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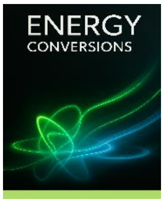

Recent Progress in Microbiological Energy Systems: Microbial Pathways, Reactor Design, and Scale-Up Challenges

Enzo D. Martelli[a], Lara N. Sayegh[a,b,*]

[a] *Institute for Bioenergy Systems, Università di Roma Verde, Rome, Italy*

[n] *Department of Environmental Engineering, Al-Qantara University, Beirut, Lebanon*

A R T I C L E I N F O

Keywords:

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A B S T R A C T

Microbiological energy systems exploit the metabolic activity of microorganisms to transform organic and inorganic feedstocks into useful energy carriers such as electricity, hydrogen, methane, and reduced carbon products. Their appeal lies in the simultaneous recovery of energy and treatment of waste streams, which makes them relevant to low-emission and circular resource systems. This review examines the principal microbiological energy routes—anaerobic digestion (AD), microbial fuel cells (MFCs), microbial electrolysis cells (MECs), and microbial electrosynthesis (MES)—with emphasis on extracellular electron transfer, biofilm development, reactor architecture, and materials selection. The discussion also addresses operating variables including pH, temperature, loading rate, hydraulic retention time, and electrode properties, all of which strongly influence conversion efficiency and operational stability. The evidence reviewed indicates that AD remains the most mature and economically established option, whereas MFCs, MECs, and MES offer important opportunities for decentralized treatment, renewable hydrogen generation, and carbon utilization. Advances in metabolic engineering, omics-based microbial analysis, and electrode design have improved performance, but low power density, electron-transfer resistance, membrane fouling, and scale-up losses still limit deployment. Overall, microbiological energy represents a promising platform for integrating energy recovery, waste valorization, and environmental remediation within future sustainable infrastructure.

1. Introduction

Over the last century, rapid industrial growth, urban expansion, and population increase have driven a steep rise in global energy demand. At the same time, continued reliance on fossil resources has intensified greenhouse gas emissions, accelerated climate change, and heightened concern over long-term resource depletion. These pressures have strengthened interest in renewable options that can deliver both environmental and operational benefits. Microbiological energy has emerged as one such pathway because it uses microbial metabolism to convert organic matter into useful energy forms, most commonly electricity, hydrogen, or methane [1]. Unlike conventional energy systems, these processes are rooted in biological transformations such as fermentation, anaerobic digestion, and extracellular electron transfer occurring within single strains or complex microbial consortia. This broad decarbonization backdrop parallels current work on sustainable aviation fuels in action, electrolytic hydrogen, alternative-fuel portfolios, SAF deployment pathways, green-hydrogen roadmaps, and scalable carbon-capture systems [2], [3], [4], [5], [6], [7], [8].

Anaerobic digestion (AD) is among the earliest and most established microbiological energy technologies. In AD systems, anaerobic microorganisms decompose organic wastes and generate biogas composed primarily of methane and carbon dioxide. The technology is already implemented at large scale in wastewater treatment and agricultural applications, and current research continues to improve reactor operation, microbial ecology, and methane productivity [9]. Microbial fuel cells (MFCs), by contrast, represent a more recent bioelectrochemical platform in which electrogenic microorganisms oxidize substrates and transfer electrons to an anode, thereby generating electricity [10]. This controlled electrochemical harvesting of microbial redox activity has opened new possibilities for simultaneous wastewater treatment and power production. The same waste-to-resource logic also appears in adjacent reviews on ammonia plants, waste-food valorization, solid-biomass conversion, biomass constraints, and sustainable biomass pathways [11], [12], [13], [14], [15], [16].

Microbial electrolysis cells (MECs) build on the MFC concept by applying a small external voltage to drive hydrogen evolution at the cathode, making them attractive for renewable hydrogen production [17]. Microbial electrosynthesis (MES) expands the field further by using cathodic biofilms to reduce carbon dioxide into compounds such as acetate or methane [18]. Across these platforms, system performance depends strongly on how efficiently microorganisms exchange electrons with solid surfaces. Electron transfer may occur directly through conductive appendages and membrane-bound proteins, or indirectly through soluble redox mediators [19]. More broadly, hydrogen-centered and thermodynamic transition studies on aviation routing, gas turbines, numerical energy modeling, ammonia roadmaps, humidified cycles, and hydrogen futures highlight the importance of coupling reactor chemistry with whole-system performance [20], [21], [22], [23], [24], [25].

In recent years, microbiological energy research has broadened through advances in synthetic biology, metabolic engineering, and systems-level microbial analysis.

