Engineering Perspectives in Filtration and Separation, Vol. 4, No. 1, March 2026
ISSN:3107-5290

Optimization of Microbial Fuel Cell Performance Using Agricultural Waste-Derived Carbon Electrodes for Sustainable Bioelectricity Generation

Dr. Srishti Singh Chauhan[1] and Dr. Abhijeeta Nandha[2]*

[1]Assistant Professor, Department of Biotechnology, Kalinga University, Naya Raipur, Chhattisgarh, India.*
E-mail: ku.srishtisinghchauhan@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0001-3116-2016

[2]Assistant Professor, Department of Biotechnology, Kalinga University, Naya Raipur, Chhattisgarh, India.
E-mail: ku.abhijeetanandha@kalingauniversity.ac.in, Orcid: https://orcid.org/0009-0009-9958-0175

Abstract--- Microbial fuel cells can be considered a sustainable technology in wastewater treatment and electricity production; however, the low power density, costly electrodes, and unpredictable operation performance have prevented practical use. In this research, agricultural waste-based carbon electrodes are investigated, and the current study attempts to present an evidence-based optimization approach for materials selection and electrochemical performance through investigating the following aspects: electrode fabrication, carbonization temperature, chemical activation, power density, and chemical oxygen demand (COD) removal efficiency. In the reviewed devices, the highest power densities were between 26 and 2171 mW m^{-2}. The graphitized mango-seed carbon generated 2171 mW m^{-2}, whereas the Datura peel biochar generated 584 mW m^{-2} power density with COD removal efficiency of 85.4%. In addition, increasing the graphitization temperature of mango-seed from 1000 to 1100 °C increased power density from 1351 to 2171 mW m^{-2}. Cathode modification enhanced the obtained power density from 542 to 2178 mW m^{-2} using similar experimental conditions. The results obtained through comparison show that carbonization temperature, activation techniques, electrode loading, compaction, and cathode setup are key variables affecting optimization. The suggested model considers all the aforementioned variables, electricity production, and wastewater treatment analysis. Waste agricultural products-based carbon electrodes have shown promise as a sustainable source of energy, but there is need for further research before implementing them in actual wastewater treatment plants.

Keywords--- Microbial Fuel Cell, Agricultural Waste, Biochar, Carbon Electrode, Power Density, Wastewater Treatment.

Received: 22 - 12 - 2025; Revised: 12 - 01 - 2026; Accepted: 24 - 02 - 2026; Published: 30 - 03 - 2026

I. Introduction

Microbial fuel cells (MFCs) are one of the innovative bioelectrochemical processes which combine the purification of the organic wastewater stream along with renewable power production. Such systems use electroactive microbes to degrade organic matter by transferring electrons to the anode via oxidation reaction. Therefore, the production of the electrical power becomes possible due to the external circuit connection. However, low electrical power generation, internal resistance, and expensive electrodes are considered the key problems which hinder the applicability of MFCs (Chao, 2025; Merga et al., 2025).

The materials used for the electrodes are highly significant in the microbial attachment, the efficiency of electron transfer, and conductivity of the reaction medium. Carbon cloth, graphite felts, and carbon papers are some examples of electrode materials; however, they may add to the expense of the process since they possess the required electrochemical qualities. Agricultural residues are considered an inexpensive option due to their easy availability and the presence of carbon-based structure (Cao et al., 2022; Javanmard et al., 2024).

Examples of agricultural waste include fruit skins, seed shells, and rice husk which generate porosity in carbon to encourage biofilm formation by microbes. The electrochemical characteristics of carbon depend on the temperature of carbonization, chemical activation, functional groups on the surface, porosity, and electrode

configuration. Suitable processing techniques enhance the electrical conductivity and microbial adhesion, while poor processing leads to lower carbon production or high electrical resistance (Zhao et al., 2023; Mishra et al., 2024).

