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Development of bioelectrochemical systems and their relationship to the sustainable development goals

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Abstract

Bio-electrochemical systems (BES) have become increasingly popular in recent years because of their novel and environmentally friendly construction. They use the interaction of microorganisms and electrodes to transform organic matter into useful chemicals or energy. BESs are used in bioremediation, wastewater treatment, and energy production from organic waste. Their eco-friendliness highlights their current significance, potential for circular economy integration, and capacity to address environmental concerns. BES is now regarded as an exciting potential for sustainable biotechnology. In this paper, we explored the concept of Plant-Based Bioelectrochemical Structures (PLBES) and how they can be used for pollution control and power generation. MFC maximum voltage and power density PLBES achievements were identified. Aerated and Unarearted group's boron removal efficiencies were analyzed. The efficacies of removing various organic and inorganic pollutants and the factors that affect both were demonstrated. It was also discussed how Devices of bioelectric chemistry constructed around plants contribute to meeting the Sustainable Development Goals (SDGs). The SDGs encourage governments, corporations, and communities to work together to achieve sustainable development that balances human needs with environmental protection.

Keywords: Bio-Electrochemical Systems (BES), Sustainable Development Goals (Sdgs), Organic Waste, Plant-Based Bioelectrochemical Systems (PLBES).

1. Introduction

Implementing the strength of microorganisms BESs are innovative invention to make electricity or useful chemicals through biological processes. These systems combine biology and electrochemistry (Shanbhag *et al.,* 2023). Microbes speed up chemical processes that release electrons, which can then be used to make electricity or change other chemicals. BES is used to clean up pollution, make energy from biological waste, and healthily make biofuels and specialty chemicals. By using the ability of microorganisms to turn organic matter into energy or goods that people want, BES contributes to today's search for sustainable technologies by assisting to find environmentally friendly ways to deal with garbage and make clean energy. By using bacteria's innate capacity to exchange electrons with solid-state conductive materials (Tan *et al.,* 2022), BES continues to provide a one of a kind platform for investigating innovative methodologies for energy conversion, management of waste, and biosignal sensing. BES explores the fascinating relationships between microbes and sensors (Gu *et al.,* 2021), based on the notion of Extracellular Electron Transfer (EET). This complex interaction allows bacteria to breathe on solid surfaces, which may then be used to generate power or valuable molecules from organic supplies.

The Microbial Electrolysis Cell (MEC), which operates in the opposite direction of an Microbial Fuel Cells (MFC), is an additional intriguing variety of BES. Here, microbes are given electrical energy to force them to perform harmful activities, such as producing hydrogen or eliminating carbon dioxide. MECs have received much attention as a means to store excessive green energy as high-energy compounds. This allows us to store energy in an environmentally responsible manner, compensating that renewable energy sources might not always be accessible. Bacteria accelerate the decomposition of contaminants when BES is employed for environmental cleanup. Electro-assisted bioremediation employs BES technology (Bhagchandanii *et al.,* 2020) to accelerate the decomposition of difficult to degrade compounds. BES can also be used as biosensors using microbial reactions to particular analytes. This makes detection quick and affordable in numerous sectors, from healthcare to environmental consumption.

BES emerges from a fusion of diverse disciplines, including microbiology, electrochemistry, materials science, and engineering. To fully unlock the potential of BES applications, scientists are delving into understanding microbial behavior, electrode fabrication, electron transfer mechanisms, and optimal system operation. The advent of bio-electrochemical systems has ushered in fresh scientific and technological prospects. Remarkably, microorganisms can exchange electron with solid conductive materials (Aiyer, 2020), paving the way for sustainable energy generation, environmental cleanup, and advanced biosensing capabilities. Innovations like “microbial fuel cells and electrolysis cells address energy and environmental concerns” and propel the advancement of microbial-electrode studies. As research progresses and interdisciplinary cooperation flourishes, the transformative potential of BES spans across energy, biotechnology, and environmental stewardship, poised to reshape these domains.

2. Materials and methods

Fundamentals of Plant-based BES (PLBES)

Through photosynthesis, chlorophyll in leaves enables plants to produce carbohydrates. For creatures that consume them directly or indirectly, these carbohydrates is their main energy source. The remainder reaches roots, whereas only around 40% is used by plants. Plants within anode chambers in Plant-Based Bioelectrochemical Systems (PLBES) generate power. Following photosynthesis, plants transfer leftover carbohydrates into the soil, where microbes produce electrons. Protons and these electrons go from the external circuit and ionic electrolyte to the cathode. They produce water by fusing with oxygen or electron acceptors there. **(Figure 1)** shows the diagram of PLBES.

