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Radiation-resistance in alternative energy systems: A critical approach to microbial fuel cells adapted for extreme environments

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The quest for sustainable energy systems that function in severe settings has generated interest in microbial fuel cells (MFCs) utilizing radiation-resistant bacteria. These extremophiles, such as Deinococcus radiodurans, Thermococcus gammatolerans, and Rubrobacter radiotolerans, exhibit remarkable DNA

repair systems, antioxidative defenses, and protein-protection mechanisms that facilitate prolonged metabolic activity in the presence of strong ionizing radiation. This review aims to critically assess recent advances in electrode nanomaterials, biofilm engineering, and system optimization approaches to improve microbial fuel cell (MFC) performance. In contrast to traditional electrogens like Shewanella oneidensis and Geobacter sulfurreducens, which quickly deteriorate under radiation stress, these organisms preserve their extracellular electron transfer (EET) capability and biofilm integrity in adverse conditions. Their incorporation into MFCs broadens prospective uses in space exploration, radioactive waste treatment, deep subterranean bioenergy extraction, and autonomous environmental surveillance. In interplanetary environments, radiation-resistant microbial fuel cells could supply continuous electricity for life-support systems and instruments in scenarios where solar energy is inconsistent. In nuclear reactors and polluted locations, they could concurrently immobilize radionuclides and produce power for distant sensors. Deep systems may utilize native extremophiles to facilitate seismic and hydrogeological monitoring, whilst autonomous biosensors could function in disaster areas for prolonged environmental surveillance. By integrating extremophile resilience with MFC adaptability, these systems provide a self-sustaining, low-maintenance power source that operates effectively in environments where traditional bio-electrochemical technologies are ineffective. The review examines microbial adaptations to radiation, material degradation in radioactive conditions, electron transport pathways, and the contribution of extremophiles to the enhancement of MFC performance. Utilizing these creatures for energy production signifies a new frontier in bioenergy research, with considerable ramifications for planetary science, nuclear safety, and sustainable infrastructure in harsh conditions.

Keywords: microbial fuel cells; radiation-resistant microorganisms; extremophiles; extracellular electron transfer; and bioenergy.

Introduction

The worldwide quest for sustainable and renewable energy sources has escalated in recent decades, propelled by the pressing necessity to alleviate the environmental impacts of fossil fuel reliance, diminish greenhouse gas emissions, and satisfy the increasing demands of industrial, urban, and remote populations [1, 2]. Microbial fuel cells (MFCs) represent a promising bio-electrochemical technology within the renewable energy sector, efficiently transforming chemical energy from organic substrates into electrical energy through microbial metabolism [3]. MFCs provide unique benefits compared to traditional renewable technologies, such as functioning at ambient temperatures, treating waste streams while generating power, and utilizing the metabolic variety of microorganisms to operate under diverse environmental conditions [4]. Notwithstanding these advantages, the practical application of microbial fuel cells (MFCs) in extreme environments, such as deep-space missions, nuclear waste treatment facilities, polar regions, and high-radiation zones, is constrained by the vulnerability of traditional electrogenic microbes to environmental stressors, including ionizing radiation, desiccation, and temperature fluctuations [5].

Extremophiles, microbes that flourish in environments once deemed uninhabitable, constitute an underutilized biological asset for the advancement of MFC technology [6]. Radiation-resistant bacteria, a distinct category of extremophiles, exhibit exceptional DNA repair systems, protein safeguarding techniques, and antioxidative defenses that allow them to endure and maintain metabolic activity in high-ionizing radiation settings [7, 8]. Deinococcus radiodurans is the most renowned bacterium, capable of withstanding up to 5,000 Gy of gamma radiation without substantial loss of viability, a tolerance threshold hundreds of times greater than that of other eukaryotic organisms [7]. Additional significant examples comprise Kocuria rosea, Rubrobacter radiotolerans, and certain archaea like Thermococcus gammatolerans, which are suited to radiation-dense environments

including uranium mines and nuclear reactor cooling ponds [9]. The exceptional durability of radiation-resistant bacteria makes them optimal candidates for MFC systems designed for challenging environmental applications. These habitats encompass extraterrestrial areas subjected to cosmic radiation, deep subterranean biospheres linked to geothermal or radioactive resources, and industrial locations polluted with radionuclides. In these situations, traditional MFC consortia led by Shewanella or Geobacter species may experience metabolic inhibition or viability loss, while extremophiles can sustain electroactive metabolism and biofilm stability [10, 11]. Utilizing these characteristics not only extends the operational capacities of MFCs but also generates prospects for integrated energy generation and bioremediation in radiation-impacted areas [12].

Ionizing radiation, including alpha particles, beta particles, gamma rays, and cosmic radiation, significantly jeopardizes microbial viability in bio-electrochemical systems situated in high-radiation areas [13]. Damage primarily arises from direct DNA strand breakage and indirect oxidative stress caused by water radiolysis, resulting in the formation of reactive oxygen species (ROS), including hydroxyl radicals, hydrogen peroxide, and superoxide anions [14]. Traditional electrogenic bacteria frequently possess inadequate ROS-detoxifying mechanisms, making them vulnerable to fast population reductions in these conditions. Consequently, the performance of MFC, assessed by voltage output, current density, and power density, may decline markedly under radiation exposure [14].

