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Review Article

Conventional, Renewable and Bi-electrochemical/alternative Energy Sources. A review

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SUMMARY

Energy availability is a critical driver of socioeconomic growth. Major conventional means of energy generation, such as fossil fuel, nuclear, solar, biomass (crops), and hydropower has not successfully solved the challenges of high cost of production, health damages, environmental damages, and sustainability. Fossil fuel is non-renewable and not eco-friendly; similarly, the utilization of Uranium of nuclear energy has been associated with health and environmental challenges. On the other hand, solar, hydropower, and biomass (crops) energy, though renewable and ecofriendly, are constrained by finances, ecological issues etc. Microbial fuel cell (MFC) technology is a recent method for producing clean energy from biomass through the action of microorganisms. In an MFC, microorganism's breakdown organic matter, releasing electrons that generate cellular energy in the form of ATP. The electrons released are diverted towards an anode. The electrons are then transferred through an external circuit or load to the cathode thereby, transforming energy derived from microbial metabolic activities into electrical energy. Direct generation of green energy from biowaste and organic matter with no energy loss, simultaneously treating wastewater, has been achieved in MFC technology. However, problems like low power output, high cost of fabrication, membrane challenges, etc., are equally observed. Solving these challenges soon is realistic, as advances in MFC is focused on optimizing parameters involved in power generation, exploring cost-effective materials and designs; usage of AI tools in optimization, harnessing MFC for industrial applications other than electricity generation. Therefore, MFC technology will revolutionize energy generation.

Keywords: Microbial Fuel Cell, Clean Energy, Renewable Energy, Revolutionize, Energy Generation

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INTRODUCTION

Access to energy or electricity is indispensable for humanity and socioeconomic development. Energy consumption is closely linked to wealth creation, since wealth is a key indicator of development, energy evidently plays a crucial role in the development process [1, 2]. The rate of a nation's economic and socio-economic progress largely depends on its energy production level, as energy is considered the driving force of the economy. Studies in energy economics indicate that electricity occupies a leading position among energy resources. Energy serves as a foundation for growth; access to electricity is essential for sustainable economic development as it supports continuous industrial expansion, technological advancement, and employment generation [3]. [2] reported that in sub-Saharan Africa (SSA) rural migration accounts for at least 75% of total internal movements with lack of electricity or epileptic electricity supply as one of the leading causes of migration.

Energy and food

The food industry is an extensive and intricate global system that comprises of the production, processing, distribution, and consumption of food and related products. It encompasses diverse enterprises, ranging from small-scale farmers and local food markets to multinational companies and international supply network. The food industry forms a fundamental part of the global economy, providing employment for millions and generating significant annual revenue. Globally, the food sector is among the highest energy consuming industries, contributing roughly 30 % of total energy use [4]. Energy is required for different food processes such as heating, cooling, drying, refrigeration, processing, packaging, and transportation. In general, food processing equipment and machinery require electricity to run, while refrigeration systems use energy to maintain temperature control and prevent spoilage. For instance, to extend food shelf life, enhance its availability over time, or minimize post-harvest losses, energy is needed such as in refrigeration and freezing. Additional processes that require high energy input include baking, frying, canning, and bottling operations [5, 4]. Just as energy is important in food industry, it is also important in food preparation and preservation in households. However, limited access of low-income households to modern energy for food preparation has resulted in adverse effects on their economic status, health, and nutritional condition. Energy deficiency is strongly associated with income levels, as low income households are faced with various challenges related to obtaining traditional fuels sources [6].

In recent years, there has been a rapid increase in the global population, leading to a significant rise in the demand for food and energy resources. This trend, which is projected to persist, has exerted considerable pressure on food and energy systems. As energy needs continuity to grow meeting these demands is becoming more complicated. This is due to the dependence of conventional energy systems on fossil fuels and other energy technologies that are often inefficient or unsustainable, thereby placing greater strain on the environment and worsening climate change [7, 8]

Energy and health

A country with a healthy and productive population is more likely to achieve improved wellbeing and sustainable economic growth. Access to clean water is one of the United Nation’s sustainable development goals and a prerequisite for a dignified and healthy life [9]. Furthermore, consistent electricity supply strengthens healthcare systems by ensuring uninterrupted operation of essential services. However, insufficient and unstable energy supply restricts residents access to basic needs such as clean water, proper lighting, and adequate heating. This increases the risk of disease transmission and affects the general health condition of the community [10, 11].

West Africa relies primarily on natural gas and crude oil for energy. In Nigeria and Ghana electricity generation depends on fossil fuels [10]. However, the burning of Fossil fuel releases CO_2 emissions, that significantly lead to alterations climatic conditions. In recent times, West Africa has experienced more unpredictable weather patterns [12, 10]. Furthermore, lack of sustainable energy access results in heavy dependence on traditional, highly polluting, and environmentally harmful fuels like firewood and coal [13]. Moreover, the use of clean cooking fuels lowers indoor air pollution, thereby significantly decreasing early deaths from respiratory illnesses, particularly among women and children. [14] also reported that increase in carbon dioxide emissions from fossil fuels increased mortality rate and respiratory diseases in children less than five while the reverse was the case in the use of renewable energy in Sub-Saharan Africa.

Energy and education

Literature reveals that energy and education are often interwoven and dependent on the other. Schools exist at the intersection of global changes and disruptions that influence energy usage. Education is essential for sustainable resource management as it promotes social unity, builds human capacity, stimulates economic development, and encourages environmental responsibility. Education is a weapon used in improving the energy sector as well as educating the public about global trends. However, sustainable energy is very crucial for effective education [15, 16, 17, 11]. [1] reported that the general belief that the availability of electricity enables learners to continue their studies tends to be true. [15] reveals that in the near future, access to education is expected to increase, and schools as centers of learning, will expand rapidly, leading to a higher energy demand and associated costs. Furthermore, [11] emphasizes that air pollution a major challenge of fossil fuel impairs cognitive development and increases absenteeism and underscores carbon emissions as a universal constraint on educational outcomes.

