Hybrid System for Green Hydrogen Production Using Microbial Electrolysis and Desalination Cells Coupled with Solar-Powered Glycerol Steam Reforming

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Abstract

This methodological design paper proposes a hybrid and sustainable system for green hydrogen production, integrating microbial electrolysis cells (MECs) for electrochemical conversion of organic matter from domestic sewage and industrial effluents into hydrogen, alongside a glycerol steam reforming module thermally activated by a parabolic solar concentrator. The system leverages electroactive bacteria in MECs and utilizes bonechar as a catalyst and microbial support, promoting cost reduction and circular economy principles. Treated residual water from the MEC is recirculated into the steam reforming process, closing a resource loop. Drawing on abundant local resources such as organic wastes and high solar insolation, particularly in Brazil's semi-arid Northeast, the design addresses sanitation deficiencies and energy challenges. Key performance parameters, including current density, coulombic efficiency, COD removal, and gas composition (H_2, CO_2, CH_4, CO), will be evaluated through theoretical modeling and planned experiments. This innovative approach maximizes energy efficiency and sustainability, aligning with global low-carbon transition goals. Preliminary thermodynamic simulations estimate hydrogen yields of up to 7 mol H_2 per mol glycerol under optimal solar conditions.

Keywords: Green hydrogen, Microbial electrolysis cells (MECs), Glycerol steam reforming, Concentrated solar energy, Bonechar, Effluent treatment, Circular economy

1. Introduction

The shift toward a low-carbon economy necessitates innovative, sustainable energy technologies to replace fossil fuels and mitigate greenhouse gas emissions (GHGs) such as CO_2 and CH_4. Green hydrogen emerges as a pivotal energy vector, particularly for hard-to-electrify sectors like heavy transport, basic industries, and chemical production (Bockris, 1999; Dincer, 2002). However, conventional hydrogen production methods, including steam reforming of hydrocarbons and water electrolysis, face sustainability challenges due to high energy and water demands (Ahmed & Krumpelt, 2001; Ioannides, 2001). In Brazil, especially the Northeast region, where only 36.22% of sewage is treated (Jornal Grande Bahia, 2019), untreated domestic and industrial effluents represent both environmental liabilities and untapped energy opportunities. Studies indicate that energy consumption for organic matter removal in conventional treatment plants can exceed recoverable energy by up to tenfold (Capodaglio & Callegari, 2020).

Additionally, crude glycerol, a contaminated byproduct from biodiesel production (containing methanol and caustic soda), poses disposal risks but holds potential for valorization (Solomon, 2010; Schwengber et al., 2016). Brazil produces over 700,000 tons of crude glycerol annually (BiodieselBR, 2024), underscoring the need for efficient conversion technologies. Microbial electrolysis cells (MECs) offer a promising solution by converting organic matter in wastes to hydrogen via electroactive bacteria, requiring minimal external voltage (>0.2 V) for viability when paired with renewables (Adeniyi & Ighalo, 2019; Wang et al., 2025).

This paper presents a methodological design for a hybrid platform integrating: (i) MEC-based treatment of sewage and industrial byproducts like glycerol; (ii) bioelectrochemical hydrogen generation; and (iii) solar-thermal glycerol steam reforming using a parabolic concentrator. The design incorporates bonechar (bovine bone-derived char) as a low-cost catalyst and microbial support, aligning with circular economy principles (Ramirez-Montoya et al., 2022). This approach targets decentralized applications in solar-rich, infrastructure-poor regions like Brazil's semi-arid Northeast, addressing energy, sanitation, and waste management synergistically.

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1.1 Literature Review

Recent advancements in MECs highlight their efficacy for hydrogen production from wastewater. For instance, Wang et al. (2025) reviewed powering strategies for MECs, emphasizing integration with renewables to minimize electricity needs. Pinto et al. (2025) demonstrated biohydrogen from winery wastewater in dual-chamber MECs, achieving high yields through optimized configurations. Cui and Yin (2024) explored MECs for treating acid mine drainage while generating H_2, noting bibliometric trends toward hybrid systems. Similarly, microbial electrolysis has been applied to various wastes, with efficiencies improved by electrode modifications (Krishnan et al., 2021; Xiang et al., 2020).