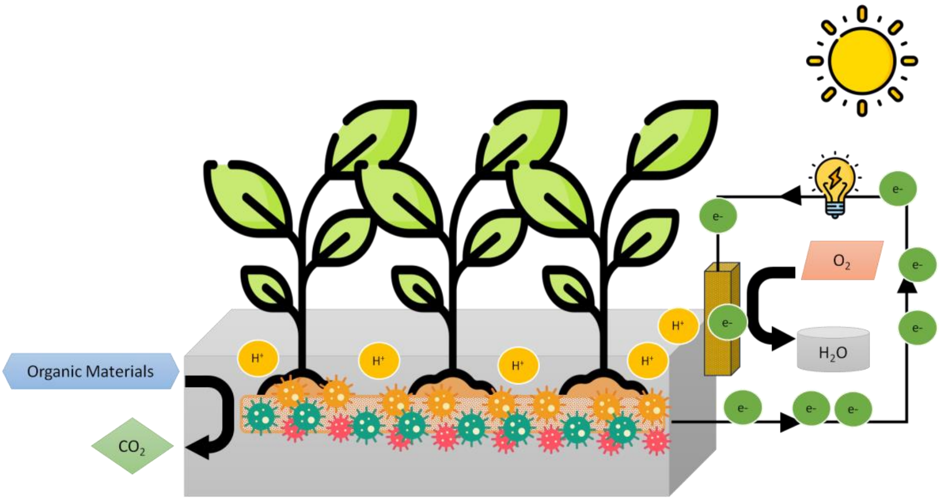

Figure 1: *Plant-based MFC (PLBES)*

The function of the plant

Water is absorbed by plant roots, and stems carry it to leaves. Using carbon dioxide, carbon monoxide, and sunshine, leaves photosynthesize to produce carbohydrates. Rizodeposition produces the migration of about 47.25 billion tons of fixed carbon from plants to the roots where it is converted into carbohydrate-rich discharges. Exudates fuel cell respiration and activity by giving bacteria nutrition like carbohydrates and amino acids. Photosynthesis divides plants into three groups: C3, C4, and CAM. C4 plants work effectively in hot, dry areas by transforming CO2 into 4-carbon sugars. This gives them a lot of biogas. Through more rhizodeposition, they increase the amount of power made by plant-based microbial fuel cells (P-MFC). C4 fixation is used by about 3% of plants, such as grasses. Microorganisms in the rhizosphere act as biocatalysts in PLBES (Kang *et al.,* 2022). They use root exudates to give electrons directly or indirectly to the anode surface.

Bio photovoltaics (BPHV)

A bio-photovoltaic (BPHV) system uses cyanobacteria, algae, and plants to capture green energy through natural photosynthesis. These organisms utilize sunlight to transform water into protons and electrons. They serve as their main energy source by releasing oxygen and converting carbon dioxide into multi-carbon molecules. In plant-based BPHV, plant root bacteria digest organic matter during photosynthesis, negating the requirement for foreign microorganisms. This system uses CO2, water, and sunlight to produce electricity. It produces two currents: photocurrent, which is created during photosynthesis utilizing sunlight, and dark current, which is produced when microbes use internally stored carbohydrates in the absence of light.

PLBESs performance affecting factors

The microbes mechanically supplied to PLBES or found in the soil around root systems employ root exudates to produce bioelectricity. “Humidity, pH, temperature, weather, soil type,” plant type, light, microbes, system design, electrode type, and membrane type all impact PLBES efficiency, as displayed in **(Table 1)**.

Table 1: Performance-affecting factors

References	Factors	Impacts	Findings
Zwart *et al.,* (2020)	Configurations	Energy production, root growth, and photosynthesis	The anode shouldn't impede the spread of the roots. The design shouldn't avoid sunshine or prevent CO2 from reaching the plant's leaves.

Khudzari *et al.,* (2019)	Electrodes	Energy production	Mass transfer, electron transfer rate, and the growth of biofilms are all influenced by the anode electrode. A change in the cathode electrode can speed up the Oxygen Reduction Process (ORR).
Ng *et al.,* (2021)	Illuminations	Energy production and photosynthesis	Improved rhizosphere biomass production by increasing photosynthesis.
Osorio de la Rosa *et al.,* (2019)	Soil	The metabolism and generation of energy	Root-zone biota consists of the available biomass and microbes.
Zhao *et al.,* (2019)	Plants	Energy production and photosynthesis	The accessible biomass and microbes in the root area

PLBES Application

PLBESs provide power while removing hazards, making them green energy sources. To eliminate contaminants, the plant converts "sunlight directly to energy through the rhizosphere. PLBES applications such as sediment MFC, rice paddy field", and phytoremediation (Kafle *et al.,* 2022) are reviewed.

