Review Article

Industrial Scale-Up Variability and Life Cycle Assessment of Microbial Fuel Cells

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In the instantaneous global industrialisation, there has been an increase in the generalised waste, one of the major pollutants of wastewater. There should be advancements in the existing wastewater treatment technologies to cater for the current water demands. Wastewater treatment requires the oxidation and reduction of organic and drug molecules. Conventional wastewater technologies are expensive for such degradation, and the treatment efficiency is inadequate per the current demands. Hence microbial fuel cells, which are affordable, multi-applicability systems, should be considered for wastewater treatment technologies. This study analyses various country- and industry-wise wastewater production to demonstrate microbial fuel cell treatment technology requirements. According to the Sustainable Development Goals (SDG), this review also thoroughly discusses the Life Cycle Assessment of various types of Microbial Fuel Cells in order to observe which microbial fuel cells could be applied for different levels of wastewater accumulated geologically as well as industrially. For a thorough treatment of wastewater through MFCs, the review also economically analysed the microbial fuel cells both component-wise and unit-wise, especially towards scale-up. A comprehensive socioeconomic and technological perspective has also been portrayed in order to showcase the need to transition from conventional wastewater treatment technologies towards microbial fuel cells.

1. Introduction

Microbial Fuel Cells are the biological instruments that help generate bioelectricity (in the form of current) with the help of bacterial catalysation. The main working principle of MFCs is the degradation of organic matter through micro-organisms, which produces electrons travelling in a series of respiratory enzymes and makes energy for the cell in the form of adenosine triphosphate (ATP). The principal framework of the microbial fuel cell is shown in Figure 1[1][2][3]. The MFCs comprise several compositions, which include anode, cathode, and membrane (even membranes) as internal components. In contrast, several external analytical compositions exist, including resistors, multimeters, wires and characterisation instruments for assessing wastewater[4]. The various fundamental reactions used in the MFCs, which depend on the wastewater inside the MFCs, are shown in Figure 1[5][6].

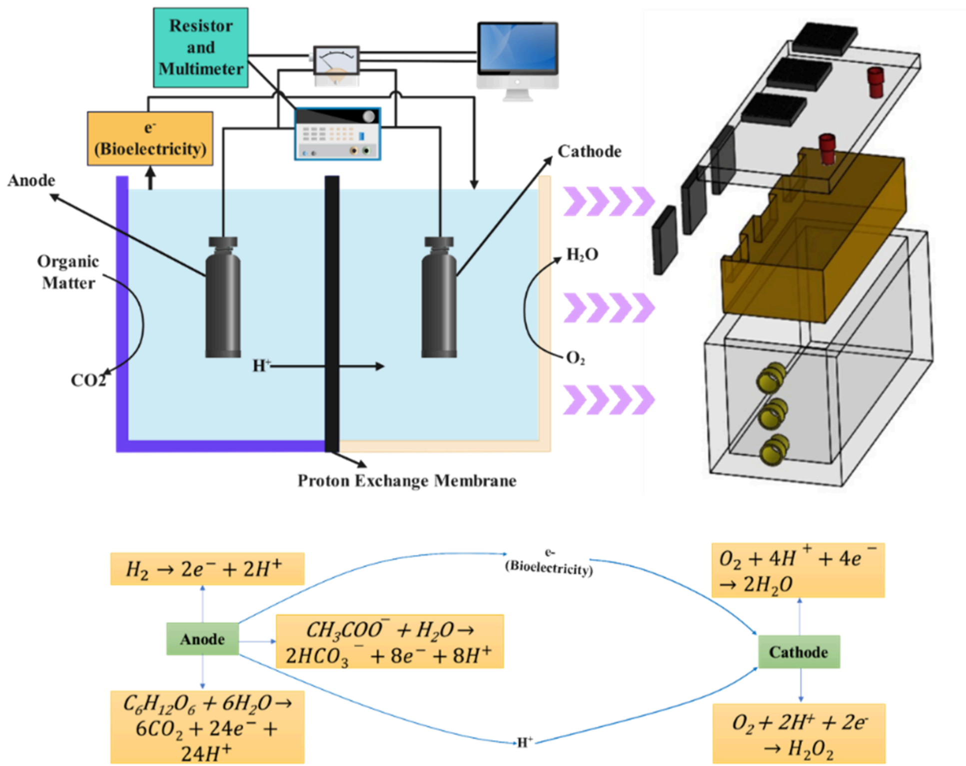

Figure 1. Principal Framework of Microbial Fuel Cells[5][4].

Even though several analytical measures are taken to calculate the efficiency, efficacy and performance of microbial fuel cells, at the same time, several factors cause microbial fuel cell losses, including ohmic, activation, bacterial metabolic, and concentration losses[7][8]. Ohmic losses consist of both the resistance to the flow of electrons through electrodes and interconnection and the resistance to the flow of ions through the cationic exchange membranes and the anodic and cathodic electrolytes[9][10]. These losses could be reduced by minimising the electrode spacing, using a

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membrane with low resistivity, checking all contacts, and increasing the solution's conductivity to the maximum tolerated by bacteria.

Activation losses occur during the transfer of electrons from or to a compound reacting at the electrode surface[11][12]. Low activation losses can be achieved by increasing electrode surface area, improving electrode catalysis, increasing the operating temperature, and establishing an enriched biofilm. Concentration losses entail around the rate of mass transfer of a species to and from the electrode, which limits the current production. The summarization of the factors affecting microbial fuel cells' performance is showcased in Figure 2[9][13][12].

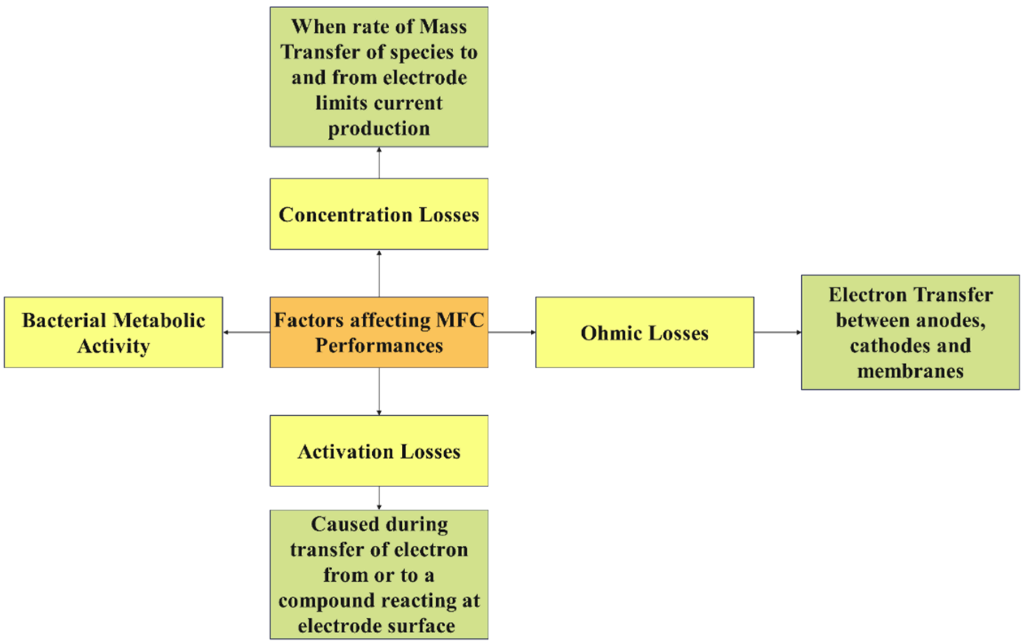

Figure 2. Factor Affecting Microbial Fuel Cells Performances[9][13][12].

