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REVIEW ARTICLE

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Recent advances in enzymatic fuel cells, biocatalytic fuel cells, biofuel cells for clean and efficient energy harvesting

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Abstract

In this study, demand for catalysis is also being propelled by its use as a feasible alternative to inefficient non-selective metal catalysts used in low-temperature fuel cells. Selective oxidation of fuel and oxidants, the backbone of biofuel cells where biofuel catalysis is used to drive them. The requirement for a fuel cell shell and membrane is eliminated by the catalytic selectivity. Biofuel cell configurations suitable for miniaturization can thus be constructed and perfected. The selectivity also liberates fuel cells if the catalysts attach to the anode and cathode materials, otherwise inert. A few of the potential areas for which these configurations have been proposed are power generation specialties. These include distantly situated electronics, portable devices, and implanted biomedical devices. In this investigation, we focus on current efforts to improve electron transport between anode and cathode, which are also referred to as enzymatic electrodes. This situation persists irrespective of the presence of mediators. Predominantly, our focus is oriented towards the exploration of enzyme fuel cells, which may be classified as either implantable or semi-implantable. These particular cells demonstrate a capacity to extract glucose from the circulatory system while simultaneously

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modulating oxygen levels throughout the process. We are still in the early stages of this ambitious goal, and key challenges include maintaining the device's power output and stability. This review attempts to compare the performance of microbial fuel cells (MFCs), enzymatic fuel cells (EFCs), biofuel cells, and biocatalytic fuel cells, as well as electrodes and assembled fuel cells.
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Keywords: Biofuel cells; Biocatalytic fuel cells; Enzymatic fuel cells (EFCs) and Microbial fuel cells (MFCs).

1. Introduction

Biofuel cells are electrochemical devices that produce electrical energy through the biological oxidation of organic molecules. [1], [2], [3], Such energy is called bioelectricity [4], [5], [6]. It is possible to generate energy from natural sources in biological processes because of the existence of such cells. [7], [8], [9], [10]. Biofuel cells generate energy via the transference of electrons amid the electrodes of the cells consequent to the oxidative processes involving organic molecules. [11], [12], [13], [14], [15]. Biofuel cells are regarded as possessing considerable merit in comparison to traditional fuel cells. [16], [17], [18]. Biofuel cells constitute an economical and renewable energy source, characterized by environmentally favorable attributes and the generation of minimal pollution emissions. [7], [19], [20]. Additionally, when comparing them to other renewable energy sources, biofuel cells occupy less land and produce fewer greenhouse gases overall. [21], [22], [23]. The root of the problem lies in the fact that they produce energy from natural sources through biological processes. [24], [25], [26]. Biofuel cells, in general, have a promising future as the demand for renewable energy outstrips the supply and people seek a more environmentally friendly way of producing said energy. [27], [28], [29], [30], [31]. It is anticipated that more research and development will result in improvements in both the performance and economic viability of biofuel cells.

Many different types of biological materials can be converted into usable energy by using biofuel cells. [32], [33], [34]. Biofuel cells can be powered by any renewable ecological sources, such as food waste, agricultural waste, grass biomass, household waste, and feeds, both cellulose and lignocellulose. [35], [36], [37], [38]. The utilization of these fuels makes it possible for biofuel cells to be regarded as an energy source that is both sustainable and kind to the environment. [7], [30], [39]. Biofuel cells can be of many different types. These comprise microbial fuel cells, enzymatically driven fuel cells, along with biocatalytic fuel cells. [40], [41], [42], [43], [44]. Microbial fuel cells (MFC) embody a biotechnological schema whereby microorganisms engage in the utilization of organic substrates for the production of electrical energy, thereby evading the necessity for oxygen. [45], [46], [47], [48]. This particular configuration is designated as a fuel cell. Fuel cells are characterized by their potential to generate energy via the direct oxidation of biodegradable materials, which may encompass organic waste, effluent, agricultural residues, or through diverse biochemical processes. [49], [50], [51], [52].