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* Corresponding author at: Institute for Bioenergy Systems, Università di Roma Verde, Rome, Italy.

E-mail addresses: l.sayegh@alqantara.edu.lb (Lara N. Sayegh)

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Nomenclature

Abbreviation
AD – Anaerobic Digestion
MFC – Microbial Fuel Cell
MEC – Microbial Electrolysis Cell
MES – Microbial Electrosynthesis
OMICS – High-throughput molecular analysis methods
COD – Chemical Oxygen Demand
BOD – Biological Oxygen Demand
EET – Extracellular Electron Transfer
EPS – Extracellular Polymeric Substances

Symbol
μ – Microbial growth rate (h^{-1})
η – Efficiency of energy conversion (%)
P – Power output (W)

These tools allow more deliberate control over metabolic pathways and enable the development of strains or consortia tailored for higher conversion efficiency and better operational resilience [26]. In parallel, progress in materials science has yielded improved electrode materials, including graphene-based structures, carbon nanotubes, and other high-surface-area conductive supports that strengthen microbial adhesion and facilitate electron transport [27]. Omics approaches have also enhanced understanding of community dynamics, enabling more rational design of biocatalytic systems [28]. This trend is consistent with recent literature on catalytic innovation, broader bioelectrochemical technologies, green-fuel production, carbon-capture materials and process integration, solar-conversion progress, and infrastructure-scale CO2 capture [29], [30], [31], [32], [33], [34].

Despite these advances, several barriers continue to constrain wider implementation. MFCs still deliver modest power densities relative to conventional energy technologies, and performance often deteriorates during scale-up because of internal resistance, pH gradients, and nonuniform substrate distribution [35]. Microbial communities may also lose stability when exposed to fluctuating operating conditions or inhibitory contaminants [36]. Addressing these limitations requires integrated efforts across microbiology, electrochemistry, reactor engineering, and environmental process design. Comparable scale-up and resilience questions have also been examined in CFD and building-energy studies addressing airflow control, natural ventilation, indoor air quality, and office-scale thermal performance [37], [38], [39], [40], [41].

A particularly important application area is the coupling of microbiological energy systems with wastewater treatment and broader waste-management infrastructure. Such integration enables simultaneous pollutant removal, energy recovery, and in some cases nutrient recycling. Against this backdrop, the present review compares the main microbiological energy routes, outlines the methodological frameworks used to study them, and assesses their performance, scalability, and future role in decentralized and circular energy systems. At the system level, this integration mindset aligns with broader work on clean-air science, the future built environment, hybrid cooling-desalination systems, desalination-at-scale pathways, and ventilation-path design in occupied spaces [42], [43], [44], [45], [46].

2. Methodology

The methodological framework for microbiological energy systems spans microbial selection, reactor configuration, operating-condition control, and downstream system integration. Choosing an appropriate microbial culture is fundamental to performance. Electrogenic species such as Geobacter sulfurreducens, Shewanella oneidensis, and mixed anaerobic consortia are frequently used in MFCs because of their established extracellular electron transfer (EET) capacity [1]. In anaerobic digestion, substrate conversion depends on a sequential consortium of hydrolytic, acidogenic, acetogenic, and methanogenic microorganisms that collectively transform organics into methane and carbon dioxide [9]. Community profiling tools such as metagenomics and high-throughput sequencing are now central to these studies because they reveal diversity, metabolic potential, and community response to environmental disturbances [10]. That multidisciplinary structure is also reflected in recent topic-spanning reviews on microbiological energy, power quantification, combustion-to-work conversion, organic Rankine heat recovery, and bioelectrochemical deployment [47], [48], [49], [50], [51].

In MFC operation, the anodic compartment is typically inoculated with wastewater sludge or a prepared microbial culture and maintained under anaerobic conditions so that electrons are directed toward the electrode rather than molecular oxygen [17]. The cathodic compartment may be exposed to air or supplied with an oxidant such as ferricyanide to close the electrochemical circuit [18]. Charge balance is maintained through a proton exchange membrane (PEM), cation exchange membrane (CEM), or salt bridge that permits ion transport between chambers [19]. Common MFC architectures include dual-chamber, single-chamber, air-cathode, and stacked configurations, each involving a different compromise between output, cost, and design complexity [26]. Foundational comparisons of membrane-based and salt-bridge MFC designs remain important benchmarks for interpreting these configuration trade-offs [52], [53]. Methodological lessons from airflow and built-environment CFD studies likewise emphasize the importance of boundary-condition realism, spatial distribution, and configuration sensitivity during reactor or system evaluation [54], [55], [56], [57], [58].