1.1. Architecture of Microbial Fuel Cells

During the development of microbial fuel cells, several practical implications are vital, which involve high power, coulombic efficiencies, and economics. Based on the specific needs of industrialists and academics, microbial fuel cells could be divided into air cathode MFCs, two-chamber air cathode systems, new bottle reactor MFCs, single-chamber MFCs, flat plate MFCs, U-shaped MFCs, double-chambered Microbial Fuel Cells, Biohydrogen MFC and Stacked MFCs[14][15]. Single Microbial Fuel

Cells produce low voltage; hence, the stacking of MFCs causes an increase in voltage; there can also be losses when individual cells are joined in series so that the final voltage may not be equal to the sum of individual cell voltages. Such reactors are connected in either series or parallel with wires made of copper or silver[16][17][18].

Some of the primary reasons microbial fuel cells over activated sludge or trickling filters is the production of a valuable product in the form of electricity (the current generation is dependent on the wastewater strength and coulumbic efficiency), lack of a need for aeration (aeration in anaerobic sludge can consume 50% of the electricity used at a treatment plant), reduction of the solid output and potential for odour control (omitting high surface area need in trickling filters exposed to air and the flow of large amounts of air through the aeration basin in the anaerobic sludge process could significantly reduce the potential for odour generation)[19][10][20].

1.2. Commercialisation and Applications of Microbial Fuel Cells

Commercialising lab-scale technology on an industrial scale is necessary due to its impact, sustainability, funding, and evaluation of research excellence[21][22]. For MFCs, the significant commercialisation aspects revolve around working with chemical catholyte such as ferricyanide should be abandoned, focusing on the placement of atmospheric oxygen at the cathodes, and materials and different methods to treat materials must be examined that is efficient both in terms of power generation and cost[23]. One of the most critical challenges is the use of cost-effective cathodes, anodes and membranes, which majorly control the overall cost of the systems. The primary material compositions are showcased in Figure 3[24][25][26][27][28][29].

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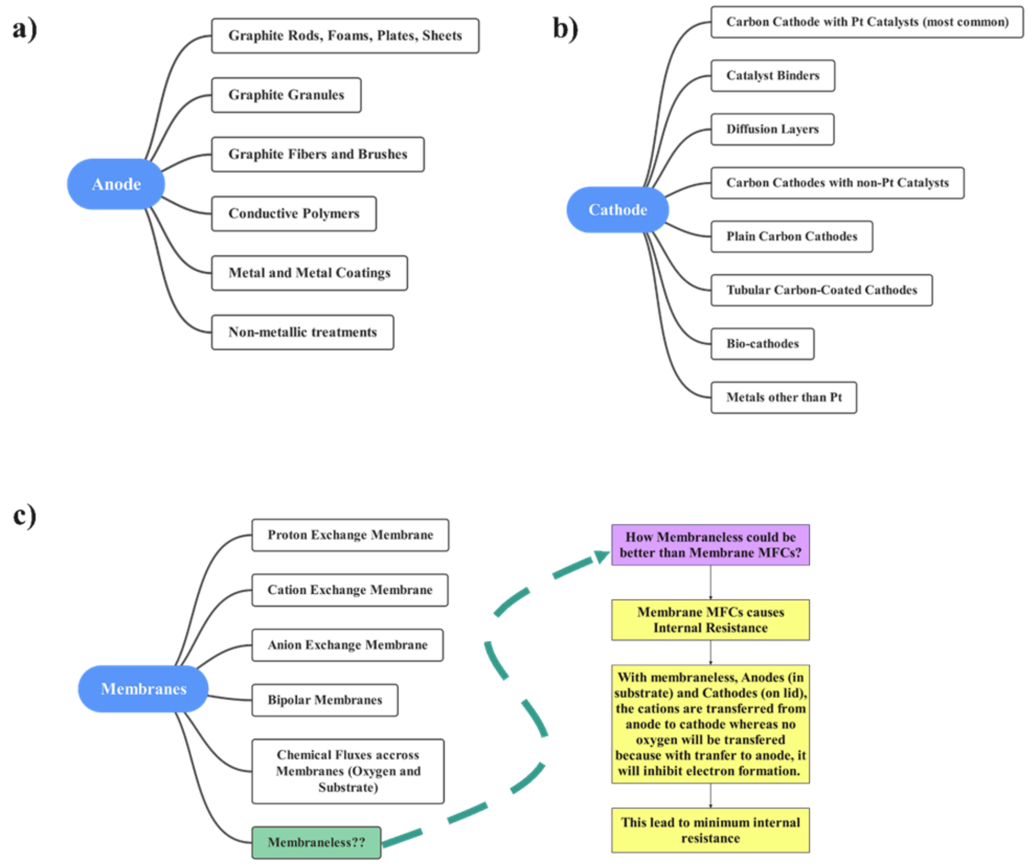

Figure 3. Primary Composition of Materials in Microbial Fuel Cells[24][25][26][27][28][29].

The various applications of MFCs include wastewater treatment, hydrogen production, biosensors, microbial electrosynthesis, and seawater desalination. The elucidation of these applications is showcased in Table 1.

Applications	Elucidation	Ref.
Wastewater Treatment	The generation of electricity and the purification of wastewater by removing pollutants can occur in microbial fuel cells. The micro-organism breaks down organic compounds, cleaning the water while producing usable energy.	[17]
Hydrogen Production	Biohydrogen production occurs inside MFCs through microbial activity. This is one of the alternatives for green, low-carbon hydrogen production.	[30]
Biosensors	The detection of specific pollutants or pathogens based on changes in electrical output. Hence, MFCs also help in environmental monitoring.	[31]
Microbial Electrosynthesis	The MFCs help convert carbon dioxide into valuable chemicals. The micro-organisms inside the MFCs use electrons from the anode to reduce carbon dioxide into biofuels, biogases, biomethanol, bioethanol, and other compounds.	[32] [33]
Seawater Desalination	The desalination of seawater through energy generation during microbial metabolism and also help in the testing of freshwater in coastal areas could be done through MFCs.	[34] [35]

Table 1. Elucidation of MFCs Applications.

1.3. Need for Life Cycle Assessment and Industrial Scale-Up Variability in MFCs

There is an existential necessity for Life Cycle Assessment (LCA) and Industrial Scale-Up Variability in Microbial Fuel Cells[36][37][38]. Some primary reasons behind the need for LCA in MFCs include environmental impact evaluation, avoidance of burden shifting, materials and energy use optimisation, and critical comparative analysis. LCA assesses the environmental performances of MFCs throughout the overall working cycle, from raw materials to disposal, based on several impact categories. This helps in the identification of ecological hotspots and potential areas for improvement. LCA analyses and ensures that any improvements in one of the stages of MFCs do not lead to negative impacts elsewhere, either in the MFC cycles or outside. The most significant role of LCA for MFCs is that it benchmarks MFCs and other energy systems based on applications through which MFCs work[39][40].