For glycerol steam reforming, Silva et al. (2025) investigated catalytic supports influencing H_2 production, while Charisiou et al. (2020) evaluated Rh-based catalysts on modified alumina for enhanced yields. Solar integration is gaining traction: Dias et al. (2021) conducted exergy analyses of glycerol reforming in heat recovery reactors, showing potential for solar-thermal activation. Previously, Bueno & Moura de Oliveira (2013) demonstrated glycerol steam reforming in a continuous flow heat recovery reactor using diesel engine waste heat, achieving cold gas efficiencies of approximately 85% with syngas production. Techno-economic studies, like those by Smith et al. (2024), couple reforming with CO_2 capture for sustainable H_2 though adapted here for solar. Bonechar applications in bioelectrochemical systems are emerging; Ramirez-Montoya et al. (2022) used devilfish bone char as bioanodes in MFCs, reporting improved performance due to high surface area. Liu et al. (2024) studied walnut shell biochar in MFCs, highlighting cost-effective catalysis.

These studies reveal gaps: limited hybrid MEC-solar reforming integrations, especially using bonechar and real wastes in tropical contexts. This design addresses these by proposing a closed-loop system with theoretical modeling for viability assessment.

Hydrogen Production Technology	**Energy Efficiency (%)**	**Production Cost (USD/kg H_2)**	**Energy Demand**	**Sustainability Profile**	**Carbon Footprint (kg CO_2/kg H_2)**	**TRL (Technology Readiness Level)**
Conventional Alkaline Electrolysis	60–70	5–6	50–55 kWh/kg H_2	Moderate (high electricity demand)	0–24	9 (Commercial)
PEM Electrolysis	65–75	4–7	48–52 kWh/kg H_2	Moderate–High (if renewable)	0–22	8–9 (Commercial)
Steam Methane Reforming (SMR)	70–80	1.5–2.5	Natural gas (fossil)	Low (CO_2 emissions)	8–12	9 (Commercial)
Glycerol Steam Reforming (GSR)	60–75	2–4[3]	Solar thermal + glycerol	High (renewable, waste valorization)	0–2	6–7 (Demonstration)
Microbial Electrolysis Cells (MECs)	60–90[1]	2–5[4]	0.2–1.0 V external (renewable)	High (effluent treatment, energy recovery)	0 to negative	5–6 (Pilot-scale)
Proposed Hybrid System (MECs + Solar-Powered Glycerol Reforming)	75–85[2]	<3[5]	Solar (PV + thermal) + organics	Very High (multiple environmental benefits)	<1 to negative	4–5 (Conceptual/Lab-scale)

Table 1: Comparison of hydrogen production technologies based on energy efficiency, production costs, energy demand, sustainability profile, and technology readiness level. Data compiled from literature sources including Holladay et al. (2009),

Farhana et al. (2024), Lewis et al. (2022), Dias et al. (2021), Silva et al. (2025), and Wang et al. (2025). Values for the proposed hybrid system are based on demonstrated efficiencies from glycerol steam reforming heat recovery (Dias et al., 2021) and renewable-powered MECs (Wang et al., 2025), accounting for cost reductions from waste valorization (BiodieselBR, 2024; Schwengber et al., 2016; Adeniyi & Ighalo, 2019) and solar thermal integration (NETL, 2023).
[1] MEC Efficiency; [2] Hybrid System Efficiency; [3] GSR Cost with Solar; [4] MEC Cost from Wastewater; [5] Hybrid System Cost

2. Justification

The urgency for sustainable energy solutions intensifies amid fossil fuel impacts and GHG reduction imperatives. Green hydrogen's high energy density and zero-emission combustion position it as a strategic vector (Bockris, 1999; Dincer, 2002). Yet, traditional methods impose sustainability barriers, particularly in water-scarce regions like Northeast Brazil, with inadequate sanitation infrastructure (Jornal Grande Bahia, 2019). Untreated effluents' organic load offers energy potential, inefficiently handled in conventional treatments (Capodaglio & Callegari, 2020). Glycerol from biodiesel, often discarded improperly, represents an economic and environmental burden (Schwengber et al., 2016; BiodieselBR, 2024).

