Comparative Review of Natural and Synthetic Binders for Microbial Fuel Cell Electrodes

Andhika Putra Agus Pratama,[a,b] Sri Suhartini,[a,b,*] Novita Ainur Rohma,[a,b] Nimas Mayang Sabrina Sunyoto,[a] Ika Atsari Dewi,[a] Widya Fatriasari,[c] Lynsey Melville,[d] and Ioannis A. Ieropoulos,[e]

* *Corresponding author: ssuhartini@ub.a.c.id*

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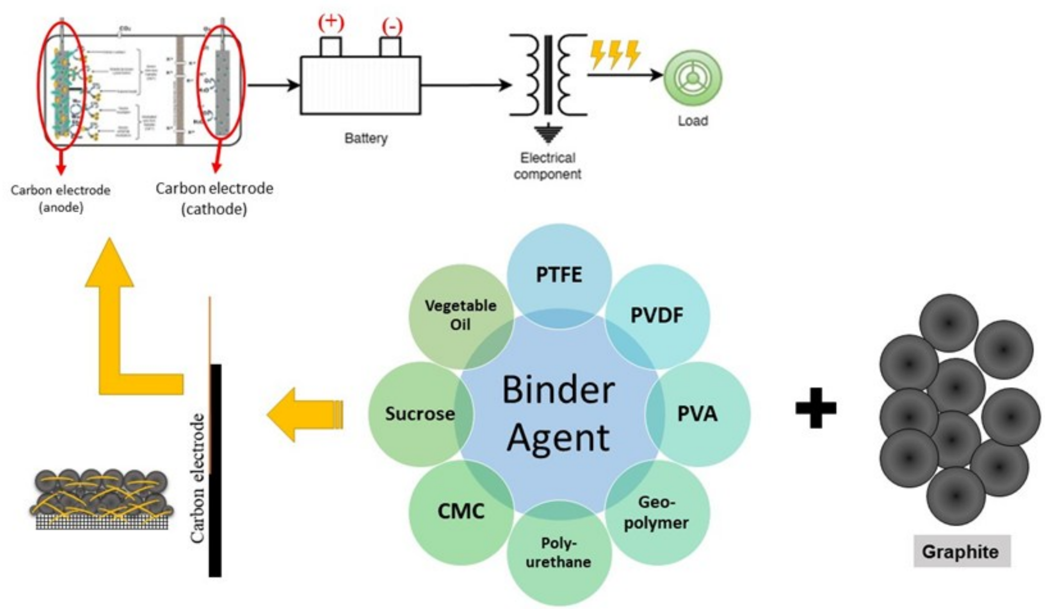
GRAPHICAL ABSTRACT



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Microbial fuel cells (MFCs) are a promising technology for renewable energy and environmental remediation. The performance of MFCs is greatly influenced by the binder materials used on the electrodes, which must have good conductivity, stability, and compatibility with microorganisms. Synthetic binders, such as polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyuretane (PU), geopolymer binder, and polyvinyl alcohol (PVOH), are commonly used due to their electrochemical properties but are expensive and not environmentally friendly. In contrast, natural binders, such as chitosan, sucrose, carboxymethylcellulose (CMC), and vegetable oils, provide cost-effective and environmentally friendly alternatives. This review synthesizes findings from various studies, comparing the electrochemical properties, stability, and sustainability of chemical and natural binders. The review identifies key research gaps and suggests future directions to improve the performance of natural binders in MFCs, making them more viable for large-scale applications in terms of cost and environmental impact. Natural binders have the potential to be a sustainable alternative in MFC electrode development.

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Keywords: Binding materials; Bioelectrochemical system; Electrode; Environmental sustainability; Microbial fuel cell

Contact information: a: Department of Agro-Industrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, Indonesia; b: Centre of Excellence Bioenergy and Biorefinery, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, Indonesia; c: National Research and Innovation Agency (BRIN), Cibinong, Indonesia; d: The Global Environmental Challenges Research Group, Faculty of Computing, Engineering and Built Environment, Birmingham City University, Birmingham, West Midlands, United Kingdom; e: Civil, Maritime and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, SO167QF, United Kingdom;
** Corresponding author: ssuhartini@ub.a.c.id*

INTRODUCTION

A fuel cell is an electrochemical device that directly converts chemical energy into electrical energy (Ali *et al.* 2024). In similar schemes involving microorganisms, the term microbial fuel cells (MFCs) is also used. MFC offers a promising approach to renewable energy generation and environmental remediation. The MFC involves the decomposition of contaminants by microorganisms, thus producing electrical energy (Hernández-Fernández *et al.* 2023; Zamri *et al.* 2023; You *et al.* 2024). One of the potential raw materials for MFC is tofu wastewater (Satar and Permadi 2022; Hadiyanto *et al.* 2023). An MFC consists of anode, cathode, and separation membrane compartments (Hernández-

Fernández *et al.* 2023; Yalcinkaya *et al.* 2024). The electricity generated comes from the decomposition of microorganisms at the anode (Gajda *et al.* 2020; Roy *et al.* 2023). The cathode will undergo an oxygen reduction reaction (ORR), thus producing H_2O (Anjum *et al.* 2021). This reaction generally requires a long time, so a catalyst is needed in the cathode, for example platinum (Pt). Pt catalysts are expensive and relatively unstable in the long term (Salar-García and Ieropoulos 2020). An alternative catalyst in the cathode is a carbon-based electrode, such as activated carbon or graphite (Anjum *et al.* 2021; Mahmoud *et al.* 2021). Alternative electrodes are required to have good conductivity properties, porous microstructure, and long term stability (Agrahari *et al.* 2022).

Despite the promising potential of MFCs, their commercial viability is hindered by certain technological limitations, particularly related to the electrode materials. The key to improving MFC performance lies in optimizing the electrodes, especially in terms of the binder materials used to hold the electrodes together. The binder material plays an essential role in maintaining the electrode's mechanical stability, ensuring conductivity, and enhancing the efficiency of electron transfer (Walter *et al.* 2018; Agrahari *et al.* 2022). Currently, most MFC systems rely on synthetic binders such as polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), and polyvinyl alcohol (PVOH), which are well-regarded for their electrochemical stability and conductivity (Jadhav *et al.* 2022; Salleh *et al.* 2023; Anit *et al.* 2024). However, these materials come with significant drawbacks, including high costs, environmental impact, and limited long-term stability under operational conditions (Salleh *et al.* 2023).

In light of these challenges, there is growing interest in exploring natural binders as a more sustainable and cost-effective alternative. Natural materials, such as chitosan, sucrose, carboxymethylcellulose (CMC), and vegetable oils have emerged as promising candidates for binder materials in MFCs. These binders offer several advantages over synthetic polymers: they are biodegradable, less expensive, and environmentally friendly (Anjum *et al.* 2021; Xu *et al.* 2022; Akhlaq *et al.* 2023; Cai *et al.* 2023). Furthermore, certain natural binders can contribute to enhanced microbial growth, leading to improved electron transfer and MFC performance. Despite the potential of these materials, their use in MFCs is still under-researched, and their performance remains less understood compared to traditional synthetic binders (Xu *et al.* 2022).

The novelty of this review lies in its focused and timely comparative analysis of natural versus synthetic binders in MFC systems, particularly in the context of sustainability and scalability. As global efforts intensify to promote environmentally friendly technologies and reduce reliance on fluorinated materials, this comparison addresses a critical and underexplored research area. Current literature predominantly centers on synthetic binders such as PTFE and PVDF, often overlooking the performance and feasibility of biomaterial-based alternatives. This review aims to fill that gap by systematically evaluating and comparing the electrochemical properties, stability, and commercialization potential of various binders, thereby highlighting some important recent research results that are beginning to show promising approaches from natural and synthetics binders and their roles.