The primary need to thoroughly analyse and assess industrial scale-up variability is due to the scale-up challenges and potential of industrial applications. The significant scale-up challenges include energy consumption, cost and efficiency. Due to the growth in the size of microbial fuel cells, energy consumption increases due to the large volume, membrane resistances, and electron transfer losses[41]. Materials, maintenance, and construction expenditures increase on an industrial scale. One of the significant challenges also arises in the mutuality of efficient energy and maintaining performance. The potential industrial applications include the research and development of large-scale MFCs for water treatment, biosensors and bioenergy production[42].

The significant need for this review is due to the exigency of such LCA and industrial scale-up variability in microbial fuel cells. When the research & development activities are analysed of Life Cycle Assessment and Industrial Scale-Up Variability concerning the current MFCs activities, it was found that not much focus is dived into these crucial aspects[43][44]. The significant statistics of such research and development activities are showcased in Figure 4[7][42][14][45][46].

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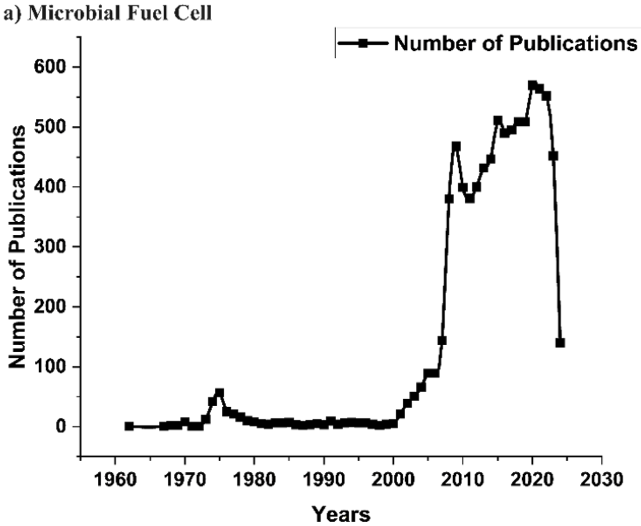
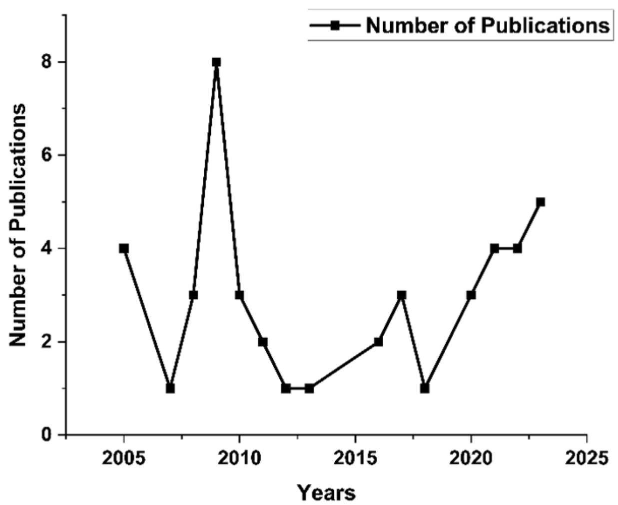
a) Microbial Fuel Cell



b) LCA in Microbial Fuel Cell



c) Industrial Scale-Up in Microbial Fuel Cell

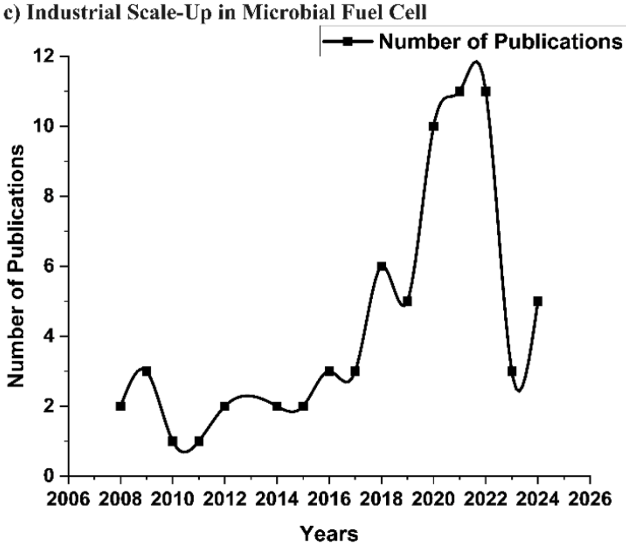


Figure 4. Research and Development Activities of MFCs, LCA and Industrial Scale-up Variability[7][42][14][45][46].

2. Structurisation of LCA in MFC

Life cycle assessment could be fundamentally divided into goals and scope, life cycle inventory, life cycle impact assessment and life cycle interpretation[47]. The goals and scope could be step-wise interpreted as primary objectives, the potential environmental impact of MFCs, the entire working cycle of MFCs and maintenance assessment[48][49]. The life cycle inventory includes material and energy consumption during construction and the developmental and operational stages. The tabular formation of the stepwise analysis of Life Cycle Assessment in MFCs is elucidated in Table 2[50]. The steps involve goal definition and scope, inventory analysis, impact assessment, interpretation, sensitivity analysis, scenario analysis, recommendations and improvement strategies.

Steps	Elucidation
Goal Definition and Scope	Defining the purpose of the assessment and specification of the system boundaries
Inventory Analysis	Data collection of all MFCs inputs and outputs. This includes raw materials, energy consumption, water usage, and emissions during the working cycle.
Impact Assessment	Quantification of the environmental impacts using various impact categories as well as application of the characterisation factors for the conversion of inventory data into impact scores.
Interpretation	Identifying hotspots is done by analysing the results and comparing MFCs with other energy systems.
Sensitivity Analysis	Assessment of the variations caused in impact categories due to the change in parameters and identification of critical factors affecting environmental performances.
Scenario Analysis	Exploration of the alternative material, wastewater and disposal methods in MFCs.
Recommendations and Improvement Strategies	Proposing of the strategies for the reduction of environmental impacts.

Table 2. Stepwise Analysis of Life Cycle Assessment for Microbial Fuel Cells[50].

The life cycle impact assessment contains an analysis of impact categories involving the selection of impact categories, global warming, fine particulate matter formation, human carcinogenic toxicity, terrestrial acidification, freshwater eutrophication, marine ecotoxicity, fossil resource scarcity, and mineral resource scarcity[51]. The following impact categories are based on various types of wastewater used in microbial fuel cells. Besides wastewater impact categories, several material-based MFC impact categories are also required, including anode, cathode, and membrane impact categories. The flowchart for Microbial Fuel Cells for Life Cycle Assessment is shown in Figure 5[52][53].