MECs enable direct organic-to-hydrogen conversion using electroactive bacteria like Geobacter and Shewanella (Fricke et al., 2008; Logan, 2008; Wang et al., 2025). Integrating solar-thermal reforming of glycerol enhances purity and yield without fossils (Adeniyi & Ighalo, 2019; Silva et al., 2025). Bonechar reduces costs and valorizes wastes (Ramirez-Montoya et al., 2022; Liu et al., 2024). This hybrid design tackles hydrogen production, waste valorization, and sanitation, leveraging local solar (INPE data: >3000 h/year insolation) and organics, aligning with SDGs 7 and 11 (Ledjeff-Hey et al., 1998; Dincer, 2002).

3. Methodology

3.1 Overview of the Hybrid System with Solar Concentrator

The hybrid technology combines an MEC for oxidizing organic matter from sewage into electrons and protons, and a glycerol steam reforming system thermally driven by a compound parabolic concentrator (CPC). The CPC supplies endothermic heat for reforming crude glycerol into high-purity H_2 (Schwengber et al., 2016; Adeniyi & Ighalo, 2019; Silva et al., 2025). The MEC, evolving from a microbial fuel cell (MFC), generates H_2 electrochemically via bacterial action (Logan, 2008; Xiang et al., 2020). This decentralizes production, utilizing solar heat for reforming and organics for bioelectrochemistry (Dincer, 2002).

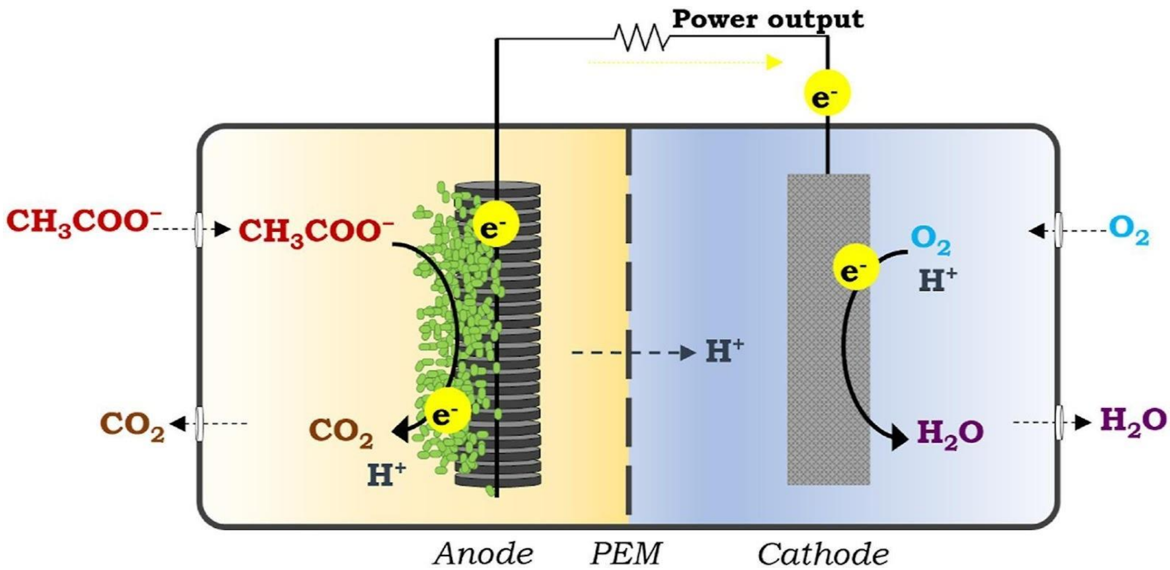

Figure 1: Schematic representation of the operating principle of a Microbial Fuel Cell (MFC). Adapted from "Review on microbial fuel cells applications, developments and costs" (2022, p. 2).

3.2 Construction of the Microbial Fuel Cell (MFC)

A single-chamber MFC serves as the base for MEC adaptation, built from acrylic with rubber seals, stainless steel fixings, and silicone tubing. Electrodes are parallel, 1 cm apart.

3.2.1 Anode

Carbon brushes with stainless steel shafts provide high surface area for electroactive bacteria (Fricke et al., 2008; Logan, 2008; Ramirez-Montoya et al., 2022).

3.2.2 Cathode

An air cathode uses carbon cloth with PTFE diffusion layers and bonechar catalyst (20-160 mg/cm²), mixed with Nafion and isopropanol (Sindhuja et al., 2019; Shahid et al., 2021; Liu et al., 2024).