The findings presented in this review not only contribute to the advancement of MFC research but also promote the development of more sustainable, cost-efficient, and environmentally friendly technologies for energy recovery and wastewater treatment. Given the growing interest in renewable energy and waste-to-energy technologies, the results of this review are expected to inform future research and applications, driving innovations in MFC design and material selection.

THE MICROBIAL FUEL CELL AND ITS COMPONENTS

The Microbial Fuel Cell

Microbial fuel cell is a bio-electrochemical device capable of generating electrical energy through a series of anaerobic reactions on organic substrates. Generally, MFCs are composed of a container, anode, cathode, and proton exchange membrane (Ucar *et al.* 2017). Electrical energy comes from electrons from the respiration of microorganisms at the anode, then electrons flow on the conductor, while protons will go through the membrane to the cathode. At the cathode, electrons and protons will bind back together with the help of free oxygen to form H_2O (Harimawan *et al.* 2018b; Gajda *et al.* 2020; Salar-García and Ieropoulos 2020). The MFC media can include various types, such as acetic acid, and/or lactate acid, ethanol, cysteine, and other organic materials. MFC can reduce contaminants up to 80%, in soil or water. Such action can be a solution to remediate the environment as well as an alternative energy source (Permana and Djaenudin 2019). Therefore, MFC technology can be applied to wastewater treatment systems rich in organic matter, such as starch and protein (Hadiyanto *et al.* 2023). This system can also be used to remediate environments polluted by hazardous waste (Chandrasekhar *et al.* 2020; Vijay *et al.* 2020).

The MFCs are popularly applied in environmental remediation, hydrogen production, and biosensors. Although the technology can be integrated with other sectors, the challenge in MFC is to enlarge the energy output produced (Boas *et al.* 2022). Improving the performance of MFCs can basically be done by focusing on MFC cells, such as electrode materials, to increase the oxygen reduction reaction (ORR) and electron collecting potential at the anode.

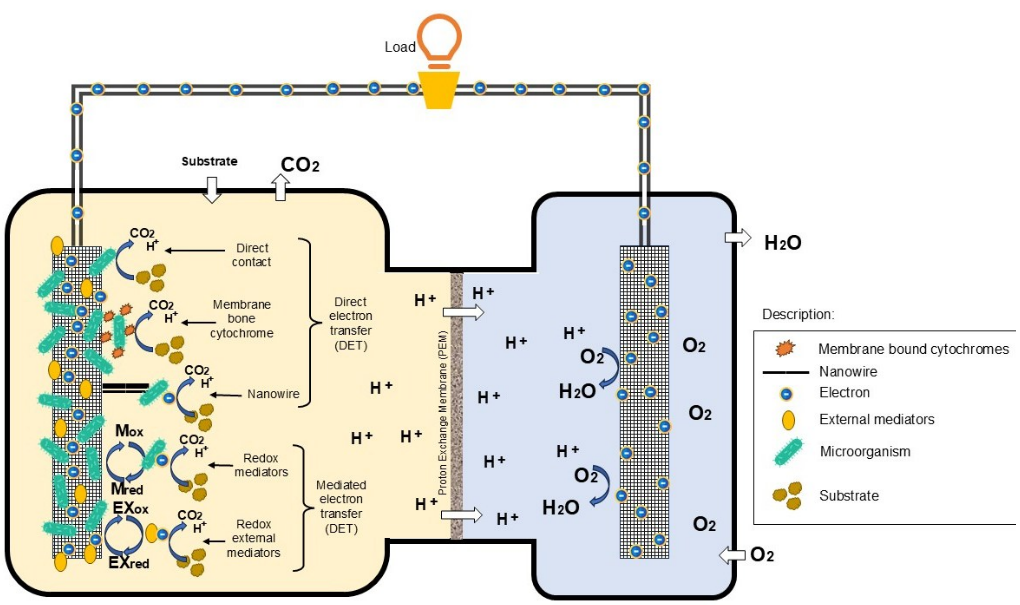

Fig. 1. Schematics of microbial fuel cell
Source: Adapted from Borja-Maldonado and López Zavala (2022)

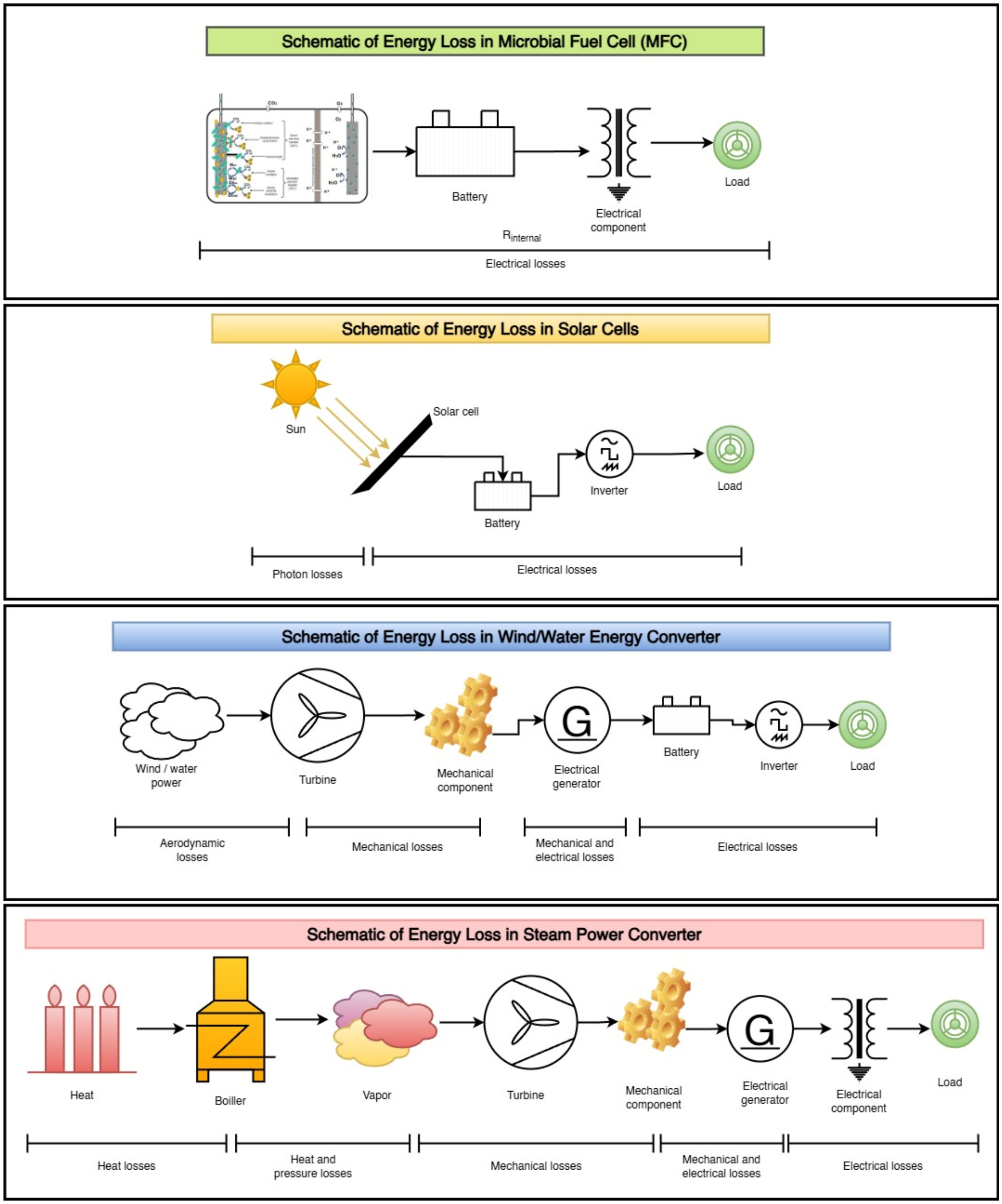

Fig. 2. Schematic of energy loss in every energy converter
Source: Adapted from (Bickerton and Fox 2017; Zheng *et al.* 2021; Desalegn *et al.* 2022; Khaleel *et al.* 2022)

Electrode selection is also based on cost efficiency (Rezaei *et al.* 2023). MFC is influenced by several parameters such as temperature, type of microorganism, type of anolyte (substrate in the anode compartment), hydraulic retention time (HTR), catholyte, and type of membrane. The anode, cathode, and separation membrane are important parameters in the MFC system (Borja-Maldonado and López Zavala 2022). The fundamental scheme of MFC can be seen in Fig. 1.

