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Progress in plant-based bioelectrochemical systems and their connection with sustainable development goals

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ABSTRACT

Living organisms' energy conversion is considered as an essential and sustainable green energy source and future bio-hybrid technologies. Recently, plants were used after harvesting as biomass in bio-fermentation as an energy source. In bio-electrochemical systems, microorganisms work with plants to generate electricity, hydrogen, or methane. This work discusses the simultaneous pollutant removal and electricity generation in plant-based bio-electrochemical systems (P-BES). Factors affecting the P-BES performance and the removal efficiencies of the different organic and inorganic pollutants were illustrated. Furthermore, the plant-based bioelectrochemical systems' role in achieving the sustainable development goals (SDGs) was discussed. The SDGs contribution of plant-based bioelectrochemical systems were presented and discussed to evaluate such systems' ability to achieve the three pillars of sustainable development, i.e., economic, environmental, and social.

1. Introduction

Fossil fuel is a form of solar energy stored in the dead organisms and transferred into fuel by a natural process, i.e., anaerobic decomposition. This process takes millions of years to occur, producing coal, natural gas, or petroleum containing high carbon content. Due to the depletion and the environmental problems of fossil fuels [1–3], using renewable and sustainable energy sources has become a critical request to reduce greenhouse gas emissions [4,5]. The earth received a massive amount of solar radiation, around 174 PW (petawatts). Landmasses, oceans, and clouds absorb 70% of this amount. Renewable energy sources such as solar [6,7], geothermal [8,9], biomass [10,11], wind [12], and ocean [13] energies are sustainable with low environmental impacts. Therefore there is a rapid growth in applying renewable energy sources in different applications. Among the various renewable energy sources, biomass [11,14] and solar energies are the most abundant with cost-effective energy conversion technologies. Bio-electrochemical systems (BESs) are devices that use the catalytic activity of living microorganisms to metabolites high molecular weight organic matter into simple ones or CO_2 (end product) through a series of biological reactions [15,16]. There are various types of BESs such as microbial fuel cell (MFC) [17], sediment microbial fuel cell (SMFC), BESs for hydrogen or chemical production, i.e., microbial electrolysis cell (MEC), microbial electrolysis chemical production cell (MECC), microbial desalination cells (MDC), and microbial electrolysis desalination cell (MEDC). These systems are efficient energy conversion devices that demonstrated promising results in different applications such as CO_2 capturing [18], bioremediation [19], wastewater treatment [20,21], and water desalination [22]. Such systems are flexible in operation, easy installation, and environmentally friendly technology. BESs are considered energy harvesting devices that use living microorganisms to extract the chemical energy stored in different wastes and convert them directly to other energy forms. Photosynthetic organisms can use light energy to produce electricity or any other energy carrier using BESs. The light-based BESs can be categorized according to the type of organism used at the anode side to i) photosynthetic BESs where anoxic photosynthetic organisms are used at the anode side to produce energy, ii) biophotovoltaic systems (BPV) using oxygenic photo organisms (OPM) which can perform

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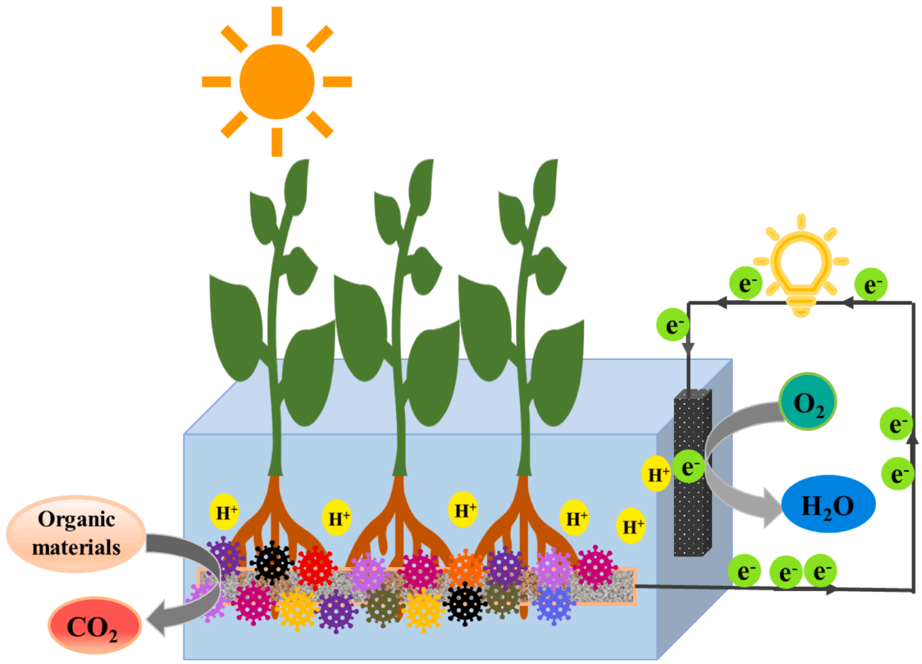