Therefore, Renewable, Clean, energy is essential for modern educational settings, as it supports the use of technology and allows for extended learning periods and also important in meeting the 2030 SDGs [11].

Energy and industrialization

Importance of industrialization in economic growth cannot be overemphasized. It reduces unemployment, enhances technological advancement and aids collaborations with other nations. Industries rank among the highest consumers of energy within an economy. This is due to its direct relationship with economic growth [18]. Energy plays a pivotal role in industrialization, serving as a crucial input in production processes and driving economic growth by enabling technological advancements and increased output. Reliable and affordable energy supply is essential for powering machinery, supporting industrial processes, and fostering research and development [19]. To promote economic development, many African nations have strengthened their industrial sector to lessen their reliance on imports [18]. [19] reported that energy development significantly increases industrialization in Africa. However, the process of industrialization has largely been driven by the consumption of fossil-based energy sources such as petrol and diesel in most parts of Africa due to unreliable electricity supply from the national grids of its countries [18, 20].

Historically, industrialization has been associated with higher energy use and increased greenhouse gas emissions. According to [21], the adoption of energy efficient technologies alongside the development of renewable energy sources helps reduce energy intensity during the industrialization process. Therefore, the advent of clean energy technologies presents an opportunity of economic growth without carbon emissions [22].

CONVENTIONAL ENERGY SOURCES

Power generation utilizes primary energy resources including fossil fuel, nuclear, solar, wind and biomass. These energy sources are either renewable or non-renewable.

Fossil fuel

Fossil fuel, which are non-renewable energy sources, has been a major source of energy particularly in developing countries for decades. According to [23] Oil, coal, and natural gas which are different forms of fossil fuel accounted for about 30 %, 26 %, and 23 % of the global energy supply respectively in 2020 (Fig 1). This reflects a strong alliance on fossil fuels for electricity generation, largely because of their high-capacity factors [24, 25].

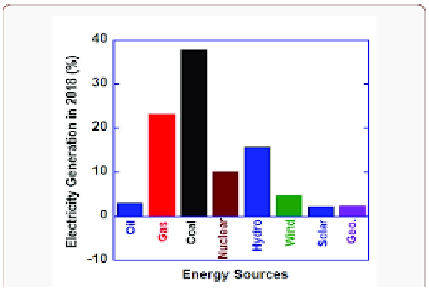

Figure 1. Electricity Generation Through various sources (He et al., 2024)

Challenges

Fossil fuels, while currently a primary energy source, face significant challenges, which include:

1. Environmental degradation: fossil fuel promotes serious environmental degradation through the release of greenhouse gasses (GHG) such as carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), nitrogen oxides (NO_2), tropospheric ozone (O_3), carbon monoxide (CO); particulate matter (PM) and non-methane volatile organic compounds (NMVOCs), from power plants fueled by it [26]
   Among all GHG, CO_2 is less potent but highly concentrated and it long atmospheric lifetime make it the most relevant [27]. [28], increase in population, which subsequently led to increase in energy consumption, has accelerated environmental degradation because fossil fuel sources (particularly coal and oil) which play a major role in energy generation in some countries, such as China and India, are responsible for considerable carbon dioxide (CO_2) emissions.

i. Climate change: Global climate change remains one of the most critical challenges confronting humanity today. It is considered a major factor responsible for the increasing occurrence of extreme weather conditions, alterations in disease distribution, and damage to agricultural systems [26]. This is attributed to continuous climatic changes observed over time, including rising global average temperature, sea level increase, heat waves, recurrent flooding events, intensified and more frequent ocean waves, as well as prolonged drought across various regions of the world [27]. Furthermore, weather conditions in West Africa have become progressively irregular over time due to increase in use of fossil fuel [12, 10].

ii. Air pollution and health concerns: Coal stands out as the most abundant fossil fuel and is the largest contributor to carbon emissions. It also has the potential of harbouring heavy metals, which threatens human health and the environment. Environmental emissions of pollutants and GHGs occur during every stage of coal use (mining, processing, utilization and waste disposal) and processing cum refining of oil. The use of coal in traditional heating or cooking stoves generates dangerous levels of indoor air pollution, due to the emission of substances such as carbon monoxide CO, particulate matter (PM), and harmful organic compounds [26]. [14] reported that emissions from fossil fuel sources have detrimental impacts on human health, causing respiratory diseases and increase in mortality rate. Although GHG contributed to air pollution by natural gas is reduced compared to oil and coal, its drilling process serves as a contributor to volatile organic compounds (VOCs). The considerable water requirements and the chemicals used during the process may negatively affect both the quality and availability of water resources [26].

iii. Land scape alteration: mining fossil fuels transforms the surrounding mines causing pits, quarries and mine tailing piles. Furthermore, waste generated are disposed resulting in irreversible repercussion on disposal sites. Pollutants from these mines leads to runoffs polluting nearby water bodies rendering water unsuitable for drinking, agricultural and industrial use. It also poses threats to organisms in it [26].

1. Economic issues: other issues attached to production of energy using fossil fuel has been found to impact economy of nations depending on it

i. Price volatility according to [26], electricity generated from fossil fuels carries the highest external costs. [29] observed that there is a rise in the price of fossil fuel products in china results in shift to renewable energy sources. [30] concluded in their research work on "crude oil price volatility and the Nigerian economy" that increases in crude oil price hurts Nigerian economy.

ii. Resource depletion: oil and gas are confronting dwindling reserves, which has a great impact on the economies of country depending on it [27, 26, 31]. The gradual reduction of fossil fuels results in inflation of fuel prices and higher cost implications in the long run [32]. According to [33], reduction in natural resource availability increases long term threat to global energy security.