Previous studies have highlighted major differences in the performance of agricultural carbon electrodes with regard to electricity production. The difference is not only due to the nature of the feedstock but is also caused by the electrode manufacturing process, reactor design, substrate components, and microbial behavior. As such, it is important to consider these factors when designing an electrode.

This research explores the existing data regarding the performance of carbon electrodes produced from agricultural waste in experimental settings and formulates an optimized strategy for bioelectric power production based on that evidence. The primary research goals include evaluating the performance of the electrodes, determining the impact of the process variables, assessing wastewater treatment efficacy, and formulating a strategy for electrode optimization.

II. Literature Survey

Agricultural Waste-Derived Carbon Electrodes

Carbon materials from agricultural wastes have been considered as sustainable materials as a substitute for traditional MFC electrodes. Agricultural biomass waste contains carbon material which can be made into porous electrode material by thermal treatment. This approach could limit the reliance on commercial carbon materials, in addition to valorization and recycling of agricultural waste resources (Cao et al., 2022; Javanmard et al., 2024). Biochar-based electrodes serve as an available substrate for the immobilization of microorganisms and electron transfer. Properties such as porosity, surface chemistry, electrical conductivity, and interaction with the electroactive microorganism determine their performance in the MFC process (Zhao et al., 2023; Mishra et al., 2024).

Previous Studies on MFC Electrode Performance

The graphitized mango-seed carbon has shown an attained power density of 2171 mW m^{-2} that shows the potential of thermo-treated agricultural waste in bioelectricity production. Studies have further evaluated biomass-based anode and carbon nanotubes cathodes for improving the electrochemical performances (Barakat et al., 2024; Barakat et al., 2023). The biochar from Datura peel obtained through pyrolysis and KOH activation showed a power density of 584 mW m^{-2} and 85.4% COD removal suggesting the simultaneous generation of electricity and degradation of organic contaminants (Vempaty et al., 2023). Biochars from different nuts shells such as peanut shell, coconut shell, and walnut shell produced power densities of 165, 101, and 56 mW m^{-2}, respectively (Sonu et al., 2025a). The orange peel-based activated carbon produced 164 mW m^{-2}, whereas the carbon from Trapa natans hulls was studied for the application in plant MFC (Sonu et al., 2025b; Włodarczyk & Włodarczyk, 2024). Other studies on activated carbon from coconut and rice-hulls as the electrodes also stressed the significance of material processing and reactor design (Taniguchi et al., 2021; Aleid et al., 2023). The use of sugarcane waste has also been studied as the MFC substrate (Yaqoob et al., 2023).

Research Gap

While previous studies have shown the feasibility of agricultural carbon electrodes, it is difficult to make comparative evaluations because of varying feedstocks, carbonization temperatures, chemical activation, electrode construction, and reactor configuration. In addition, some previous studies focus on electricity production while neglecting the efficiency of the wastewater treatment process, electrode longevity, and cost of electrode production.

Hence, there is need for a comprehensive evaluation strategy for understanding the important electrode preparation parameters and their future optimization. The current research aims to fill the gap through performance evaluation of previously published studies.

III. Methodology and Proposed Optimization Framework

Research Design

This research uses a comparative methodology that involves the analysis of literature on the performance of carbon electrodes made from agricultural wastes in MFCs. Research findings obtained within the period 2022 and 2025 were analyzed in order to determine the relationships among electrode material, process parameters,

electricity production, and efficiency of wastewater treatment. The methodological approach entails data analysis, performance assessment, comparative analysis, determination of optimization variables, and formulation of electrode optimization framework.

Data Collection and Selection Criteria

Experimental research papers using carbon electrodes made from agricultural waste were chosen from the available literature. The materials examined include mango seed carbon, biochar from Datura peels, biochar from nutshells, activated carbon from orange peels, carbon from Trapa Natans husks, and activated coconut carbon. The main parameters that have been extracted are the kind of material used for making carbon, the carbonization temperature, the activation method, electrode design, maximum power density, COD removal percentage, and reference.