Fig. 1. Schematic diagram of the plant-based MFC.

photosynthesis process at the anode chamber producing energy directly, and iii) complex photosynthetic BESs that uses two types of microorganisms at the anode side (one is anoxic photosynthetic microorganism and the other type is heterotrophic microorganisms) [23].

In 2015, 17 Sustainable Development Goals (SDGs) were adopted by all the world nations. The SDGs covered the three pillars of sustainable development, namely prosperity, planet, and people. The SDGs provide a platform for all countries to measure the contribution toward sustainability. United Nations Conference on Trade and Development estimates that to meet the SDGs by 2030, a total of $3.3 trillion and $4.5 trillion investments are required annually by developing countries [8]. Determining and analyzing the contribution of the products or services into SDGs can help the stakeholder create a policy supporting SDGs' work. Therefore, finance and allocate the investments into the correct place or technology. Target 7.2 under SDG 7 (Affordable and Clean Energy) is calling to "increase the share of renewable energy in the global energy mix substantially by 2030". The latest number from United Nations indicates that the current share is far from aimed Targets [24]. Moreover, Target 6.3 under SDG 6 calls to "improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally" by 2030. Like Target 7.2, the latest number shows that this Target requires a lot of effort as it is far from being achieved [25]. One of the promised technologies that can aid in reaching the SDGs is P-BES. P-BES have the capabilities to treat the wastewater (SDG 3: Good Health and Well-being and SDG 6: Clean Water and Sanitation), provide a sustainable source of energy (SDG 7: Affordable and Clean Energy and provides), add a value (SDG 9: Industry, Innovation, and Infrastructure), and reduce the overall emissions SDG 13: Climate Action). These contributions and other contributions will be discussed in this work.

Although a large number of work was done to summarize the different types of bio-electrochemical systems, i.e., microbial fuel cells [16], microbial desalination cells [22], microbial electrolysis cells [26], few efforts have been made to summarize plant-based BES. Moreover, based on the authors' best knowledge, there is no work done to link plant-based bio-electrochemical systems with the SDGs. This work summarized the recent progress in plant-based bio-electrochemical systems and their contribution in the SDGs.

2. Principles of Plant-based BES (P-BES)

Plants produce organic materials (carbohydrates) during the photosynthesis process using the green pigments in their leaves (chlorophyll). These carbohydrates are the primary energy source for living organisms that directly ate the plants or fed on other organisms that ate the plants. Around 40% of carbohydrates produced are consumed by the plants themselves with perfusion of the residual half to the root (rhizosphere), where they are broken by the microorganisms existing in the soil producing electrons. If the plants are used in the anode chamber of BESs, they will produce electricity. Such a system is known as plant-based BES (P-BES). The P-BESs depend on the photosynthesis process by the plant to produce the carbohydrates (organic compounds). Then the plant excretes the unused carbohydrates by rhizodeposition where they are electrochemically oxidized by the microorganisms existing in the soil around the plant root or externally added from another source to produce electrons and protons. The electrons and protons are transferred to the cathode side through an external circuit and ionic electrolyte, respectively. The electrons and protons react with oxygen from the air or any other electron acceptor producing water at the cathode. The mechanism of the plant-based MFC is shown in Fig. 1.