Sediment MFC (SDMFC)

Antimicrobial fuel cells, or SDMFCs, use soil-dwelling bacteria to metabolize biological substances and release energy. They have an anode in the ground and a "cathode floating in the water. "Plants at the anode add more nutrients, which helps microbes interact. Because of interactions among "aerobic and anaerobic organisms in the rhizosphere and sediment," the Acoruscalamus in sediment increased the removal of HMW-PAHs by 70%. The SDMFC, made from Eichhorniacrassipes, cleaned up wastewater and increased power production. It also eliminated more COD, sediment, "VFA, nitrate, and color. The root exudates from Ipomoea Aquatica were used in a single-chamber MFC". Compared to an unplanted MFC, a planted MFC enhanced COD removal by a small amount and raised energy density by 141%. Plants improve the productivity of SDMFC by improving bacteria interactions and adding more organic material.

Rice paddy field MFC

A prospective setting for effective plant-based Microbial Fuel Cells (PLMFCs) is rice paddy fields (Sarma *et al.,* 2023). The anode of an MFC was positioned in rice rhizospheres, and the MFC was set up on a paddy field. Soil microbes used root-exuded acetate to generate protons and electrons. With plant shade and cathode covering, the power production, dependent on photosynthetic activity, drastically decreased. When plants couldn't manufacture organic compounds at night, acetate supplementation increased power, reaching a level that was roughly half that of the day. In a different investigation, Geobacteraceae, in particular G. Psychrophilus, flourished on the rhizosphere of the anode in a rice paddy MFC, promoting the secretion of electron donors for energy production. Anode materials included carbon felt and biochar, with P-MFC outperforming Systems without Plants as displayed in **(Figure 2)**. Biochar reduced methane emission without impacting plant biomass results, but carbon felt shown greater power production.

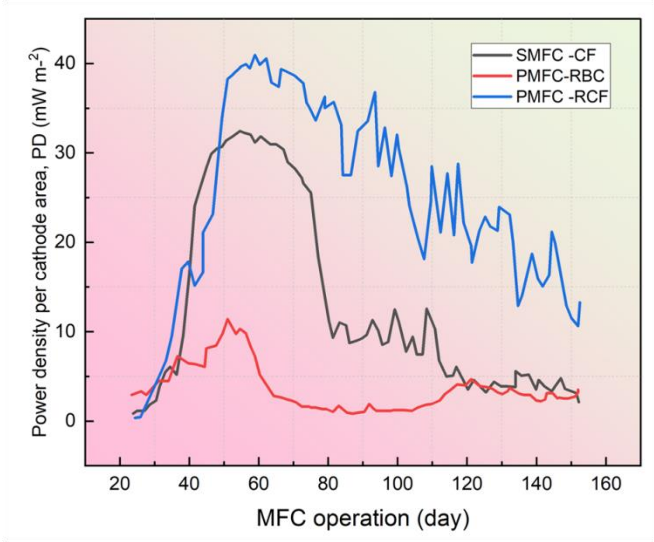

Figure2: *Effects of the rice plants*

Methanogenic microbes convert organic materials into acetic acid, hydrogen, carbon dioxide, and methane in anaerobic processes. This was the problem that Oryza sativa rice was developed to resolve with its PLBES (Neelam *et al.,* 2020). Methane emissions decreased through the current produced by a BES anode placed in the rice rhizosphere before the emissions occurred. Anoxic system current generation caused a temporary halt in methane production. Nevertheless, the rice season's modest emissions decrease was unsustainable due to the organic matter's persistence. Methane synthesis in the rhizosphere-anode research required H2. For widespread methane reduction, a combination of bioelectrochemical and other approaches is essential. With the use of MFC, rice farmers were able to reduce contaminants such as Cd, Ni, Cu, and Cr by 33%, 36%, 22%, and 57% in the grain.

Hybrid system of Phytoremediation-PLMFC

Inorganic and organic contaminants affect water and soil, affecting the environment and health. Pollutant reduction depends on phytoremediation by plants and microbes. In the rhizosphere, plants absorb, digest, and contribute to decomposition contaminants. Phytoremediation removes surface and groundwater, soil, sediments, and sludge (Polińska *et al.,* 2021). The PLBES/phytoremediation hybrid Phyto-power system generates bioenergy and eliminates organic and inorganic pollutants from water or soil. This clean, affordable, reliable source of energy uses microorganism-driven anaerobic respiration surrounding plant roots. **(Table 2)** shows the description of studies integrated with phytoremediation. Hybrid systems combine PLBES with phytoremediation for sustainable energy generation and pollution reduction.