Figure 1 shows that there are four schemes of electron collection by the anode, namely direct contact with microorganisms, where electrons are transferred directly from microbial cells to the anode through physical contact (Borja-Maldonado and López Zavala 2022). The second is membrane bone, which facilitate electron transport across the cell membrane to the anode. The third is nanowires in the form of conductive protein fibers (bacteria wire) as electron pathways, *i.e.* electrical conductors (Zhang *et al.* 2020; Borja-Maldonado and López Zavala 2022). The fourth pathway employs redox mediators, which are small molecules that shuttle electrons from the microbial cell to the anode. These can be either endogenous compounds secreted by the microbes or exogenous substances such as yeast extract added to enhance electron transfer (Mohamed *et al.* 2018). Due to these direct electron conversion processes, MFCs are categorized as direct energy converters, enabling them to achieve relatively high energy conversion efficiencies—up to 80% (Lee and Rittmann 2010). In contrast, conventional energy systems such as generators or steam turbines rely on multiple energy conversion stages, which lead to lower overall efficiencies. For example, boiler-steam turbine systems typically achieve 34 to 58% efficiency (Bickerton and Fox 2017; Khaleel *et al.* 2022), wind and hydro turbines about 30% (Desalegn *et al.* 2022), and solar photovoltaic systems around 24.8% (Zheng *et al.* 2021). The energy loss model can be seen in Fig. 2.

Carbon-Based Electrode

In the MFC system, the electrode becomes one of the important parts because it plays a role in the output of the power produced. MFC electrodes are divided into two types, namely anode and cathode (Mashkour and Rahimnejad 2015). Reduction reactions occur in the cathode compartments. Oxidation reaction occurs in the anode compartment (Rikame *et al.* 2018). The reactions that occur in the two compartments are as follows (Agrahari *et al.* 2022):

Anode reaction: $C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^-$ (oxidation)

Cathode reaction: $4H^+ + O_2 + 4e^- \rightarrow 2H_2O$ (reduction)

Essentially, electrodes should be compatible, have good conductivity, and long-term stability (Agrahari *et al.* 2022). A common material used for electrodes is platinum (Pt), but this material lacks long-term stability and involves high investment costs. In contrast, Pt also has an unfavourable effect on the environment (Salar-García and Ieropoulos 2020; Agrahari *et al.* 2022). Alternatives that can be used are carbon-based, such as activated carbon, carbon nano tubes, graphite, and so on (Mashkour and Rahimnejad 2015; Li *et al.* 2017; Rusli *et al.* 2019; Huang *et al.* 2021a). Carbon-based electrodes can provide improvements to MFC performance due to their porosity. This allows microorganisms to thrive in them (Huang *et al.* 2021b). In addition, the use of carbon enhances the growth of microorganisms and the kinetics of electron transfer without giving side effects in the form of corrosion as occurs in metals (Slate *et al.* 2019). Side effects that need to be controlled include the onset of cellular stress that can reduce the efficiency of MFCs (Godain *et al.* 2024). The appearance of microorganisms on the carbon-based anode can be seen in Fig. 3a. Meanwhile, the cathode must have a good gain in oxygen reduction reaction (ORR) so that the cations that accept electrons can quickly react to oxygen (Huang *et al.* 2024).

Microorganisms will naturally form bacteria wire from protein fibers on the surface of the anode, so material selection and anode modification can be the right step to increase MFC power density. The anode material must have structural strength and porosity to multiply microorganism colonies. The use of activated carbon modified to resemble a brush is a good alternative to increase the surface area of the anode and has good conductivity. Meanwhile, cathodes with activated carbon have an economic life of 1.5 to 5 months longer and smaller power loss than metal-based cathodes (Bhargavi *et al.* 2018; Slate *et al.* 2019; Rezaei *et al.* 2023).

Binding Material

In general current practice, the binders used are fluorinated polymers, as they have good conductivity properties dan mechanical stability at the molecular level (Azega *et al.* 2022). Binder material is used as a binder for the electrode constituent materials. The binder material must demonstrate adequate conductivity, be environmentally friendly, and involve a simple electrode manufacturing process (Walter *et al.* 2018). Some types of binders used for making electrodes in general can be seen in Table 1. On the other hand, the nature of the binder can affect the stability of the electrode and its mechanical properties in current collection. Binders also provide different properties in terms of flexibility, toxicity, solubility, and moisture chemistry. Organic and inorganic binders have different properties (Salleh *et al.* 2023). Some research trends related to MFCs using synthetic and natural binders and their performance on MFCs can be seen in Table 2.

Table 1. Commonly Used Binder Types for Manufacturing Lithium-ion Batteries, Supercapacitors, and MFCs

Binder	Type of Binder	Recognized by Lithium-ion Battery (LiB)	Reference
Polytetrafluoroethylene (PTFE)	Chemical	Yes	(Wang *et al.* 2023)
Polyvinylidene Fluoride (PVDF)	Chemical	Yes	(Anit *et al.* 2024)
Polyvinyl Alcohol (PVOH)	Chemical (easily degraded)	Yes	(Dennis *et al.* 2023)
Polyurethane (PU)	Chemical	Not yet, need more research	(Loeffler *et al.* 2015; Park *et al.* 2017)
Sucrose	Natural	Not yet, high potential	(Song *et al.* 2019; Cai *et al.* 2023)
Carboxymethylcellulose (CMC)	Natural	Yes	(Qiu *et al.* 2014; Eliseeva *et al.* 2020; Yi *et al.* 2021; Oli *et al.* 2024)
Chitosan	Natural	Not yet, high potential	(Zhang *et al.* 2013; Li *et al.* 2024)
Vegetable oil	Natural	No yet, need more research	(Chen *et al.* 2021; Liu *et al.* 2023)

Polytetrafluoroethylene (PTFE)

In general, PTFE is used as a bonding material for electrodes that have good hydrophobic properties towards electrolytes. This results in increased oxygen solubility and conductivity. As a binder, PTFE plays a role in bonding the conductive material so that it does not come off during the usage process (Priyono *et al.* 2019; Salleh *et al.* 2023). PTFE is basically composed of hydroxyl groups, so it will form strong hydrogen bonds with conductive materials. This provides an advantage in minimizing the absorption of excess electrolyte and good current collection (Priyono *et al.* 2019). This is because PTFE has a low level of molecular orbitals, making it easier to absorb electrons. This causes the PTFE binder to have a lower PTFE initial coulombic efficiency than the filling and discharges coulombic efficiency. This causes PTFE to be less suitable for use as an anode bonding material (Zhang *et al.* 2022; Zhang *et al.* 2024). The PTFE undergoes a fibrillation (fiber formation) process during the electrode molding process. This increases its specific area binding properties, so the energy density increases (Han *et al.* 2024a). The PTFE bonding scheme on the electrode can be seen in Fig. 3.