2.1. *The function of the plant in plant-based BESs:*

Plant roots absorb water from the soil and transfer it to the leaves through the stem. Water reacted with carbon dioxide fixed from the atmosphere by plant leaves in sunlight via the photosynthesis process using chlorophyll. Almost 47.25 billion tons of carbon that the plants fix transported to the root and then to the rhizosphere as exudates rich in carbohydrates, gases, ethylene, dead cell materials, enzymes, and CO_2

Table 1
Factors affecting the efficiency of P-BES.

Factors	Impact	Result	Ref
Plant	Photosynthesis and power generation	the availability of organic matter used by microorganisms in the root zone is increased	[43,44]
Temp.	The photosynthesis process and the power generation	High and low temperature affect badly on the photosynthesis process and the catalytic activity of microorganisms	[45–48]
Soil	Plant growth rate and power generation	The biomass and microorganisms available in the root zone	[47,49]
Illumination	Photosynthesis and power generation	Enhanced the photosynthesis process, thereby, the amount of the biomass in the rhizosphere	[41,50]
Microorganisms	The performance of the BES (power density, coulombic efficiency, COD removal)	Biomass degradation rate and efficiency. Rate and mechanism of electron transfer.	[51–53]
Configuration	Photosynthesis, root propagation, power generation	The configuration should not hinder the photosynthesis process by obstructing the sunlight or CO_2 diffusion.The anode should not clog the root propagation	[48,49,54,55]
Electrodes	Power generation	Anode electrode affects the biofilm formation, electron transfer rate, and mass transfer. Cathode electrode affects the oxygen reduction reaction (ORR) rate	[44,53,56–59]

via rhizodeposition process [27,28]. The exudates supply the rhizospheric microorganisms with carbohydrates, amino acids, and others to perform cell respiration and other cell activities [29].

Plants are classified according to the photosynthesis pathway to C3, C4, and CAM [30]. C4 plants are the most proper type as it converts the CO_2 to a 4-carbon sugar compound and enters the Calvin cycle [31]. This plant type is highly efficacious in the dry, hot atmosphere and produces a considerable amount of bioenergy [32]. C4 plants introduce more rhizodeposition as a substrate for the microorganisms near the root, enhancing the power regeneration in the plant-based microbial fuel cell (P-MFC) [33]. Around 3% of the plant species (8100), including grass species, employ C4 carbon fixation [34]. The rhizospheric microorganisms are used as biocatalysts in P-BES; these microorganisms use the root exudates as electron donner and transfer the liberated electrons to the anode surface directly or indirectly.

2.2. Bio-photovoltaics (BPV)

Bio-photovoltaic **(**BPV) system harvests green energy directly using the natural photosynthesis process [35]. BPV system uses photosynthetic organisms such as cyanobacteria, algae, and green plants. These organisms use the sunlight to convert water to electrons and protons, produce oxygen as a by-product, and reduce the carbon in the carbon dioxide molecule and fix it into multi-carbon units considered the main energy source organisms [36]. For the plant-based BPV, the microorganisms in the plant roots themselves are used to metabolite the plant's organic material during photosynthesis without using any other (external) microorganisms or substrate. Thus, BPV systems use sunlight, water, and CO_2 to produce electrical energy directly. Two types of current could be acquired in the BPV system; i) photocurrent, which is the current produced during the photosynthesis process using the sunlight (illumination source), and ii) dark current (delayed photocurrent), which is the current generated in the absence of light where the microorganisms used the endogenously stored carbohydrates (excess carbohydrates that produced during photosynthesis process) [37]. A BPV was studied using two different plants *Oryza sativa L.* and *Echinochloa glabrescens (Munro ex Hook. f),* under same operating conditions [38]. The two plants were kept to growth for 8 days; the average power generation of BPV based on O. sativa was 0.980 ± 0.059 GJ / ha year compared to 0.088 ± 0.008 GJ /ha year in the case of BPV using *E. glabrescens.* This was related to the higher electrogenic activity of *O. sativa* than that of *E. glabrescens* (produced charge around six times faster). Algae (*Chlorella Vulgaris*) based BPV was recently constructed for the generation of green energy. The surface area, total pore volume, and the electron transfer rate were enhanced by modifying the carbon cloth (anode) with a nanocomposite of hierarchical nanostructure of $FeWO_4$/CeO_2 on rGO [39]. The modified anode cell demonstrated a higher performance as the maximum power density increased from 8.34 to 80 mW/m^2 (nearly ten times higher). Embolization of algae in alginate gel improved the power output of algae-based BPV by 18%, reaching a maximum power density of 0.289 mW/m^2 [40]. The influence of light quality on photosynthesis efficiency, biomass production, and power output was also investigated in algae "*Chlorella UMACC 313*" based BPV; a maximum power density of 0.45 mW/m^2 was achieved [41]. Two types of light, programmable LED arrays (PLA) and white LED were examined in BPV based on *Chlorella*, showing that when PLA was used as a light source, a maximum power density of 0.581 mW/m^2 was obtained, which was 188% higher than that using white LED light source [42].