Table 2: Phytoremediation relevant researches

References	**Pollutant types**	**Power (mW/m2)**	**The anode of the P-MFC**	**Remarks**
Xu *et al.,* (2019)	Saline wastewater	16.3	Wetland	NaCl concentrations over 5 g/L were shown to improve wastewater treatment efficiency, but lower concentrations had no impact.
Xie *et al.,* (2018)	Nitrobenzene (NB) wastewater	1.51	Wetland	The addition of a wetland improved the efficiency of MFC. Considerations for electrode

				spacing, substrate loading, and hydraulic time of retention.
Di *et al.,* (2020)	NB	19.6	Wetland	The inner resistance was lowered over a range of NB concentrations because of the plant in the anode chamber.
Pamintuan *et al.,* (2018)	Cu	1.074	Plant (L. minor)	The ohmic resistance, power generation, and absorption of copper ions are all enhanced by the hybridization of “plant-MFC with phytoremediation."
Mu *et al.,* (2020)	Cr	458.1	Wetland	Wetland MFCs performed better with a longer hydraulic retention period, higher initial chromium content, and higher initial COD.
Wang *et al.,* (2020)	Zn	3.66	Wetland	Zn(II)'s presence was detrimental to the MFC's efficiency.
Zhao *et al.,* (2020)	Pb	7.429	Wetland	Long-term use resulted in microbial community adaptation to Pb(II).
(Türker 2018)	B	17,779	Varieties of duckweed-inspired MFC modules include L. gibba, L. minor, and others.	When B > 4, module elimination efficiency dropped.

Boron removal: Boron removal is removing boron from the environment using live plants and electrochemical principles. Boron is a naturally occurring trace element that, in excess, may harm ecosystems and crop production (Bhagyaraj *et al.,* 2021). These systems combine plant physiology and microbial responses to electrodes to create a structure in which plants absorb boron-containing water and, as the water moves through the plant and soil, boron ions are adsorbed onto the electrodes via electromagnetic attraction and specific binding processes. This synergistic strategy takes advantage of the plants' inherent filtering abilities as well as the system's electrochemical capabilities to accomplish excellent boron removal. The relevance stems from its potential for environmentally benign and energy-efficient boron remediation, solving water pollution issues while leveraging the advantages of plant growth and microbial activity.

Lead removal: Lead removal is the process of extracting lead out of different things, like contaminants or water, by using live plants and electrochemical methods. These methods utilize the reality that plants naturally take in and preserve heavy metals like lead. Electrochemical ways make this process even better by making an electric field that helps lead ions move toward plates so they can be taken out (Thakur *et al.,* 2020). At the top of the electrode, the lead ions are immobilized or reduced, which cleans up the surroundings. The method combines the benefits of plant-based remediation with the speed of electrochemical technology. This could be a good way to deal with lead pollution while reducing its effect on the environment. The MFC scored the high-level voltage and “power density of 1.3 V and 34.6 mW/m2” when plant material was used and under aeration levels, as mentioned in **(Figure 3)**. The MFC with plant had a significant % boron removal efficiency of 70%; aerated and Unaerated group's boron removal efficiencies were mentioned in **(Figure 4)** and **(Figure 5)**.