MECs employ a similar reactor philosophy, but an external bias of roughly 0.2-0.8 V is applied to make hydrogen evolution thermodynamically favorable at the cathode [27]. Recent work on non-precious cathode catalysts, including Ni-Mo alloys and MoS2-based nanostructures, has improved hydrogen-generation efficiency while reducing reliance on platinum materials [28]. MES systems differ in emphasis by focusing on cathodic biofilms that use supplied electrons and protons to reduce CO2 into products such as acetate, methane, or other reduced organics, depending on the microbial catalyst and applied potential [35]. Comparable model-building practices are also visible in thermodynamic and combustion studies on CARSOXY systems, gas-turbine controllers, unconventional-cycle analyses, separation-process frameworks, and laser-based combustion diagnostics [59], [60], [61], [62], [63].

System output is highly sensitive to temperature, pH, substrate loading, external resistance, and hydraulic retention time (HRT). Most MFCs perform best under mesophilic conditions near 25-35°C, whereas thermophilic conditions around 50-60°C generally enhance hydrolysis and reaction kinetics in AD systems [36]. A pH range of about 6.5-7.5 is typically preferred to sustain balanced microbial activity and stable membrane performance [64]. Feed concentration must also be controlled carefully, particularly in waste-fed systems where excessive COD loading can trigger inhibition, clogging, or unstable operation [65]. For this reason, real-time sensing and feedback control are increasingly incorporated into experimental and pilot-scale studies. The need for careful operating-window control is echoed in Kalina-cycle optimization, ammonia-plant heat-exchanger integration, geothermal-pathway analysis, solar-tracking assessment, and thermal-energy-storage studies [66], [67], [68], [69], [70].

Electrode composition and surface characteristics play a decisive role in microbial adhesion and electron transport. Carbon-based materials such as graphite, carbon cloth, carbon felt, and carbon nanotube composites remain widely used because they combine electrical conductivity, biocompatibility, and resistance to corrosion [71]. Surface modifications with nanostructured coatings, including polyaniline and graphene oxide, have been reported to increase accessible area and promote denser biofilm growth, thereby improving current generation [72]. Table 1 summarizes representative electrode materials used across microbiological energy systems. Similarly, advances in material architecture and control surfaces across turbine analyses, separation-process studies, control applications, and unmanned-system design underline how geometry and interface design can strongly influence performance [73], [74], [75], [76], [77].

Reactor geometry and scale strongly influence technical viability. Bench-scale units ranging from roughly 10 to 500 mL are useful for mechanistic studies and proof-of-concept testing, but their reported performance often falls during scale-up because of longer conduction paths, flow maldistribution, and microbial stratification [78]. Pilot-scale systems in the 10-100 L range have therefore been used to examine long-duration behavior, maintenance requirements, and substrate variability under more realistic conditions [79]. Modular stacking remains a common scale-up strategy for MFC and AD systems, although inter-module inconsistency and gas leakage continue to pose challenges [80]. Table 2 summarizes the main reactor configurations and their scalability considerations. Scale-up and integration thinking is likewise central in studies on methane monitoring, photovoltaic-powered direct air capture, broader CO2-capture scenario evaluation, circular hydrogen carriers, and related residential DAC designs [81], [82], [83], [84], [85].

Table 1. Common electrode materials

Material
Graphite Felt
Carbon Cloth
CNT-Coated Electrode
Stainless Steel

Table 2. Microbiological reactor configurations and scalability

Type
Single-chamber MFC
Two-chamber MFC
UASB AD Reactor
MES Reactor

Reliable evaluation of microbiological energy systems depends on a combination of chemical, gas-phase, and electrochemical analyses. Gas chromatography (GC), high-performance liquid chromatography (HPLC), and total organic carbon (TOC) measurements are routinely used to track substrate conversion, gas production, and overall process stability [86]. Electrochemical impedance spectroscopy (EIS), cyclic voltammetry (CV), and chronoamperometry provide complementary information on charge-transfer resistance, polarization behavior, and electron-transfer kinetics [87]. The principal performance indicators and their associated measurement tools are summarized in Table 3. Analytical rigor of this type is also evident in techno-economic, air-quality, combustion-imaging, control, and solar-conversion-at-scale studies that rely on multi-metric assessment rather than single-parameter reporting [88], [89], [90], [91], [92].