2.3. Factors affecting the performance of P-BESs

In P-BES, microorganisms in the soil around the plant root or externally added to the system use the plant's root exudates as a fuel to generate bioelectricity. The efficiency of the P-BESs is affected by several parameters such as the humidity, pH, temperature, weather, type of the soil, type of the plant, illumination, type of the microorganisms, the configuration of the system, type of the electrodes, and with or without membrane, as shown in Table1.

3. Application of P-BESs

P-BESs are considered renewable energy resources as they can produce electricity continuously simultaneously with hazard removal. In such a system, the plant plays a critical role in converting the sunlight directly to electricity through the rhizosphere to remove pollutants. The various applications of P-BESs such as Sediment MFC, rice paddy field, and Phytoremediation were summarized in the following sections.

3.1. Sediment MFC (S-MFC)

S-MFCs are microbial fuel cells that use the sediment's microorganisms to remove the organic materials from the sediment and produce

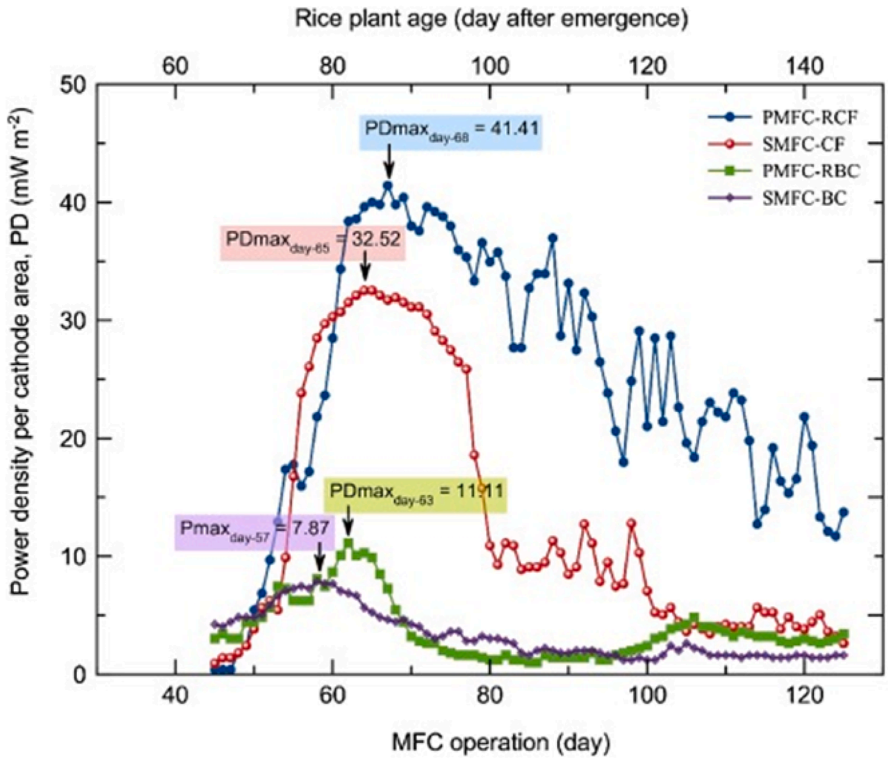


Fig. 2. Effect of the rice plant and anode material on the power generation of P-MFC, with permission from Elsevier [66].