Radiation-resistant extremophiles exhibit several protective mechanisms, including highly effective DNA double-strand break repair through homologous recombination, manganese-based antioxidants that inhibit protein oxidation, and compact nucleoid structures that reduce mutagenesis [15]. These modifications not only guarantee survival but also facilitate continuous metabolic activity, even in an extracellular environment loaded with reactive oxygen species (ROS). Comprehending and utilizing these molecular defense mechanisms could transform MFC design for harsh conditions.

Conventional MFC configurations predominantly depend on mesophilic, non-extremophilic microorganisms like Geobacter sulfurreducens and Shewanella oneidensis, which are proficient in extracellular electron transfer (EET) via conductive pili, c-type cytochromes, and redox mediators [16]. Although these organisms demonstrate efficacy in controlled laboratory settings, their performance diminishes in field applications characterized by elevated salinity, desiccation, harsh temperatures, or radiation exposure [17]. Furthermore, sustaining sterile or semi-sterile operational environments in remote and harsh conditions presents logistical challenges and is financially prohibitive.

Extremophile-based MFCs may surmount these constraints by diminishing the necessity for stringent environmental management, enabling systems to operate in situ with minimum external oversight. An MFC employing Thermococcus gammatolerans may function in geothermal areas with high background radiation, concurrently generating power and facilitating the removal of radionuclides in contaminated water sources [17]. The incorporation of Deinococcus radiodurans into space-grade MFCs may offer dependable energy for extended planetary missions with limited cosmic ray shielding [18].

Although several reviews have been published on MFC technologies in recent years, relatively few have focused on the combination of nanocomposites for electrode modification, biofilm maturation engineering, and data-driven or optimization design approaches adapted for extreme environments. Notable among recent works are the state-of-the-art review on nanocomposites [19], the WS_2 /WO_3-modified electrode study demonstrating large power density gains, and modelling/optimization studies [20, 21]. This review complements them by integrating these new findings and identifying underexplored research gaps for future work.

Radiation environments and material damage

The radioactive waste environment is characterized by a complex and hazardous mixture of ionizing radiation, including alpha particles (helium nuclei), beta particles (electrons or positrons), gamma rays (high-energy photons), and neutrons (neutral subatomic particles), as described by Yip et al. [22]. The interaction of these various forms of radiation with containment materials differs significantly in terms of penetration and ionizing potential. Although alpha particles possess low penetration ability, they have high ionizing power and can cause substantial internal damage when inhaled or ingested [23]. Beta particles, on the other hand, exhibit greater penetration capacity and can initiate ionization chains within materials, resulting in structural degradation and chemical changes [23].

Gamma rays and neutrons, due to their high energy and substantial penetrating abilities, present long-term threats to the structural integrity of storage materials [24]. El-Hameed et al. [25] also noted that ionizing radiation can degrade materials through both direct atomic interactions and secondary chemical reactions, leading to the compromise of long-term stability and performance.

As radiation passes through materials, particularly those containing water, it induces ionization processes that lead to the formation of reactive oxygen species (ROS). These include hydroxyl radicals ($\cdot OH$), superoxide anions (O_2^-), and hydrogen peroxide (H_2O_2), which contribute to oxidative stress and further degradation of the material. These reactive oxygen species (ROS) initiate a series of oxidative reactions that degrade materials. They break down polymer chains, corrode metals, and destabilize composite structures by compromising their integrity [26, 27]. Bronstein et al. [28] reported that due to the ionizing nature of radiation, there is a potential for the disruption of chemical bonds within polymer-based containment systems, which can lead to chain scission and, consequently, material embrittlement. Conversely, in certain polymers, radiation exposure may initially induce cross-linking, resulting in enhanced mechanical properties. However, with prolonged exposure, these materials may also undergo degradation, leading to bond breakage and increased brittleness over time [28]. Radiation can degrade structural materials by weakening passive protective layers, accelerating corrosion processes, and altering internal microstructures in concrete and steel constructions [29]. Neutron radiation can displace atoms within a material's crystal lattice, gradually creating defects that compromise

the mechanical integrity of the structure [30]. Such defects in metals can lead to phenomena such as swelling, embrittlement, and eventual fracture. Radioactive wastes are often immobilized in ceramic or glass matrices through vitrification; however, these materials may undergo devitrification or experience a reduction in chemical durability over time, potentially compromising their long-term stability and containment performance [29].

A particularly concerning aspect of material degradation in nuclear waste management is the extended timescale over which containment must remain effective. Engineered barriers within nuclear repositories are required to maintain their integrity over centuries or even millennia [31]. Conventional materials often fail to perform reliably under such prolonged exposure, increasing the risk of radionuclide leakage into surrounding ecosystems [32, 33]. This situation reveals the urgent need for advanced materials that are not only resistant to ionizing radiation but also capable of withstanding oxidative stress, preserving their structural integrity. An emerging alternative lies in the use of biological systems. Brumwell et al. [33] in their independent reports presented that microorganisms have evolved to survive extreme conditions by neutralizing reactive oxygen species (ROS) with potent antioxidants, rapidly repairing DNA and protein damage, and producing robust extracellular polymers. These features can be replicated in synthetic materials [33]. Such biological strategies offer promising pathways for developing biohybrid and bioinspired materials with enhanced durability and environmental compatibility for use in nuclear facilities.

