



META-ANALYTICAL ASSESSMENT OF BIOCHAR-BASED ELECTRODES IN MICROBIAL FUEL CELLS FOR BIOMASS-TO-ENERGY CONVERSION

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Highlights

- First meta-analysis of biochar electrodes in MFCs reveals pooled output of $\approx 2,481 \text{ mW/m}^2$.
- Electrode position, cathode co-material, and pre-treatment shape MFC performance.
- High heterogeneity urges standardized benchmarking and cross-variable modeling.

Introduction

Microbial fuel cells (MFCs) represent a promising approach to integrate wastewater treatment with direct electric energy recovery (Ahanchi et al., 2022). However, their broader implementation remains limited by the performance and cost of conventional electrode materials, such as carbon or metal (Wang et al., 2025). Biochar, a porous carbon obtained through biomass pyrolysis under limited oxygen conditions and controlled temperatures ($<900 \text{ }^\circ\text{C}$), has gained attention as an alternative low-cost electrode material. With a high surface area, biochar derives from biomass residues and costs a fraction of conventional carbon materials. Early studies using waste-derived biochar (e.g., sewage sludge, walnut shell, coffee grounds) demonstrated power density improvements (up to three times higher) while reducing material costs (Huang et al., 2019; Hu et al., 2024).

A growing number of studies have investigated biochar from various feedstocks (Ahanchi, 2022). Reported outcomes vary based on operating conditions, inoculation, and reactor design. This heterogeneity makes it difficult to extract clear design principles or compare performance metrics. Prior meta-analyses have clarified performance trends in pilot-scale MFCs (Bird et al., 2022) and the use of complex substrates (Zafar et al., 2022). To provide a quantitative overview, this study presents a systematic review and meta-analysis on how biochar, as an electrode material in MFCs, affects power density and identifies factors that moderate this effect. Drawing from peer-reviewed data (1974-2025), performance metrics were statistically analyzed to evaluate the influence of variables (e.g., precursor material, cell configuration, operational conditions). As the first meta-analysis focused specifically on biochar-based electrodes in MFCs, this study benchmarks progress and contributes to a more consistent understanding of how biochar impacts MFC performance, while aligning with Sustainable Development Goals (i.e., SDG 6, 7, and 12) by advancing knowledge in clean energy, water treatment, and resource-efficient technologies.

Material and Methods

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and was prospectively registered on Open Science Framework (Sanches-Simões & Müller, 2025), ensuring transparency and reproducibility. A systematic search was conducted as described in Figure 1, with steps peer-checked to reduce selection bias. After the Identification and Screening steps, original research articles fitting the following criteria were included: (i) operation with liquid substrates, (ii) studies on electrode development, and (iii) biochar incorporation in electrode composition. Articles lacking data on biochar application/modification or with negligible amounts of biochar were excluded. Included articles were screened and elected if scoring 5 out of 8 quality criteria: (i) realistic operating time, (ii) replicates (when applicable), (iii) statistical reporting, (iv) clarity of sample information, (v) representativeness, (vi) replicability, (vii) key operational parameters, and (viii) consistency between results and discussion. Data from eligible articles was extracted and organized into ten analytical tables representing distinct analysis dimension: (i) general metadata, (ii) biochar feedstock and production, (iii) material characterization (e.g., FTIR, SEM, BET, XPS), (iv) electrode configuration, (v) inoculum



origin, (vi) operational parameters, (vii) performance metrics, (viii) pollutant removal, (ix) reactor design, and (x) interpretation and discussion.