A MFC, which refers to a microbial fuel cell, functions within a singular cell structure that encompasses both anode and cathode electrodes [53], [54], [55]. At the anode electrode, microorganism oxidizes organic matters, producing electrons [56], [57], [58]. These electrons reach, after passing an external circuit, the cation electrode where they combine with oxygen or an oxidant in this electrode and in result they produce an electric current [59], [60], [61]. MFCs offer various benefits, including the ability to create electrical energy in addition to their contribution to the elimination of organic waste [62], [63]. They are also less expensive and more sustainable in comparison to traditional fuel cells, offering an ecologically benign energy source by lowering emissions of carbon dioxide and serving as an alternate method for the disposal of waste generated locally [64], [65], [66]. However, even though MFCs currently have lower energy efficiencies than other technologies, efforts are being made to develop and broaden the usage of more efficient MFCs shortly [67], [68], [69]. MFCs are also referred to as biofuel cells, and they have the potential to be utilized in a variety of settings, particularly those that generate organic waste, such as wastewater treatment facilities and agricultural settings [50], [70], [71]. Additional possible applications for MFCs include portable electronic devices, low-power sensors, and other devices that are functionally analogous to these.

Enzymatic fuel cells (EFCs) are a class of biological fuel cells where enzymes have the capability of generating electric power from biological processes. [13], [69], [72]. Instead of consuming oxygen or other oxidants, enzymes in these cells create electrons and protons from organic matter, and that tension between the two is what creates the electric potential. In enzymatic fuel cells, glucose is catalyzed by enzymes, which adsorb to electrodes, promoting the redox reactions. [42], [72], [73]. This reaction starts from the enzymes adsorbed with the anodic electrode, which decompose the organic material, and the anode collects the free electron that is liberated from that oxidation process. These electrons are captured in the external circuit to the cathode electrode. [75], [76], [77]. Upon arrival at the designated location, the substances undergo a combustion process in the presence of oxygen or alternative oxidizing agents, thereby resulting in the generation of an electric current. [74], [78], [79]. The direct transformation of organic refuse and biomass into electrical energy represents but one of the myriad potential applications associated with enzymatic fuel cells. [74], [80], [81]. Enzymatic fuel cells might also be employed in a variety of other. In addition to this, they are also a potential source of power for biological sensors and other medical equipment. [16], [43], [82]. In addition, in comparison to traditional fuel cells, these types of fuel cells have the potential to deliver cheaper prices and improved energy efficiency. [16], [74], [83].

Benefits of Enzymatic Fuel Cells An example of the study is enzymatic fuel cells, the kind that are cheaper and more ecologically sound than traditional fuel cells. Because of the type of catalyst used, the fuel cells can operate at lower temperatures as well as at lower pH levels than others reported earlier; they are more akin to conventional fuel cells. Upping the ante still further are enzymatic fuel cells, which require almost no chemistry at all, only the life processes that take place as a result. [27], [84], [85], [86]. Biocatalytic fuel cells provide the same function as enzymatic fuel cells, but they make use of different catalysts. [36], [87]. Enzymatic fuel cells are a type of biofuel cell that make use of enzymes from living organisms. Biocatalytic fuel cells are biofuel cells employing biological catalysts. [32], [88], [89]. These catalysts include microorganisms, such as bacteria and fungi, as well as enzymes and redox proteins. [36], [73], [90], [91]. The selection of the catalyst that will be utilized is determined by the functional and operational needs. In most cases, the operation of a catalyst takes place in a cell that is governed by a membrane and is coupled to an electrode.

Recently, nanotechnology has become a powerful tool for enhancing the performance of fuel cells, as nanoparticles provide unique properties that improve efficiency and catalytic activity [92], [93]. For instance, adding nanoparticles of platinum, gold, and silver to fuel cell electrodes can make them more active by increasing the surface area and improving electron transfer. This makes the process of turning energy into electricity more efficient [94], [95]. Additionally, nanotechnology helps reduce production costs by minimizing the amount of catalyst material required. These advancements make fuel cells more cost-effective and viable for widespread applications in clean energy.

2. Biofuel cells technology

In recent years, there has been a lot of interest in the technology known as Biofuel fuel cells. [34], [96], [97]. In the context of the generation of renewable energy from biological sources, these cells, which generate electrical energy by using the electrochemical activities of microorganisms, are regarded as an essential alternative production method. [42], [73], [98]. Consequently, owing to the immediate production of electrical current that transpires during the oxidation process of organic substances, microbial fuel cells exhibit the capacity to function as a potentially efficient and economically viable energy source for applications that are of a lesser magnitude. [7], [16], [27], [33] (Table 1).

Table 1. Components and materials: Biofuel Cells.