In summary, fossil fuel is faced with the following challenges: cost intensity, scarcity, pollution, depletion, health issues, eco-unfriendliness and climate alteration leading to insecurity of nations' economy depending on it.

Nuclear energy

Nuclear energy harnesses the power of atomic nuclei for electricity. As the primary fuel used in nuclear reactors, Uranium is characterized by a very high energy density. It is not faced with challenges such as dwindling reserves and adverse environmental impacts compared to fossil fuel [26] offering a high-density, low-emission source of power and heat that supports energy independence and drives scientific advancement [34]. According to [35], Nuclear energy ranks as the second most significant source of low-carbon energy.

Challenges

Despite the immense benefits proffered by this technology over fossil fuel, it is faced with the following significant challenges.

1. Environmental issues

i. Radioactive waste: The most critical environmental challenge associated with nuclear energy is the disposal of long-lived radioactive waste [35]. Such waste from nuclear plants remains dangerous for thousands of years and may present long-term health challenges due to exposure to radioactive materials that pollute soil and water.

ii. Poor construction of tailings dams increases their vulnerability to hazards like earthquakes, which can pose as risk to public health [26]
iii. Ecological consequences: in the occurrence of nuclear accidents, it triggers deep and persistent ecological consequences that surpass direct human health implications, affecting biodiversity and the stability of ecosystems. These effects reflect in decreased genetic diversity, lowered reproductive potential, and behavioral modifications, thereby limiting population resilience and adaptability [36,24]

2. Public perception and social acceptance: In developing countries, nuclear energy is less attractive compared to cheaper and renewable alternatives. Concerns about harmful materials linked with nuclear energy as well as military use of nuclear technology also contribute to this resistance [36]. Furthermore, Safety concerns are also fueled by previous nuclear disasters like Three Mile Island, Chernobyl and Fukushima, continue to shape public opinion [34, 36]
3. The high expenses involved in plant establishment and decommissioning: high cost and long development time needed for constructing and managing nuclear plants, because of design complexity, strict regulations, and safety measures is another limitation in nuclear technology [37].

Nuclear energy, though remarkably defeating some challenges confronted by fossil fuel, environmental issues related to its waste and public perception still abound as some of its major limitations.

Solar energy

Solar energy is harnessed via photovoltaics (PV) which transform sunlight directly into electrical energy or through concentrating solar power technologies (CSP) which converts sunlight into high-temperature heat, which drives conventional steam turbines to generate electricity [38, 23]. PV can be adapted to suit end-users in both residential and commercial sectors, taking form of large-scale solar (LSS) or stand-alone systems due to their modularity and scalability thereby offering decentralized energy systems. Small-scale solar installations are suitable for residential or business buildings, whereas large scale systems can provide energy for whole communities [23, 9]. It also contributes to electricity generation with lower carbon emission and reduced environmental risks compared to other renewable sources particularly in Africa [38].

Challenges

Being one of the most acceptable and safe renewable conventional technologies, it is however confronted with following challenges:

1. Climate dependency and environmental conditions: power generation and output are often inconsistent because it is solely climate dependent and Irradiation also, is often time variable. Additional protection is required to manage overcurrent, undercurrent, and frequency stability [39, 40]. This challenge is more pronounced in LSS PV where fluctuations in power generation and output are relatively higher [39]. In regions characterized by extreme temperatures, high humidity, or frequent dust storms such as the northern Nigeria, solar panels are exposed to harsh environmental conditions including elevated heat levels and dust intrusion from the Sahara Desert. However, to ensure durability, resilience, and optimal performance across diverse environments, extensive testing, design optimization, and adaptation of technologies to local conditions are necessary [9].

2. lack of adequate infrastructure: due to its dependence on climate, vital components like energy storage technologies including batteries system (PV) or thermal storage (CSP) are needed to sustain its use even when the climatic conditions are not favourable and even at night. Furthermore, the absence of efficient grid integration systems, and limited maintenance systems is common in regions with substantial solar energy demand [40, 9].
3. Environmental degradation: Extensive installation of solar panels or solar dish systems may lead to ecological disturbances, including deforestation or loss of habitat and alteration or loss of biodiversity, especially if they require significant land area [40, 41, 9].
4. High upfront cost: substantial capital, installation and operational costs associated with solar technologies, particularly PV systems is one of the limiting factors to the wide adoption of this technology particularly in Africa [38, 40].
5. Health risk: Solar panels consist of toxic materials such as lead, cadmium, and silicon, which if not properly disposed of can result in environmental pollution [41, 9]. Molten salt used in CSP as thermal energy storage compose of nitrate salts (sodium nitrate, potassium nitrate) which can be harmful, if not properly managed. Furthermore, heat transfer fluid, a synthetic oil used in some CSP technologies, is very toxic and can be harmful if leaked into the ground. These can result in health hazards [40].