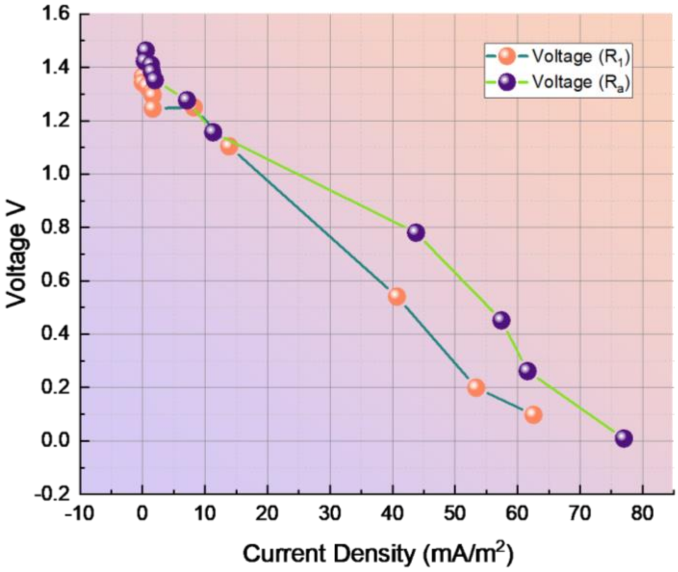

***Figure3:** Power curves and polarization*

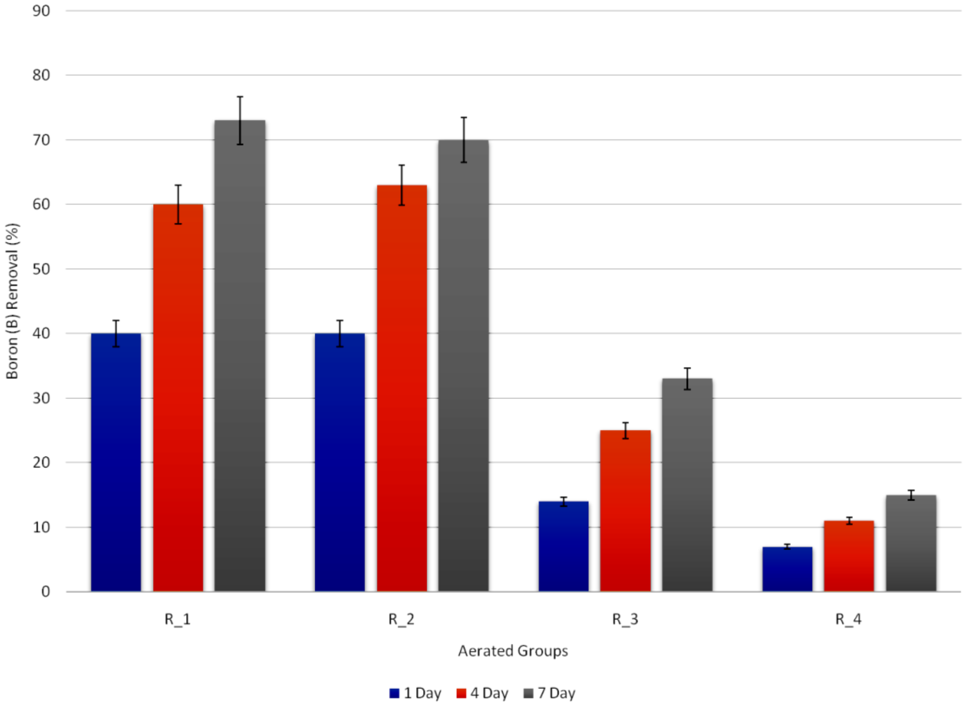

***Figure 4:** Aerated groups boron removal efficiencies*

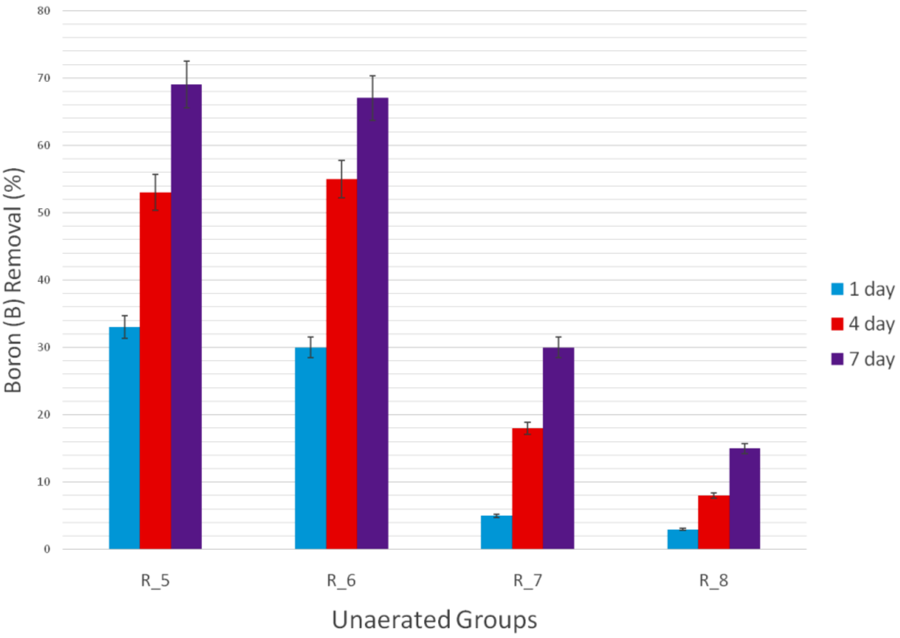

Figure 5: *Unaerated groups boron removal efficiencies*

Zn removal: Zinc is one of the most common elements on our planet, ranking 24th in terms of abundance. As a component of many proteins and a cofactor for many enzymes, zinc is a mineral that all organisms require for survival. Zn removal is the process that removes zinc ions out of BES that are built on plants (Ali *et al.,* 2019). These systems use actual trees or parts of them to facilitate electrochemical processes that are used for activities such as producing energy and cleaning up the surroundings. But excessive Zn may damage the performance of a system and the health of plants. Some ways to eliminate Zn are to use specific anode materials, improve system design, and make it easier for microbes to connect. These methods are meant to stop Zn from building up, which can slow lower electron transfer and biological processes in the BES. Effective removal of Zn from plant-based BES maintains electrochemical performance, reduces possible environmental effects, and improves the total effectiveness of these.