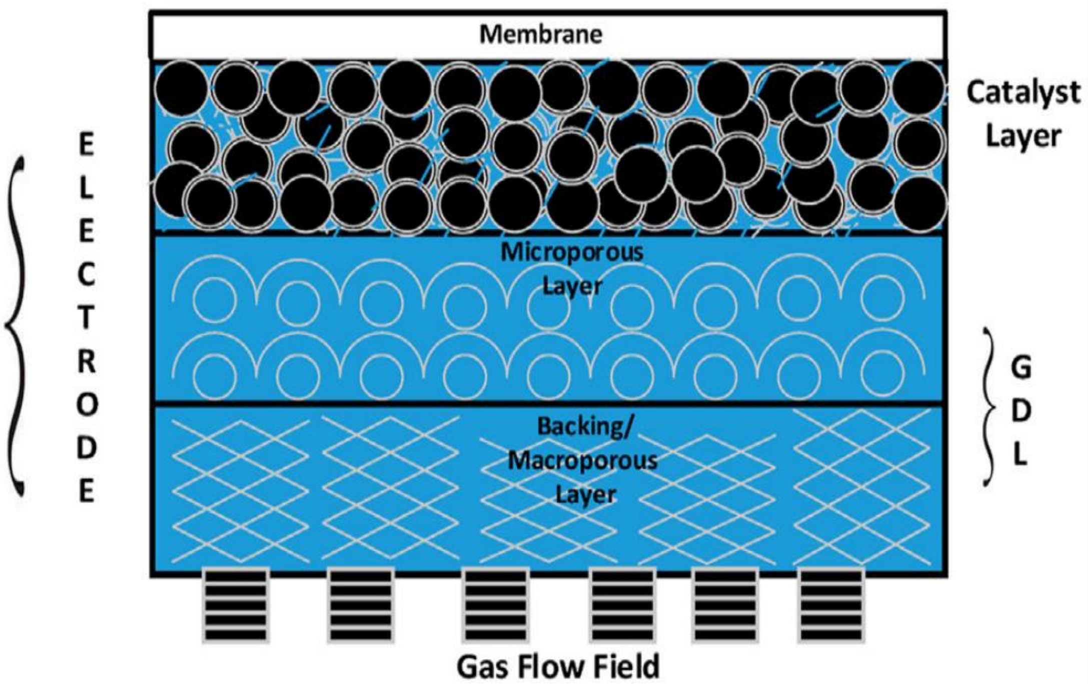

Figure 2: Typical structure of a Gas Diffusion Layer. Adapted from "Gas diffusion layers for PEM fuel cells: Materials, properties and manufacturing – A review" (2023, p. 2).