Material	Explanation	References
Anode	Usually, an enzyme is used that catalyzes the oxidation of organic substances, for example, glucose oxidase or lactate oxidase.	[73], [98]
Cathode	An electron-accepting enzyme is used, for example, laccase or peroxidase.	[42], [98]
Proton	A membrane between two electrodes, usually Nafion, is used.	[7], [33]

Exchange Membrane		
Electrolyte	Usually, buffer solutions are used, for example, phosphate buffer or sodium phosphate buffer.	[7], [27]

2.1. Microbial fuel cells Technology

The technology of microbial fuel cells might be categorized as an example of an environmental technology. [99]. It is counted as one of the forms of renewable energy technology. These subjects can also include the field of microbial fuel cell technology, which is a technology that integrates the fields of electrical technology with biology. [100], [101], [102]. Electronic technology is concerned with the generation of electrical energy, in contrast to biotechnology, concerned with the utilization of microorganisms. [86], [103] (Table 2).

Table 2. Components and materials: Microbial fuel cells.

Material	Explanation	References
Anode	Usually, carbon-based materials are used, for example, graphite or carbon fibers.	[100]
Cathode	Usually, a material in contact with air is used, for example, platinum, gold, or carbon-based materials.	[101]
Proton Exchange Membrane	A membrane between two electrodes, usually Nafion, is used.	[102]
microorganisms	In MFCs, bacterial strains are often used, for example, bacteria of the genus Shewanella or Geobacter.	[103]
Electrolyte	Usually, salt solutions are used, for example, sodium chloride (NaCl) or potassium hydroxide (KOH).	[86]

Classification based on the kind of electrode Microbial fuel cells can be categorized based on the types of cathodes and anodes that are used [58], [104]. Cathode aerobic microbial fuel cells (H-MFC), bio-cathode microbial fuel cells (B-MFC) and metal anodic microbial fuel cells are some of the numerous varieties (M-MFC) [62], [105], [106], [107], [108], [109]. as well, Microbial fuel cells can be categorized in a variety of ways, one of which is based on the microorganisms that are used to power the cells [110], [111], [112]. Bacteriostatic fuel cells are one kind of microbial fuel cell; they are so named because they employ bacteria as a fuel source [113], [114]. Furthermore, the categorization of Microbial Fuel Cells (MFCs) according to the origins of the fuel can be conducted based upon the type of organic materials employed. The organic substrates utilized for this purpose derive from an assortment of sources, which encompass wastewater, extracts from vegetation, by-products from agricultural practices, as well as excrement from animals [8], [115], [116], [117]. Alternative references encompass extracts derived from flora. Ultimately, these can be organized into a typology based on their diverse spheres of applicability, with microbial fuel cells standing out due to their numerous prospective utilizations. Areas of interest include the processing of wastewater, sectors within the food industry, agricultural practices, generation of electrical energy, endeavors related to space exploration, and various medical applications, which collectively represent the breadth of potential engagement.

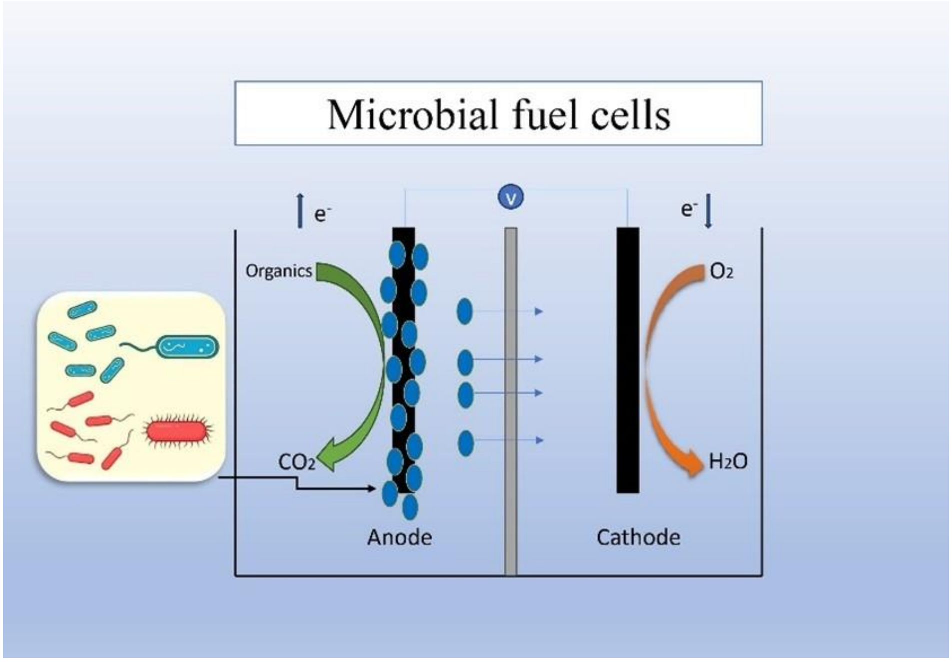

Fig. 1. Microbial fuel cells.