Performance Evaluation Metrics

Maximum power density was used to assess electricity-generation performance equation (1):

$$P_{\max} = \max\left(\frac{VI}{A}\right) \quad (1)$$

Where V is the measured cell voltage, I represents current, and A is the normalization area.

COD removal efficiency was calculated using equation (2):

$$\mathrm{COD}_{\mathrm{removal}}(\%) = \frac{\mathrm{COD_i} - \mathrm{COD_f}}{\mathrm{COD_i}} \times 100 \quad (2)$$

Where $CODi$ and $CODf$ represent initial and final chemical oxygen demand concentrations.

For matched experimental comparisons, relative power improvement was defined as equation (3):

$$R_P = \frac{P_{\max,\mathrm{test}}}{P_{\max,\mathrm{control}}} \quad (3)$$

Where RP represents the relative power-density improvement of the tested electrode compared with its control.

These are the formulas that allow to explain the experimental results that were found in the scientific literature. The polarization curves and measurements of wastewaters were not recalculated independently.

Proposed Electrode Optimization Framework

The proposed framework for optimization includes the selection of the agricultural residue, treatment of the carbon, evaluation of the electrode properties, functioning of the microbial fuel cells and performance evaluation. Initially, agricultural residues are selected based on the presence of carbon, processes involved in the treatment, and possible usage of the materials as electrodes. Further, the materials are treated either by carbonization or chemical activation to alter the properties of conductivity, porosity, and surface properties. The treated carbon is then tested for its use in forming an electrode. The process of electrode loading, compacting, and electrode-cathode connections are also evaluated as they affect microbial attachment, electron transfer, and internal resistance.

This step includes evaluation of maximum power density, COD removal efficiency, and system stability. The results obtained from the above evaluations will be useful in further improving the carbonization parameters, electrodes loading, and reactor design. The whole process of optimization is shown in figure 1 below.

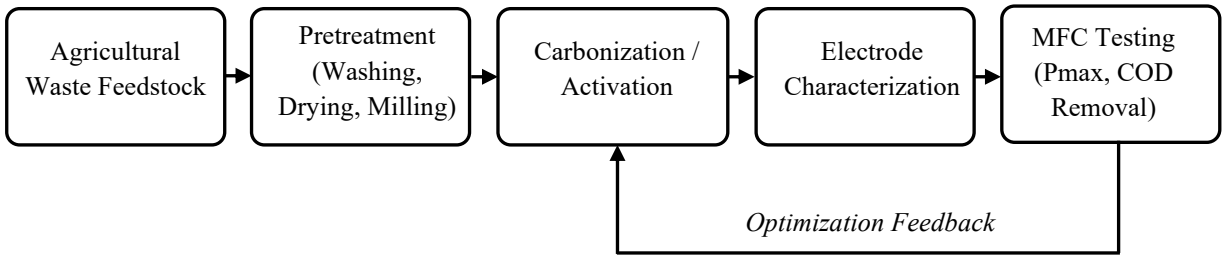


Figure 1: Proposed Optimization Framework for Agricultural Waste-Derived Carbon Electrodes in Microbial Fuel Cells

Comparative Evaluation Procedure

Comparisons of the extracted studies have been made in relation to maximum power density, removal of COD, and processing of the electrodes. Emphasis was placed on the effects of carbonization temperature, chemical activation, loading of the electrodes, cathode modification, and mechanical compaction.