Table 3. Key performance metrics and measurement tools

Parameter
Voltage
Current density
Methane yield
Coulombic efficiency
COD removal

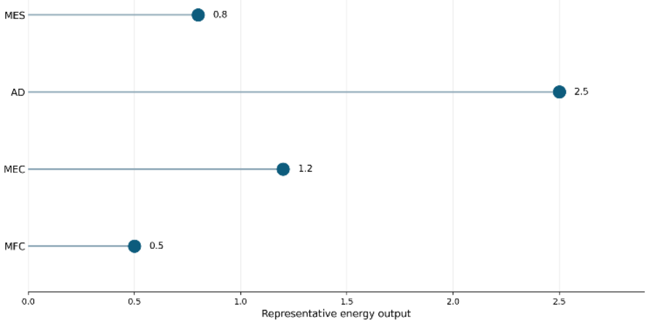
Overall, the methodology of microbiological energy research is inherently multidisciplinary, combining microbiology, electrochemistry, materials engineering, and process design. The incorporation of omics tools, advanced electrode materials, and automated process monitoring has substantially improved how these systems are developed and evaluated. As the field moves toward application-focused deployment, pilot-scale validation and integration with existing infrastructure will be essential for translating laboratory performance into practical operation. In the same spirit, recent adjacent literature on drop-in SAF, aircraft-engine SAF performance, direct-air-capture patent pathways, and policy-oriented net-zero flight analysis also points toward increasingly integrated, multi-scale research workflows [93], [94], [95], [96].

3. Results

The performance of microbiological energy systems varies markedly with microbial ecology, reactor layout, substrate properties, and operating conditions. Energy recovery, pollutant removal, and long-term biological stability therefore need to be assessed together rather than in isolation. Figure 1 provides a comparative view of representative energy-output levels reported for four major platforms: microbial fuel cells (MFCs), microbial electrolysis cells (MECs), anaerobic digestion (AD), and microbial electrosynthesis (MES). Within this comparison, AD exhibits the strongest overall energy recovery because complete biodegradation of organics can sustain values approaching 2.5 W/m² under optimized conditions, while MECs and MES occupy an intermediate position and MFCs remain lower because of voltage limitations and resistance losses [1]. Even so, MFCs retain value in low-power niches such as remote sensing and decentralized wastewater treatment [9]. Comparable comparative-ranking approaches are increasingly used across adjacent decarbonization fields, including aviation-route optimization, biomass pathway assessment, and ammonia-based DAC concepts [97], [16], [98].

For MFCs specifically, power density depends strongly on electrode surface properties, microbial adhesion, and substrate composition. Nanostructured electrodes and surface-functionalized materials have improved laboratory-scale performance, with some controlled glucose-fed systems reaching about 1.5 W/m² [10]. In practical wastewater applications, however, power output usually declines because feed composition is less uniform and competing microbial pathways consume part of the available substrate [17]. MECs can outperform MFCs in energy-product recovery when supported by renewable electricity inputs, making them particularly attractive for coupled hydrogen-generation schemes [18]. Recent studies using Ni-Mo cathodes report favorable hydrogen productivity together with positive net-energy behavior when the system is properly optimized [19].

The strong performance of AD in Figure 1 reflects both the maturity of the process and the efficiency of its sequential microbial conversion steps. MES shows lower direct energy output than AD, but its ability to convert carbon dioxide into reduced products makes it strategically important where carbon utilization is prioritized. These differences highlight an important point: the most suitable system is not necessarily the one with the highest absolute output, but the one whose product slate and operational characteristics align best with the target application.



Relative comparison adapted from the manuscript's reported representative values.

Fig. 1. Lollipop comparison of representative energy-output levels across microbiological energy systems

Microbial community structure exerts a direct influence on durability and process efficiency. Figure 3 compares Shannon diversity indices across the major systems and shows the highest value for AD (2.8), followed by MFCs and MECs, with MES displaying the most specialized community structure [35, 36, 64]. The elevated diversity observed in AD is consistent with its layered trophic organization, in which hydrolytic, fermentative, acetogenic, and methanogenic groups coexist and support sequential conversion steps [35]. By contrast, MFCs and MECs are generally dominated by electroactive organisms such as Geobacter and Shewanella, while MES communities are often shaped by the selective cathodic environment and enriched in specialized CO2-reducing microorganisms such as Sporomusa ovata and Clostridium ljungdahlii [36, 64].

Community resilience is equally important for sustained operation under variable conditions. AD typically shows the highest robustness because functional redundancy allows the community to reorganize under stress; for example, methanogenesis can shift from acetoclastic to hydrogenotrophic pathways during ammonia or pH disturbances [65]. MFCs are generally more vulnerable because oxygen leakage or biofilm disruption can rapidly depress performance [71]. To address this limitation, recent studies have explored synthetic consortia and encapsulated biofilms as means of preserving electroactive function and improving operational stability [72].