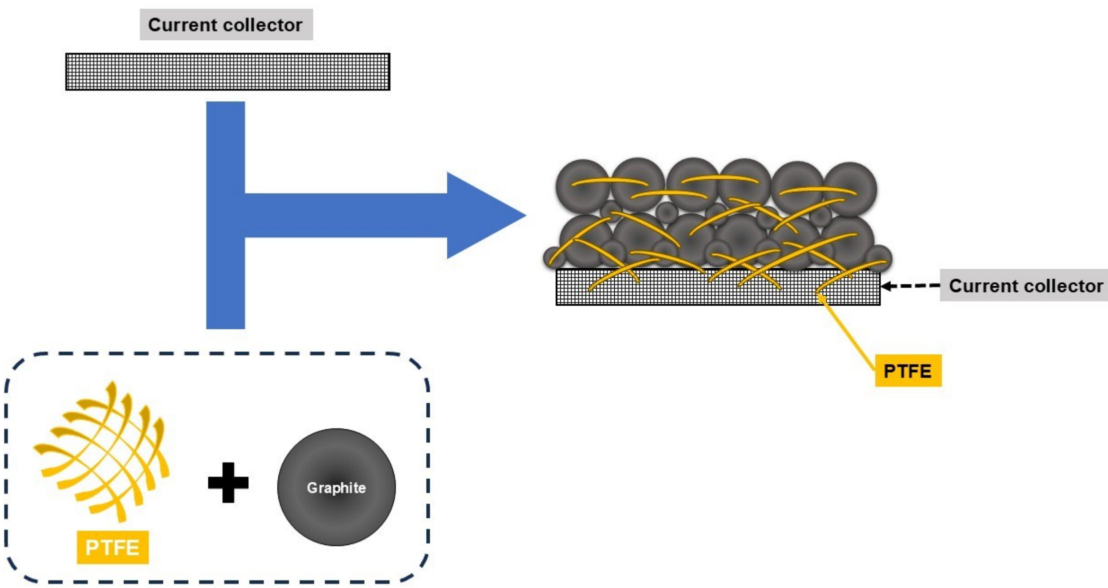

Fig. 3. The PTFE bonding scheme on the electrode
Source: Adapted from Han *et al.* (2024a)

Polyvinylidene Fluoride (PVDF)

Lithium (Li) battery electrodes use commercial materials such as PVDF. This is due to its good dimensional properties and good electrochemical stability (Priyono *et al.* 2019). PVDF is also commonly used as a bonding material for supercapacitor electrodes. The presence of interactive groups makes PVDF resistant to oxidizing in organic electrolyte solutions. However, excessive use of PVDF can reduce the conductivity of the material, while using less PVDF can weaken the bond between active materials (Priyono *et al.* 2019; Salleh *et al.* 2023). So far, PVDF gives good results compared to Nafion as a binder with only 5% PVDF added. PVDF is also reported to provide a good level of conductivity (Rajeevan *et al.* 2021). PVDF combined with activated carbon will form a phase layer for electrons, protons, and oxygen to meet. In addition, PVDF also forms a porous structure for oxygen diffusion (Wang *et al.* 2018). In addition, for use as an electrode, PVDF can also be used as a proton exchange membrane due to its proportionality (Priyono *et al.* 2019). The role of PVDF as a binding agent can be seen in Fig. 4.

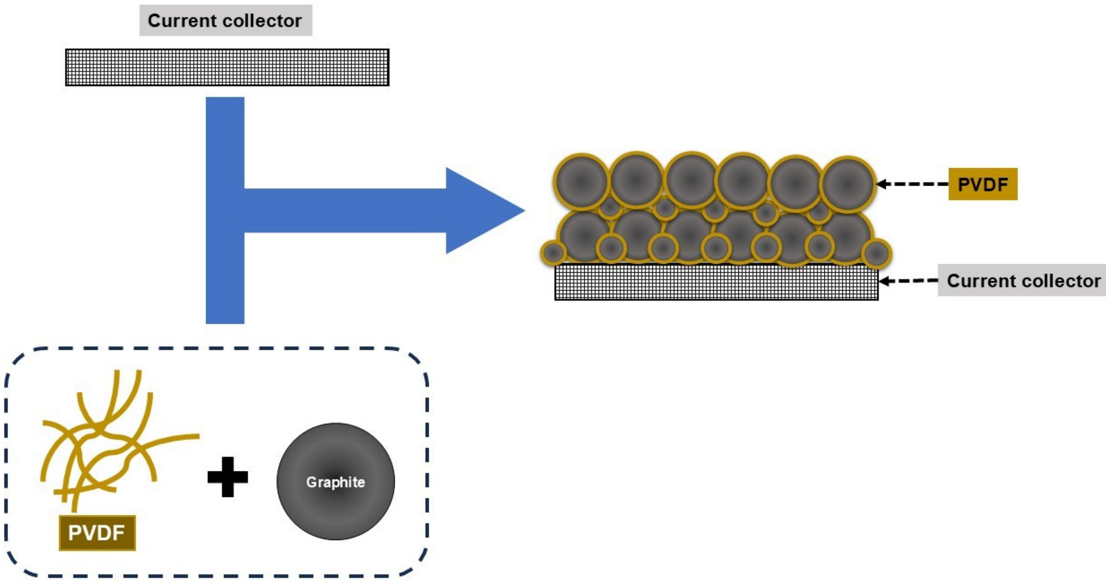

Fig. 4. PVDF as binding agent for electrodes
Source: Adapted from Rajeevan *et al.* (2021)

Polyvinyl Alcohol (PVOH)

Polyvinyl alcohol is made by hydrolysis of polyvinyl acetate (PVAc). It is classified as a heat-resistant polymer that is polar, water-soluble, odourless, non-toxic, and biocompatible, PVOH contains at least 1 to 2% moles of acetyl groups. As a result, PVOH also has environmentally friendly properties, as it tends to degrade easily. Photodegradation occurs readily, and PVOH is not a fluorinated polymer, so it can be regarded as much more eco-friendly (Feldman 2020). In addition, the by-products of burning PVOH are H_2 and CO_2, so it is classified as more environmentally friendly (He *et al.* 2019). On the other hand, after going through the heating process, the structure of PVOH becomes harder and more compact. This compatibility property affects the growth of electroactive microorganisms due to the presence of repeating -OH groups. This facilitates biofilm formation, which can enhance electron transfer when used as an anode or cathode (Dessie and Tadesse 2022). The PVOH can be rated as more efficient than PTFE because it produces greater power with the same proportion of catalyst material. In contrast, PVOH is also cheaper (USD 2/kg) than PTFE (USD 6/kg) (Walter *et al.* 2018; Christwardana *et al.* 2023). Generally, PVOH is used as a thickening agent, coating, adhesive, stabiliser, and gelatine. Although it has lower power than PTFE, the stability and difference in output power produced is not too far. As in the research conducted by Walter *et al.* (2018), the power output provided by the activated carbon cathode with PVOH binder produces 24% lower power than PTFE but has a relatively more stable power. The role of PVOH binder as binding agent can be seen in Fig. 5.