The nature of material influences the efficiency of the innovated MFCs, For example, Kordek-Khalil et al. (2023) provide a comprehensive survey of nanocomposites used in recent MFC electrodes, revealing how surface area, conductivity, and microbial adhesion are enhanced by combining carbon, metal, and polymer phases. Similarly, a WS_2 /WO_3-modified carbon paper anode achieved a maximum power density of $\sim 2.32\ \mathrm{W \cdot m^{-2}}$ in 2025, outperforming bare electrodes by over 3-fold in some metrics.

Radiation resistant microorganisms

Biologically inspired approaches to nuclear waste management are increasingly being driven by the study of radiation-resistant microorganisms [7, 34]. The findings of Makarova et al. [35] reaffirms that among the most notable of these are extremophilic bacteria such as Deinococcus radiodurans, which can survive exposure to ionizing radiation levels up to 10 kGy (10,000 Gy), a dose that is lethal to most other forms of life. This remarkable resistance is not unique to Deinococcus radiodurans, as closely related species within the Deinococcus genus, including Deinococcus deserti and Deinococcus geothermalis, also exhibit high levels of radioresistance. For example, Deinococcus deserti has demonstrated the ability to rapidly repair extensive chromosomal damage [36, 37]. In addition to bacteria, certain archaea such as Thermococcus gammatolerans have also shown exceptional resilience, surviving gamma radiation doses as high as 30,000 Gy. This suggests that multiple survival strategies against ionizing

radiation have independently evolved among different microbial lineages [32]. The basis of such extraordinary resistance lies in the robust antioxidant defense systems of these microorganisms. In Deinococcus radiodurans, these systems include enzymatic antioxidants such as superoxide dismutases (SODs), catalases, peroxidases, and DNA-binding proteins from starved cells (Dps), which work synergistically with non-enzymatic scavengers including manganese complexes and the ketocarotenoid deinoxanthin. Qi et al. [38] argued that these defense mechanisms are capable of neutralizing reactive oxygen species (ROS), thereby protecting cellular components from radiation-induced oxidative damage. Recent studies suggest that the primary damage caused by reactive oxygen species (ROS) during radiation exposure affects proteins rather than DNA. This finding shifts the paradigm of radiation resistance from a focus on genome protection to the preservation of the proteome [39, 40]. One contributing factor to this resistance in Deinococcus radiodurans is its high intracellular manganese-to-iron (Mn/Fe) ratio. Intracellular Mn^{2+} concentrations can reach up to 2 mM, while Fe^{2+} levels remain comparatively low [41]. This metal profile facilitates the formation of Mn-metabolite complexes that act as efficient non-enzymatic ROS scavengers. Complexes formed between Mn^{2+} and orthophosphate, nucleosides, amino acids, and peptides enable rapid detoxification of superoxide and hydrogen peroxide, thereby preserving essential proteins, including DNA repair enzymes [42]. The findings of He et al. [43] strengthens the theory that mutational studies of manganese transporters such as MntH and MntE have demonstrated that disruptions in manganese homeostasis significantly reduce radioresistance, further underscoring the critical role of metal regulation in microbial survival under extreme oxidative stress.

The defense mechanisms employed by radiation-resistant microorganisms constitute a complex and highly coordinated system. This includes high-capacity non-enzymatic scavenging of reactive oxygen species (ROS), enzymatic antioxidant activity, tightly regulated metal homeostasis, carotenoid-based protection, protein stabilization, dedicated DNA repair pathways, and reinforcement of the cell envelope structure [44, 45]. The integration of these systems enables microbial survival under extreme conditions involving radiation, desiccation, and oxidative stress. These are challenges that conventional materials typically cannot withstand [45]. These microbial adaptations are increasingly relevant to materials science and nuclear waste management. Jin et al [45] reported that the coordinated radiation response systems facilitate efficient DNA repair, as illustrated in Figure 1. Insights into manganese-based antioxidant chemistry, the structural and functional properties of DNA repair enzymes, and the formation of bio-assembled protective matrices support the conceptual development of biohybrid and bioinspired materials. For example, the incorporation of microbial Mn-metabolite complexes into polymer composites may provide intrinsic ROS-scavenging capabilities [43]. Microbial biofilms or exopolysaccharides can be bioengineered and applied as self-healing barrier layers in radioactive environments, offering a promising strategy for enhancing long-term containment performance.