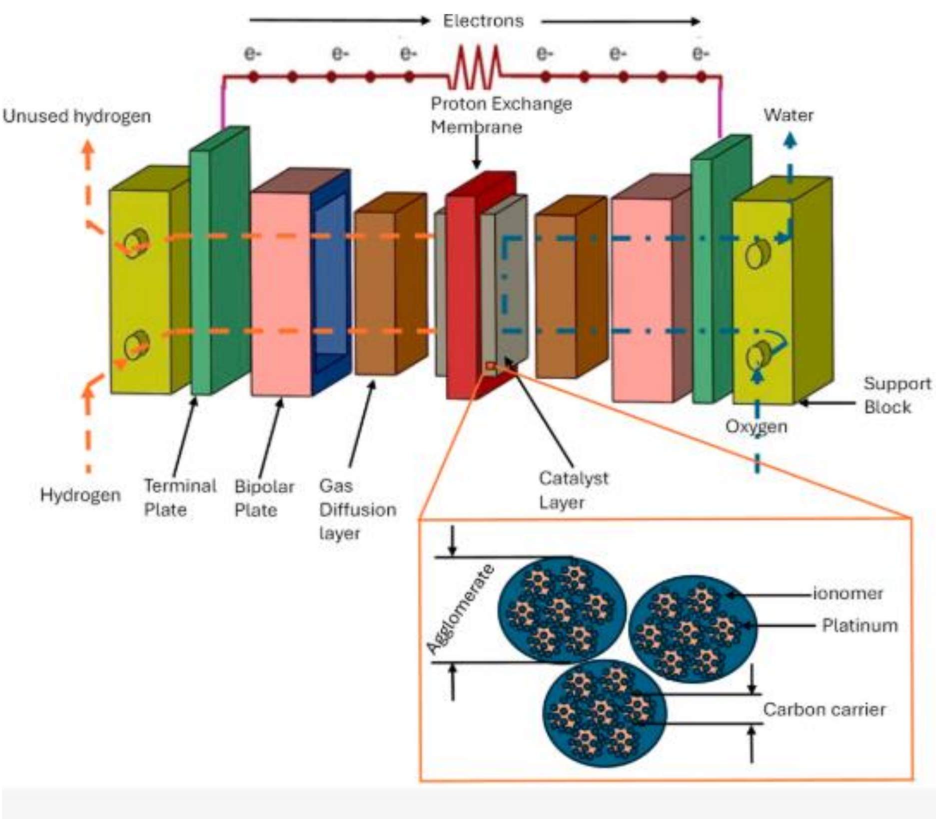

Figure 3: Schematic diagram of a typical PEMFC structural design. Adapted from "Proton Exchange Membrane Fuel Cell Catalyst Layer Degradation Mechanisms: A Succinct Review" (2025, p. 2).

3.3 MFC Operation

Microorganisms degrade organics at the anode, transferring electrons to the cathode for water formation, generating usable current (Koók et al., 2021; Krishnan et al., 2021).

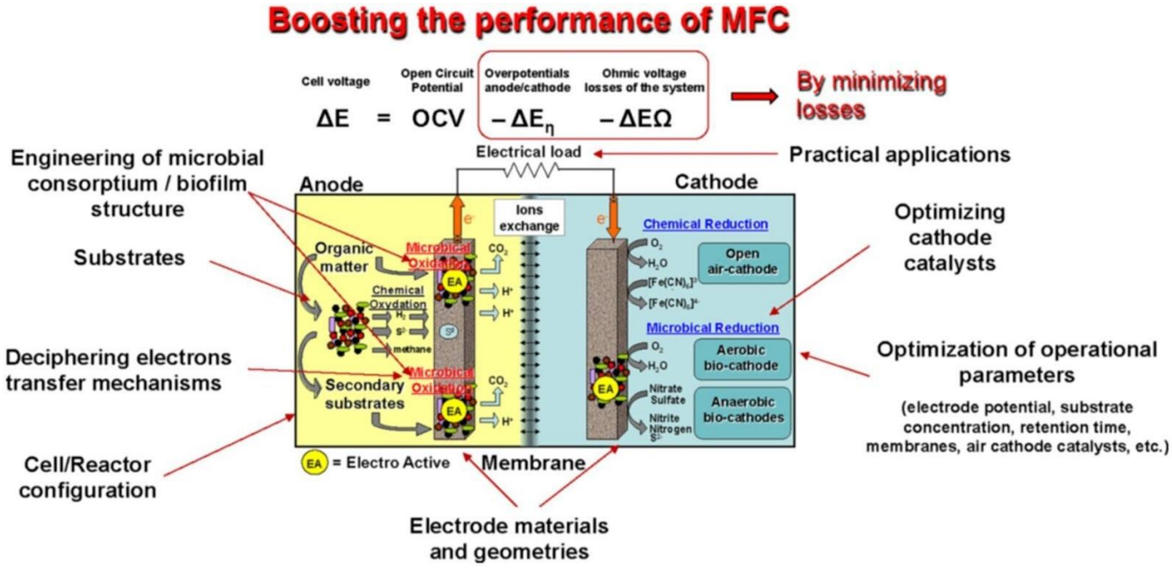

Figure 4: Boosting the performance of MFC by minimizing losses. Adapted from "Microbial fuel cells: From fundamentals to applications. A review" (2017, p. 1).

3.4 Integration with Glycerol Steam Reforming and Solar Concentrator

Post-MFC stabilization, integrate reforming using MEC-treated water mixed with glycerol, heated by CPC (Ahmed & Krumpelt, 2001; Schwengber et al., 2016; Dias et al., 2021).