Biomass energy

Biomass energy serves as a renewable energy source derived from organic materials including agricultural residues or municipal solid waste, industrial waste, household waste, wastewater and microalgae, offering a sustainable and decentralized energy source [23]. It can be conveniently stored, transported, and utilized at locations distant from its source of origin. Biomass energy systems are recognized for their capacity to generate both thermal energy and electricity, while utilizing widely available feedstock. Through different conversion methods, biomass has been extensively used to produce heat, electrical energy, chemical feedstocks, and other forms of energy [42, 43]. In thermochemical conversion processes, energy stored through photosynthesis is liberated through the breaking of bonds between carbon, hydrogen, and oxygen molecules in thermochemical, physicochemical and biochemical conversion processes into bioenergy [42, 44, 45]. Biomass, in contrast to other renewable energy sources, has the capability to yield fuels and chemical compound simultaneously [42, 43]. Biofuel, a substantial product from biomass, includes biogas, biodiesel, bioethanol and biohydrogen [45]. Bioenergy production is widely regarded as a net zero carbon (CO_2) emitted during energy transformation is believed to have been previously absorbed by biomass through photosynthesis. As a result, carbon dioxide removed from the atmosphere during photosynthetic activity is subsequently released during energy generation process
[23]

Challenges

Although, the environment is protected from improper waste disposal by converting waste into energy, which is an important advantage of biomass energy. it is not totally a green technology. Hurdles include:

1. Air pollution and health concerns: The release of toxic gases like SO_x, CO, and NO_x together with unstable chemical compounds produced during combustion and incomplete oxidation are unhealthy for the environment and human [45, 46].

2. High Production and operational cost: high cost is associated with land utilization, equipment requirements, and feed needed to get a substantial yield, operational cost for maintenance and labour and cost of storage and transportation. [45, 43, 46].
3. Ecological consequence: alteration of biodiversity is yet another challenge. The use of land and conversion processes involved destabilizing the ecological chain. To satisfy the rising demand for agricultural feedstocks, may lead to increased deforestation and land conversion, majorly in biodiversity rich regions [43, 46].
4. Competition with food resources: there is conflict between allocating land for biomass production and sustaining food security. The production of crops such as sugarcane, corn, wheat, and soybeans (first generation feedstock) to produce biofuels leads to competition with food production, posing as challenges when food supplies are not sufficient to meet demand [43].

Hydropower

Hydropower stands out as a leading renewable energy technology globally, offering substantial potential for generation of clean electricity [47]. It harnesses the kinetic energy of flowing or falling water such as rivers and dams for electricity generation [47, 48]. Hydropower as well provides services such as flood control, irrigation and potable water reservoirs aside from its ability to generate electricity [49]. Unlike other renewable energy sources, it is not a decentralized energy technology and is confronted with other impediments.

Challenges

1. Environmental and social impact:

i. Large scale projects such as hydroelectric dam construction and reservoir formation lead to significant disruptions in aquatic and terrestrial ecosystems, resulting in biodiversity loss, sedimentation, eutrophication and community displacement [50, 47, 51]. Displaced communities may encounter difficulties in accessing adequate housing, infrastructure, and social services, exacerbating poverty and social inequalities [52].

ii. Land use and resettlement: Hydrological and climatic factors govern water resource availability for energy production. Changes variables such as rainfall duration and intensity, river discharge volume, reservoir evaporation rates, and plant evapotranspiration rates which are all susceptible to alteration under global warming may result in unintended consequences, including shifts in land use and increased irrigation demand [49]. deforestation associated with hydropower projects lead to erosion and increased extinction risks for aquatic species. The loss of floodplain forests, as further contributes to altered sediment transport dynamics, exacerbating environmental impacts [50, 47].

iii. Carbon emission: When areas are flooded with reservoirs, submerged vegetation and soil decompose, releasing carbon dioxide and methane, especially in tropical zones. Methane released by reservoirs is a potent greenhouse gas, making some projects' emissions higher than expectated. Emissions are typically higher in tropical regions due to faster decomposition compared to temperate regions [49].

2. Climate change vulnerability: hydropower is dependent on the climate. Shifts in climatic condition such as rainfall and high temperature can reduce inflow into rivers hence, reducing water levels of reservoirs. Changes in precipitation patterns also affect both thermal and non-thermal electricity generation, since water availability is crucial for cooling processes in thermal power plants and

for direct energy production in hydropower systems. [49]. According to [53], In recent decades, reduced rainfall and recurring droughts across West Africa have placed significant pressure on the region's water systems. This resulting in power rationing in countries like Sub-Saharan Africa. The drop in reservoir levels had a profound effect on Ghana's hydropower output, cutting generation capacity by nearly 1,000 megawatts.

3. Sedimentation and flooding*:* Sediment buildup within reservoirs may cause depletion of capacity of the reservoir, Downstream channel sections often experience degradation, while the dam's structural elements, waterways, metallic components and machinery are subjected to abrasion. Thereby reducing efficiency in electricity generation [54]. Furthermore, when reservoirs release water heavily laden with sediment, it can cause harmful impacts on the downstream of the hydropower facility. Downstream channels may undergo increase in erosion and sediment deposition, which in turn affects aquatic habitats and water quality [55]. Storms and floods are as result of extreme weather events (such as heavy rainfall) on the other hand, damage infrastructure, disrupt supply, and heighten operational risk. According to [56], floods in Blue Nile River Basin (BNRB)- a crucial shared water resource for Ethiopia and Sudan, has suffered infrastructure damage and incurred repair expenses amounting to millions of dollars.
4. Capital constraints: Hydroelectric developments demand substantial investment, covering construction costs, electrical infrastructure, and the installation of transmission lines that extend from remote sites to major urban centers [52]
5. Health impacts: it was documented by [57] that the occurrence of potentially toxic elements (PTEs)—including lead (Pb), zinc (Zn), nickel (Ni), copper (Cu), mercury (Hg), arsenic (As), and cadmium (Cd)—within sediments of a hydropower reservoir situated in the Brazilian Cerrado biome pose potential risks to human and animal health. These metals pose serious risks due to their capacity to disperse across different environmental compartments, such as water, soil and sediment. They exhibit low solubility thereby accumulating in organisms and Coupled with their inherent toxicity, excessive concentrations of these metals can pose severe threats to the health and survival of living organisms [55]. PTES can cause health issues such as skin irritation and respiratory complications through ingestion, dermal or oral contact, and inhalation, as well as cancers linked to the consumption of contaminated foods (e.g., vegetables and fish) [57]. Furthermore, Reservoirs can provide favorable breeding habitats for disease vectors such as snails and mosquitoes, which are vectors for schistosomiasis and malaria, respectively [58]

Microbial fuel cell technology

excessive energy demands and limitations associated with conventional energy technologies have intensified efforts in the research and development of renewable and sustainable energy sources [59]. According to [38], renewable sources of energy play a pivotal role in addressing global sustainable development challenges, including food insecurity, poverty, and climate change. Although it was not explicitly listed among the technologies for achieving the United Nations Millennium Development Goals (MDGs), renewable energy contributed indirectly to meeting these targets particularly in areas such as household applications, healthcare, education, and poverty reduction across Africa.