2.2. Enzymatic fuel cells Technology

Enzymatic fuel cell technologies might be employed as an alternate source of energy, particularly for machines that need less power. [41], [82], [118], [119]. As compared to other fuel cell technologies, these fuel cell technologies are thought to be more ecologically friendly, as well as less expensive than the other fuel cell technologies. [57], [80], [120]. Types of this technology are:

It is possible to categorize enzymatic fuel cell technologies according to the fuels they use [121], [122]. For a demonstration, Biofuel cells (BFC) could be one of them, fuel enzyme-focused cells getting power from sugars such as glucose, cellulose, or even starch for their energy origins. Enzyme-packed fuel cell setups get put into groups with the sorts of enzymes they're using too. [76]. Take an example where there's this enzymatic fuel gadget relying on enzymes counting glucose oxidase or lactate oxidase; it might fall under a GFC or perhaps an LFC label. Tiny living stuff kind. Then indeed, sorting out enzyme-driven fuel cell technologies like BES and NFC is doable by the micro tiny beings involved in running them. Imagine having this bacterial enzymatic fuel gadget tagged a BES (bio-energetic system) that manages to operate through bacteria types Schewanella or maybe Geobacter. [123], [124], [125]. Technologies based on enzymatic fuel cells can also be categorized according to the type of electrode that is utilized. An enzymatic fuel cell that uses metal or carbon electrodes, for instance, can be categorized according to the kind of electrode used in the device. [86], [126], [127], [128]. Enzymatic fuel cells, despite several technical challenges, including the synthesis and immobilization of high-purity enzymes, enzymatic fuel cells hold promise as a more affordable and environmentally friendly energy source (Table 3).

Table 3. Components and materials: Enzymatic fuel cells.

Material	Explanation	References

Anode	Usually, platinum or gold is used.	[123], [124]
Cathode	An electron-accepting enzyme is used, for example, laccase or glucose oxidase.	[124], [125]
Proton Exchange Membrane	A membrane between two electrodes, usually Nafion, is used.	[86], [126].
Electrolyte	Usually, buffer solutions are used, for example, phosphate buffer or sodium phosphate buffer.	[127], [128].

2.3. Biocatalytic fuel cells Technology

Biocatalytic fuel cell technologies can be categorized according to the type of electrode that is utilized in the process. [129], [130]. For instance, a biocatalytic fuel cell that utilizes metal or carbon electrodes can be categorized according to the kind of electrode used. Biocatalyst type, the various biocatalytic fuel cell technologies can be categorized by the biocatalyst type that is utilized. [131], [132]. For instance, a biocatalytic fuel cell that makes use of biocatalysts like enzymes, cells, or microbes might be categorized differently depending on the particular biocatalyst that it employs. [131]. Classification based on the kind of fuel used, several types of fuels may be used to categorize the various biocatalytic fuel cell systems. For instance, a biocatalytic fuel cell that operates on fuels like methane, hydrogen, or ethanol can be categorized according to the type of fuel it uses [129], [131]. Classification according to the field of application, the technologies behind biocatalytic fuel cells may also be categorized according to their field of application. [130], [131]. For instance, a biocatalytic fuel cell that was developed especially for use in medical or industrial [133]. Applications can be categorized by the field to which it is most suited. Organic materials used, and lower the associated costs. On the other hand, biofuel cells have the potential to become a key part of the low-carbon energy source landscape in the future.

Table 4. Components and materials: Biocatalytic fuel cells.

Material	Explanation	References
Anode	Usually, carbon-based materials are used, for example, graphite or carbon fibers.	[130], [131].
Cathode	An electron-accepting enzyme is used, for example, laccase or glucose oxidase.	[129], [131].
Proton Exchange Membrane	Two	[131], [132].