Salinity removal: Saline wastewater is a byproduct of several sectors, including the leather, agro-food, and petrochemical sectors. There are serious ecological consequences to discharging untreated salty wastewater. Traditional chemical or physical approaches for treating salty wastewater are either prohibitively costly or cause unintended environmental harm. Biological therapy is better from both a financial and ecological standpoint. To deal with salty water, engineers developed an MFC that uses wetlands. The salinity of the wastewater quadrupled the amount of energy produced by the system because it enhanced the ionic strength and lowered the inner resistance. A low influence of salinity on “TP and COD removal efficiencies and a significant negative impact on TN and NH4 + -N removal efficiencies” was observed.

Chromium removal: Industries as varied as electroplating, pigment production, and metal utilize chromium in various ways. As a result, these industries produce an enormous amount of wastewater that is polluted with chromium. Chromium removal is effectively eliminating chromium contaminants from water or soil using plants in motion and electrochemical methods (Panneerselvam and Priya, 2023). These systems use some plants' innate capacity to absorb and store heavy metals like chromium. Plant roots are stimulated by the system's integrated electrodes, which increases metal digestion. Chromium is concentrated inside the tissues of the plant as it develops. Chromium ions are simultaneously reduced and immobilized by the electrochemical component, which makes them less mobile and poisonous. Utilizing both electrochemical remediation and plants' ability to gather metals, this environmentally benign strategy provides a dual-benefit method (He *S* 2020) for removing chromium pollutants from the environment.

Cu removal: Copper is a crucial element classified as metalloenzymes, which function as either electron acceptors or donors. An elevated concentration of copper has detrimental effects on human health, leading to the development of serious illnesses and inducing toxicity in plants. Cu removal is the electrochemical method of removing copper (Cu) ions from aqueous solutions using specialized apparatuses that include plants in motion (Mohamed *et al.,* 2023). These systems take advantage of some plants' innate capacity to absorb and accumulate metal ions from their surroundings. Bioelectrochemical systems can improve Cu ion absorption by integrating electrodes and electron-transfer processes into the plant's root-soil interface. Through redox processes, these ions are then propelled toward deposition onto electrode surfaces. With the potential for resource recovery and ecological restoration, while reducing the harm caused by copper pollution to ecosystems, this novel strategy provides a green and environmentally friendly way for effectively removing Cu from polluted water sources. **(Table 3)** provides an overview of the various algae and plants that can be found in the anode of a PLBES electrode.

Table 3: Comprehensive descriptions of BESs generated by various plants

References	Description	Remarks
Pamintuan *et al.,* (2018)	Eichhorniacrassipes, water hyacinth, utilizes Considering the use of separators and carbon rods for both anodes and cathodes, a "maximum power density of 0.86 mW/m² in its cubic MFC design" was attained.	The effectiveness of both photochemical microbial fuel cells and phytoremediation of Ni ions were improved by hybridization.
Helder *et al.,* (2010)	The plant type used in the experiment was Spartinaanglica. The MFC (Microbial Fuel Cell) employed was cylindrical in shape. Graphite grains were utilized as the anode material, whereas the cathode material was felt-based and formed from graphite. Between the anode and cathode categories, a membrane that exchanged ions functioned as the separator. "The maximum power density achieved was 222 mW/m²."	By week 10, the current generation had reached 2.6 mA/m2, having begun at the conclusion of week 3. After that, this PMFC produced 21 mW/m2 of average output till week 17.
Yan *et al.,* (2015)	The plant type used in the experiment was	The degradation of HMW-PAHs in sediments was improved by the

	Macrophyte, specifically Acoruscalamus. The MFC (Microbial Fuel Cell) setup included an anode and a cathode, both utilizing graphite felt as the electrode material. The separator, which maintained there existed a graphene material divider between the anode and cathode as well. The maximum power density achieved in this configuration was expressed in terms of mW/m^2 in the Sediment MFC setup.	addition of SMFC and the macrophyteAcoruscalamus.
Lu *et al.,* (2015)	The plant type used in the experiment was Canna indica. The microbial fuel cell (MFC) employed was of cylindrical shape. Graphite felt served as the anode, while carbon cloth/activated carbon (AC) was used as the cathode. A separator was also employed in the setup. The maximum efficiency of 18 mW/m^2 was attained.	P-MFC was used to cultivate Canna indica because it provides the anode of MFC with substrate constantly. After 20 days, the current density peaked at 105 mA/m2, where it remained stable between 50 and 80 mA/m2.
Mohan *et al.,* (2011)	The plant type used for the experiment was Eichhorniacrassipes. A Cubic-MFC configuration was employed with “graphite discs as the anode and cathode. The separator material used is not specified. The maximum power density achieved was approximately 80 mW/m^2.”	Power production and the removal of 86.6% of COD and 72.3% of VFA from wastewater were both facilitated by the synergistic connection between distillery effluent from dark fermenting, residential, and the soil's rhizosphere.
Liu *et al.,* (2013)	The plant type used in the experiment was Ipomoea	The power density of the MFC's anode was increased from “5.13