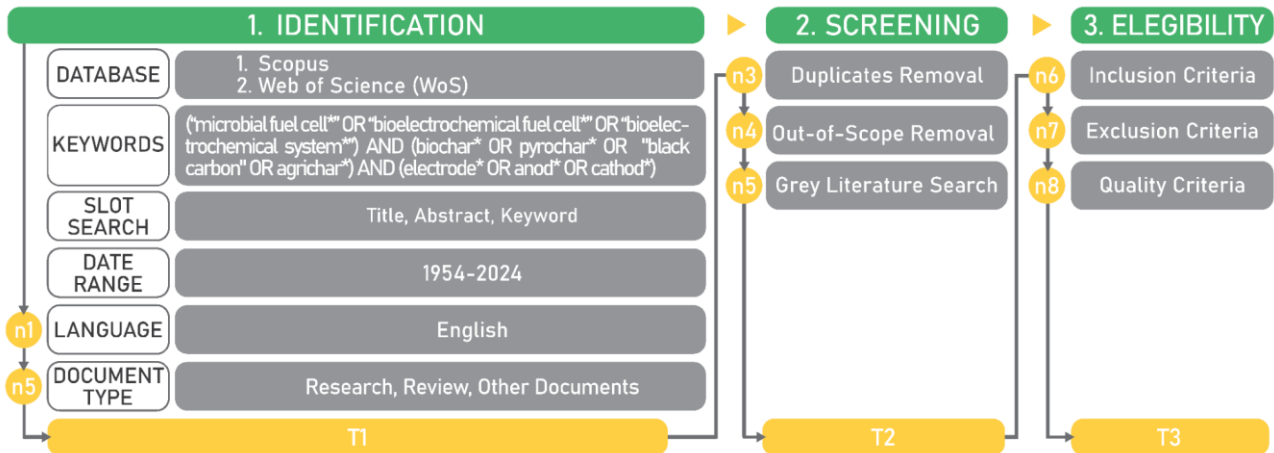


Figure 1 Meta-analysis framework (Checkpoints n_i , with $i = 1-8$, and total articles T_j , with $j = 1-3$, after each phase)

Meta-analytic modeling, using the metafor package in R, was used to estimate pooled performance metrics and explore heterogeneity (Viechtbauer, 2010). The primary effect metric was mean power density (mW/m^2), log-transformed to normalize skewed distributions and stabilize variance. Final pooled estimates were exponentiated to return to the original scale. The analytic dataset initially contained one effect size per study, representing the contrast between biochar and conventional electrodes. However, several records lacked variance information (NA values), which were automatically excluded by the metafor package. To address potential exclusion bias, we confirmed that their exclusion did not affect the direction or magnitude of pooled estimates, leaving 28 independent effects for the random-effects model. Numerical and categorical moderator variables were selected based on data availability and theoretical relevance, including biochar precursor, pretreatment of biochar's precursor, electrode focus, cell chamber type, and publication year. Influence diagnostics assessed studies' weight on pooled estimates. Egger's regression test on the 28 independent study-level effects did not indicate significant asymmetry ($p = 0.25$).

Results and Discussion

The meta-analysis comprised 88 comparisons extracted from 28 studies, with an overall log-transformed mean power density of 7.82 (SE = 0.22; $p < 0.0001$), corresponding to approximately $2,481 \text{ mW}/\text{m}^2$ after back-transformation. This pooled value aligns with or exceeds typical outputs reported for low-cost MFCs, suggesting biochar's competitive potential relative to standard carbon materials. The high heterogeneity ($I^2 = 100\%$ and $\tau^2 = 1.32$) observed across studies indicated the variance between studies, reflecting the diversity of materials, reactor configurations, and experimental conditions reported. This level of heterogeneity is not uncommon in emerging fields and justifies the use of random-effects models and moderator analyses to explore potential sources of systematic variation. These results also justified the application of subgroup and meta-regression analyses to investigate sources of variability in effect sizes. The forest plot presented in Figure 2 highlights the wide confidence intervals across individual studies and their distribution around the pooled estimate. The value range supports the interpretation that context-specific factors significantly influence the performance of biochar electrodes in MFCs.