According to [60], achieving the 1.5 °C climate target by 2050 will necessitate a substantial increase in bioenergy production. This remains a challenge without diversified use of sustainable biomass, as current bioenergy deployment is far below the level required for a successful energy transition. Microbial fuel cell (MFC) technology has emerged as one of the most recent innovations for generating clean and renewable energy from biomass using microorganisms to generate electrical energy from chemical energy. MFC functions as a biologically catalyzed bio electrochemical systems in which microorganisms drive redox reactions that transform the chemical energy of organic substrates into electricity without oxygen [59]. [61] characterizes them as bioreactors that exploit microbial activity under anaerobic conditions to release electrical energy from organic compounds"

Evolution of MFC

Fuel cell research gained attention from 1960-1970 following fuel price surge. The Fuel cells are generally classified into two main categories: abiotic fuel cells and biotic fuel cells. MFC is categorized under the latter [62]. However, the origins of microbial fuel cell (MFC) research can be traced back to the early 18th century, beginning with Luigi Galvani's pioneering work on galvanic cells. In 1780, an Italian physician and physicist, Luigi Galvani demonstrated relationship between electricity and biology [59, 62]. In 1791, he explored the effects of electricity on animal tissue, and he was the first to identify a bioelectric phenomenon when an isolated frog's leg twitched under a brief electrical discharge an observation that gave rise to the term "bioelectricity". Later, in 1838, the Welsh scientist and lawyer William Robert Grove introduced the "Grove cell" a wet-cell battery. This two-fluid electrochemical device employed amalgamated zinc in dilutin sulfuric acid as the anode and a platinum cathode immersed in concentrated nitric acid, separated by a porous ceramic barrier, producing approximately 12 amps of current at 1.8 volts. In 1893, Friedrich Wilhelm Ostwald, regarded as the founder of physical chemistry, early pioneers experimentally established the relationships among the fundamental components of fuel-cells, including electrodes, electrolytes, oxidizing and reducing agents, as well as ionic species—by linking their physical properties to chemical reactions [63]. Later, in 1910, Michael Cresse Potter, a Botany professor at the University of Durham in the UK, demonstrated that microorganisms could generate electrical current and voltage while degrading organic compounds, marking a key milestone in bioelectrochemical research. Later in 1911, He generated current with *Escherichia coli* and *Saccharomyces* using platinum electrodes [63, 62, 61]. "In his experiment (Fig. 2), a glass jar containing nutrient solution was inoculated with a microbial culture. A platinum electrode placed in this medium functioned as the anode. A second platinum electrode, serving as the cathode, was immersed in liquid within a porous cylinder that acted as a proton exchange membrane (PEM). When the C–A terminal was closed, current flowed from the cathode to the anode, charging the capacitor. Closing the C–B terminal discharged the capacitor, and the resulting current was detected using a galvanometer [59]. However, the study did not gain prominence, as it received limited attention and no detailed analysis was conducted to clarify the mechanisms of proton and electron transfer [62, 59].

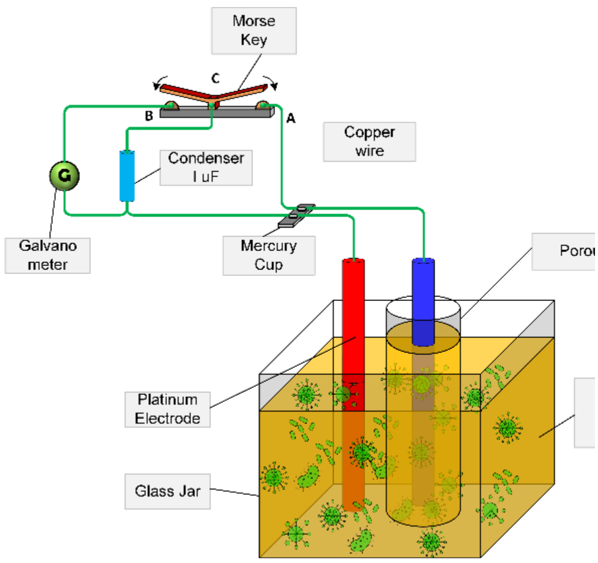

Fig. 2: MFC illustration by M.C. Potter (Source: Murugesu et al., 2022)