The attributes associated with the trio of fuel cell varieties have been delineated in Table 4, located below. The characteristics encompassed by this table comprise aspects such as the fuel sources utilized, the electrodes involved, the electron transfer mechanisms enacted, the efficiency rates, the energy density parameters, and the systemic stability metrics [99], [134], [135], [136], [137]. These characteristics enable each cell type to determine the regions in which it may be applied and provide assistance in selecting various strategies for addressing the benefits and drawbacks presented by those applications.

Table 5. Compare the Characteristics of Microbial Fuel Cells, Enzymatic Fuel Cells and Biofuel Cells.

Properties	Microbial Fuel Cells	Enzymatic Fuel Cells	Biofuel Cells
Fuel	Organic materials	Organic materials	Many forms of biomass
Electrodes	Anode and Cathode	Enzymatic electrodes	Anode and Cathode
Electron transfer mechanism	Electron transfer is carried out by bacteria	Electron transfer via enzymes	Both bacteria and enzymes can transfer electrons
Productivity	Low	Low	Low
Energy density	Low	Low	Low
Stability	Relatively stable	Relatively stable	Relatively stable
Scope of application	Wastewater treatment, sensors, low-energy devices	Biosensors, biosensors, low energy devices	Wastewater treatment, biosensors, biofuel production
References	[138], [139], [140], [141], [142]	[13], [55], [143], [144], [145], [146], [147]	[11], [13], [15], [148], [149]

In the following table 5, the qualities of microbial fuel cells (MFCs), enzymatic fuel cells (EFCs), and biofuel cells are contrasted with one another. These cells are essential gadgets that produce electrical energy by making use of biologically active substances. Microbial fuel cells, commonly denoted as MFCs, represent systems that enable the transformation of organic substances into energy, utilizing microorganisms that are accountable for the performance of electron transfer processes. The structural design of MFCs includes electrodes that can be classified into two types: anodes and cathodes. Despite exhibiting relatively low efficacy, energy density, and overall stability, these systems do possess several niche applications, notably in wastewater treatment, sensor fabrication, and powering devices that operate with minimal energy requirements. Enzymatic fuel cells, also known as Enzymatic fuel cells (EFCs), utilize electrodes that are enzymatically based. Notwithstanding their suboptimal efficiency, energy density, and stability, these cells find applications within various domains, including but not limited to biosensors and low-energy devices. It is noteworthy to mention that the energy density remains comparatively low. A diversity of biomasses is applicable for biofuel cell utilization, with both bacterial entities and enzymatic components possessing capabilities for electron transfer. A biofuel cell is composed of two electrodes; one anode and one cathode. Although biofuel cell has a low efficiency, low energy density and are not stable, they can be used in many applications such as the production of biofuel, the fabrication of biosensors, and wastewater treatment.

Table 6. compares the material, potency, and temperature ranges between microbial fuel cells, enzymatic fuel cells and biofuel cells. The anode, cathode, and electrolyte materials used and their positive and negative effects.

Materials	Microbial Fuel Cells	Enzymatic Fuel Cells	Biocatalytic	Biofuel Cells

			fuel cells	
Anode	Carbon or metals	Enzymatic materials or redox molecules	Enzymatic materials	Carbon or metals
Cathode	Air or oxygen metal catalyst	Enzymatic materials or redox molecules	Enzymatic materials	Air or oxygen metal catalyst
Electrolyte	Salt solution or organic matter	Salt solution or organic matter	Salt solution or organic matter	Salt solution or organic matter
References	[109], [150]	[118], [151]	[145], [153]	[11], [13], [42], [154]

Table 7 mentions the potential for not-so-high power generation with MFCs, as well as how the growth circumstances of microbes might influence their production speed. The table highlights the potential of MFCs to eliminate organic waste and generate renewable power. Observations suggest that EFCs align well with energy-efficient needs and could be suitable for medical devices that are friendly to biological systems, although the stability of enzymes may vary depending on the operational environments. BFCs have the potential to produce renewable energy from biomass, but the quality and biological activity of the biomass can influence the production rate. BCCs, on the other hand, offer advantages such as high efficiency and low cost; however, enzymes can produce unwanted by-products, which can be difficult to dispose of.

Table 7. Advantages and disadvantages of fuel cells.