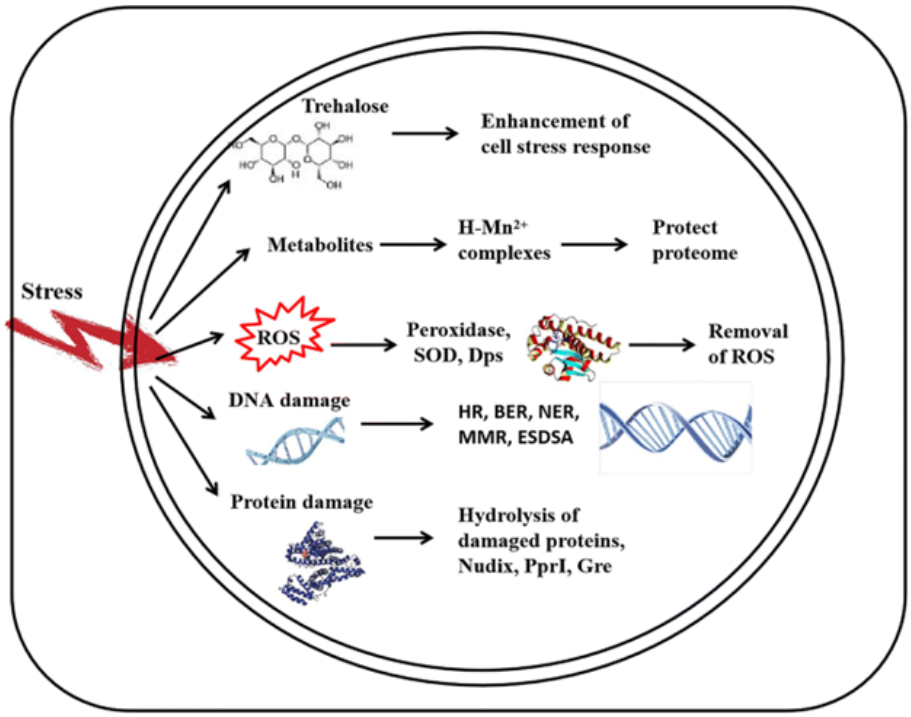


Figure 1. Mechanism of radiation resistance in Microbes [32].

Critical Appraisal of Microbial Radiation Resistance Research

Though the radiation resistance of Deinococcus radiodurans has been significantly characterized, the existing information is mainly limited to controlled laboratory experiments. There are several radiation-resistant microbes with dynamic defense mechanisms, as presented in Table 1. Regarding the environmental applicability of these microbes in real-world settings, there is a need to explore this further, including in geological disposal facilities (GDFs). Some variables, such as other microbial communities, changing pH, salinity, temperature, and nutrient availability, may hinder the long-term survival of these extremophiles [45, 46]. The one more unsolved problem is the long-term performance of microbial biofilms or biopolymers under conditions of prolonged radiation and hydrothermal stressing. Short-term efficacy is demonstrated in most experimental studies due to the absence of long-term data on the timescales required to isolate nuclear waste (hundreds to thousands of years). Secondly, there is limited validation regarding the assessment of microbial activity in a field-like environment [34, 35, 40]. As a solution to these gaps, further studies should focus on in situ evaluation of performance, long-term microbe survivability, and the techno-economic viability of bio-based barrier technologies. In addition, these potentially promising microbial processes will require interdisciplinary efforts, as microbiologists, materials scientists, and environmental engineers share ideas and information, which may ultimately lead to scalable nuclear waste management systems [8, 47, 48].

Table 1.
Radiation-resistant microorganisms and their defense mechanisms.

Microorganism	Radiation Tolerance (Gy)	Key Mechanisms	Notable Biomolecules	Verified References
Deinococcus radiodurans	∼10,000	Mn^{2+} complexes, DNA repair systems, carotenoids	Deinoxanthin, DeinPol, Mn peptide complexes	[35]
Thermococcus gammatolerans	∼30,000	DNA repair, thermostable protein expression	Antioxidant enzymes	
Rubrobacter radiotolerans	∼6,000	Carotenoid antioxidants, oxidative stress defenses	Uncharacterized carotenoids	[47]
Geobacter sulfurreducens	∼5,000 (indirectly)	Anaerobic metal reduction via extracellular electron transfer	c-type cytochromes, nanowires	[49]

Electrogenic Microbes in MFCs

Boas et al. [50] shown that microbial fuel cells (MFCs) are a category of bioelectrochemical systems (BES) that may directly transform the chemical energy contained in organic substrates into electrical energy via the catalytic actions of microorganisms. Central to these systems are electrogenic bacteria that oxidize organic matter and transmit electrons to an anode, so completing an electrical circuit through an external load to a cathode, where reduction reactions, predominantly oxygen reduction to water, occur as represented in Figure 2.

Verma et al. [51] indicated that electrogenic bacteria, referred to as exoelectrogens or electricigens, exhibit the extraordinary capability to transport electrons extracellularly to insoluble electron acceptors, including electrodes. The most thoroughly researched electrogens comprise Geobacter sulfurreducens, Shewanella oneidensis, and certain species from the genera Pseudomonas, Clostridium, and cyanobacteria. Jayathilake et al. [52] demonstrated that metagenomic analyses are perpetually broadening the diversity of recognized electrogens, uncovering novel strains from extreme environments that possess characteristics such as high-temperature tolerance, salinity resistance, and pH stability, which correlate with radiation resistance in extremophiles.

Roy et al. [53] categorized electron transfer pathways in electrogens into three principal forms. Initially, direct electron transfer (DET) occurs when outer membrane c-type cytochromes or conductive pili (nanowires) physically convey electrons to the electrode. Secondly, mediated electron transfer (MET) includes

endogenous or exogenous redox mediators, including flavins and quinones, as well as synthetic shuttles [54]. Conductive biofilms, as delineated by Conners et al. [55], have biofilm matrices with elevated electrical conductivity, facilitating the flow of electrons from deeper microbial strata to the electrode surface.