IV. Results and Discussion

Comparative Performance of Agricultural Carbon Electrodes

There was much diversity in the performance of electricity generation using the reviewed agricultural waste-derived carbon electrodes. The values of the maximum power density varied from 26 to 2171 mW m^{-2} and are shown in table 1 below. Graphitized mango seed carbon was reported to have the highest value of power density at 2171 mW m^{-2} and 85% COD removal (Barakat et al., 2024). The biochar made from the peel of Datura using pyrolysis and KOH activation had a power density of 584 mW m^{-2} with 85.4% COD removal (Vempaty et al., 2023). The biochar from the Bixa orellana fruit shells and a ceramic rice-husk-ash anode produced 300 and 250 mW m^{-2}, respectively, having COD removal efficiency of 88.4% and 88%, correspondingly (Sonu et al., 2025a; Sonu et al., 2025b). The activated coconut carbon with carbon fiber support had an energy yield of 26 mW/m^2 and COD removal of 33% Włodarczyk & Włodarczyk, (2024).

Such results indicate that the efficiency of electrodes is determined by the properties of the biomass used, the method of electrode production, and the parameters of the reactor operation. Nevertheless, differences between the experimental setups discussed prevent direct performance comparisons. The table below provides the comparison of maximum power density and COD removal efficiency of agricultural waste-based carbon electrode designs. Graphitized carbon from mango seeds showed the greatest efficiency in producing electrical energy; at the same time, other discussed materials exhibited various combinations of both performance aspects.

Table 1: Reported Performance of Agricultural Waste-Derived Carbon Electrodes in Microbial Fuel Cells

Feedstock and treatment	Pmax (mW m^{-2})	COD removal (%)	Ref.
Mango seed, graphitized at 1100 °C	2171	85	Barakat et al., (2024)
Datura peel, 800 °C + KOH	584	85.4	Vempaty et al., (2023)
Bixa orellana fruit-shell biochar, 1.5 g	300	88.4	Sonu et al., (2025a)
Rice-husk-ash ceramic anode, 50% RHA	250	88	Sonu et al., (2025b)
Activated coconut carbon, fiber support	26	33	Włodarczyk & Włodarczyk, (2024)

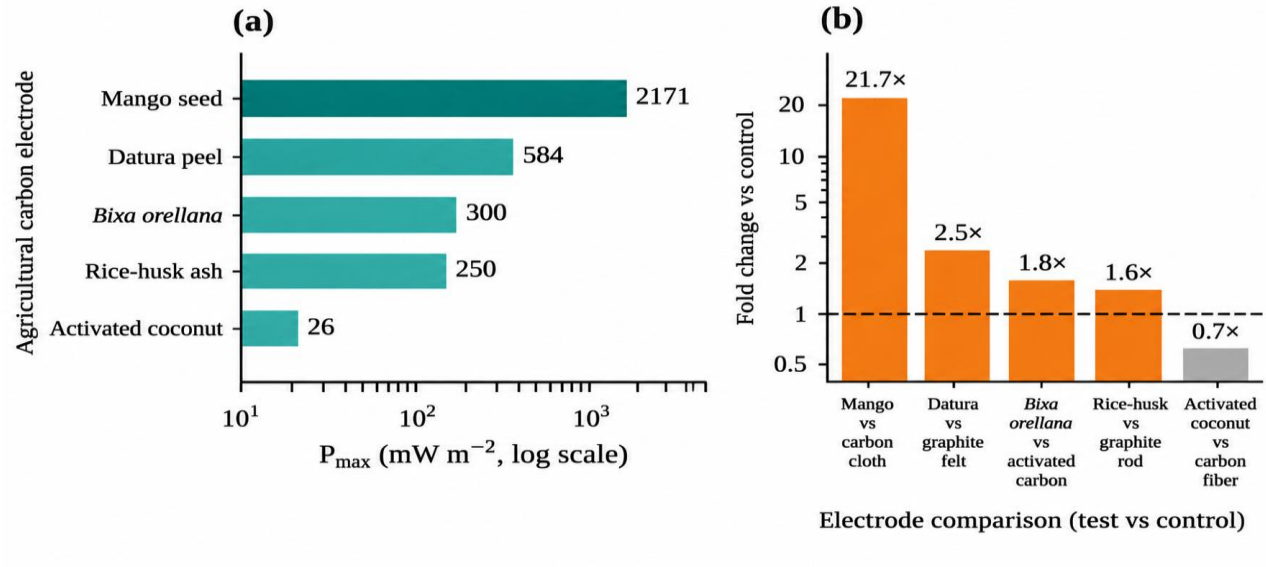


Figure 2: (a) Reported Maximum Power Density of Agricultural Waste-Derived Carbon Electrodes and (b) Relative Power-Density Changes Compared with Matched Control Electrodes