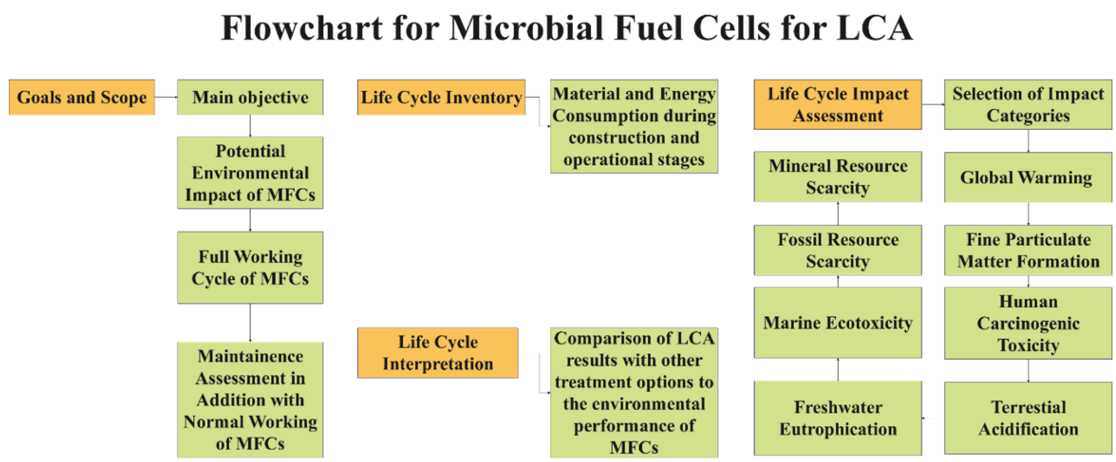


Figure 5. Flowchart for Microbial Fuel Cells for Life Cycle Assessment[52][53].

3. System Boundaries for LCA in MFCs

The most crucial components of system boundaries include functional units, boundary inclusions, boundary exclusions, allocation methods, cradle-to-grave approach, and functional equivalence[54][55]. The system boundaries could be divided based on different treatment systems, including MFCs, MEC, MDC, constructed wetlands, agricultural sludge treatment and activated sludge. The primary reason behind the system boundaries is to include construction, operation, maintenance and end-of-life assessments[56][57][58]. Bound exclusions entail upstream and downstream processes. The upstream processes exclude the processes related to the raw material extraction done before the construction of MFCs. Downstream processes exclude the impacts that are beyond MFC disposal. Figure 6 discusses the system boundaries for Life Cycle Assessment and comparative results for MFC through LCA[59][60][61].

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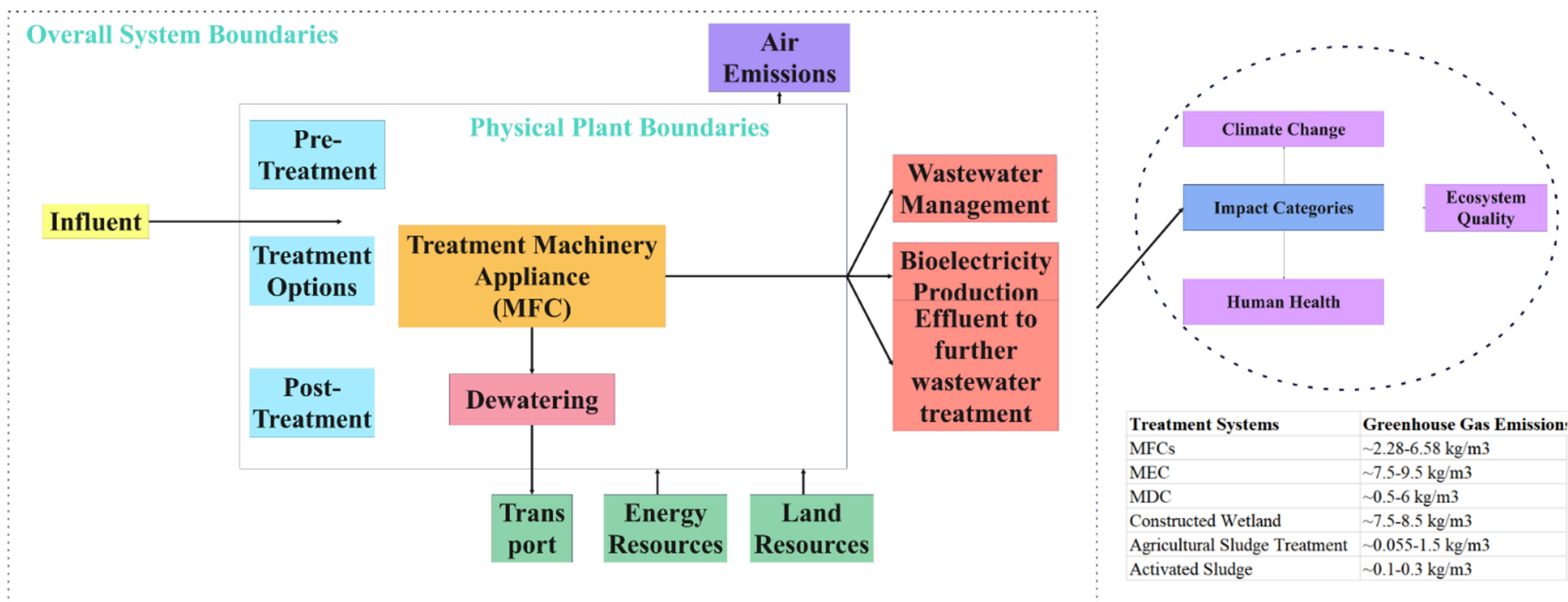

Treatment Systems	Greenhouse Gas Emission:
MFCs	~2.28-6.58 kg/m3
MEC	~7.5-9.5 kg/m3
MDC	~0.5-6 kg/m3
Constructed Wetland	~7.5-8.5 kg/m3
Agricultural Sludge Treatment	~0.055-1.5 kg/m3
Activated Sludge	~0.1-0.3 kg/m3

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Figure 6. System Boundaries and Comparative Results for MFC through LCA[59][60][61].

Upon observing several reports, several treatment systems were considered as a dataset to give a comparative analysis of greenhouse gas emissions for MFCs. It was found that the greenhouse gas emissions were reported to be the minimum in Microbial Desalination Cells (MDC) as per the microbial setups[62]. In contrast, agricultural sludge treatment and activated sludge produced the minimum greenhouse gas emissions. The impact categories upon which the total system boundaries are calculated gave aspects on three categories: climate change, ecosystem quality and human health.

4. Challenges and Solutions in Industrial Scale-Up of Microbial Fuel Cells

Energy consumption, Cost, Operational fouling, and voltage and current reversals are essential challenges in the industrial scale-up of MFCs. Significant challenges involving these parameters include higher energy consumption, overall system costs, lower power density during scale-up, electrode, membrane fouling, and stacked or series MFCs, which face such problems[63]. Several solutions have been proposed to tackle these challenges. Improving electrode materials, reactor configurations, microbial community management, advanced control strategies, optimising stack arrangement, managing internal resistances, regular maintenance, proper cleaning protocols, use of innovative materials, optimisation of reactor designs and modifying operational parameters are some of the core solutions which could be applied to tackle the challenges of industrial scale-up of microbial fuel cells[64][65]. The detailed flowchart of the challenges and solutions of industrial scale-up of MFCs is discussed in Figure 7[66][67][68].