Components of MFC

MFCs are composed of an anode, a cathode, a membrane or separator, electroactive microorganisms, and a nutrient source. Their performance is strongly influenced by physicochemical parameters such as system temperature and pH which are also important parameters in governing the homeostasis and providing optimal growth conditions are essential for bacterial species to thrive [64, 62, 65, 61]. MFC utilizes a wide variety of organic substrates, including alcohols, sugars, acetate, complex organic compounds, and even wastewater [60]. The anode material (Fig. 3) must be conductive, resistant to corrosion, and capable of supporting biofilm formation by bacteria. In contrast, the cathode is typically equipped with catalyst materials to facilitate the oxygen reduction reaction [62]. The surface topology and physical characteristics of the electrode are critical in maximizing bioelectricity generation [64]. Electron transfer from the anode to the cathode through the external circuit can occur via several mechanisms: direct electron transfer through membrane-bound electrochemical pili, endogenous mediators produced by bacteria, or synthetic mediator compounds. In membrane based MFC, the membrane usually an Ion permeable membrane such Proton Exchange Membrane (PEM) separates the anode and cathode chambers, preventing the mixing of reactants [64]. However, membrane less MFC do not need it as part of their components. Microorganisms are the true catalysts in microbial fuel cells (MFCs). Under anaerobic conditions, they break down energy-rich organic substrates and release electrons [61]. Microorganisms used are exoelectrogens which release electrons to extracellular acceptors [66]. Microbial species that efficiently utilize carbon sources are considered strong candidates for biofuel generation. In microbial fuel cells (MFCs), exogenous compounds or mediators are often employed to enhance electricity production, acting as electron shuttles between microbial components and the anode. Although many studies have reported higher power and voltage outputs in mediator-based systems compared to mediator-free designs, excessive mediator use can negatively impact microbial viability [64]. MFC configurations may be single- or double-chambered, with the anode chamber maintained under anaerobic conditions and the cathode typically operating in an aerobic environment. [67, 68]. Different materials can serve electrode, some of the materials used are illustrated in Fig. 4.

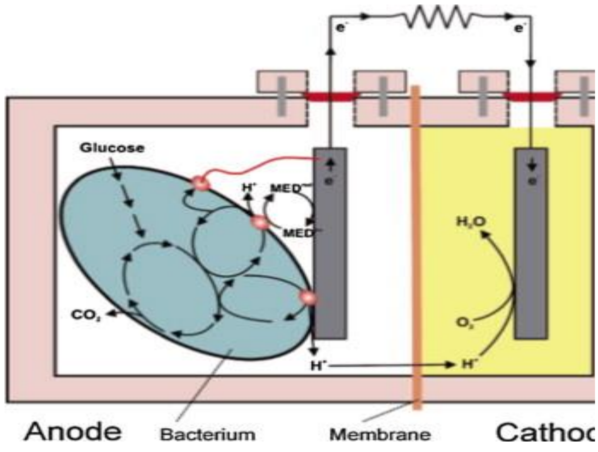

Fig. 3: Components of an MFC setup (Source: Rahimnejad et al., 2015)

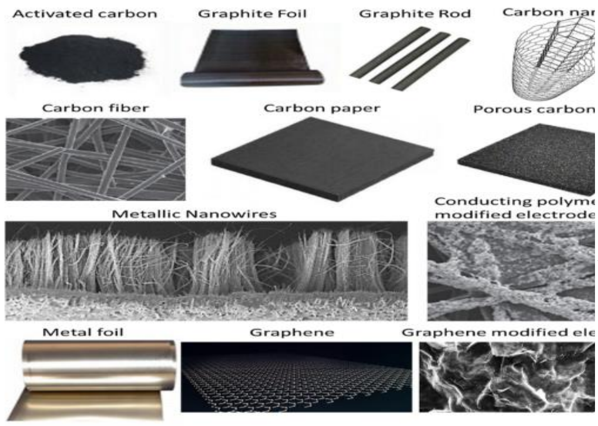

Fig. 4: Electrode materials (Source: Pandey et al., 2025)

Principle of MFC operation

MFCs can generate electricity from a wide spectrum of biodegradable substrates, ranging from simple organic matter to complex compounds found in animal, human, and food-processing wastewaters

In an MFC, At the anode, microorganisms oxidize organic substrates, releasing carbon dioxide, protons, and electrons that support ATP generation within the cell [63]. The electrons are captured by the anode and conducted through an external load to the cathode, thereby transforming microbial energy directly into electrical energy [65]. Meanwhile, protons migrate across the ion-exchange membrane or diffuse toward the cathode, where they combine with incoming electrons to complete the electrochemical circuit [62]. Within the cathode chamber, an electron acceptor such as oxygen or ferricyanide is introduced. This acceptor undergoes reduction reactions, most notably forming water when the incoming electrons combine with protons [63, 65]. The generation of water as a byproduct makes microbial fuel cell (MFC) operation environmentally sustainable [62].

Application and advantages of MFC over conventional energy sources

Advantages of MFC compared to other technology of power generation cannot be overemphasized. Its mechanism of energy generation is accompanied by solving other challenges and this has led to numerous applications of MFC aside generation of electricity.

1. **Direct conversion of chemical energy to electric energy:** MFC technology enables the direct transformation of waste into electrical energy in a single step, ensuring high conversion efficiency [62]. It offers practical solutions such as waste water treatment (WWT). MFC are can treat diverse wastewater streams, including those from industrial, agricultural, and municipal sources [68].
2. **Eco-friendliness**: MFC has gained attention in eradicating pollutants (environmental cleanup) while producing clean energy (electricity) [71]. According to [67], it produces note that microbial fuel cells generate less sludge than conventional wastewater treatment, eliminate the need for oxygen aeration, are simple to operate, require minimal space, and achieve substantial COD reduction, enabling safer effluent discharge with reduced environmental impact.
3. **Customizability**: MFCs can utilize a broad spectrum of organic waste materials, such as wastewater as a power source, making them suitable for diverse

environments. Unlike conventional fuel cell technologies that require high temperatures and pressures, MFCs operate without expensive energy inputs [72].