Fuel Cell Type	Advantages	Disadvantages	references
Microbial Fuel Cells	They can be used for the disposal of organic waste and the generation of renewable energy.	They have the potential for low power output. The growth conditions of bacteria and other microorganisms can affect the rate of production.	[155], [156], [157], [158]
Enzymatic Fuel Cells	It is suitable for low-power applications and the use of enzymes may be particularly suitable for biocompatible medical devices.	The stability of enzymes can vary depending on the conditions in which they are used.	[11], [13]
Biocatalytic fuel cells	It shows potential for renewable energy generation through the use of biomass.	The quality and biological activity of biomass can affect the rate of production.	[131]
Biofuel Cells	They can offer advantages such as high efficiency and low cost and have a variety of application areas.	They can produce unwanted by-products of enzymes, and these by-products can be difficult to dispose of.	[13], [37], [159], [160]

The output of Microbial Fuel Cells (MFCs) is also strongly influenced by temperature in a significant way. [161], [162]. It affects the metabolic processes of microorganisms, the electrochemical reactions, and the change in Gibbs free energy that the reactions undergo.[116]. There is a temperature at which enzymes in the MFCs perform at their absolute best, and the pace of the electrochemical reaction increases as the temperature rises. [163], [164], [165]. In the MFC framework, a decrease in the operational thermal conditions adversely influences the output, initiation duration, and the rate at which substrate oxidation occurs. When operating at lower temperatures, MFCs often exhibit greater Coulombic efficiency. [166], [167]. This is one of the benefits of operating at lower temperatures. Using low-temperature MFCs in devices with low power consumption, such as sensors that are designed to operate reliably over an extended length of time, is an interesting and potentially useful use of these materials (Table 8) [168].

3. Role of Nanoparticles in Enhancing the Catalytic Activity of Fuel Cells

Nanoparticles are key factors that enhance catalytic activity in fuel cells, providing a large surface area, improving electron transport, and facilitating chemical reactions at the electrodes. Among them, platinum (Pt) nanoparticles are the most widely used, especially in proton exchange membrane fuel cells (PEMFCs), due to their high efficiency in the oxygen reduction reaction (ORR) at the cathode and hydrogen oxidation reaction (HOR) at the anode. In addition, the performance of platinum can be improved by mixing it with other metals such as cobalt (Co) or nickel (Ni) to form nanostructured alloys that enhance catalytic activity and reduce the amount of platinum required [169], [170], [171].

Palladium (Pd) and gold (Au) nanoparticles are also used as catalysts, especially in alkaline environments, where they show good efficiency in redox reactions. In addition to precious metals, iron (Fe) and cobalt (Co) nanoparticles embedded in nitrogen-like carbon structures are promising cost-effective alternatives for their effectiveness in the oxygen reduction reaction [172], [173].

Also, nanoparticles of metal oxides such as titanium dioxide (TiO_2) and cerium oxide (CeO_2) play an important role as supports or co-catalysts to enhance the stability and efficiency of the main catalysts. In addition, carbon-based nanoparticles such as carbon nanotubes (CNTs) and graphene are used as supports to improve the electrical conductivity and distribution of metal particles [174], [175].

Finally, bimetallic and trimetallic nanoparticles (such as Pt-Pd or Pt-Ni-Co) exhibit synergistic effects that enhance catalytic activity and durability, making them ideal options for improving fuel cell efficiency and reducing their costs. Through careful design of these.

4. Conclusion

Using various biosystems, such as microbial cells, biocatalytic biosystems, and enzymes, has allowed for the production of all forms of biofuel that were previously thought to be theoretically conceivable. Pseudo biodevices, double-layer biodevices, and hybrid biodevices have all been built and tested in the past few years. This is mostly attributable to the fact that the regimes in which they operate include low levels of voltage and current. Yet, these devices are essential from a fundamental standpoint because they enable the analysis of electron transfer processes between various biocatalysts and electrode surfaces. This is an extremely significant aspect of the field. We believe that a greater understanding of the fundamentals of biological electron transfer mechanisms in bacteria and photosynthetic systems, as well as the interactions between such systems and electrodes, will pave the way for further rapid development in this area. This understanding, combined with the rapid development of conducting nanomaterials, will make it possible for further rapid development to occur in this area. This understanding will pave the way for further rapid development in this area because it will allow for a more efficient transfer of electrons. The advancement of this technology is still in its infancy, and there are a few obstacles to overcome along the way.

Author Contribution

F.M., and H.E.; Conceptualization, Methodology, Data curation, Writing- Original draft preparation, Visualization, Investigation. R.M. and E.H. Methodology; F.S.; Writing- Reviewing and Editing.

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