectroscopy, BET, porosimetry analyser, modified Bradford protein assay kit	NC@CCT electrode gives higher power output in MFC than carbon felt	[139]
Nitrogen-doped biochar	Watermelon rind	400, 500, 600 700 °C, 2 h, protection of N_2 at 5 $°C \cdot min^{-1}$ rate	477	SEM, EDS, XRD, XPS, FTIR	The biochar is highly cost effective with promising potentials for MFC	[116]
CuO/Cu_2O carbon nanocomposite	Bamboo leaves	600 °C with N_2 atmosphere for 2 h, 1 $°C \cdot min^{-1}$ heating rate was employed	301.85	X-ray diffractometer, thermo scientific spectrometer, FTIR spectrometer, BET, TGA/DTA, FE-SEM and TEM, XPS	The fabricated electrode demonstrates its efficiency in energy storage application	[140]
Graphitic biochar	Wood waste	1000 °C, 1 h, and ramp rate of 16 $°C \cdot min^{-1}$	183	TGA, ICP-MS, XRD, BET, XPS	The work reveals effectiveness of BC as low-cost material for MFC use	[141]

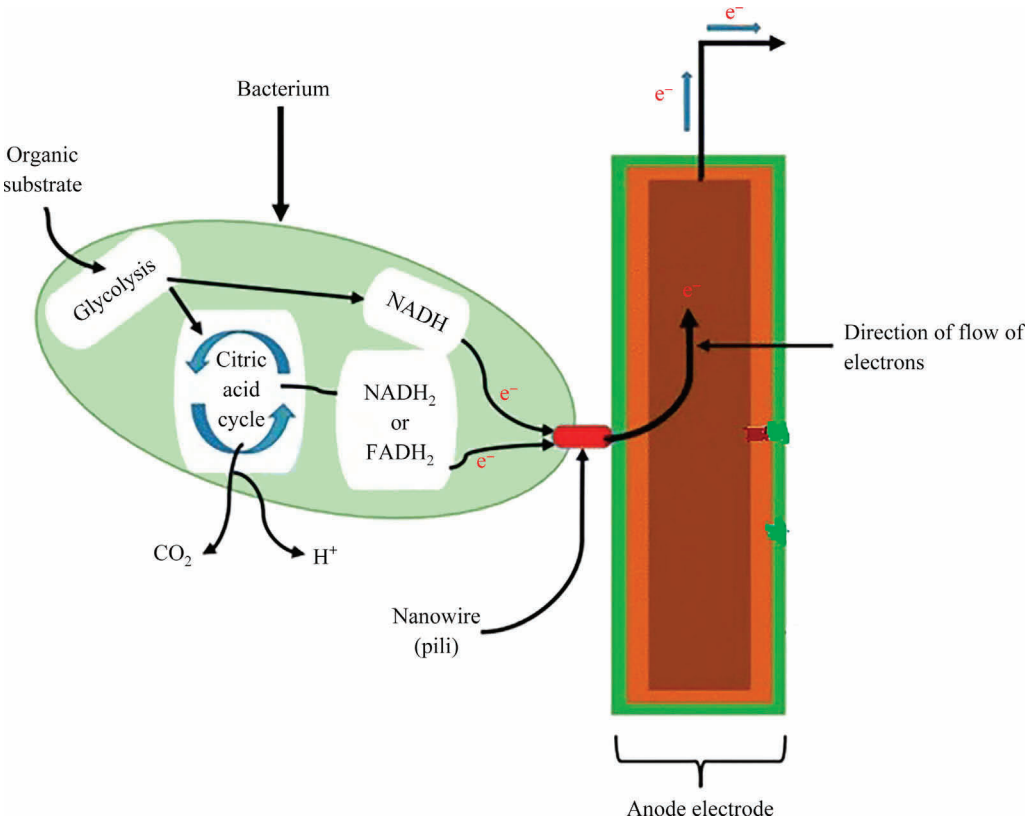

Fig. 8. Schematic presentation of bacterial-anode interaction in MFC system (reproduced from Ref. [142] with copyright permission from Springer Nature).

Table 4
Cost analysis of commercial and biomass-based anode electrodes in MFC application

Materials	Anode	Specific surface area /$m^2 \cdot g^{-1}$	Cost of material /USD·kg^{-1}	Power output /mW·m^{-2}	Ref.
Commercial-based	GG	9.84	0.8–1.2①	900	[152]
	AC	879	1.0–2.0②	1287	[153]
	GCC	379	1.0–1.5①	53.30	[102]
Biomass-based	WBC	469	0.05–0.38③	41.41	[154]
	CBC	48.77	0.05–0.38③	48.77	[155]
—	PBC	698	0.05–0.38③	2025	[156]

Note: GG—graphite granule; AC—activated carbon; GCC—graphene/carbon cloth; WBC—wood-derived biochar; CBC—Cocklebur fruit-derived biochar; PBC—peanut shell-derived biochar.
① https://www.dmcarbon.cn.
② Ref. [157].
③ Ref. [158].

modification of these materials is vital in order to achieve the required anode essential properties. Most importantly, anode material modification should promote increased electron transport. The transfer of electrons from microbes to the anode and subsequent transportation to the cathode electrode is a critical factor in determining the electrical output performance of an MFC. As a result, improving the electron transport rate requires developing and modifying the anode electrode material. Recent research has shown that graphene-based derivatives derived from biomass can be used as anodes in metal oxide composites; however, this material does not completely solve the problem of fast electron transport. As a result, future research should focus on increasing electron transport rates by modifying and improving the graphene-based derivative metal oxide material used as an anode electrode in MFC. In this regard, reducing GO derivatives to rGO derivatives can be very promising. This is due to a reduction in the number of oxygen molecules present, which improves conductivity. However, the increase in conductivity will be proportional to the degree of GO reduction. Highly reduced rGO derivatives, like pure graphene, are almost superconductors. Furthermore, reducing GO to rGO improves the biocompatibility of the resulting material with microbes, which is an important property of an anode electrode in MFC. Conclusively, biomass/waste-derived materials for anode electrode fabrication appear to be more viable than traditional commercial materials for addressing the problem of commercializing MFC systems. This will aid in the reduction of production costs while effectively addressing long-term sustainability concerns. Furthermore, waste-derived materials and their

modifications to elaborate low-cost anodes have emerged as critical research areas for the development of large-scale MFC with improved electrical output performance and high bioremediation efficiency.

Data Availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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