4. **Water reclamation**: [73] demonstrated field application of a stack of soil microbial fuel cells (SMFCs) operated in air-cathode mode and supplied by a gravity-fed system, which generated renewable energy to power an electrochemical reactor for water treatment. In the research work, A stack comprising of 64 fuel cells was able to generate 85 mA of power and charge a 600mAh battery in about 8.5 h. this battery sustained 1.5h, treating 1.4 L of water thereby, Using an electrochemical advanced oxidation process, the system treated up to 2.8 liters of water per day. According to the report, "The integrated system developed presents a sustainable, decentralized solution for generating power and enabling self-sufficient water treatment.
5. **Bio-sensitivity**: Microbial fuel cells (MFCs) are increasingly acknowledged as effective biological monitoring tools, owing to their capacity to rapidly detect organic indicators such as biological oxygen demand (BOD) and chemical oxygen demand (COD) in assessing water quality [74]. [75] demonstrated that MFCs can be transformed into biosensors capable of detecting the adverse effects of suspended solids and acidic content in potato chips. processing wastewater (PCPW) on the biomass activity. [76] also reported that a passive capillary-based carbon source delivery system was utlilized for anode-sensing MFC biosensors enabling continuous water quality monitoring in carbon deficient conditions.
In the research, the designed MFC was able to sense low concentration of some toxic contaminants including microcystins and formaldehyde in portable water. Furthermore, [77] developed an MFC made of kestamid to detect lead in wastewater. The use of biosensors in medical diagnostics has also been reported [78]

Challenges

Despite the enormous benefits MFC offers over major conventional power sources, MFC is faced with some operational challenges and low power output for large scale usage. These challenges include:

1. Low power output: the MFC output power remains insufficient for practical applications such as powering sensing devices or large-scale deployment when compared with other energy technologies. Moreover, the power generated does not scale linearly with system size [60]. Losses in output are primarily attributed to resistance from conducting materials, separation media, and electrolytes. Additional energy losses arise from activation barriers at the electrode surface and mass transfer resistance of chemical species at the electrodes [79, 80]
2. Membrane challenges: membrane challenges include proton transfer limitations, oxygen leakage, elevated internal resistance, and the high initial cost and clogging of membranes for large-scale wastewater treatment [81]. [82], reported high internal resistance due to conventional membranes, which leads to oxygen ingress and subsequent aerobic biofilm formation on the cathode surface, causing cell disconnection and low power density.
3. Large scale implementation risk: other constraints in achieving large-scale implementation goals apart from low power output, include Instability of microbial communities under diverse environmental conditions, along with the possibility of ecological disturbances, has been observed. [83,84, 85]
4. Cost: cost drivers include cost associated with materials used and manufacturing

process of MFC. Major components such as Proton Exchange Membranes (PEMs) such as Nafion, electrodes such as platinum, and other specialized materials used in MFC setup are costly. [79, 80]

Advances in MFC

A. Performance

Current research on MFC performance, increasing power output for large scale use, improving components and optimizing operational parameters. However, following are some research attempts to address these areas:

1. **Development of suitable and cost-effective electrodes**: materials used for electrodes are one of the factors contributing to power output. Conventional electrodes such as platinum is expensive [86] therefore, research is ongoing in using other suitable materials for electrodes as well as optimizing electrode materials for better power output. [67] reported that MFC equipped with a graphite flexible powder (GFG) anode achieved a power density 4.4 times higher than that of conventional carbon felt (CF) anodes, while simultaneously reducing production costs by 90%. Utilizing Recycled Chopped Carbon Fibre (RCCF) yielded a 7% increase in power density compared to carbon felt (CF), while reducing costs by as much as 87%. However, there was low mechanical stability of the anodes. [87] reported that Anodes enhanced with carbon dot nanoparticles displayed improved electrical conductivity and increased hydrophilicity. [88], demonstrated in research whereby 6-anodes were used, that increasing the anodes of MFC increases its operational life for approximately 74 days. However, there was an increase in the costs and emission of environmental pollutant. [89], reported in a study titled "facile and scalable synthesis of vertically oriented TiS2 nanosheets for green energy harvesting in a microfluidic Microbial Fuel Cells", that titanium disulfide (TiS_2) nanosheets as an electrode (3D configuration) in a microfluidic-based MFC system Under optimal conditions, the system demonstrated a peak power density of 169.4 $W\,m^{-3}$ and a current density of 1270 $A\,m^{-3}$. *Escherichia coli* as the microorganism.
2. **Optimization of operational parameters**: [90] reported that the use of H_2O_2 (hydrogen peroxide) for oxygenation improved the voltage and current generation and stability of UASB-MFC (Up flow anaerobic sludge blanket MFC). [91] demonstrated the use of Cu(II) as Serving an electron-shuttle mediator in microbial fuel cells (MFCs), carbon dots enabled efficient and cost-effective Cr(VI) reduction under neutral pH conditions in wastewater treatment. [92], reported the use of pretreated banana peels slurry as substrate at controlled temperature and resistance which achieved a high-power density and can be used at pilot and industrial scale.
3. **Optimization of microbial activity**: [93] has shown that Magnetic fields enhance electron transfer and microbial activity in microbial fuel cells (MFCs). At 2 mT, current density increased to 0.88 $mA\,m^{-2}$, while a field strength of 3 mT produced the highest power density (0.125 $mW\,m^{-2}$) and achieved 98% COD removal efficiency. According to [94], improved MFC performance was linked to a microbial community dominated by electrogenic, sulfide-oxidizing, and methanotrophic bacteria, alongside reduced populations of sulfate-reducing bacteria and methanogen .in their research to treat waste water with high sulfide. In a research titled "Development of wheat straw based catholyte for power generation in microbial fuel cell" conducted by [95], It was revealed that

microbial fuel cells (MFCs) operated with a cathode chamber containing continuously laccase-producing fungi, together with yeast functioning as the exoelectrogen, achieved enhanced electricity generation and improved the efficiency of oxygen reduction to water in the catholyte.