electricity [51]. The S-MFC consists of an anode electrode that is immersed in the sediment and a cathode electrode that is suspended in overlying water [60]. Recently, different plants are planted in the anode of S-MFC; therefore, the plant introduces more organic materials to the microorganisms. Also, the interaction between the microorganisms in the rhizosphere and those in the sediment could enhance the biodegradation process [61]. The removal of high molecular weight polycyclic aromatic hydrocarbons (HMW-PAHs) was improved when the macrophyte Acorus calamus was planted in the anode of sediment microbial fuel cell (S-MFC) as the degradation rate of pyrene and benzopyrene was increased by 70% because of the interaction between aerobic and anaerobic consortia in rhizosphere and sediment, respectively, which perform aerobic/anaerobic metabolism [62]. S-MFC with Eichhornia crassipes was constructed for wastewater treatment and power generation [63]. The plant rhizosphere increased the organic substances in the wastewater, which positively affected the power generation, and COD, turbidity, volatile fatty acid (VFA), nitrate, and color removal efficiencies [63]. The root exudates of wetland " Ipomoea Aquatica " were used as a substrate in a single chamber, membrane-free MFC. However, the COD removal efficiency in planted MFC was slightly higher than that of unplanted MFC; the power density of planted MFC was significantly higher by 142% than that of the unplanted one [64].

3.2. Rice paddy field MFC

Rice paddy field is a good medium to build effective plant-based MFCs. An MFC was constructed to harvest energy in a rice paddy field as the anode was placed in the rice rhizosphere [50]. The acetate was the primary organic substance exhausted from the roots and used by the soil's microorganisms as a fuel for producing electrons and protons. The photosynthesis process is essential for the power output as shading of the plants dramatically decreased the power generation, whereas there was a remarkable change when the cathode surface was shaded. Adding acetate to the anode rhizosphere promoted the power output during no sunlight (dark) where the plants could not produce organic materials. The power output reached around 50% of its value during the daytime. Another study was conducted to identify the microorganisms in the anode of S-MFC operated in a rice paddy field [65]. This study demonstrated that the *Geobacteraceae* species, especially *G. Psychrophilus*, grew on the anode's rhizosphere region and interacted with the microorganisms secrete electron donors, causing power generation. Biochar granules or carbon felt were used as anode materials P-MFC where rice plant was grown in the anode chamber [66]. The performance was evaluated with and without rice plant (SMFC). It was observed that the performance of P-MFC was higher than those of SMFC, and the performance using the carbon felt was better than that using the biochar in terms of power generation, as shown in Fig. 2. However, the biochar decreased the emission of methane without affecting the yield of plant biomass.

One of the problems associated with rice agriculture is methane emission, as it produced 9–19% of the total emission of methane. This occurs due to the series of anaerobic biochemical reactions in which the complex organic matters are decomposed to simple ones than acetic acid, hydrogen, and carbon dioxide. Finally, they are converted to methane via methanogenic microorganisms (acetoclastic or hydrogenotrophic methanogens). A plant-based BES was investigated to overcome such an environmental issue by introducing a rice plant, "Oryza sativa". Also, the anode of a BES was introduced in the rhizosphere of rice plants (Oryza sativa), and the effect of the methane emissions was investigated. The current generated from this system delayed the emission of methane. The bioelectrochemical method in the water-logged Rhizosphere contributed to a current-generation before methane emissions began, likely leading to a short-term pause in methane emissions from such anoxic systems. However, due to excess

Table 2
P-MFC studies integrated with phytoremediation.