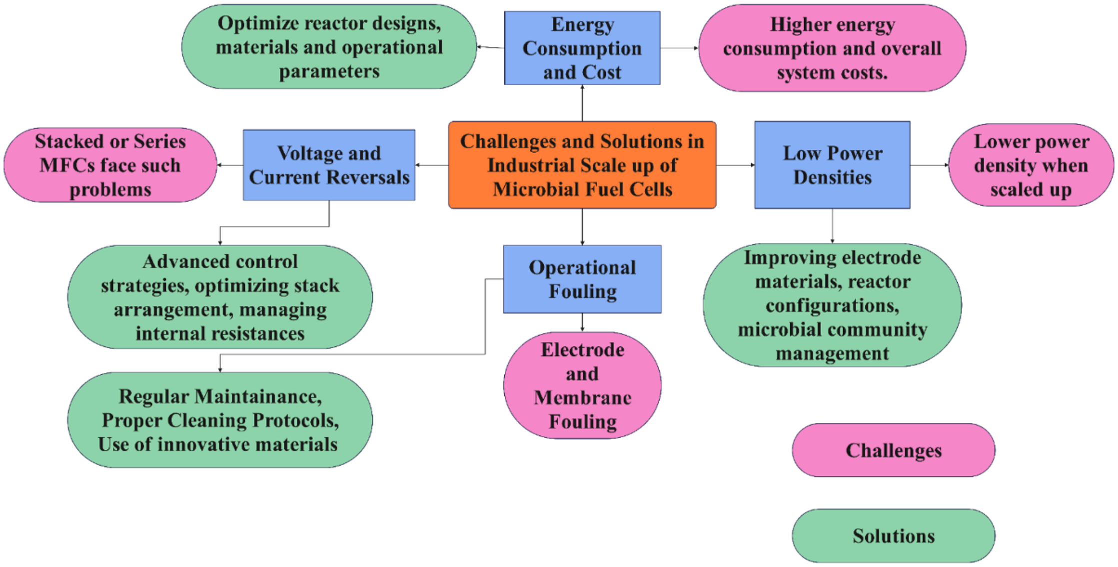

Figure 7. Challenges and Solutions in Industrial Scale-Up of Microbial Fuel Cells[66][67][68].

When we look at the scale-up of MFCs, the materials used in the membranes, anodes and cathodes play a crucial part in calculating its treatment efficiency, overall costs of MFCs, COD levels and power density. Hence, it is essential to analyse the majority of materials used in the components of MFCs to commercialise industrial applications[69][70].

5. Majority of Materials Used in the Components of MFCs for Commercialisation

To check the majority of materials used in the components of microbial fuel cells, the volume taken from the previous project was set as more than 20 litres. 24 reports were gathered through various setups of microbial fuel cells, including double-chambered microbial fuel cells, single-chambered microbial fuel cells, and 3-phase single-chambered microbial fuel cells. The material dataset used in most industrial scale-up MFCs includes carbon brushes, activated carbon, carbon cloth, activated semicoke, carbon felt, granular graphite and stainless steel. The most used materials involve carbon brushes and activated carbon, used in 25.1% and 33.2% of the industrial scale-up MFCs[71].

The criticality of the analysis is that even though most materials are carbon brushes and activated carbons for industrially scaled MFCs, they are not the materials with the most efficient

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performances[69][72]. Carbon Cloth and Granular Graphite showcased maximum COD, which is 98.3% and 96%, respectively, and the power densities of the materials were 1680 and 3500 mW/m3. The overall material analysis pie chart has been assessed in Figure 8. The tabular format of each MFC reported has been showcased in a tabular format in Table 3.

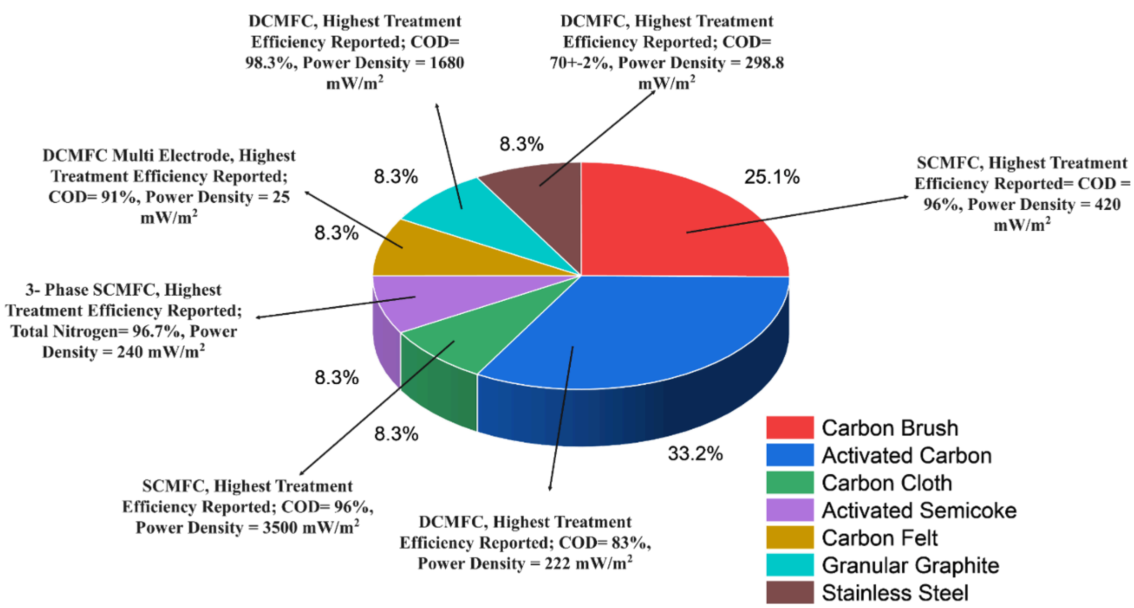

Figure 8. Material Analysis of Industrial MFCs[42][24][10][11][27][60][8][44].

The primary electron transfer occurring in the electrodes mainly happens to the biofilm material, which formulates on the materials[73][74]. The formation of biofilms is highly significant for both the wastewater treatment and bioelectricity production in Microbial Fuel Cells . Hence, the materials used in the MFCs help formulate consistent biofilms. The overall mechanism through which electron transfer happens through biofilm is demonstrated in Figure 9[75][76][77].