	aquatica. The MFC (Microbial Fuel Cell) setup employed was a single chamber flow configuration. The anode was constructed using granular activated carbon, while the cathode was made of stainless steel mesh. A membrane-free separator was utilized in the setup. The maximum power density achieved in this setup was 12.42 mW/m².	to 12.42 mW/m2 and the COD removal efficiency was raised from 92.1% to 94.8% after Ipomoea Aquatica" was planted there.
Türker *et al.,* (2019)	The plant type used for the experiment was Lemnagibba. They employed a dual-chamber microbial fuel cell (MFC) with Mg alloy as the anode, graphite as the cathode, and glass wool as the separator. The highest energy density of 17,783 mW/m² was attained.	Boron was removed from the irrigation water using PMFC, and the results showed that monoculture was superior to polyculture. This "MFC is effective up to 4 mg/L of boron" despite the fact that a very large "quantity of boron, 32 mg/L, inhibited the development of microorganisms and chlorophyll synthesis".

Nitrobenzene removal: Wastewater from the pharmaceutical, colorant, organic intermediate, insecticide, and explosives industries typically contains significant levels of nitrobenzene. It is an exceptionally dangerous pollutant with a stable chemical structure that has been linked to serious health problems. "Active carbon adsorption or supercritical water oxidation" are often used to remediate Nitrobenzene -contaminated wastewater. High energy use, secondary pollutants, and a slow deterioration rate are all characteristics of these processes. Nitrobenzene is reduced at the cathode by microorganisms associated with the plant's roots (Di *et al.,* 2020), producing safer byproducts. The anode, meanwhile, promotes plant development by releasing electrons and increasing nutritional availability. Because of the complementary relationship between plants and electrochemistry, the system is self-sustaining and can effectively remove nitrobenzene from polluted areas. This sustainable approach has the potential to reduce pollution while encouraging plant growth and restoring ecosystems, thereby making a more sustainable future more likely.

Oil removal: Large amounts of oily wastewater are released by the petrochemical, transportation, and oil refining sectors. Drainage of oily wastewater is detrimental to human health, aquatic life, crop production, and groundwater resources. The traditional methods for treating oily wastewater involve extremely energy-intensive procedures. Oil removal is essential because it improves system performance and guards against potential environmental impact (Liu *et al.,* 2022). Plants contribute to converting oil contaminants into harmless byproducts through processes including phytoremediation and microbial degradation. The ability to use natural processes for environmental restoration and preservation is demonstrated by the efficient removal of oil, which helps to sustainably reduce pollution while generating cleaner environments.

Ni removal: Several items, including the steel industry, catalysts, lithium-ion batteries, plating, and coins, employ nickel (Ni). Ni is a trace element that is necessary for all living things, but when it reaches a certain threshold, it may be hazardous. Serious illnesses can be brought on by high Ni concentrations in both people and animals. Ni removal refers to the targeted extraction of Ni ions from diverse environmental sources through the utilization of actual plants and electrochemical methodologies (Garcia-Montoto *et al.,* 2020). These methods capitalize on the innate ability of certain species of plants to gather metals from their surrounding soil and water sources. The process of nickel absorption by plant roots is followed by the transport of metal ions to an electrode inside a bioelectrochemical system. Subsequently, electrochemical processes occur, enabling the removal of these metal ions from the immediate vicinity of the plant. The method has the potential to address the issue of heavy metal contamination while also offering valuable insights into the interplay between plants, microbes, and electrodes002E. Consequently, it contributes to the advancement of environmental remediation approaches and research in sustainable energy.

3. Contribution of BES to sustainable development goals

Sustainable development depends on a balance between the economy, the environment, and society. Using the PLBES scenario as an example, **(Figure 6)** explains how the SDGs emerged to achieve a balance between all of these elements. **(Table 4)** presents the results of an in-depth investigation of the PLBES's direct impacts and objectives.

Table 4: Comprehensive descriptions of BESs generated by various plants

SDG	Goals	Contributions	Targets
1	No Poverty	Enhance the low-income farmer's profits.	End extreme poverty
2	No More Hunger	Increase small farmers' output and income through agriculture.	Double agriculture productivity
4	Quality Education	Boosting energy levels has been related by several studies to better educational outcomes.	-
5	Gender Equality	There was a connection established in some earlier works between bias and violence against women.	• End gender discrimination • Eliminate women violence
6	Clean Water and Sanitation	Removal of B, Lead, Zi, Cr, Ni, Cu, Oil, NB, and Salt from Water.	• Availability of potable drinking water for all • Hygiene and sanitation should be available everywhere. • Improve water quality