Pollutant type	Type of plant used in the anode of the P-MFC	Pollutant conc.(mg/L)	Pollutant Removal %	Power density (mW/m^2)	Remarks	Ref.
Remove the boron (B) from the water of the irrigation	Different MFC modules based on duckweed i.e., L. gibba, L. minor, or both.	4	71% (L.gibba -MFC)	17,783 (L. gibba-MFC)	B > 4, the removal efficiency decreased for all modules.	[76]
Remove Pb from wastewater	Wetland-MFC	5	85%	7.432	The microbial community was adapted to Pb(II) with long-term operation.	[88]
Remove Zn(II) from wastewater	Wetland- MFC	~ 0.144	98.5 %	3.67	The presence of Zn(ll) had negative effect on the performance of the MFC.	[93]
Remove chromium from wastewater	Plant ((Lolium perenne)-MFC	19	99%	55 mA/m^{2*}	The higher chromium concentration, the higher current generation.	[97]
Remove chromium from wastewater	Wetland- MFC	60	90.7%	458.2	Convenient hydraulic retention time, initial concentration of chromium and initial COD improved the performance of wetland MFC	[121]
Remove of Ni	Plant (Water hyacinth)MFC	2.5	-	0.86	The combination of P-MFC and phytoremediation enhanced the performance of both solo processes.	[104]
Remove of copper	Plant (L. minor) MFC	10	-	1.076	Hybridization of plant-MFC with phytoremediation decreases the ohmic resistance, improves the power output, and enhances the copper ions uptake.	[74]
Remove of oil from wastewater	Wetland-MFC	235	95.7%	102	Although MFC with wetland did not affect the oil removal efficiency, the power density was highly enhanced.	[59]
Remove of nitrobenzene (NB)	Wetland-MFC	200	93.9%	19.5	The plant in the anode chamber decreased the internal resistance at different concentrations of NB.	[113]
Remove of nitrobenzene (NB) from wastewater	Wetland-MFC	-	92.89%	1.53	Incorporating wetland enhanced the performance of MFC. The hydraulic retention time, electrode spacing, and the loading of the substrate.	[114]
Treatment of saline wastewater	Wetland-MFC	5 mg/L	-	16.4	The efficiency of the wastewater treatment was increased when the conc. of NaCl was 5 g/L and no effect if its concentration less than 5 g/L.	[120]

organic matter in the rhizosphere over the long term (i.e., the entire rice season), low methane emissions could not be sustained. The rhizosphere and anode group analysis showed that H_2 is the most important precursor to methane production. A hybrid strategy with other methane mitigation methods would be envisaged for a realistic, large-scale use of a bioelectrochemical method to reduce methane emissions. The pollution of rice baddy with toxic heavy metal could also be decreased by planting the rice in MFC [67]. Applying MFC in the rice plant reduced the masses of Cu, Cd, Ni, and Cr in the grains by 32.8%, 35.1%, 21.3%, and 56.9 % [67].