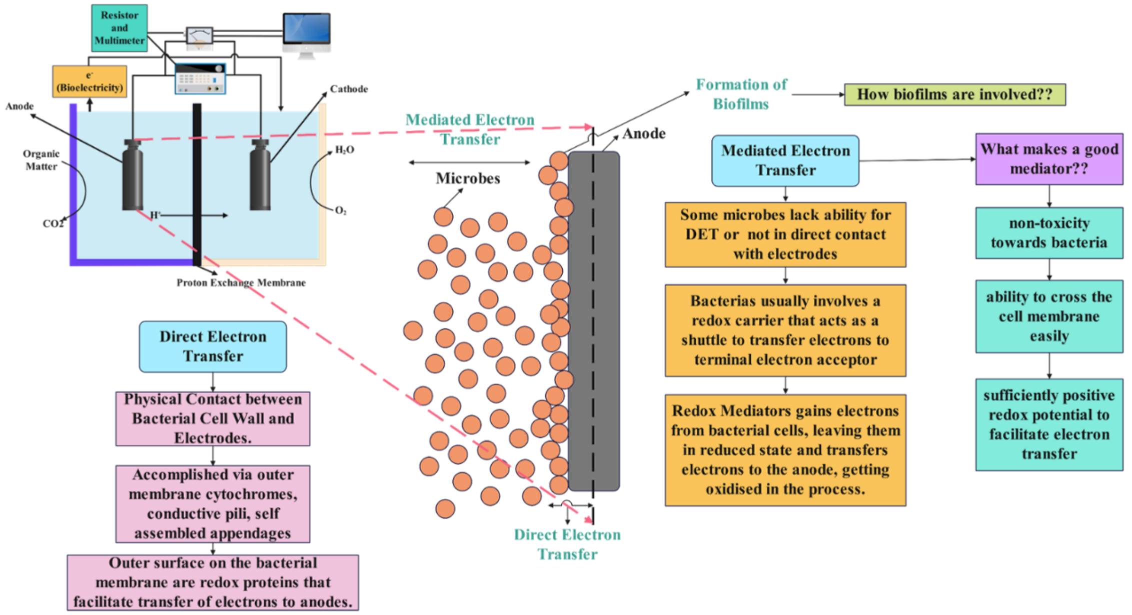

Figure 9. Biofilm mechanism for electron transfer in Microbial Fuel Cell[75][76][77].

To comprehend the performance of the electrode, it is necessary to evaluate the surface area (cm2), Imax (A/m2) and Pmax (mW/m2). Various carbon-based electrodes are evaluated from previous literature, involving carbon nanotubes, carbon nanofiber, carbon mesh, tubular bamboo charcoal, granular activated carbon particles, multi-brush carbon, carbon paper, and carbon paper. The tabular representation of the electrodes, MFC configuration, substrate and anode surface area, Imax and Pmax is shown in Table 3[78][34][79].

Electrode	MFC configuration	Substrate Used	Electrode Surface Area (cm^2)	I_{max} (A/m^2)	P_{max} (mW/m^2)	Ref.
Corrugated Carbon	Three-electrode cell	Synthetic Wastewater	26.52	390	NA	[76]
Graphite Rod	Three-electrode half cell	Synthetic Wastewater	11.5	5.17	NA	[80]
Carbon Yarn	Single chamber dual cathode	Domestic Wastewater	1018	18.15	364	[81]
Carbon Nanofiber	Micro-litre sized MFC	Acetate mineral media	0.28	0.083	22000	[82]
Carbon Nanotube	Micro-litre sized MFC	Acetate mineral media	0.28	0.0234	49000	[83]
Carbon Paper	Micro-litre sized MFC	Acetate mineral media	0.28	0.096	10000	[84]
Carbon mesh	Single chamber	Domestic wastewater	7	NA	1330	[85]
Multi-brush carbon	Single chamber	Acetate media	8	4.2	1200	[86]
Porous carbon with a defined pore size	Single chamber	Glucose phosphate-buffered basal medium	9	13.4	1606	[87]
Granular activated carbon particles	Dual chamber	Acetate Media	10	2.6	951	[88]
Tubular bamboo charcoal	Tubular two-chamber MFC	Synthetic Media	NA	NA	1652	[76]

Table 3: Carbon-based electrode material based on their performance.

6. Industrial Scale Up Variability in MFCs

Based on different types of industrial MFCs with separate volumes and factors that contribute to the overall performance of such MFCs, several models of such MFCs were taken into account, which involved stacked MFC with 96 tubular modules, stacked MFC with 50 modules, stacked MFC with 18 modules, 10 dual chambers in series, 2 dual-chamber in series and 1 dual chamber. The primary reason for industrial scale-up "variability" is due to various combinations of volume and cost differences in the industrial microbial fuel cells[89][90].

There is an urgent need to scale up MFCs, and stacking modular multiple units with improved power management systems appears to be an efficient solution. A potential approach is to use the modular concept of multi-MFC units in a wastewater treatment system[91][92]. The increased surface area of electrodes does not always translate into a greater proportionate power harvesting rate because microbial electrochemical methods are associated with increased Ohmic internal resistances. The tabular representation of the technical aspects of the performances of pilot-scaled microbial fuel cells is demonstrated in Table 4 based on volume, anode material, power density, COD removal % and Hydraulic Retention Time[93][94][95].

Recently, there has been a lot of interest in applying bioelectrochemical systems, such as MFCs, for treating industrial wastewater and recovering resources from the circular economy initiative. MFCs are utilised to produce power and treat wastewater. The investigation's focus may vary, as is typical for studies that combine the environment and energy. Specific research focused primarily on the characteristics of wastewater treatment and how it affects efforts to prevent environmental pollution. Other research focuses on the characteristics of energy generation and the financial implications compared to other traditional systems.

MFC Architecture	Volume (in Litres)	Electrode Material	Power Density (W/m^3)	COD Removal (%)	Hydraulic Retention Time (HRT) (days)	Ref.
Stack	10 (5 units)	Activated Semicoke	175.7	77-84	NA	[96]
Two Chambers	50	Semicoke	43.1	95	0.5	[97]
Stack	72	Activated Carbon	50.9	78-95	2	[98]
Stack	90	Carbon brush	0.12	82.7	3	[99]
Stack	94	SS mesh	2	40	NA	[99]
Stack	200	Carbon brush	0.009	75	0.75	[100]
Single Chamber	250	Carbon Brush	0.47	86	5	[101]
Stack	1000	Activated Carbon	7-60	70-80	0.08	[102]
Stack	1000	Activated Carbon	125	80-90	0.08	[18]
Bioelectric Toilet MFC	1500	Carbon brush	75	95	NA	[15]

Table 4. Industrial Performances of the Microbial Fuel Cells.