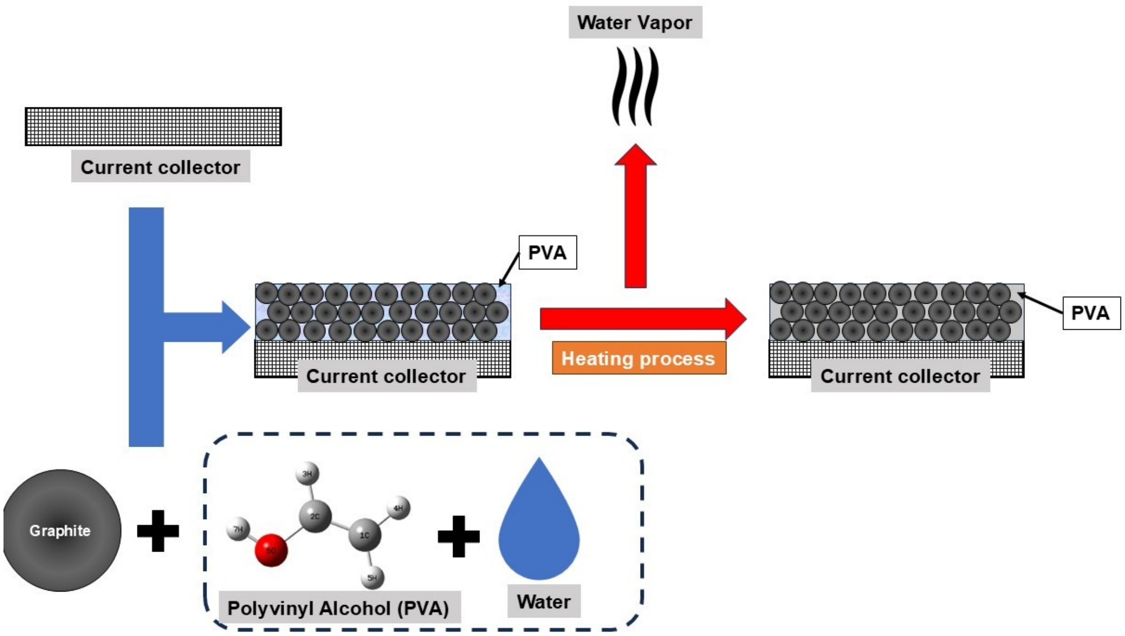

Fig. 5. PVOH binder as binding agent for electrode
Source: (modified from Ming *et al.* 2024)

Geopolymer Binder

Geopolymer binders, which are synthesized from aluminosilicate-rich precursors activated by alkaline solutions, offer a sustainable alternative to conventional cement due to their lower carbon emissions and adaptable properties. Composed primarily of Si and Al networks, their structure can be tuned through variations in the Si/Al ratio, activator type, and curing conditions to achieve desirable mechanical and chemical performance. Studies such as that of Kai and Dai (2021) demonstrated that geopolymer composites exhibit strong interfacial bonding and superior tensile behavior due to the formation of covalent Al–O–Si bridges and hydrogen bonding within the interfacial transition zone (Kai and Dai 2021).

Research by Astariani *et al.* (2021) showed that adjusting the ratio of sodium silicate to sodium hydroxide in the activator significantly affects the setting time and strength of binders derived from Umeanyar slate powder, highlighting the material's tunability for field applications. Meanwhile, Schuster *et al.* (2023) introduced geopolymer matrices as functional electrodes for electrochemical CO_2 reduction, marking their potential beyond structural roles. These findings suggest that geopolymer binders not only provide environmental benefits but also hold promise for integration into bioelectrochemical systems like microbial fuel cells (MFCs), especially when combined with conductive additives (Jeremiah *et al.* 2021; Schuster *et al.* 2023).

Polyurethane (PU)

Polyurethane is an artificial polymer widely used for buildings, polymer composites, biomedicine, and electronics. It has good flexibility and compatibility, and is an insulator, so that it can keep heat from escaping (Okokpujie *et al.* 2024). In the utilization scheme for electronic components, PU acts as an insulator that holds the electric current. However, in other studies it was found that PU can be used as a carbon binder material for flexible and porous electrodes for capacitors (Loeffler *et al.* 2015; Park *et al.* 2017). PU also has high absorbency due to its porosity, so it has a large surface area. This provides great potential for electron capture on PU electrodes (Munir *et al.* 2021). PU synthesis can be done by mixing polyols with para-paraffenylene diisocyanate. Synthesized PU can be made by mixing polyols with para-paraffenylene diisocyanate. The aim is to have all hydroxyl groups (-OH) reacted with isocyanate groups. The water in the mixture is then dehydrated to 100 °C. After that, it is mixed with fullerenol so that there is a bond between -OH and -NCO. (Ohmukai and Kyokane 2017).

Research conducted by Cotta *et al.* (2024), crosslinking between PU with poly(3,4-ethylenedioxythiophene) (PEDOT) provides good porosity, which is used as a biosensor to detect *Oscillatoria* sp. bioelectricity due to Ca^{2+} stimulus. Therefore, this biosensor scheme can be used as a detection of cyanobacteria and the source of their metabolites to provide an alternative solution to remove their metabolites. In another study, electrodes with PU binder were modified by making rigid PU foam (RPUF). The RPUF was carbonized and activated. This capacitor can store up to 458.2 F/g. The application of PUs as bio-sensors and capacitors that can accept electrical charges demonstrates that PUs have strong potential to become MFCs, although their application is still not widespread (Han *et al.* 2024b). The manufacturing scheme of the supercapacitor electrode with RPUF can be seen in Fig.6.

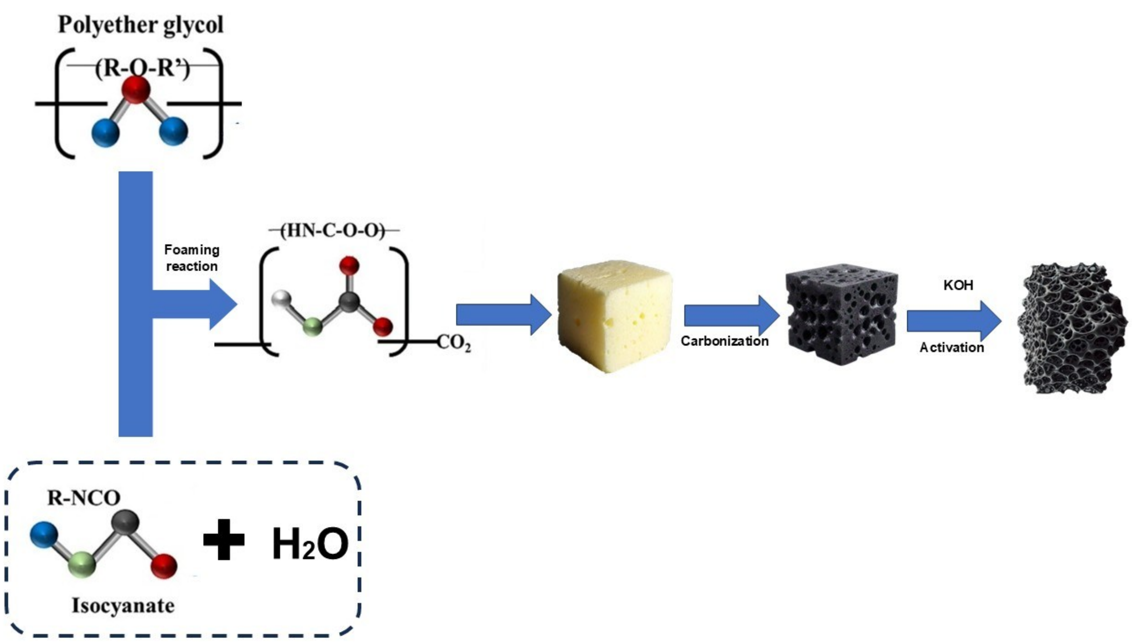

Fig. 6. The manufacturing scheme of the supercapacitor electrode with RPUF
Source: Adapted from (Han *et al.* 2024b, Creative Commons CC-BY

Sucrose

Sucrose is a disaccharide formed from fructose and glucose. It is the sugar of the end product of photosynthesis. In general, sucrose is used by plants for biochemical efficiency in metabolic processes, which are related to development, inter-tissue signalling, and tissue control (Lara-Cruz and Jaramillo-Botero 2022). Sucrose is classified as a carbohydrate polymer, making it suitable for use as a bonding agent. It also provides environmentally friendly properties and flame retardants (Kundu *et al.* 2021).