3.3. Phytoremediation-PMFC hybrid system

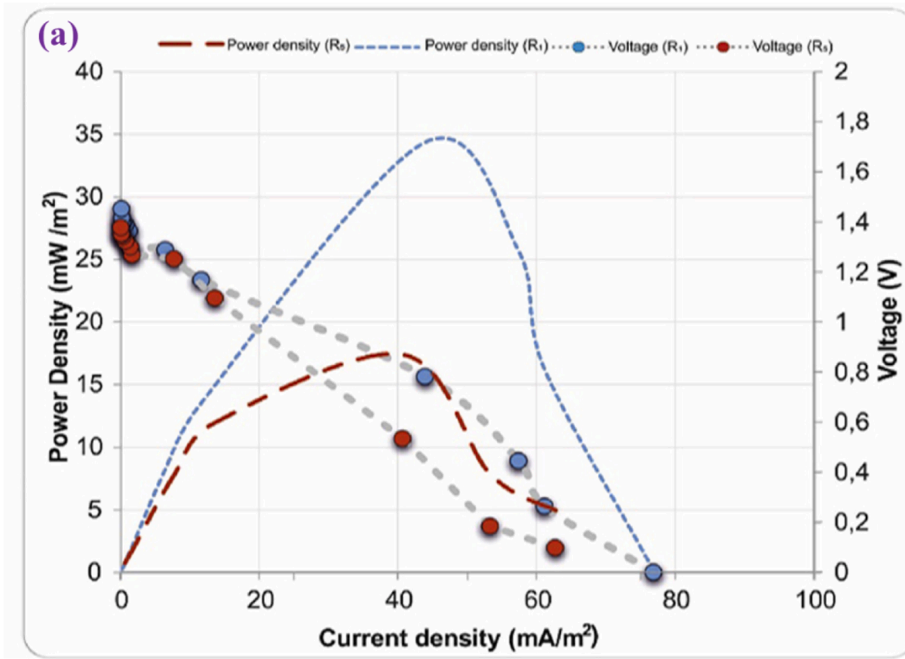
Contamination of water and soil with organic or inorganic pollutants demonstrates severe environmental impacts that cause many health threats for humans and all life forms. Plants play a significant role in removing contaminants with their attendant microorganisms via the phytoremediation process [68,69]. During this process, the plant accumulates the organic and inorganic pollutants, metabolizes the organic wastes, and stimulates the microbial decay of organic wastes in the rhizosphere zone [70,71]. Phytoremediation is an autonomous method for pollutant removal that is environmentally friendly, cost-effective, relevant for surface and groundwater, sediments, soil, and sludge [72]. Phyto-power system is a hybrid system of P-BES and phytoremediation for simultaneous bioenergy generation and contaminants removal (organic and/or inorganic) from the soil or water [73]. This system can sustainably harvest energy from anaerobic respiration of microorganisms around the plant root in a clean, low-cost, and effective way [74,75]. The combination between plant based MFC and phytoremediation was summarized in table 2. Some examples of the application of a hybrid system of P-BES and phytoremediation are given below.

- **Boron removal**

Boron (B) is sometimes found in irrigation water. If the concentration exceeds, it will affect aquatic, wild organisms, and human beings. Removal or reducing the concentration of B with conventional methods is comparatively difficult. Türker et al. examined different MFC modules based on duckweed with mono or polycultures, i.e., *L. gibba, L. minor*, or both, to determine the most proper duckweed species to remove the boron from the water of irrigation [76]. This study revealed that for an initial B concentration of 4 mg/L, the MFC based on *L.gibba* achieved the highest B removal of 71% and generated a maximum power density of 17783 mW/m^2. When the B concentration exceeds 4 mg/L, the removal efficiency decreased for all modules, and when it reached 32 mg/L, it drastically reduced because the biomass production was deficient and the chlorophyll level was decreased remarkably. *Duckweed, Lemna gibba L*, based MFC (DWWT-MFC) was constructed and operated to remove boron from domestic wastewater [77]. The MFC performance and the boron removal efficiency were investigated under various conditions such as the presence and absence of plant and aeration. The highest voltage and power density of 1.4 V and 34.8 mW/m^2, respectively, were realized for MFC using plant and under aeration conditions, as seen in Fig. 3(a). A high boron removal of 71% was achieved for MFC with plant, while aeration has a negligible effect, as seen in Fig. 3(b).

- **Lead removal**

Lead is a hazardous material that negatively affects the human body as it piles in the skeletons, damages DNA, proteins, and lipids. It can also replace the ions of the essential metals such as Fe, Zn, and Ca ions [78–80]. Lead is present in the wastewater from the battery industry with a high concentration (5–15 mg/L) [81,82] and must be decreased to 0.015 mg/L according to the US EPA [83,84]. Such wastewater is