Long-duration pilot studies provide a more realistic view of system reliability. Under municipal wastewater conditions, pilot-scale MFCs have maintained power densities near 0.35 W/m^2 together with COD removal of about 78%, although electrode fouling becomes noticeable over multi-month operation [78]. MECs have reported hydrogen production rates close to 0.9 m^3 H2/m^3/day, but stable operation often requires periodic management of cathodic scaling and local pH imbalance [79]. AD systems processing mixed agricultural residues have achieved methane yields of approximately 0.32 m^3 CH4/kg VS and have also benefited from downstream biofiltration for biogas desulfurization [80].

Internal resistance remains one of the main determinants of energy efficiency in bioelectrochemical systems. In MFCs, overall resistance includes ohmic, activation, and concentration components, all of which reduce voltage recovery if reactor architecture is not optimized. Studies using hierarchical porous electrodes and 3D-printed conductive structures have demonstrated reductions in internal resistance of up to 35%, alongside improved biofilm development and higher energy recovery [86]. In MES, limitations at the cathode-microbe interface continue to restrict electron uptake. Redox mediators such as neutral red and riboflavin have been investigated to improve electron transfer, although toxicity, stability, and cost remain important concerns [87]. More generally, interface-level losses and transport bottlenecks are recurring themes across combustion-system theses, patent pathway disclosures, and hydrogen-carrier reviews, which likewise stress the importance of coupling local transport with overall system efficiency [99], [100], [101].

Tables 4-7 extend the comparison beyond single performance values by summarizing energy product ranges, environmental benefits, microbial community features, and techno-economic indicators. Together, these tables show that AD offers the highest level of technological maturity and the shortest payback period, while MES provides the strongest carbon-utilization potential. MFCs and MECs occupy intermediate positions, combining useful treatment performance with promising but still developing energy-recovery capabilities. This multidimensional comparison is important for identifying appropriate deployment niches rather than treating all microbiological energy technologies as interchangeable options.

Table 4. Energy output ranges across major microbiological systems

System	**Typical Energy Product**	**Energy Output Range**	**Units**	**Remarks**
Anaerobic Digestion (AD)	Methane	0.2 – 0.35	m^3 CH_4/kg VS	Mature technology, co-digestion enhances yield
Microbial Fuel Cell (MFC)	Electricity	0.1 – 1.5	W/m^2	Highly dependent on electrode and substrate
Microbial Electrolysis Cell (MEC)	Hydrogen	0.4 – 1.2	m^3 H_2/m^3/day	Requires external voltage
Microbial Electrosynthesis (MES)	Acetate, Methane	0.2 – 1.0	g/L/day	Product depends on microbe and cathode potential

Gas composition and product quality also vary substantially among systems. Biogas from AD typically contains 55-70% methane together with carbon dioxide and trace hydrogen sulfide, which usually necessitates post-treatment before end use. MECs can deliver hydrogen streams of high purity, though cathodic overpotentials still limit overall conversion efficiency. MES platforms are able to produce acetate, ethanol, or methane depending on the microbial catalyst and imposed cathode potential. Enhanced reactor designs based on graphite felt or granular carbon beds have improved electron capture and product selectivity, with acetate productivities reported up to 0.85 g/L/day [102].

Table 5. Emission reduction and environmental benefit comparison

System	GHG Reduction	Nutrient Recovery	Sludge	Environmental Impact
AD	High (up to 80%)	Yes (N, P)	Moderate	Very favorable
MFC	Moderate	Partial	Low	Decentralized use
MEC	High (renewable power)	Yes	Low	Enables H2 economy
MES	Very High (CO2 use)	No	Low	Carbon-negative

Durability of materials is a central issue for long-term operation. Carbon cloth and carbon felt generally retain performance over many cycles with limited degradation, whereas metal electrodes such as stainless steel are more susceptible to corrosion in acidic or sulfide-containing environments [103]. Membrane fouling is another persistent concern in two-chamber MFC and MEC configurations because it suppresses ion transport and raises maintenance requirements. Antifouling surface treatments and periodic polarity reversal have been proposed as practical mitigation measures [104].

Integrated process configurations are increasingly attractive, particularly for distributed applications. Hybrid AD-MFC arrangements have shown that residual organics leaving a digester can be further valorized through electricity generation, thereby raising total energy recovery. One pilot study treating food waste and wastewater reported an overall recovery improvement of about 20% relative to standalone AD [105]. MES has also been coupled with CO2 capture systems to convert industrial flue gases into acetate, illustrating how bioelectrochemical conversion can function as part of a carbon-negative process chain [106].