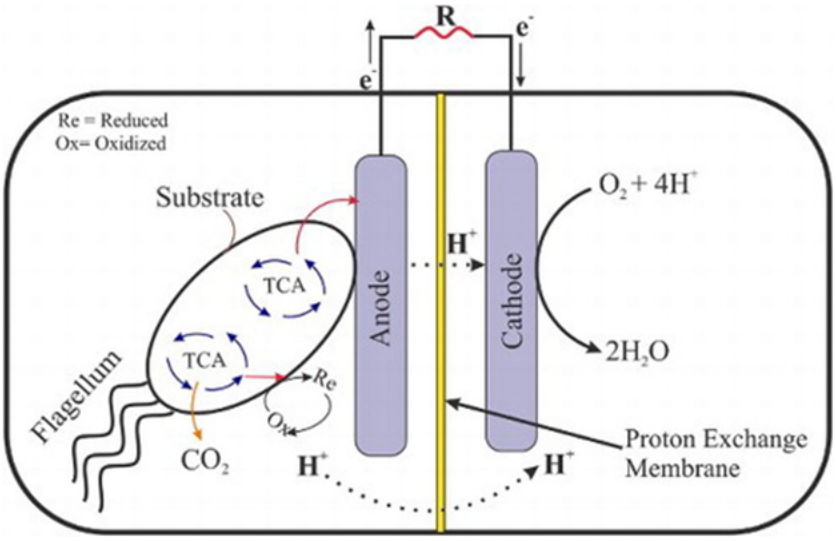


Figure 2. A typical Microbial Fuel cell involving electron exchange through a Proton exchange membrane [56].

Role of Extremophiles in Improving MFC Performance

Gavas et al. [57] showed that extremophiles, which are microorganisms adapted to survive in extreme physicochemical conditions, provide unique benefits for improving the performance of microbial fuel cells (MFC). Thermophiles enhance metabolic rates and reaction kinetics at higher temperatures, facilitating improved electron transfer rates and minimizing activation losses [58]. Jamal et al. [59] indicated that halophiles sustain metabolic activity in high-salinity environments, facilitating MFC operation in saline wastewaters without osmotic inhibition. Additionally, alkaliphiles, acidophiles, and piezophiles exhibit tolerance to extreme pH or pressure conditions, thereby expanding the operational range of MFCs for specific industrial or environmental applications [60].

Qiu et al. [61] emphasized that radiation-resistant extremophiles, including Deinococcus radiodurans, integrate these environmental tolerances with remarkable resilience to ionizing radiation and oxidative stress. This dual resistance allows for their application in specialized MFC scenarios like radioactive waste remediation, deep-space missions, and monitoring contaminated sites, where traditional electrogens frequently fail to remain viable.

Rationale for Using Radiation-Resistant Microbes in MFC in Harsh Conditions

Toczylowska-Maminska et al. [62] highlighted that MFCs utilized in extreme environments, including polar outposts, deep subsurface facilities, space habitats,

or nuclear reactors, encounter multiple challenges such as ionizing radiation, oxidative stress, nutrient scarcity, and temperature extremes. Swaminaathan et al. [63] showed that species resistant to radiation, such as Deinococcus radiodurans, Chroococcidiopsis thermalis, and specific haloarchaea, utilize remarkably effective DNA repair systems and antioxidant defenses to preserve their viability and metabolic functions under these stressors, thereby ensuring consistent electrochemical output.

Saini et al. [64] demonstrated that microbial mix possess the ability to safeguard and restore redox-active enzymes that are crucial for extracellular electron transfer (EET), even following exposure to high doses of radiation as illustrated in Figure 3. Chebbo et al. [65] observed that these characteristics minimize operational downtime, rendering radiation-resistant microbes beneficial for prolonged MFC operation in contexts such as nuclear waste monitoring, extraterrestrial exploration, and high-radiation industrial environments. Hu et al. [66] detailed the genetic engineering of Deinococcus radiodurans to express Shewanella outer-membrane cytochromes, resulting in sustained measurable current production under high-radiation test conditions. Stefano et al. [67] additionally noted that Cyanobacteria species sustain photosynthetic activity and oxygen production when exposed to simulated Martian radiation, allowing for their incorporation into photomicrobial fuel cell systems.

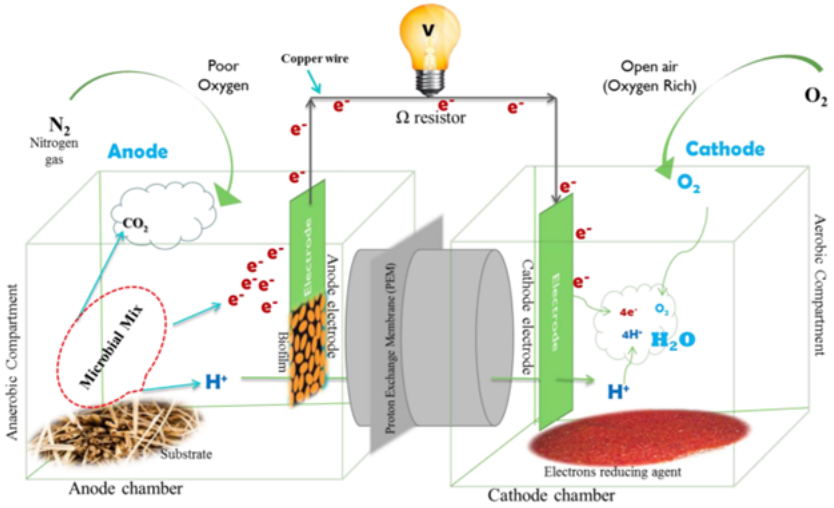


Figure 3. Radiation dependent MFC using Microbial mix and Co2 rich substrate [68].