7	Clean, low-cost energy	providing essential support to the energy industry	• Universal access to energy • Increase renewable energy • Double energy efficiency
10	Reduced Inequality	Enhances activity levels and has the potential to reduce inequalities.	• Reduced inequalities • Eliminate discrimination
13	Climate Action	Assisting in enhancing environmental resistance	Strengthen resilience to climate change
14	Life Below Water	Enhances activity levels and has the potential to reduce inequalities.	Reduce marine pollution
17	"Partnerships to Achieve the Goal"	Encouraging to improve the target alliances	Uncertain

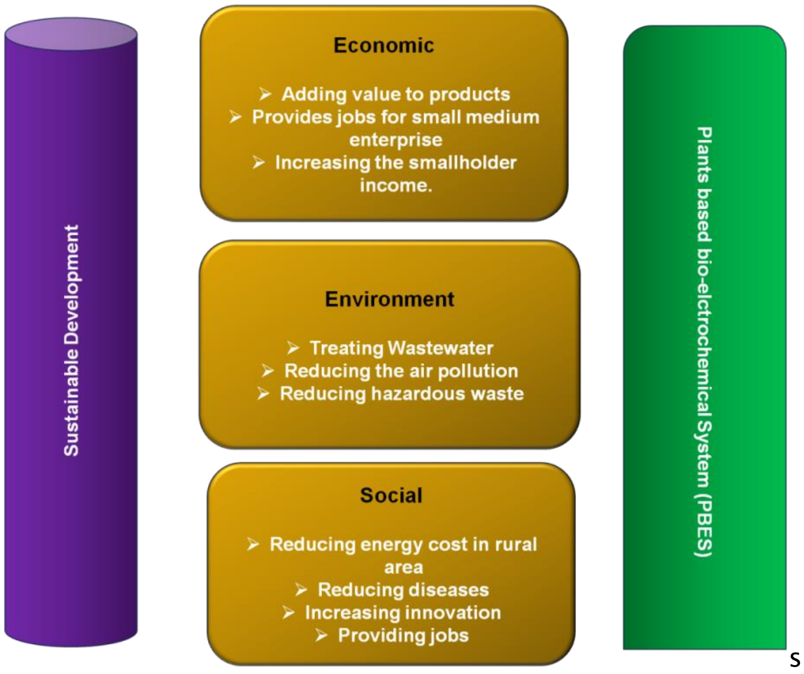

Figure 6: *Unaerated groups boron removal efficiencies*

The primary focus of this study is in the examination of SDG 1, which regards the eradication of poverty. Additionally, it explores Sustainable Development Goal 6, which addresses the provision of clean water and sanitation, Sustainable Development Goal 7, which emphasizes the importance of affordable and clean energy, and Sustainable Development Goal 13, which centers on taking action against climate change. Energy and wastewater treatment are two sectors where the PLBES provides substantial advancements, therefore directly supporting the achievement of "Sustainable Development Goal 7 (Affordable and Clean Energy) and Sustainable Development Goal 6 (Clean Water and Sanitation)". These devices combine microbial activity with electrodes to generate electricity, clean wastewater, and salvage materials. Renewable energy generation, less environmental pollution, and improved water management are all ways in which BES helps achieve sustainable developments. BES exemplifies a viable approach for attaining many sustainable developments simultaneously, building a more sustainable and linked future, by permitting simultaneous advantages like power production from organic waste while treating it.

BES plants depend on availability, usage, and weather. Plant density, structure, and placement greatly impact system performance. P-BES power output is severely; thus, cell architecture, electrode spacing, and cost-effective "cathode catalysts such nitrogen-doped graphene and nanocarbon materials" like carbon nanotubes and nanofibers must be improved. P-BES applications need constant high-power generation. Commercial viability requires electrode materials with sufficient surface area, electrical resistance, cost-effectiveness, biocompatibility, and chemical resistance. Electrode material development, temperature effects, and phytoremediation hybridization require long-term investigations. Hybridization and non-hybridization degradation rates reveal system robustness. System characteristics and vitality show environmental impacts.

4. Conclusion

P-BESs generate bioelectricity from plant root exudates and soil microbes. Plant type, light, temperature, microbes, system setup, electrode material, and so on all have an impact on efficiency. This strategy has potential in sediment, rice paddies, and phytoremediation since it may generate power while also removing contaminants. Microbial fuel cells (MFCs) that are planted outperform unplanted or phytoremediation-only systems in terms of energy generation and pollutant removal. AI tools such as VOS Viewer evaluate the alignment with the SDGs. P-BESs contribute to achieving several of the "Sustainable Development Goals, including clean Energy (SDG 7), No Poverty (SDG 1), Water and Sanitation (SDG 6) and Climate Action (SDG 13)". P-BESs provide smallholders with access to renewable energy and income possibilities, therefore reducing poverty and assisting in the cleaning of waste and the disposal of hazardous materials (SDG 15).

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