From an economic standpoint, AD remains the most competitive and commercially mature technology, with reported payback periods of roughly 3-7 years depending on feedstock availability and gas-use strategy. MFCs and MECs are still constrained by relatively high capital costs and limited power density, which currently confines them to specialized applications [107]. MES is less mature still and only limited economic evidence is available, but its potential role in carbon utilization and specialty biochemical production continues to attract attention [108]. This interpretation is also consistent with broader energy-systems studies linking emissions accounting, cooling-performance metrics, and fuel-transition scale-up to eventual commercial readiness [109], [110], [111].

Table 6. Dominant microbial groups and community-stability indicators

System	**Dominant Microbes**	**Diversity Index (Shannon)**	**Tolerance to pH/Temp Fluctuation**	**Biofilm Stability**
AD	Methanogens, Firmicutes	2.8	High	Moderate
MFC	*Geobacter*, *Shewanella*	2.3	Low–Moderate	High
MEC	Mixed electrogens	2.0	Moderate	Medium
MES	*Sporomusa*, *Clostridium*	1.9	Low	Low–Medium

Environmental assessment further strengthens the case for microbiological energy. Life-cycle studies indicate that AD can cut greenhouse-gas emissions by as much as 80% relative to landfilling of organic wastes, while MFCs offer low-emission wastewater treatment with limited sludge production and low chemical demand [112]. When driven by renewable electricity, MEC and MES platforms can approach very low or even negative net carbon footprints under favorable conditions. Figure 2 synthesizes the COD-removal trends discussed across the four systems and confirms that AD leads overall treatment performance, followed by MFCs and MECs, while MES shows more moderate removal because waste degradation is not its primary objective. Parallel environmental framing is also evident in adjacent literature on solar-energy transitions and building-performance case studies reported in allied journals [33], [113], [114].

Table 7. Techno-economic indicators and technology readiness levels

Parameter	AD	MFC	MEC	MES
Capital Cost (USD/kW)	2,000–4,000	5,000–10,000	7,000–12,000	>15,000
O&M Cost (USD/year)	Moderate	Low	Moderate	High
Payback Period (years)	3–7	10–15	8–12	>15
TRL (Tech Readiness Level)	9	5–6	4–6	3–4

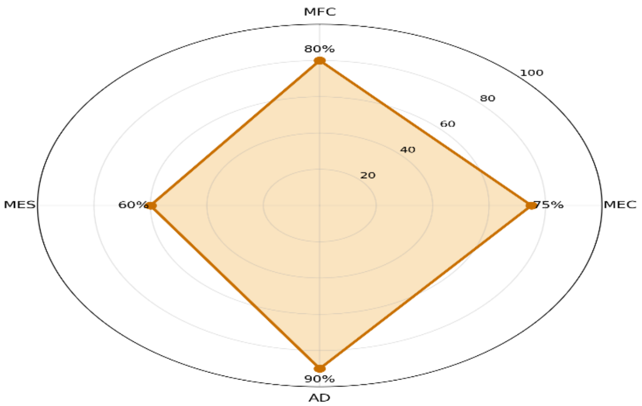


Fig. 2. Radar-chart summary of COD-removal performance across microbiological energy systems

Taken together, these results confirm that microbiological energy technologies are viable across several application contexts, but their suitability is highly system-specific. Reactor design, microbial community structure, electrode material, and process integration all exert strong control over performance. Continued advances in synthetic biology, electrochemical engineering, and process control are therefore likely to determine how quickly these systems move from specialized demonstrations toward broader implementation [115][116]. Accordingly, the pathway from promising prototype to deployable system depends not only on performance optimization but also on implementation strategy and deployment fit, a point echoed in controller-oriented studies of technology translation [117].

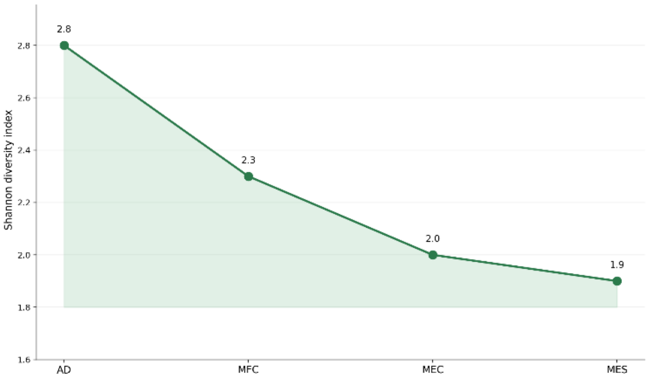


Fig. 3. Ranked point-profile of Shannon diversity across microbiological energy systems

4. Discussion

The findings synthesized in this review highlight both the promise and the complexity of microbiological energy technologies. A central theme is the persistent trade-off among energy recovery, reactor complexity, and microbial robustness. Although anaerobic digestion continues to dominate in terms of maturity, output, and practical deployment, newer bioelectrochemical platforms such as MFCs, MECs, and MES broaden the functional scope of the field by coupling energy conversion with wastewater treatment, hydrogen generation, and carbon utilization [118]. Determining where each technology fits best requires evaluating biological, engineering, and environmental dimensions together rather than focusing on a single performance metric.