Biofilm Formation and Electron Transfer Capabilities

Xiao et al. [69] demonstrated that the presence of stable and conductive biofilms on the anode surface is essential for maintaining consistent performance in MFCs. In radiation-resistant microbes, biofilms acquire enhanced protection via oxidative damage tolerance and the effective repair of extracellular polymeric substances (EPS). Lin et al. [70] noted that while ionizing radiation can induce EPS degradation and biofilm dispersal in susceptible species, Deinococcus radiodurans biofilms maintain their structural integrity even after exposure to gamma irradiation levels surpassing 5 kGy.

Lovley and Holmes [71] noted that specific extremophiles have naturally conductive pili or redox-active pigments that enable direct electron transfer (DET). Meanwhile, Fang et al. [72] showed that co-culturing radiation-resistant microbes with high-performance electrogens like Geobacter sulfurreducens can effectively merge environmental resilience with enhanced electron transfer efficiency while producing biofilms (Figure 4).

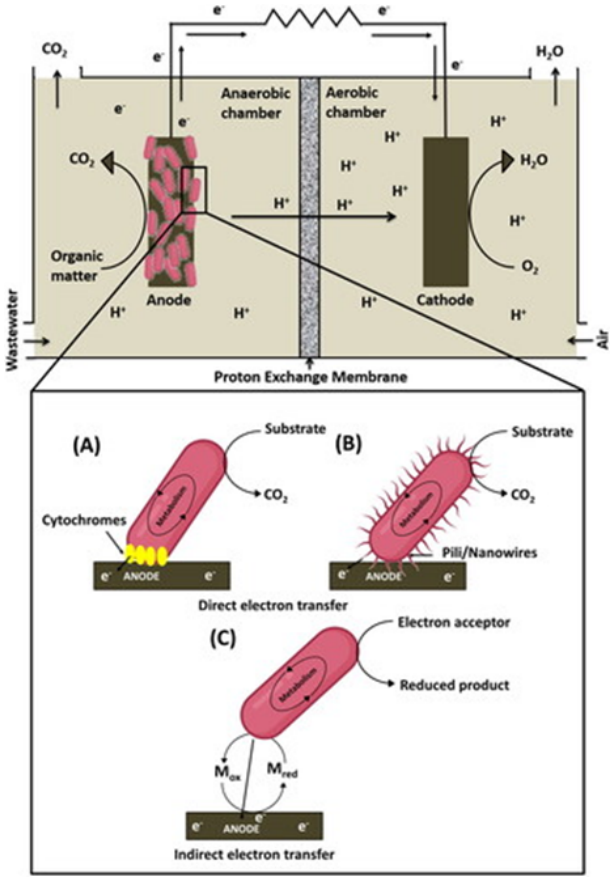


Figure 4. Biofilm in anaerobic and Aerobic MFC utilized in wastewater remediation [73].

Performance under High-Radiation or Extreme Environments

Baldanta et al. [74] showed that phototrophic Chroococcidiopsis-based MFCs subjected to simulated space radiation experienced only slight decreases in photovoltage and current density, indicating a promising potential for power applications beyond Earth. Zhou et al. [75] detailed the use of MFC biosensors that integrate Deinococcus radiodurans for the in-situ assessment of redox conditions and radionuclide mobility in high-radiation waste repositories, with the MFC functioning both as a power generator and an environmental sensor.

Verseux et al. [76]. observed that cyanobacteria exhibiting resistance to radiation sustained consistent current generation for several months in both desert and polar settings, even in the absence of nutrient replenishment, despite exposure to elevated UV levels and temperature variations. Kuity et al. [77] found

that integrating extremophiles into MFC designs facilitates strong, sustained bio-electrochemical performance in environments once deemed unsuitable for biological systems.

Applications of Radiation-Resistant MFCs

The introduction of radiation-resistant microorganisms in microbial fuel cell (MFC) technology marks a notable advancement in bio-electrochemical engineering. These systems utilize the metabolic functions of extremophilic microorganisms that can endure and flourish in extreme environmental conditions, such as elevated levels of ionizing radiation, to produce electricity. Integrating these microbes into MFC designs allows for the extension of operational viability into environments that were once deemed too hostile for traditional bio-electrochemical systems. These advancements present significant potential across various sectors, including space exploration, nuclear remediation, deep subsurface bioenergy, and environmental monitoring. The subsequent subsections outline the primary application domains in which radiation-resistant MFCs have the potential to transform sustainable power generation and data acquisition.