The role of sucrose as a binding agent, particularly in electrode fabrication, is seen in the conversion of sucrose to carbon layer during the heating process. This shows that sucrose has a dual role, namely as a binding agent and as a carbon source. After heating, the structure and mechanical properties of sucrose change to become more dense and compact in binding particles (Cai *et al.* 2023). The utilisation of sucrose as a binding agent for electrodes has been done by Agüero-Quinones *et al.* (2023). Sucrose is added to activated carbon and formed into a paste, then dried. Sucrose can increase the power density in MFCs and provide economical and environmentally friendly materials. Sucrose undergoes caramelization then carbonization, so that it has a dual function (as an adhesive and carbon source) (Cai *et al.* 2023). The schematic of sucrose binder can be shown in Fig. 7.

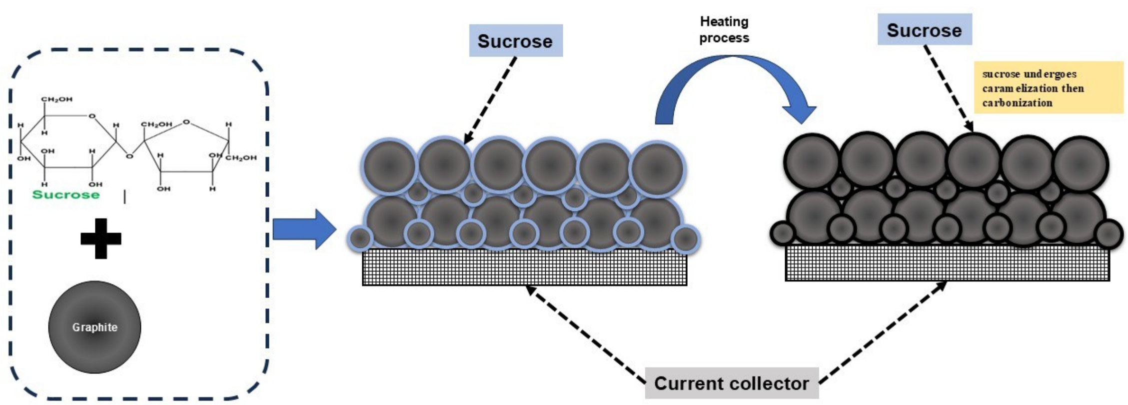

Fig. 7. Schematic of manufacturing carbon-based electrode with sucrose binder
Source: Adapted from (Cai *et al.* 2023)

Carboxymethylcellulose

Carboxymethylcellulose (CMC) is a carboxymethyl derivative of cellulose that is classified as an environmentally friendly polymer and has good biocompatibility. In addition, CMC has chemical resistant properties and can form cross-links between ions through charge interactions (Xu *et al.* 2022). The main difference between CMC and cellulose is the carboxy-methyl ($-CH_2COOH$) group, which causes this cellulose derivative to have conductive properties (Rahman *et al.* 2021). A comparison of cellulose and CMC structures can be seen in Fig. 10. CMC is commonly used as an electrolyte mixture together with other mineral salts. This mixture forms an electrolyte paste that has good conductivity in terms of energy storage. For example, mixing mineral Na with CMC forms a potential cross linking for Li-ion batteries (Akhlaq *et al.* 2023). CMC can increase the negative charge on cellulose so that it can attract cations. CMC also shows positive results in terms of mass and electron transport (Fu *et al.* 2015). The utilisation of CMC as an electrode has been carried out in the research of Xu *et al.* (2022). CMC-PANI/CNT provides good stability and electrical conductivity. On the other hand, the carbon nanotubes (CNTs) make the electrode more flexible, have a high-power density (400.02 $\mu W/cm^2$), and good electrochemical activity (Xu *et al.* 2022). Cheng *et al.* (2020) fabricated supercapacitors using CMC-polypyrole (PPy) crosslinking. These electrodes have properties that are flexible, soft, and conductive. The power capacity that can be stored is 126.38 F/g.

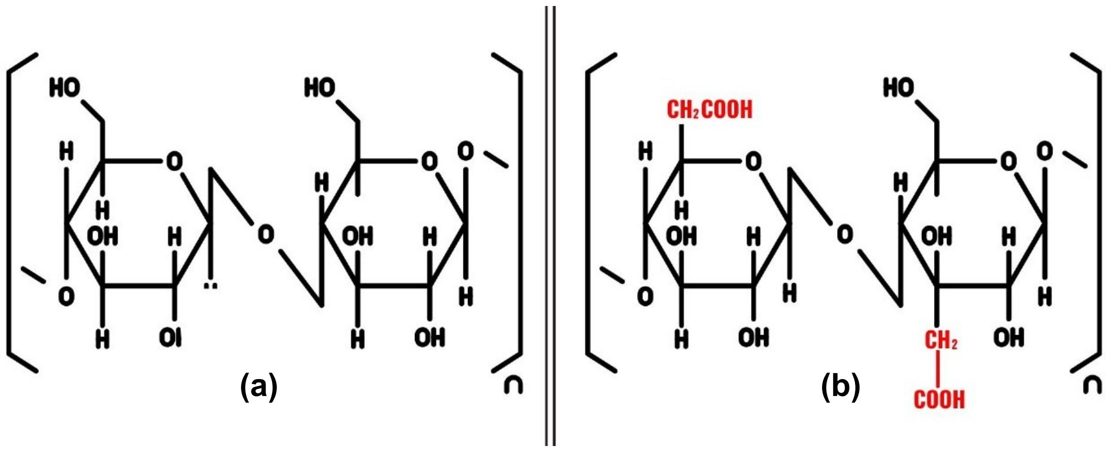

Fig. 8. Comparison of cellulose (a) and CMC (b) structure (red lettering is carboxy-methyl group)
Source: modified from (Rahman *et al.* 2021)

Chitosan

Chitosan is composed of 2-deoxy-2-amino-D-glucopyranose that is bonded with β-(1,4) glycosidic linkages. Chitosan is derived from chitin, which is commonly found in animal shells, such as crabs. The structure of chitosan is similar to cellulose, with the only difference involving the positive glucosamine unit (R-NH3+), while in chitin, the group is replaced with an acetamide group (-$NHCOCH_3$) (Srivastava *et al.* 2024).

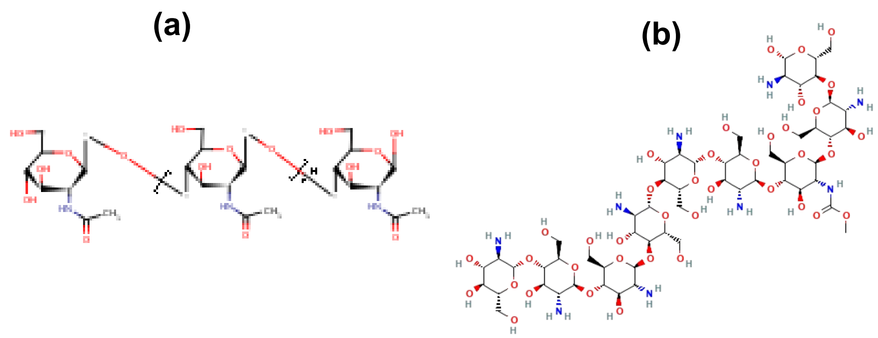

Fig. 9. Comparison of chitin (a) and chitosan (b) chemical structure
Source: (Haz-Map, 2025; PubChem, 2025; Bargnesi *et al.* 2022)

Chitosan is not electronically conductive by nature; thus, it often requires the addition of highly conductive materials such as copper, carbon nanotubes (CNT) (Liu *et al.* 2011), or combined with conductive binders, such as polyaniline (PANI) (Xu *et al.* 2020). A comparison of the structures of chitosan and chitin can be seen in Fig. 9. The characteristics of chitosan are its rigid structure and high crystallinity due to three hydrogen atoms. However, it exhibits intrinsic protonic conductivity due to the presence of amine (–NH_2) and hydroxyl (–OH) groups, which can participate in proton hopping under acidic or hydrated conditions (Bai *et al.* 2022). This causes chitosan to be selective in proton conduction. In addition, it tends to attract water due to its polycationic nature (Hanna Rosli *et al.* 2020). Chitosan can be an alternative water-soluble natural binder for the manufacture of non-aqueous Li-ion batteries (dry Li-ion batteries). It is commonly used as a battery paste. However, recent developments have shown that chitosan can be a binder for making flexible, lightweight, and low-cost electrodes (Bargnesi *et al.* 2022; Srivastava *et al.* 2024).