The maximum power density of the carbon electrodes developed from agricultural waste has been shown in figure 2(a), showing the variation depending on the choice of feedstock and development of the electrodes. Relative power density variations when compared to their respective control electrodes in individual experiments have been shown in figure 2(b). The values that are above unity imply superior performance, while those below unities imply inferior performance to the control.

Effects of Electrode Processing and Design

Electrode processing parameters have considerable impacts on the electrical performance. For the mango seed system, the power density was raised from 1351 to 2171 mW m^{-2} when the graphitization temperature was raised from 1000 to 1100 °C, which was about 61% enhancement (Barakat et al., 2024). Chemical activation can change the pore availability and surface features. For example, Datura peel biochar processed by KOH activation yielded 584 mW m^{-2}, whereas the 1 mg cm^{-2} electrode loading correlated with the greater biofilm biomass (Vempaty et al., 2023). The modification of the cathode affected the electricity production as well. In particular, the 7 wt% CNT carbon nanotube cathodes treated at 350 °C was linked with the reported increase in power density from 542 to 2178 mW m^{-2} (Barakat et al., 2023). Fivefold enhancement of a rice-husk based configuration was found using mechanical compaction with a 3D printed case (Aleid et al., 2023).

The variables involved in MFC performance are described in table 2. The carbonization temperature, chemical activation, electrode load, cathode configuration, and mechanical compacting contributed to better results in the reviewed literature. However, their combined influence needs to be experimentally confirmed.

Table 2: Processing and Design Variables Associated with MFC Performance

Optimization variable	Reported evidence	Ref.
Carbonization temperature	1000–1100 °C; 1351–2171 mW m^{-2}	Barakat et al., (2024)
Chemical activation	KOH after 800 °C pyrolysis; 584 mW m^{-2}	Vempaty et al., (2023)
Electrode loading	1 mg cm^{-2}; increased biofilm biomass	Vempaty et al., (2023)
Cathode design	7 wt% CNT at 350 °C; 2178 vs. 542 mW m^{-2}	Barakat et al., (2023)
Electrode compaction	3D-printed case; approximately 5× improvement	Aleid et al., (2023)
Feedstock selection	Peanut vs. walnut shell; 165 vs. 56 mW m^{-2}	Sonu et al., (2025)

Wastewater Treatment Performance

The effectiveness of wastewater treatment is one of the aspects taken into account when evaluating the practical application of microbial fuel cells. The maximum power density is the indicator of the amount of electricity produced by microbial fuel cell, while the COD removal rate is the number of organic substances removed from wastewater. The maximum COD removal was 85.4% at 584 mW m^{-2} for datura peel biochar (Vempaty et al., 2023). At the same time, the maximum COD removal achieved using the activated coconut-carbon was 33% at 26 mW m^{-2} Taniguchi et al., (2021). The usage of sugarcane waste as MFC substrate was correlated with the COD removal higher than 90%, which shows its possible effectiveness in the reduction of organic pollutants in wastewater. However, such comparison is not appropriate as it is related to the substrate efficiency (Yaqoob et al., 2023). These results point to the consideration of electricity production and wastewater treatment as complementary tasks. This approach is corroborated by existing research on the role of reactor design and operating parameters in MFC treatment effectiveness.