Categorical and numerical variables that met data quality criteria were selected to explore potential moderators, leading to the identification of several significant predictors of variability in power density outcomes. The publication year explained 6.55% of the variance ($Q(1) = 4.52$, $p = 0.0335$), indicating a progressive improvement in MFC performance over time, likely driven by advances in biochar materials and system design (Figure 3). This variance also indicates the need for clearer benchmarking to understand and track recent technological developments. The cathode material significantly influenced outcomes ($Q(4) = 11.23$, $p = 0.0245$), accounting for 24.76% of the variance. The effects of cathode co-material suggest synergistic or antagonistic interactions with



biochar in oxygen reduction reaction (ORR) zones, influenced by material conductivity and catalytic activity (Ahanchi et al., 2022). Pretreatment of biochar's precursor explained the largest share of heterogeneity ($Q(9) = 26.09$, $p = 0.0020$; $R^2 = 37.13\%$), confirming that surface modifications significantly affect electrode performance. Pre-treatment effects likely reflect changes in biochar porosity, functional groups, and conductivity, influencing microbial adhesion and electron transfer efficiency (Hu et al., 2024). Lastly, statistical significance was also found on whether the biochar was applied at the anode or cathode ($Q(1) = 9.78$, $p = 0.0018$; $R^2 = 22.57\%$), likely due to differing mechanisms of electron transfer and surface redox compatibility between anodic and cathodic environments, supporting the need for electrode-specific design strategies (Huang et al., 2019). Nonetheless, the observed heterogeneity may also derive from factors known to shape MFC performance but not consistently reported, such as differences in internal resistance and mass transport regimes.

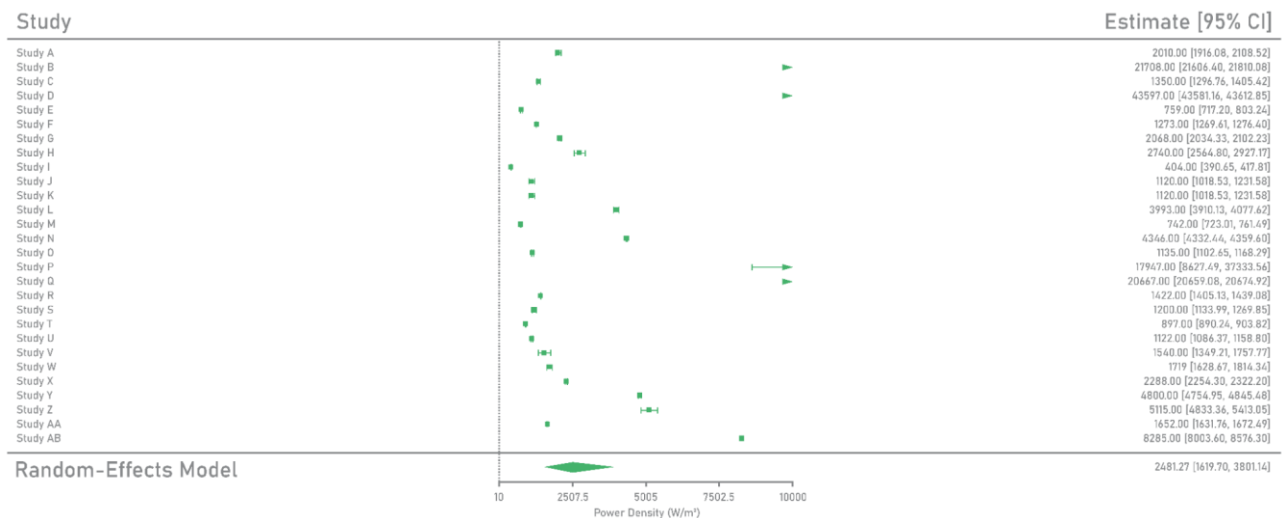


Figure 2 Forest plot of all included studies with pooled estimates.