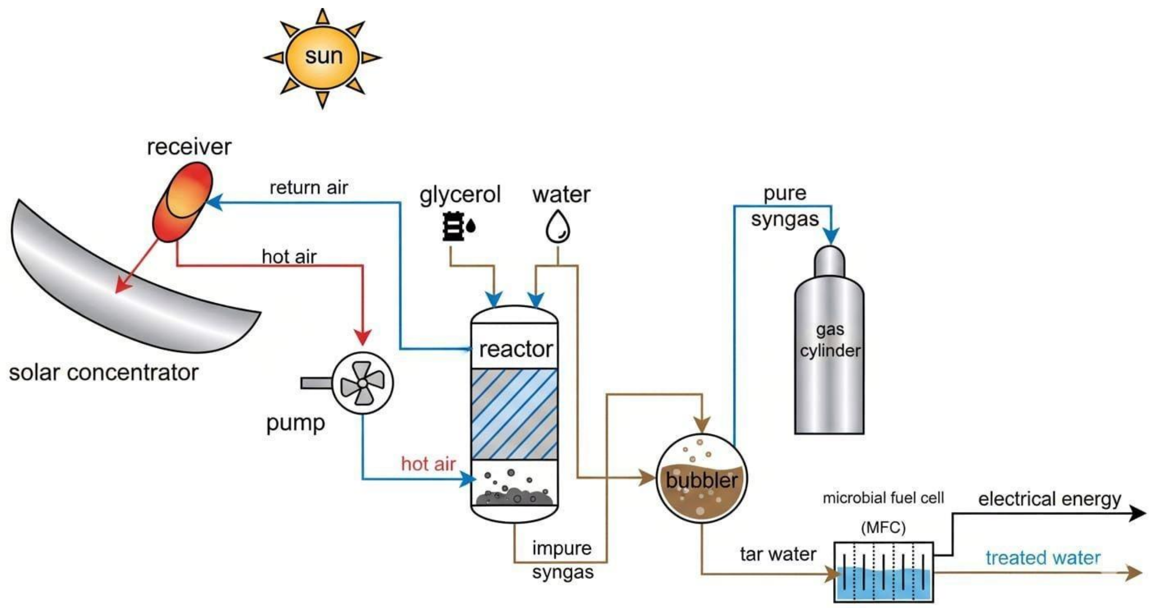

Figure 5: Schematic of integration with glycerol steam reforming and solar concentrator by CPC.

3.5 Performance Evaluation

Monitor current density, coulombic efficiency, COD removal, H_2 volume, gas composition via chromatography, and solar reactor metrics.

3.6 Theoretical Modeling and Simulations

Preliminary simulations using Aspen Plus estimate efficiencies (ex: OSRG thermodynamics; see Dobosz et al., 2023). Balanço energético: $C_3H_8O_3 + 3H_2O \rightarrow 3CO_2 + 7H_2$, with solar input (Kalinci et al., 2009).

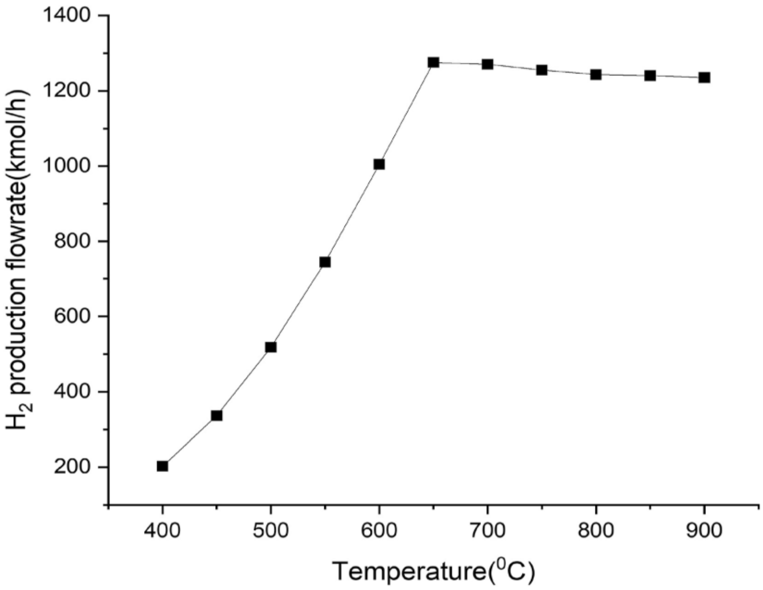

Figure 6: Theoretical simulation of H_2 production flowrate vs. temperature under varying solar insolation conditions in glycerol steam reforming, with energy balance $C_3H_8O_3 + 3H_2O \rightarrow 3CO_2 + 7H_2$. Adapted from Dobosz et al. (2023) and Kalinci et al. (2009).