Optimization Implications

These results indicate that electrode optimization must balance the issues of electrical behavior, wastewater treatment performance, preparation demands, and durability. The process of high-temperature graphitization enhances the conductivity, but at the same time increases energy costs. Chemical activation enhances the accessibility of pores, adding more demands of chemical processing. The electrode loading and pressing must be done in such a way as to allow microbial growth and electrical contact while maintaining substrate access. Thus, electrode optimization strategy must take into consideration maximum power density, COD reduction, electrode stability, material availability, and preparation cost simultaneously. The proposed framework offers a structured foundation for identifying potential agricultural carbon materials and conducting future controlled experiments.

Limitations and Future Research

The first constraint of this study is the diversity in the reviewed experimental research. Divergence in reactor configuration, microbial inoculum, substrates, electrode surface area, and operational parameters

makes it impossible to compare directly the maximum power density and COD removal efficiency. In some research, the information about uncertainty, stability over time, and performance in wastewater treatment is incomplete. Therefore, the highest measured electrical power does not necessarily indicate the most cost-effective electrode. In addition, the influence of variables was studied in different experimental setups, and their combination does not have an additive effect. Future research should focus on investigating agricultural carbon electrodes in reactors that are identical in terms of conditions to commercial ones, using replicate experiments and consistent performance measures.

V. Conclusion

This study involved assessing the performance of microbial fuel cell agricultural waste-derived carbon electrodes via the comparative synthesis of experimental studies in the field and the development of an evidence-based optimization framework. The configurations presented in this review offered maximum power densities between 26 mW m^{-2} and 2171 mW m^{-2}, indicating great variance that is related to feedstock properties, electrode preparation, and reactor operating conditions. The graphitized mango-seed carbon provided the highest reported power density of 2171 mW m^{-2}, whereas the KOH-activated Datura peel biochar produced 584 mW m^{-2} with 85.4% COD reduction. Increasing the graphitization temperature of the mango-seed carbon from 1000 °C to 1100 °C increased its power density by 61%, from 1351 mW m^{-2} to 2171 mW m^{-2}. Modification of cathodes resulted in an improvement in power output from 542 to 2178 mW m^{-2}, highlighting the significance of the electrode design. The results of comparative analysis have shown that the carbonization temperature, chemical activation, electrode loading, mechanical pressing, and the cathode design are key performance parameters. The suggested approach considers all of them as components of the process of selection of agricultural residue for MFC operation, production of electrodes, and their performance evaluation. However, due to differences in the design of reactors and lack of complete information about the experiments, it is difficult to make a comparison between different papers. Future research needs to be focused on experimental standardization, comparable commercial electrodes, stability, regeneration of electrodes, and techno-economic assessment.

References

[1] Chao, Y. (2025). Microbial Fuel Cells as a Strategy for Biomass Waste Utilization and Low Carbon Energy Generation. In *MATEC Web of Conferences* (Vol. 410, p. 01032). EDP Sciences. https://doi.org/10.1051/matecconf/202541001032

[2] Merga, T., Gebreslassie, G., Hailu, T., Nwanya, A. C., Ezema, F. I., Ejikeme, P. M., & Workneh, G. A. (2025). Progress of carbon-based electrodes in microbial fuel cells: A comprehensive review. *Results in Chemistry*, 102627. https://doi.org/10.1016/j.rechem.2025.102627

[3] Cao, T. N. D., Mukhtar, H., Yu, C. P., Bui, X. T., & Pan, S. Y. (2022). Agricultural waste-derived biochar in microbial fuel cells towards a carbon-negative circular economy. *Renewable and Sustainable Energy Reviews*, *170*, 112965. https://doi.org/10.1016/j.rser.2022.112965

[4] Javanmard, A., Zuki, F. M., Patah, M. F. A., & Daud, W. M. A. W. (2024). Revolutionizing microbial fuel cells: Biochar's energy conversion odyssey. *Process Safety and Environmental Protection*, *187*, 26-58. https://doi.org/10.1016/j.psep.2024.04.066