The scalability of MFC, which can be achieved via size expansion or stacking configurations and is subject to certain operational and design constraints, is what separates the feasibility of MFC technology transition from its reality[103][104]. Research is needed to understand microbial activity in scale-up reactors, as our understanding of the microbial processes occurring within a live reactor is still in its early stages. The reactor's architecture can be updated to handle operational disruptions and allow for self-sustaining use. Due to the MFC's scalability, research has focused on modularity and

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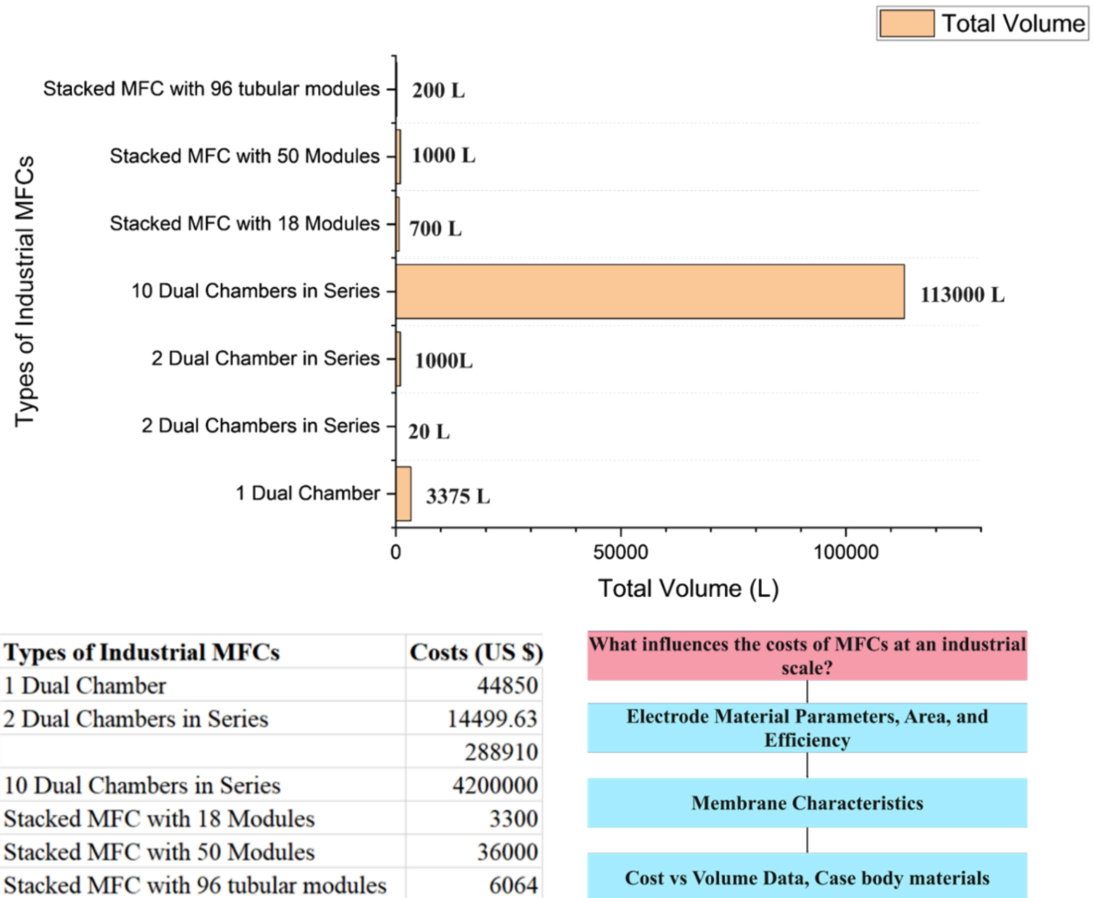
stacking small units to store charges using electrical circuitry[105]. MFC can be successfully implemented as a capable wastewater treatment option on bigger scales, but it is too far away to be used as a stand-alone external power source. The application of MFC by businesses, robots, and biosensors, in addition to recovering precious resources, is one of the central stepping stones towards commercialising such intricate bioelectrochemical systems in the future[106].

The financial impact of MFC systems on the comparatively low power densities achieved is another crucial factor that must be considered. The cost of using MFCs for wastewater treatment is substantially more significant than that of conventional wastewater treatment. Additionally, the cost of generating energy from MFCs is higher per unit than other renewable energy sources, such as biomass, solar, and wind. Chemical engineers and biotechnologists are the ones who can solve this[107]. More complex reactor layouts must be devised to obtain higher power densities at reduced operating and maintenance costs[108][109]. A more profound comprehension of microbial biofilms and the related metabolic processes can also enhance energy production. MFC reactors can also be combined with traditional wastewater treatment techniques to improve reactor performance in terms of COD removal and resource recovery. The underlying technology for MFC reactor configuration and development can also be optimised with recent research on MFC applications in robotics and artificial symbiosis . The infographics of the industrial scale-up variability in MFCs, which portray the types of industrial MFCs based on volume and cost in USD, are shown in Figure 10[107][89][108][105][109].



Types of Industrial MFCs	Costs (US $)
1 Dual Chamber	44850
2 Dual Chambers in Series	14499.63
	288910
10 Dual Chambers in Series	4200000
Stacked MFC with 18 Modules	3300
Stacked MFC with 50 Modules	36000
Stacked MFC with 96 tubular modules	6064

Figure 10. Infographics of Industrial Scale-Up Variability in Microbial Fuel Cells[107][89][108][105][109].

7. Integration of Life Cycle Assessment with Industrial Scale-Ups for MFCs

The Life Cycle Assessment (LCA) technique is utilised to assess the environmental performances of various bioelectrochemical systems (BES), such as integrated MFC systems, microbial fuel cell (MFC), microbial electrolysis cell (MEC), and microbial desalination cell (MDC). While MD + MFC (membrane distillation integrated MFC) has the least negative effects on human health and ecosystems among all integrated MFC treatment options, MEC1 (double chamber air-cathode MEC) is the most environmentally friendly option among all endpoint damage categories[110][111]. The most notable environmental hotspot is electricity consumption for operation, which accounts for 90% of the damage to the global warming effect category.

Given worldwide worries about climate change and water cleanliness, BESs may be used in various places to address these issues[112]. To verify the MFC system's viability, further research can be done in particular BES configurations, such as economic analysis of BES, uncertainty and sensitivity analyses on the electricity mix variation, and wastewater BOD or COD removal rate. The study's findings should give stakeholders in wastewater treatment plants data-driven insights to help them select the best BES configurations to reduce their influence on the environment and improve water sanitation[113].

To integrate the life cycle assessment with the industrial scale-up, it is essential to identify the environmental hotspot, optimise design constructions, energy efficiency, waste valorisation and industrial integration. Such integration helps identify areas where MFC requirements will be there. Such analysis of energy consumption, emissions and resource use. Identifying suitable materials for varied conditions helps minimise carbon footprint and maximise industrial scalability. The proposed integrated life cycle assessment and industrial scale-up variability aspects for the large-scale efficient Microbial Fuel Cells are shown in Figure 11[114][34][115][92].