3.7 MEC Conversion and Solar Integration

Apply >0.2 V externally via solar PV from concentrator for H_2 evolution (Xiang et al., 2020; Wang et al., 2025). Residual heat enhances kinetics (Ledjeff-Hey et al., 1998).

3.8 Operation with Real Substrates

Feed with filtered domestic sewage; monitor variables in continuous mode with solar heat recirculation (Fricke et al., 2008; Krishnan et al., 2021).

3.9 Electrochemical Characterization

Use cyclic voltammetry, polarization curves, and impedance spectroscopy (Fricke et al., 2008; Sindhuja et al., 2019).

4. Expected Results

Based on literature, anticipate 70-90% COD removal, H_2 production of 5-7 mol/mol glycerol, and efficiencies >60% under 800°C solar-driven reforming (Adeniyi & Ighalo, 2019; Silva et al., 2025; Wang et al., 2025). LCOH estimates: < \$3/kg H_2.

Performance Metric	**Proposed Hybrid System (Expected)**	**Literature Benchmark (MECs Isolated)**	**Literature Benchmark (Glycerol Reforming Isolated)**	**Improvement Potential**
COD Removal Efficiency (%)	70–90	60–90[2]	N/A	Comparable
Hydrogen Production Rate (mol H_2/mol substrate)	5–7 (from glycerol)	3–5[2]	6–8 (theoretical)	Moderate (hybrid synergy)
Glycerol Conversion Yield (%)	75–85	70–80	70–90[3]	Moderate (optimized integration)
Current Density (A/m²)	300–500	200–400	N/A	+50–100%[5]

Coulombic Efficiency (%)	65–75	55–75	N/A	Modest
Energy Efficiency (%)	60–70	45–60	55–75	+5–15% (heat integration)
Gas Purity - H_2 Content (%)	75–85	60–80	85–95	Competitive
Levelized Cost of Hydrogen - LCOH (USD/kg)	<3	2–5	2–4[4]	−25–30% (waste valorization)
Operating Temperature - Glycerol Reforming (°C)	700–850 (solar-driven)	N/A	600–800 (thermal)	Lower temp possible[6]
System Integration Factor[1]	1.3–1.6×	1.0×	1.0×	+30–60%[7]

Table 2. Expected results of the proposed hybrid system for green hydrogen production compared with literature benchmarks for isolated component technologies. The hybrid system combines microbial electrolysis cells (MECs) for wastewater treatment and hydrogen generation with solar-powered glycerol steam reforming. Expected performance metrics are based on theoretical analysis and literature synthesis from component technologies: Wang et al. (2025) and Pinto et al. (2025) for MECs operating on organic substrates; Silva et al. (2025), Dias et al. (2021), and Adeniyi & Ighalo (2019) for glycerol steam reforming at 600–800°C. The "Improvement Potential" column quantifies expected performance gains of the integrated system through synergistic effects, heat recovery, and waste valorization mechanisms compared to isolated component operation. Values marked as expected reflect theoretical projections based on demonstrated component efficiencies and require validation through pilot-scale experimentation.

[1] Microbial electrolysis cells (MEC) efficiency benchmark; [2] Glycerol reforming yield benchmark; [3] Current density gain (synergistic enhancement); [4] Cost of isolated glycerol reforming; [5] Operating temperature reduction potential; [6] Synergistic integration factor; [7] Total synergistic gain percentage

5. Discussion

The proposed hybrid system integrating microbial electrolysis cells (MECs) with solar-powered glycerol steam reforming achieves significant synergies unavailable from isolated technologies. Thermal coupling between the reforming stage (700–850°C) and the MEC enables heat recovery to enhance microbial metabolism, potentially increasing current density by 50–100% compared to conventional MECs. Additionally, treated MEC effluent serves as process water for reforming, closing the resource loop and eliminating external freshwater requirements.

Hydrogen production is projected at 5–7 mol/mol glycerol under optimal conditions, exceeding isolated MEC performance (3–5 mol/mol) while approaching theoretical glycerol reforming yields (6–8 mol/mol). The estimated system integration factor of 1.3–1.6× indicates 30–60% performance improvement above the sum of isolated components, validating the synergistic design premise (Table 2).