[5] Zhao, S., Wang, X., Wang, Q., Sumpradit, T., Khan, A., Zhou, J., ... & Qu, J. (2023). Application of biochar in microbial fuel cells: Characteristic performances, electron-transfer mechanism, and environmental and economic assessments. *Ecotoxicology and Environmental Safety*, *267*, 115643. https://doi.org/10.1016/j.ecoenv.2023.115643

[6] Mishra, R., Gollakota, A. R., & Shu, C. M. (2024). Cultivating eco-advantages: unleashing the distinctive potential of biochar in microbial fuel cells. *Process Safety and Environmental Protection*, *185*, 614-631. https://doi.org/10.1016/j.psep.2024.02.084

[7] Barakat, N. A., Gamal, S., Ghouri, Z. K., Fadali, O. A., Abdelraheem, O. H., Hashem, M., & Moustafa, H. M. (2024). Graphitized mango seed as an effective 3D anode in batch and continuous mode microbial fuel cells for sustainable wastewater treatment and power generation. *RSC advances*, *14*(5), 3163-3177. https://doi.org/10.1039/d3ra05084j

[8] Barakat, N. A., Gamal, S., Kim, H. Y., Abd El-Salam, N. M., Fouad, H., Fadali, O. A., ... & Abdelraheem, O. H. (2023). Synergistic advancements in sewage-driven microbial fuel cells: novel carbon nanotube cathodes and biomass-derived anodes for efficient renewable energy generation and wastewater treatment. *Frontiers in chemistry*, *11*, 1286572. https://doi.org/10.3389/fchem.2023.1286572

[9] Vempaty, A., Kumar, A., Pandit, S., Gupta, M., Mathuriya, A. S., Lahiri, D., ... & Kumar, N. (2023). Evaluation of the Datura peels derived biochar-based Anode for enhancing power output in microbial fuel cell application. *Biocatalysis and Agricultural Biotechnology*, *47*, 102560. https://doi.org/10.1016/j.bcab.2022.102560

[10] Sonu, K., Sen, H., Maheshwari, K., Tiwari, M. K., & Sogani, M. (2025). Enhanced textile dye wastewater treatment and power generation in microbial fuel cells using Bixa orellana fruit shell–derived biochar. *Biodegradation*, *36*(6), 125. https://doi.org/10.1007/s10532-025-10227-0

[11] Sonu, K., Sogani, M., Syed, Z., Rajvanshi, J., & Sengupta, N. (2025). Performance evaluation of microbial fuel cell using ceramic anode blended with rice husk ash and mild steel dust. *Scientific Reports*, *15*(1), 43791. https://doi.org/10.1038/s41598-025-27646-x

[12] Włodarczyk, P. P., & Włodarczyk, B. (2024). Effect of supporting carbon fiber anode by activated coconut carbon in the microbial fuel cell fed by molasses decoction from yeast production. *Energies*, *17*(15), 3607. https://doi.org/10.3390/en17153607

[13] Taniguchi, N., Nguyen, D. T., & Taguchi, K. (2021, June). Effectiveness of Rice Husk-Activated Carbon and Case Type in Microbial Fuel Cells. In *Euro-Mediterranean Conference for Environmental Integration* (pp. 411-413). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-43922-3_93

[14] Aleid, G. M., Alshammari, A. S., Alomari, A. D., A. Almukhlifi, H., Ahmad, A., & Yaqoob, A. A. (2023). Dual role of sugarcane waste in benthic microbial fuel to produce energy with degradation of metals and chemical oxygen demand. *Processes*, *11*(4), 1060. https://doi.org/10.3390/pr11041060

[15] Yaqoob, A. A., Fadzli, F. S., Ibrahim, M. N. M., & Yaakop, A. S. (2023). Benthic microbial fuel cells: A sustainable approach for metal remediation and electricity generation from sapodilla waste. *International Journal of Environmental Science and Technology*, *20*(4), 3927-3940. https://doi.org/10.1007/s13762-022-04236-2