Chitosan is also utilized for membranes in battery manufacturing. This shows the versatility of using chitosan includes making pastes and membranes (similar to the versatility of CMC, PVDF, and PVOH) (Bargnesi *et al.* 2022). The utilization of chitosan was also reported as a smart electrocatalyst for plant-MFC synthesized using gelatin and several metals (Cu, Pd, Mn, Pt, and Ni). The power density obtained was 1298 mW/m^2. Chitosan gives the electrode a porous structure thus enhancing the oxygen reduction reaction (Türker *et al.* 2020).

Vegetable Oil

One of the important reactions in MFC is oxygen reduction reaction (ORR) that occurs on the cathode. Optimization of this reaction has been widely researched using a variety of materials, one of which is electrode binder or binder material (Anjum *et al.* 2021; Siwiec *et al.* 2024). In general, ORR can be formed by hydrophobic solutions in polar solvents. However, on the other hand, it turns out that ORR also occurs in hydrophilic solutions that form H_2O_2. This can be found in vegetable oils and acidic solutions. The electrochemical recycling cycle can occur in a mixture of triglycerides, such as cis-9-oleic (Omega 9), linoleic and linolenic acids. Therefore, vegetable oils that can be qualified as binders or electrolyte pastes are those that contain high triglycerides and Omega 9 (Siwiec *et al.* 2024). Zabcikova and Cervenka (2015) used vegetable oil-based electrode paste using rapeseed oil (RO). RO can provide currents up to 9 μA and has good stability when used in the long term. The ORR scheme of the carbon paste with vegetable oil can be seen in Fig. 10.

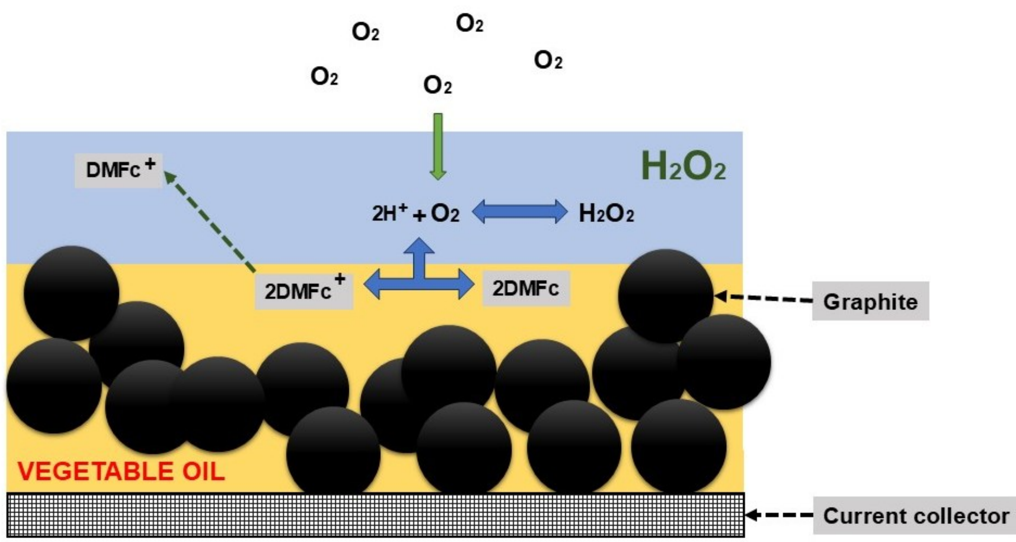

Fig. 10. ORR scheme of carbon paste with vegetable oil blend
Source: Adapted from (Siwiec *et al.* 2024, Creative Commons CC-BY-NC)

Table 2. Previous Studies on Chemical and Natural Binder for Electrode in MFC Technology

Anode	Cathode	Binder	Type of Membrane	Substrate/Electrolyte	Results	References
Carbon microparticle	Carbon microparticle	Vegetable oil	N/A	N/A	• Lowest open circuit voltage = 50 mV • Peak voltage open circuit = 300 mV	(Siwiec *et al.* 2024)
Graphite powder	Graphite powder	Rapeseed oil	N/A	N/A	Open circuit voltage = 400 to 600 mV	(Žabčíková and Červenka 2015)
Carbon black with binder	Carbon black with binder	• PTFE • PVDF • PVOH • Epoxy	No membrane (single chamber MFC)	Activated sludge and garden compost	Potential open circuit voltage (day = 0): • PVOH = 151.5 mV • PTFE = 370 mV • PVDF = -26.7 mV • Epoxy = 163 mV Power density after 54 days: • PVOH = 179.6 mW/m^2 • PTFE = 20.8 mW/m^2 • PVDF = 63.1 mW/m^2 • Epoxy = 474.6 mW/m^2	(Simeon *et al.* 2022)
Carbon veil 20 g/m^2	Activated carbon with binder	• PTFE • PVOH (5 and 10%)	No membrane (single chamber MFC)	Human urine	Power density: • PTFE = 101 mW/m^2 • PVOH 10 = 73 mW/m^2	(Walter *et al.* 2018)

Anode	Cathode	Binder	Type of Membrane	Substrate/Electrolyte	Results	References
		• PlasticDip Polymer (CPD)			• PVOH 5 = 64 mW/m^2 • CPD = 68 mW/m^2	
Activated carbon with binder	Graphite-Al_2O_3 blasted plate	Polyurethane (PU)	Cation exchange membrane	Anolyte modification with 11% v/v of mixed culture bacteria grown on acetate	Power density = 0.9 mW/m^2	(Sudirjo *et al.* 2020)
Graphite fibre brush	Carbon black with binder	PVDF	No membrane (single chamber MFC)	Modification substrate with 1 g/L NaAc dissolved in 50 mM PBS buffer	Power density = 1600 mW/m^2	(Wang *et al.* 2018)
Carbon veil	Carbon veil coated with activated carbon	PTFE for cathode coating	Ceramic	50% activated sludge and 50% (v/v) artificial urine media (AUM)	Voltage = 400 mV Power density = 46.6 to 69.7 mW/m^3	(Walter *et al.* 2022)
Activated carbon with binder	Zinc (Zn)	Sucrose	No membrane (single chamber MFC)	Wastewater from dishwashing and food remains from the Cesar Vallejo University at Trujillo, Peru	Peak value voltage = 1120 mV Power density = 0.02 mW/m^2	(Agüero-Quiñones *et al.* 2023)
Carbon veil mixed with activated carbon and binder	Carbon veil mixed with activated carbon and binder	PTFE	Ceramic	Human urine with adding disinfectant	• There was a voltage drop of 21 to 26% when the disinfectant entered the system. • The voltage dropped to 0	(You *et al.* 2024)

Anode	Cathode	Binder	Type of Membrane	Substrate/Electrolyte	Results	References
					• Power before adding disinfectant = 26 mW • Power after adding disinfectant = 15 mW, then dropped	
Activated carbon with binder	Carbon cloth coated with carbon black and binder	• Chitosan (binder anode) • PTFE (binder cathode)	• Anion exchange membrane • Cation exchange membrane	Municipal wastewater	Power density = 600 mW/m^2	(Shahid *et al.* 2021)