1. Space Exploration

Xu et al. [78] demonstrated that the severe conditions found in extraterrestrial environments, like those on Mars or the Moon, pose significant challenges for energy systems due to a mix of high radiation levels, restricted sunlight, and drastic temperature variations. The absence of protective atmospheric shielding and a global magnetic field in these celestial bodies results in continuous bombardment of their surfaces by ionizing radiation from galactic cosmic rays (GCRs) and solar particle events (SPEs). In the context of crewed missions and extended robotic operations, it is crucial to have dependable and sustainable power systems. These systems are vital not just for life-support functions like oxygen generation, water recycling, and thermal regulation, but also for the uninterrupted functioning of sensors, communication devices, and navigation systems.

Radiation-resistant MFCs provide a power solution that is informed by biological processes, suitable for these specific conditions. In contrast to solar arrays that face interruptions during dust storms or prolonged lunar nights, MFCs maintain continuous operation when supplied with organic substrates sourced from local resources or produced through waste recycling processes. For example, Deinococcus radiodurans, a well-studied radiation-resistant bacterium, has demonstrated the ability to sustain metabolic activity even under high levels of radiation exposure, positioning it as an excellent candidate for extraterrestrial bio electrochemical systems [79]. These extremophiles may be engineered or selected to improve their extracellular electron transfer capabilities, enabling them to directly transfer electrons from their metabolic processes to an electrode surface, thereby generating electricity even in high-radiation environments.

This concept is in harmony with the overarching visions of NASA and ESA re-

garding in situ resource utilization (ISRU), utilizing biological systems to generate fuel, oxygen, and energy from materials found on–site in planetary environments [80]. For instance, radiation–resistant cyanobacteria might be integrated with heterotrophic extremophiles in a hybrid MFC, where the phototroph produces biomass utilizing Martian CO_2, and the heterotroph processes the biomass in an MFC to generate electricity. This closed-loop system has the potential to deliver autonomous power for extended periods, thereby minimizing reliance on resupply missions from Earth. The ability of MFCs to function with minimal upkeep renders them ideal for extended space habitats, interplanetary probes, and self-sufficient planetary science stations situated in areas with consistently high radiation, like the surface of Europa within Jupiter's powerful radiation belts.

2. Nuclear Waste Management

Khaleel et al. [81] emphasized that while nuclear power generation is crucial for producing low-carbon electricity, it also produces radioactive waste streams that present considerable environmental and safety risks. Locations affected by radionuclides like uranium (U(VI)) and technetium (Tc(VII)) frequently necessitate extensive periods of remediation, spanning decades to centuries, and existing cleanup methods can be excessively costly and technologically challenging. Radiation-resistant MFCs present a distinctive dual-function ability, enabling both bioremediation and electricity generation concurrently.

In these systems, extremophilic electrogenic bacteria are capable of metabolizing organic compounds and simultaneously reducing soluble radionuclides into less soluble, immobile forms. For example, Geobacter species exhibit metal-reducing abilities, and recent investigations indicate that specific strains sustain metabolic activity in conditions with increased gamma radiation [82]. Integrating these bacteria with radiation-resistant groups may facilitate the sustained functioning of MFC-based bioreactors in contaminated areas, even in environments where radiation would rapidly deactivate standard microorganisms.

The deployment of these MFC systems in subsurface biobarriers or engineered wetlands around nuclear facilities presents an opportunity to utilize natural or engineered organic inputs for the purpose of radionuclide immobilization. The generated electricity, though limited, has the potential to power environmental sensors, telemetry systems, or even micro-pumps for water circulation, effectively transforming waste sites into self-sustaining monitoring and remediation centers. In more sophisticated designs, extremophile MFCs could be incorporated into nuclear cooling pond systems, enabling ongoing water quality assessment and contaminant mitigation without requiring human oversight in areas with high radiation levels.

Furthermore, the capacity to maintain bioelectrochemical activity in the presence of prolonged radiation exposure suggests that these systems could be effectively utilized in settings such as the reactor basements of Fukushima Daiichi or the contaminated groundwater plumes at Hanford, where human access is restricted [83]. These self-sustaining, biologically inspired systems have the

potential to function for extended periods without the need for replacement, significantly lowering operational expenses and improving environmental safety.

System optimization using statistical designs has recently shown promise in the environmental recovery of heavily polluted environment using MFC, Narayan et al. [20] used Box–Behnken design to maximize COD removal and electricity generation in CW-MFC treating pulp and paper industry wastewater. Also, modelling approaches [21] have leveraged data–driven techniques to predict power density and suggest optimal operating parameters.

3. Deep Subsurface Energy Systems

Holub et al. [84] noted that deep geological formations, especially those with uranium-rich deposits and mining environments, serve as naturally high-radiation habitats that support distinct microbial communities adapted to extreme conditions. These ecosystems generally exist in isolation from surface inputs, depending primarily on chemolithotrophic metabolisms that are fueled by mineral interactions and the production of radiolytic hydrogen. Extremophiles native to these environments provide a natural source of inoculum for the deployment of MFCs in situ.

Embedding electrodes within deep subsurface rock formations allows for the direct harvesting of electrical energy generated by the metabolic activity of resident microbes. The existence of radionuclides like uranium and thorium generates a high-radiation environment and introduces redox-active species that can act as electron acceptors, enhancing the electron transfer processes in MFCs. For instance, strains of Candidatus Desulforudis audaxviator, initially identified 2.8 km beneath the surface in a South African gold mine, are capable of surviving exclusively on products from water radiolysis and nutrients derived from minerals [85]. Utilizing these metabolisms within an MFC framework has the potential to create a self-sustaining power system in environments that are otherwise difficult to access.