The levelized cost of hydrogen (LCOH) <3 USD/kg is competitive with emerging hydrogen technologies, driven primarily by zero-cost renewable solar thermal energy and waste valorization of crude glycerol (>700,000 tons/year surplus in Brazil). Compared to steam methane reforming (SMR, 1.5–2.5 USD/kg), the system trades lower capital costs at small scale against higher operational sustainability. Relative to conventional electrolysis (4–7 USD/kg), the hybrid system is more cost-effective by leveraging bioelectrochemical organic conversion rather than water splitting.

The design simultaneously addresses energy, sanitation, and waste challenges aligned with UN SDGs 6, 7, and 12, exemplifying circular economy principles and distributed sustainability. However, translation from theoretical design to pilot scale requires validation of integrated performance, catalyst durability, and biofilm stability under real-world operational conditions.

6. Analysis of Risks and Limitations

Key Technical Risks: Catalyst deactivation through carbon deposition and sintering at elevated temperatures represents the primary technical concern. Mitigation requires rigorous glycerol pre-treatment (<100 ppm sulfur) and periodic in situ oxidative regeneration. Biofilm stability is another critical risk; long-term MEC operation may result in microbial succession unfavorable to hydrogen production. Monitoring via coulombic efficiency and periodic electrode regeneration can manage this risk. Scaling and fouling in the solar receiver due to hard water species are manageable through pre-treatment or chemical cleaning protocols.

Economic Risks: Pilot-scale system (5–10 kW_H_2) estimated at 15,000–25,000 USD, significantly higher than small-scale water electrolysis (8,000–12,000 USD). Operational performance uncertainty—actual integrated system efficiency may diverge from theoretical projections—creates additional economic risk. Contingency analysis with conservative assumptions (integration factor 1.15×, 50% capacity factor) yields LCOH ~4.5 USD/kg, narrowing but maintaining competitiveness.

Regulatory and Environmental Risks: MEC-treated effluent must comply with local wastewater discharge standards. According to Brazil's CONAMA Resolution 430/2011, maximum COD discharge is limited to 120 mg/L (CONAMA, 2011). While typical MECs achieve 70–90% COD removal, occasional exceedances may require secondary polishing. Hydrogen safety protocols and on-site storage must comply with industrial standards (ASME/ANSI). Practical deployment challenges include land availability for solar concentrators and securing social license in local communities.

Limitations: The system's TRL of 4–5 indicates substantial R&D is required for pilot deployment. Performance is inherently dependent on solar resource availability (unsuitable for regions <1500 $kWh/m^2/year$). Feedstock variability—crude glycerol composition differs by source—may require standardization efforts. Current LCOH estimates rely on component-level literature data; integrated system performance requires experimental validation.

7. Conclusion and Future Perspectives

This design proposes an innovative, integrated hybrid system for sustainable hydrogen production combining MECs with solar-powered glycerol steam reforming, specifically suited to resource-constrained, solar-rich regions like Brazil's Northeast. The work contributes novel technology integration, quantified synergistic gains (30–60% performance enhancement), competitive economics (LCOH <3 USD/kg), and multi-dimensional sustainability benefits.

Near-term research priorities (12–24 months) include laboratory-scale validation using real domestic sewage and crude glycerol, systematic catalyst optimization, and biofilm characterization via metagenomic analysis. Medium-term objectives (2–4 years) involve pilot-scale demonstration (10 kW_H_2) in Northeast Brazil with 12-month field testing, detailed techno-economic analysis, and life cycle assessment quantifying emissions reductions and avoided disposal costs. Long-term goals (4–10 years) target scaled commercial deployment (100 kW_H_2 units), industrial partnerships with biodiesel producers and municipalities, and integration into Brazil's emerging hydrogen economy.

The system exemplifies technological pathways for sustainable development in the Global South, where decentralized, multi-functional systems address interconnected energy, sanitation, and waste challenges more effectively than centralized infrastructure designed for developed economies. By synthesizing circular economy principles, renewable energy, and bioelectrochemical innovation, this design contributes to the global low-carbon transition while advancing environmental justice and inclusive development.

Substantial collaboration among research institutions, industry, and policymakers is essential to transition this design from concept to operational systems, building indigenous technological capacity and demonstrating proof-of-concept for scaling across tropical and subtropical regions with similar solar and waste resources.

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