THREE SCENARIOS AND FUTURE IMPLEMENTATION

MFCs have emerged as a promising technology for sustainable energy production and wastewater treatment, addressing the dual challenges of energy scarcity and environmental pollution. These bioelectrochemical systems utilize microorganisms to break down organic matter, generating electrical energy as a byproduct. As the world continues to confront the pressing issues of climate change, pollution, and growing energy demand, the potential applications of MFCs become more pertinent. However, despite the technological promise, several challenges still limit the widespread adoption of MFCs, including high operational costs, low energy conversion efficiency, and the need for better electrode materials. Among these, the development of efficient, cost-effective, and environmentally friendly binder materials for MFC electrodes plays a crucial role in improving performance and reducing costs. Therefore, there are potential scenarios and future implementation strategies for MFCs, particularly focusing on the role of binder materials, their scalability, and integration into real-world applications. Through examining the prospects for future developments in binder technology, this discussion aims to highlight how MFCs could evolve into a commercially viable solution for energy production and wastewater treatment.

Scenario 1: Integration in Conventional Wastewater Treatment Plants (WWTPs)

This scenario focuses on complementing or replacing components in existing wastewater treatment infrastructure. Natural binders offer economic and ecological advantages when scaling up anode materials within municipal or industrial WWTPs. The goal is to reduce operational costs, particularly in aeration, by enabling simultaneous wastewater treatment and energy recovery (Imani *et al*. 2021; Zamri *et al.* 2023). Here, material durability, electrochemical stability in high-load effluents, and ease of integration with existing systems are key parameters. Chitosan and cellulose derivatives may suit this purpose due to their binding strength and resistance to biological degradation in high-strength wastewater. This approach offers several benefits:

- *Energy Recovery:* MFCs can utilize organic waste found in wastewater to generate electricity. Through replacing conventional energy-intensive treatment methods with MFC technology, wastewater treatment plants can reduce their reliance on external power sources. The electrical energy produced can be used to power plant operations or even be sold back to the grid, providing an additional revenue stream for operators.
- *Reduction of Carbon Footprint:* Traditional wastewater treatment processes, such as aeration, are energy-intensive and contribute to greenhouse gas emissions. Utilizing MFC will not only reduce energy consumption for aeration but also potentially reduce emissions, supporting global sustainability goals.

Scenario 2: MFCs for Decentralized and Off-Grid Settings

In remote or underdeveloped areas with limited infrastructure, MFCs can provide decentralized energy and basic sanitation. This scenario prioritizes portability, material availability, and ease of maintenance. The binder must allow flexible fabrication methods using locally sourced biomass, such as starch-based or sucrose binders (Walter *et al.* 2018; Simeon *et al.* 2022). These systems do not necessarily aim for maximum power output, but rather long-term sustainability, minimal reliance on external resources, and communitylevel deployment. The simplicity of the design becomes an asset in regions lacking technical personnel or facilities. The implementation of MFC technology could provide a decentralized, self-sustaining solution for these communities.

- *Sustainability and Local Resource Utilization:* MFCs could be used to harness organic waste from local sources, such as agricultural residues, food waste, or organic industrial byproducts, to generate electricity. This would provide a continuous, renewable source of energy without the need for external fuel supply chains. The use of local organic waste as a substrate also ensures that the environmental impact of energy generation is minimized.
- *Modular Systems:* The scalability of MFC technology makes it suitable for implementation in smaller, modular units that can be tailored to meet the specific energy needs of remote locations. These systems can be deployed in villages, farms, or small communities, where they can power lights, communication devices, and basic infrastructure.

Scenario 3: Integration of MFCs into Smart Cities and Circular Economy Systems

Urban environments present opportunities for advanced MFC deployment integrated with IoT systems, smart metering, or waste-to-energy loops. In this scenario, natural binders must meet performance criteria suited for data-driven and modular systems. PVDF-free designs using crosslinked PVOH or hybrid organic binders could reduce toxicity concerns while ensuring high responsiveness to load variation. This setting emphasizes innovation, system feedback, and integration into multi-energy platforms. The role of MFCs is extended beyond electricity generation to include environmental monitoring and smart waste valorization (Gajda *et al.* 2020; Vijay *et al.* 2020). MFCs could play a pivotal role in these cities by contributing to waste-to-energy systems that efficiently recycle organic waste into usable energy.

- *Circular Economy:* Smart cities are increasingly focusing on implementing circular economy principles, where waste products are converted into resources. MFCs could contribute to this model by converting organic waste from households, restaurants, and food industries into bioelectricity. This would not only help to reduce the burden on landfill sites but also create a decentralized energy generation system that reduces the strain on the urban grid.
- *Integration with Other Renewable Energy Sources:* MFCs could be integrated with other renewable energy technologies, such as solar panels and wind turbines, to form hybrid energy systems. By utilizing the waste-to-energy potential of MFCs, smart cities could achieve a more resilient and flexible energy grid, reducing dependence on fossil fuels and improving energy security.

Future Implementation: Technological Advancements and Research Needs

While the three practical scenarios previously discussed outline context-specific applications of natural binders in microbial fuel cells (MFCs), broader technological advancements and targeted research are still crucial for the successful mainstreaming of these systems.

- *Enhanced Binder Properties:* One of the key challenges in improving the performance of MFCs is to develop binders that offer better conductivity, longevity and mechanical stability that includes interfacial compatibility and effective adhesion at the molecular level. While natural binders like chitosan, sucrose, and vegetable oils have shown promise in laboratory settings, they still need to be optimized for long-term use in real-world applications. Future research should focus on enhancing the electrochemical properties of these binders, possibly through modifications or hybridization with other materials (Christwardana *et al.* 2023).

- *Scalability and Manufacturing:* For MFCs to be implemented on a large scale, manufacturing processes must be cost-effective and scalable. This includes the mass production of electrodes and binders that can meet the demands of large MFC systems, particularly in industrial and municipal applications. Developing efficient, low-cost methods for producing binder materials and electrode components at scale will be critical for commercializing MFC technology (Desalegn *et al.* 2022; Sawunyama *et al.* 2024; Taha *et al.* 2024).
- *Energy Conversion Efficiency:* Another area of future implementation is improving the energy conversion efficiency of MFCs. Currently, MFCs produce relatively low power outputs compared to conventional energy sources. Future research should focus on optimizing the design of MFCs to maximize energy output, including innovations in electrode materials, the integration of catalysts, and improvements in the microbial electrochemical processes that drive the system (Walter *et al.* 2022).

Finally, future research should address long-term performance and environmental safety, ensuring that natural binder residues do not introduce new contaminants or biohazards into treated water or soil environments. Taken together, these research needs form a strategic framework that complements the practical implementation scenarios, ensuring that natural binder-based MFCs evolve not only as viable energy and treatment solutions but also as robust and adaptable technologies for the future. The future of MFCs lies in optimizing binder materials, improving energy efficiency, and scaling the technology for wide adoption in various applications. In addition, the operation of MFCs is quite simple as the reaction takes place naturally. Life-cycle assessments and techno-economic analyses will be vital tools in determining the true sustainability and feasibility of upscaled systems (Chandrasekhar *et al.* 2020; Vijay *et al.* 2020; Sato *et al.* 2023

CONCLUSIONS

MFCs provide a promising solution to energy and environmental challenges. The selection of binder materials needs to be done carefully by considering technical, economic, environmental, and sustainability factors. Further research is needed to optimize their properties and explore their performance in various MFC systems. These findings suggest that natural binders can also be an option in MFCs for waste treatment as well as alternative energy sources.

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