Practical applications encompass the provision of energy to deep subsurface sensors utilized for seismic monitoring, geological surveying, and groundwater quality assessment in areas where traditional cable-based power delivery proves unfeasible. Furthermore, in uranium mining activities, MFCs powered by extremophiles could be incorporated into waste rock or tailings management systems to reduce radionuclide mobility while also producing minor amounts of operational power. The primary benefit is the reduction of external inoculation requirements. Indigenous microbial populations have already adapted to radiation stress, nutrient scarcity, and high pressure, rendering them inherently suitable for long-term, maintenance-free operation in situ.

4. Extreme Environmental Monitoring

Dwivedi et al. [86] highlighted the substantial challenges encountered in real-time environmental monitoring within radiation-impacted areas, including post-nuclear disaster sites, high-altitude polar regions, and contaminated industrial

zones. Traditional monitoring systems necessitate regular battery changes or reliance on wired power sources, both of which can become unfeasible or hazardous in these circumstances. Radiation-resistant MFCs present an intriguing option as they function as autonomous, self-powered biosensors.

The design of these MFC biosensors allows for the coupling of their electrical output to environmental signals, including variations in pollutant concentration, pH levels, or radiation dose rates. For example, modified extremophiles might be designed using synthetic biology techniques to adjust their EET rate in reaction to a specific analyte, thereby converting environmental variations into quantifiable voltage or current changes. This method enables ongoing, extensive data collection without the need for human involvement, thereby minimizing operational expenses and lowering radiation exposure risks to staff.

In areas impacted by radiation disasters such as Chernobyl or Fukushima, extremophile microbial fuel cells could be utilized in decentralized networks, relaying wireless information on the movement of radionuclides, groundwater pollution, and the restoration of ecosystems [87]. The capacity to operate in high-radiation environments guarantees continuous functionality, even when standard electronics succumb to early failure from accumulated radiation damage. In addition to post-disaster scenarios, such systems may also be utilized in extreme terrestrial environments, such as Antarctica's Dry Valleys or the Atacama Desert. These locations are frequently employed as analogs for extraterrestrial environments, where challenges like radiation fluxes, desiccation, and nutrient scarcity pose significant difficulties for standard monitoring equipment. By integrating ruggedized electronics with extremophile-driven MFC power, it is possible to enhance the reach and longevity of autonomous environmental sensing infrastructure in the most inhospitable areas of the planet.

Research Gap and Future Directions

While extremophiles that can withstand radiation exhibit potential for use in microbial fuel cell (MFC) applications, most of the research is still limited to laboratory-scale experiments conducted under controlled environments. Genuine extreme environments like outer space, areas affected by nuclear disasters, and deep subsurface formations present varying radiation levels, limited nutrient availability, and temperature variations that remain largely unreplicated. The molecular mechanisms that facilitate sustained extracellular electron transfer (EET) during radiation stress are not well elucidated, and there is a scarcity of comparative omics studies in this area. Furthermore, the possibilities presented by mixed-species consortia that integrate radiation resistance with elevated electrogenic activity remain significantly under-investigated. Advancements will necessitate the convergence of microbiology, materials science, and engineering disciplines. It is essential to prioritize the systematic screening of various radiation-resistant species alongside the genetic enhancement of EET capabilities. The combination of extremophiles with resilient electrogens such as Geobacter sulfurreducens may yield enhanced performance through synergistic interac-

tions. The advancement of electrode materials that are resistant to radiation, conductive, and compatible with biofilms like nanostructured carbon, conductive polymers, or metal–organic frameworks will be essential. Adaptive control systems powered by AI have the potential to enhance the optimization of MFC operations in real time. Applied research must progress to pilot-scale trials under simulated extreme environments and real-world conditions. In space missions, the incorporation of in situ resource utilization may facilitate closed-loop power generation, whereas in nuclear waste management, biosensors powered by microbial fuel cells could offer long-term, self-sustaining monitoring solutions. The intersection of extremophile biology and cutting-edge materials design presents significant opportunities for sustainable energy solutions in the most challenging environments.

Conclusion

Microorganisms that can withstand radiation present a groundbreaking opportunity for enhancing microbial fuel cell technology in settings where traditional systems are ineffective. Their remarkable ability to withstand ionizing radiation, oxidative stress, and various extreme conditions allows for continuous bioelectrochemical activity, broadening the possibilities of MFCs for uses in space exploration, nuclear waste remediation, deep subsurface energy harvesting, and autonomous environmental monitoring. Integrating these extremophiles into customized MFC designs enables the development of self-sustaining, low-maintenance power systems that can operate reliably for extended durations in the most demanding environments. Ongoing interdisciplinary studies that integrate microbiology, materials science, and bioelectrochemical engineering will be essential for unlocking the complete potential of radiation-resistant MFCs in providing sustainable energy solutions in extreme environments. Emerging research areas include further development of nanocomposite electrodes, the maturation and controlled engineering of biofilm structure to reduce charge-transfer resistance, and the use of modelling/AI-based frameworks for predicting MFC behavior under varying environmental and operational conditions.

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