One of the clearest lessons from the comparative results is that microbial community composition is not a background detail but a primary design variable. Community structure influences conversion efficiency, product selectivity, operational stability, and resilience to disturbance. Highly diverse systems such as AD tend to be more robust because multiple trophic groups can compensate for environmental stress or process fluctuations. More selective systems, including MES and many MFC configurations, may offer sharper functional control but are also more vulnerable to shifts in pH, temperature, or substrate availability. This ecological perspective suggests that reactor design should account for succession, competition, and functional redundancy alongside purely physical parameters [119]. The growing use of metagenomics, metatranscriptomics, and metabolomics is therefore especially valuable because it helps translate microbial behavior into engineering decisions [120].

Electron-transfer mechanisms remain at the core of bioelectrochemical performance. Direct electron transfer is typically more efficient than mediator-based pathways because it reduces losses associated with soluble carriers, but it depends strongly on the interfacial compatibility between microorganisms and electrode surfaces. Conductive pili, outer-membrane cytochromes, and extracellular polymeric substances all influence how effectively electrons move from cells to solid supports [121]. As a result, current research is increasingly focused on electrode materials and coatings that actively promote biological attachment and interfacial charge transport, rather than serving merely as passive current collectors [122].

Electrode architecture and reactor geometry represent another major frontier. Conventional flat and tubular designs are gradually being supplemented by three-dimensional structures that expand surface area, improve mass transfer, and provide more favorable microenvironments for biofilm development. 3D-printed electrodes are particularly attractive because they allow controlled tuning of porosity, channel geometry, and local conductivity, which in turn can reduce internal resistance and enhance microbial colonization [123]. Related work on conductive hydrogels and composite electrodes further suggests that future systems may be designed as multifunctional biotic-abiotic interfaces rather than simple electrochemical containers [124].

Operating conditions must also be controlled with considerable precision. Increasing organic loading can raise energy recovery, but it may also trigger substrate inhibition, acidification, or biomass washout if retention times and mass-transfer conditions are not properly matched to microbial kinetics. Optimal HRT and SRT therefore depend not only on reactor type but also on the desired product—methane, hydrogen, electricity, or reduced organics [125]. This is one reason why real-time sensing, feedback control, and even model-based or machine-learning-assisted optimization are becoming increasingly important in advanced reactor studies [126].

The greatest near-term opportunity for deployment may lie in integration with existing infrastructure. Wastewater treatment facilities, food-processing plants, and agricultural operations already generate organic streams that are well suited to microbial conversion. Embedding MFCs within treatment trains can add electricity recovery to COD removal, while coupling AD with downstream MFC or MEC stages can increase total resource recovery from residual organics [127]. MES, meanwhile, may become especially valuable when paired with industrial CO2 sources or capture units, where its carbon-conversion function can complement broader decarbonization strategies [128].

Despite encouraging laboratory results, commercial translation remains slow because scale-up introduces a different class of constraints. Power densities that appear promising at bench scale often fall in larger reactors as flow maldistribution, electrode fouling, and spatial heterogeneity become more pronounced. Standardized modular designs, better hydrodynamic management, and closer integration of microbiology with process engineering will be essential if these technologies are to move beyond demonstration status [64][65].

Economic feasibility is equally decisive. AD already benefits from proven deployment pathways, established supply chains, and predictable waste feedstocks, all of which improve investment confidence. By contrast, MFCs and MECs still require costly electrodes, membranes, and monitoring systems, and their operation often demands technical expertise that may not be readily available in decentralized contexts. Even so, progress in low-cost carbon materials, waste-derived conductive media, and additive manufacturing suggests that capital costs can be reduced without necessarily sacrificing performance [71][72].

The environmental case for microbiological energy is strong. These systems can divert organic residues from landfills, lower methane leakage, reduce sludge formation, and recover both energy and nutrients from waste streams. Life-cycle assessments consistently show favorable greenhouse-gas and energy-demand profiles for AD and, in many contexts, for MFC-based wastewater treatment as well [78][79]. This makes microbiological energy especially relevant to circular-economy frameworks in which treatment, recovery, and decarbonization are pursued simultaneously.