4. **AI tool for optimization:** [96] reported in a study on "*Performance improvement of microbial fuel cell through artificial intelligence"* that Adaptive Network-based Fuzzy Inference System (ANFIS) in conjunction with Particle Swarm Optimizer (PSO) algorithm yielded better results compared to ANOVA when applied to estimate the optimal parameters that maximize the performance of the MFC. According to [97], in a study aimed to detect the impact of varying amounts of Wolf vitamin solution on microbial activity and impacts on MFC performance using four AI models namely AdaBoost, XGBoost, CatBoost, and SVR to predict power density. AI tool effectively predicts MFC performance revealing an optimal configuration at 5.8 mL/m2. This setup delivered a power density of 576.8 mW m^{-2}, achieved a COD removal efficiency of 78%, and recorded a coulombic efficiency of 12%.

B. Industrial Application

Advances on industrial application of MFC include wastewater treatment, using MFC as a biosensor and recovery of value-added products. Following are some research attempts:

- Waste water treatment:

[98] Highlighted the utilization of clay-based ceramic membrane as PEM with Wheat flour, alumina (Al_2O_3) and silica (SiO_2) as additives to improve porosity and proton conductivity. In the research, the ceramic membrane modified with 10% wt Al_2O_3,10 % wt SiO_2 and 10% wt wheat flour exhibited improved proton conductivity ($(9.86\pm0.26) \times 10^{-5}$ cm·s^{-1}) and high ion exchange capacity (0.236±0.015 mmol H^+·g^{-1}), COD removal efficiency of 94.9 ± 0.3 % and power density of 182.8mW.m^{-2}. 98Mohammadi et al. (2024), reported in comparative study of treatment of real municipal wastewater and dairy wastewater that MFCs perform more effectively when treating wastewater with higher strength and complexity, owing to the diverse bacterial communities colonizing the electrodes and the greater organic content available. In trials, MFCs reduced COD by 84% in municipal wastewater and 70% in dairy wastewater, with corresponding coulombic efficiencies (CE) of 37% and 17%. Scanning electron microscopy (SEM) revealed significantly greater microbial attachment to electrodes in municipal wastewater compared to dairy wastewater. The CE results further indicated that municipal wastewater allowed more organic matter to be converted into electricity than dairy wastewater.

- Biosensors:

[100] reported that MFC-based biosensor offers strong potential for continuous water quality assessment by detecting water pollutants in synthetic wastewater using *Shewanella xiamensis*. The experiment was carried out using, a two-chamber microbial fuel cell (MFC) with a 2500 mL capacity, ceramic membrane, and carbon cloth electrodes. Synthetic wastewater inoculated with *Shewanella xiamensis* (strain SH1 MF663195) served as the anolyte, while distilled water was used as the catholyte. The system achieved a maximum current density of 1.939 mA m^{-2} and a power density of 80 mW m^{-2} under near-neutral pH and an external resistance of 3 kΩ over seven weeks. A strong linear correlation ($R^2 = 0.9984$) was observed between output voltage and BOD concentration

(16–436 mg/L). In a separate study, [101] reported the development of a microbial bioanode based on recombinant *Corynebacterium glutamicum* cells enriched with a biocomposite of creatinine deiminase (CDI) co-immobilized with N-methylhydantoin-sensitive nanoparticles (nCu) to construct an amperometric biosensor. The biosensor exhibited high sensitivity (172 $A \cdot M^{-1} \cdot m^{-2}$), a low detection limit, and strong selectivity for creatine. The associated MFC generated an open-circuit potential of 520 mV and reached a maximum power density of 3 $\mu W \cdot cm^{-2}$ at an optimal creatinine concentration of 0.8 mM. The biofuel cell was successfully tested on real human serum and urine samples.

- Value added product:
  [102] reported the use of *Dunaliella salina* for desalination of brackish water and retrieval of valuable carotenoids. In the study, brackish power plant wastewater, characterized by high levels of total dissolved solids (TDS), was treated in a microbial fuel cell (MFC) using the halophilic microalga *Dunaliella salina* in the cathodic chamber, alongside a control photobioreactor (PBR). Compared with the PBR, the MFC achieved greater reductions in electrical conductivity (33.2%), TDS (60.8%), and salinity (45.5%), while also removing carotenoids and ions of value. The MFC produced a maximum voltage of 185 mV and a power density of 893.79 $mW \cdot m^{-3}$, with a coulombic efficiency of 6.9%, surpassing the performance of an MFC operated with modified Johnson's culture medium. [103], in an optimization study on critical factors such as the chemical oxygen demand (COD) of wastewater (500–2000 $mg\,L^{-1}$) and cathode aeration rate (45–135 $mL\,min^{-1}$) conducted using a pure culture of *Escherichia coli,* revealed that the system yielded an average power density of 465 $mW\,m^{-2}$, average current density of 915 $mA\,m^{-2}$ and phosphorus recovery at an extent of 40% as struvite. Additionally, a maximum reduction in the COD of 90% with an average coulombic efficiency of about 82% was obtained at a short interval of 30 days.

Conclusion

It has been established that MFC has several advantages compared to other technology of power generation such as Fossil fuel, nuclear energy, Solar energy etc. The energy generation mechanism in microbial fuel cells involves microorganisms oxidizing organic matter at the anode, releasing carbon dioxide, protons, and electrons. While the protons contribute to cellular energy in the form of ATP, the electrons are directed to the anode. These electrons then flow through an external circuit or load towards the cathode where they participate in reduction reactions, thereby converting microbial metabolic energy directly into electrical energy). This mechanism also solves other challenges, and this has led to numerous applications of MFC aside generation of electricity such as Water reclamation, Customizability, Bio-sensitivity etc. Despite all these advantages, there are several hindrances that is mitigating against its full adoption. These challenges are described as operational challenges and low power output for large scale operations. Advances in MFC technology focuses on; Improved in performance through development of suitable and cost-effective electrodes, optimization of operational parameters, optimization of microbial activities etc. With these advances, MFC has the potential of revolutionizing energy generation for industrial applications

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