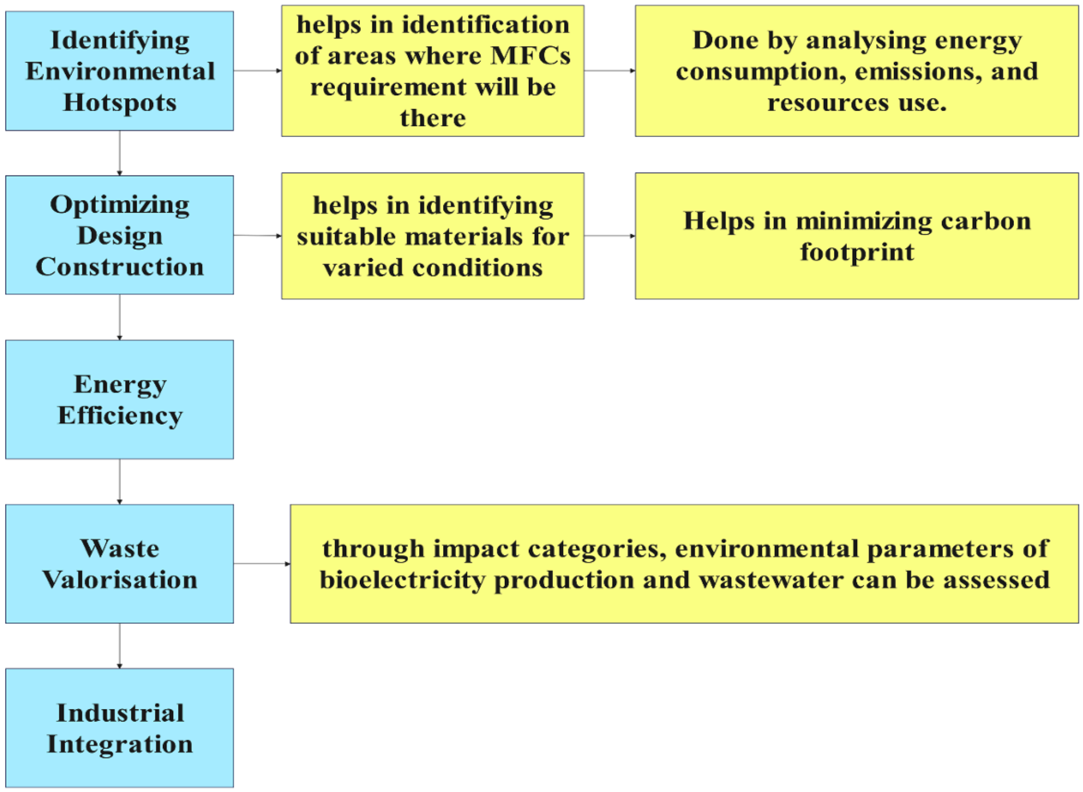


Figure 11. Step-wise Integration of Life Cycle Assessment with Industrial Scale-Ups for MFCs[114][34][115][92].

8. Future Direction of Microbial Fuel Cells

Some new perspectives from which microbial fuel cells can be incorporated into novel and innovative directions involve a thorough and complete analysis of several variations in Life Cycle Assessment, Environmental Impact Assessment, Modelling, Simulations, Machine Learning Models, Artificial Intelligence Networks, and Computational Characterisation tools[116][117]. From such computational software, several current 'idealities' in MFC could be transformed into experiments to examine the industrial scale-up[118]. To assess the building of the Microbial Fuel Cell through the modelling and simulations are demonstrated in Figure 12[119][120].

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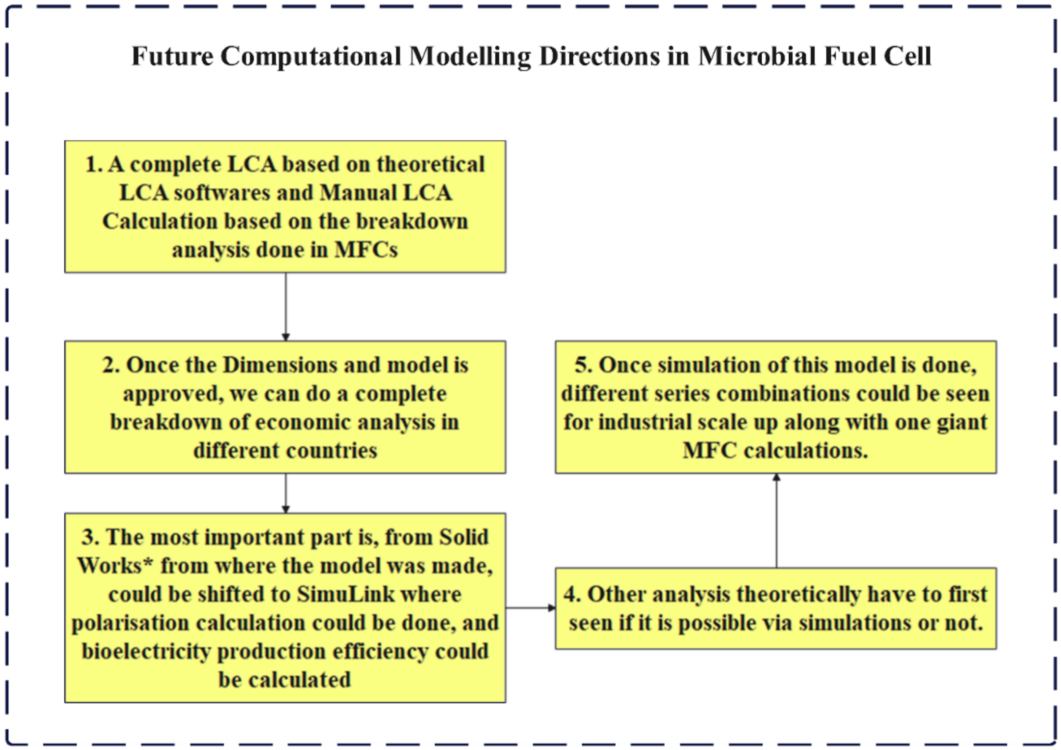

Figure 12. Future Computational Modelling Directions in Microbial Fuel Cells[119][120].

9. Conclusions

The fact that MFCs were initially created as scientific experiments remains largely accurate. MFCs, however, are a very flexible platform technology with many potential uses, according to the current study. The unique capacity of MFCs to produce energy from waste without needing an external energy source is one of its defining characteristics. Due to this feature, MFCs are suitable for remote region access via robotic systems or for generating electricity in isolated areas. Being very selective and sensitive "sensors" of their surroundings, microbes provide a clear benefit in MFCs by immediately capturing microbial reactions and metabolism and converting them into analogue electrical signals. MFCs can adapt to different conditions and work well with specific microorganisms thanks to their inherent sensing capability. Even though funding and development for MFCs are still in their infancy, further study into these systems gives hope for resolving environmental issues worldwide. By offering environmentally acceptable and sustainable solutions for energy generation and environmental remediation, MFCs can significantly impact both our planet's future and that of future generations.

Several challenges are there for MFCs, which include operational fouling, voltage & current reversals, energy consumption, cost, and low power densities. Still, with adequate solutions, such challenges can be easily tackled. Upon review, Carbon Cloth and Granular Graphite showcased maximum power density and COD removal at an industrial level and should be used for future industrial scale-up. Several influences and cost analyses were done for different industrial-scaled MFCs through infographic analysis. As mentioned, the main objectives required for LCA in Industrially Scaled Up MFCs were showcased, and specific impact categories were concluded. Several LCA reports of treatment options were also reported, and based on a standard algorithm for GHG emissions through LCA, MFCs showcased 2.28-6.58 kg/m3 of emissions for a single chamber MFC to process 1L wastewater. Identifying environmental hotspots, optimising design construction, energy efficiency, waste valorisation and industrial integration are showcased and analysed as the results of LCA, which are used for industrial scale-up of MFCs.

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