Synthetic biology and metabolic engineering may further reshape the field by enabling organisms or consortia to be tuned for specific products, improved stress tolerance, or more efficient electron transport. Engineered communities that distribute metabolic tasks among specialized members have already shown potential to improve conversion efficiency and reduce unwanted byproducts. Tools such as CRISPR-based editing expand these possibilities considerably, although biosafety, containment, and regulatory acceptance remain important limiting factors, particularly for open or semi-open systems [80][86].

Ultimately, microbiological energy is unlikely to replace large centralized renewables such as solar or wind, but that is not the appropriate benchmark for judging its value. Its real strength lies in distributed, modular, and hybrid roles where waste treatment, resource recovery, and localized energy production are all needed simultaneously. In remote communities, smart sanitation systems, biorefineries, and circular agricultural settings, these technologies may offer capabilities that conventional renewables cannot easily provide on their own [87].

5. Conclusion

Microbiological energy has introduced a different way of thinking about renewable energy, waste handling, and environmental remediation by using microbial metabolism as the basis for conversion. Through platforms such as anaerobic digestion (AD), microbial fuel cells (MFCs), microbial electrolysis cells (MECs), and microbial electrosynthesis (MES), organic residues and carbon-containing streams can be transformed into methane, electricity, hydrogen, and other valuable products. In this sense, microbiological energy systems bridge biological processing, environmental engineering, and renewable-energy development while supporting broader goals linked to circularity and emissions reduction.

This review shows that AD remains the most mature and widely implemented option within the field. Its ability to process large organic loads, generate relatively stable biogas yields, and operate within established infrastructure makes it highly attractive for municipal, agricultural, and industrial waste management. Continued improvements in pretreatment, co-digestion, and digester configuration are further expanding the range of feedstocks and operating strategies that can be treated effectively.

MFCs illustrate a different value proposition by converting organic matter directly into electricity through extracellular electron transfer. Advances in carbon nanomaterials, graphene-based coatings, and 3D-printed electrodes have improved biofilm development and current output, although membrane fouling, low cell voltage, and long-term stability remain unresolved challenges. Even with these limitations, MFCs offer distinctive opportunities in decentralized wastewater treatment, remote sensing, and other low-power applications where simultaneous treatment and energy recovery are advantageous.

MECs extend microbial electrochemistry toward hydrogen production through the addition of a modest external voltage, making them relevant to renewable-fuel strategies when coupled with low-carbon electricity. MES systems, although still less mature, are particularly interesting because they use biological catalysis to convert CO2 into acetate, methane, and other reduced products. Their future importance may lie in linking bioelectrochemical conversion with carbon capture and utilization rather than in conventional energy recovery alone.

A recurring conclusion across all four systems is that microbial community structure and electron-transfer behavior are fundamental to performance. Progress in metagenomics, transcriptomics, and biosensing has significantly improved understanding of how communities respond to operational stress and how their metabolic roles can be steered. At the same time, synthetic biology and metabolic engineering are beginning to make purposeful community design a realistic option, albeit one that brings additional ecological and regulatory considerations.

From an engineering perspective, scale-up remains the dominant obstacle. Metrics achieved in laboratory reactors often decline in larger systems because internal resistance rises, flow becomes less uniform, and microbial populations become harder to stabilize. Modular configurations, improved fluid-distribution strategies, and advanced control methods offer promising routes forward, especially when microbiological energy units are integrated into existing wastewater, agricultural, or biorefinery infrastructure.

Economic readiness also differs substantially across the field. AD is already commercially feasible in many centralized applications, whereas MFCs and MECs still depend on further reductions in material cost and improved productivity before wider deployment becomes realistic. MES is at an even earlier stage, but it may find specialized value in carbon-utilization and biorefinery settings once microbial efficiency and reactor scale are improved.

The environmental and policy implications are considerable. In addition to producing energy, these technologies can reduce pollutant loads, support nutrient recovery, displace fossil-derived products, and contribute to greenhouse-gas mitigation. Their successful diffusion, however, will also depend on regulatory frameworks, incentives, and deployment models that recognize the multifunctional nature of microbiological energy systems rather than treating them solely as niche power technologies. Experiences from other sectors also suggest that communication and stakeholder-facing dissemination can influence how technical solutions move from concept to adoption [129].

In summary, microbiological energy systems combine resource recovery, low-emission conversion, and engineering innovation in a way that makes them highly relevant to future sustainable infrastructure. Their greatest impact will likely come from targeted applications where treatment, recovery, and decentralized operation intersect. Continued collaboration across microbiology, electrochemistry, materials science, process engineering, and policy will be essential to move these systems from promising demonstrations to durable real-world solutions.

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