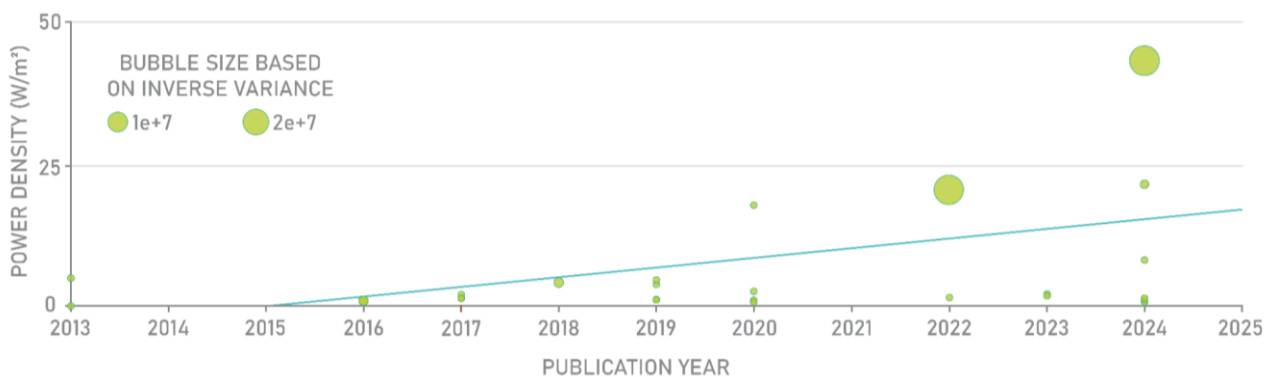


Figure 3 Bubble plot of power density versus publication year. Bubble size represents study weight (inverse variance).

A funnel plot (Figure 4) was applied to assess publication bias, suggesting some asymmetry, which could indicate small-study effects. Significant funnel plot asymmetry ($z = 1.15$, $p = 0.25$) was not confirmed by Egger's regression test, implying that any visual imbalance may not be statistically robust. The trim-and-fill method did not impute any studies ($k_0 = 0$), reinforcing that the observed asymmetry is unlikely to be due to publication bias. Therefore, there is insufficient evidence to claim a systemic bias in the literature. Although the use of biochar in MFCs has been widely studied experimentally, no prior work has aggregated performance data using a structured statistical approach. The moderator analysis highlights how configurations, environmental conditions, and material choices



drive performance variation, reinforcing the need to tailor biochar properties to specific electrochemical and operational contexts.

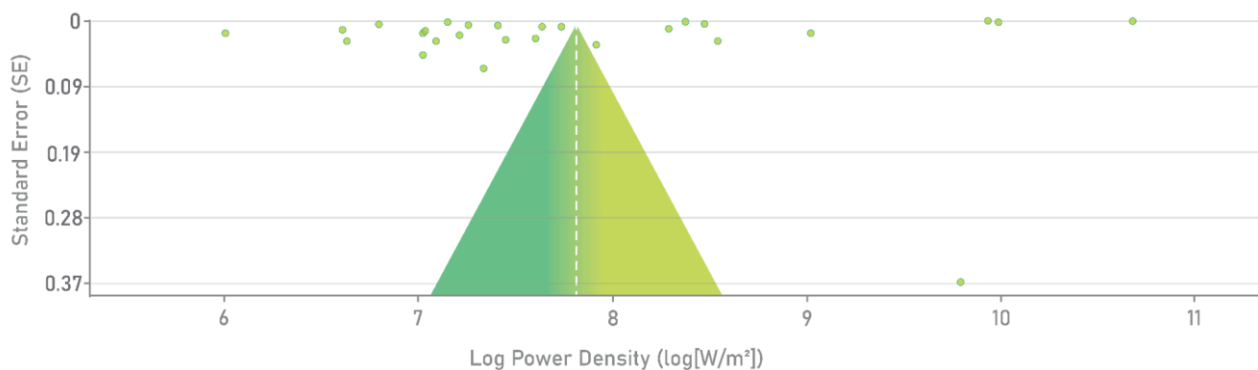


Figure 4 Funnel plot showing imputed values to account for potential publication bias.

Conclusion

This study presents the first meta-analytical synthesis that quantifies the effects of biochar electrode properties and cell configurations on MFC performance, offering key insights for material selection and system design. The pooled power density of $\approx 2480 \text{ mW/m}^2$ supports biochar's potential, though high heterogeneity indicates context-dependent outcomes. Moderator analysis showed that electrode placement, precursor pre-treatment, and cathode co-materials significantly influence results, with performance improving over time. However, the lack of standardization in reporting continues to complicate comparability. Future analyses should explore the interactions among material, operational, and biological factors to maximize the biochar's benefits at scale.

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