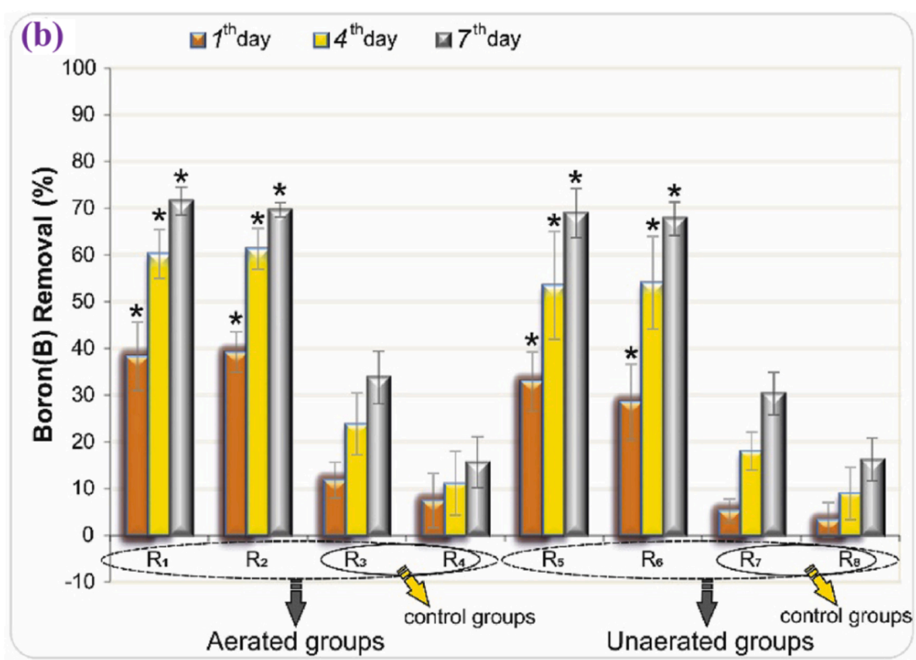
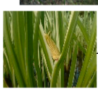
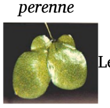


Fig. 3. (a)The polarization and power curves of DWWT-MFCs in the presence (R_1) and absence of oxygen (R_5), and (b) the boron removal efficiencies under different conditions, with permission from Elsevier [77].

Table 3
Summary of the different plant/algae-based BESs.

Plant type	MFC	anode	cathode	Separator	Max. power densitymW/m^2	The main remarks	Ref.
E. crassipes 	Cubic-MFC	Graphite rods	Graphite rods		0.86	Hybridization between PMFC and phytoremediation of Ni ions enhanced the efficiency of both processes.	[104]
 *Spartina anglica*	Cylindrical MFC	Graphite grains	Graphite felt	Cation exchange membrane	222	The current generation started at the end of week 3 and increased gradually to 2.6 mA/m2 in week 10. After that, this PMFC generated an average power density of 21 mW/m^2 until week 17	[122]
Arundinella anomala 	Cylindrical MFC	Graphite grains	Graphite felt	Cation exchange membrane	22	The bioelectricity generation started after the first day. The average power density was 10 mW/m^2 among weeks 4 and 17.	
 *Macrophyte Acorus calamus*	Sediment MFC	Graphite felt	Graphite felt	-	-	A combination between SMFC and macrophyte *Acorus calamus* enhanced the degradation of HMW-PAHs presented in the sediments.	[62]
Canna indica 	Cylindrical MFC	Graphite felt	Carbon cloth/ AC		18	*Canna indica* grew in P-MFC as the sole substrate source as it continuously supplies the anode of MFC with the substrate. The current density increased until it reached the maximum of 105 mA/m^2 after 20 days and then be constant at 50–80 mA/m^2.	[123]
Eichhornia crassipes 	Cubic-MFC	Graphite discs	Graphite discs		~ 80	The interaction between the rhizosphere, domestic sewage, and distillery effluent from dark fermentation enhanced the wastewater treatment process's efficiency as 86.6% of COD, and 72.3% of VFA were removed simultaneously with power generation.	[63]
 *Glyceria maxima*	Cubic-MFC	Graphite felt/graphite granules	Graphite felt	Cation exchange membrane	67	The Reed mannagrass was used as a source of carbohydrates to be used by the microorganism in MFC's anode to generate electricity.	[124]
	Cylindrical-MFC	Graphite granules	Graphite felt	Cation exchange membrane	80		[125]
 *Ipomoea aquatica*	Single-chamber-upflow MFC	Granular activated carbon	Stainless steel mesh	Membrane free	12.42	Planting the *Ipomoea Aquatica* in MFC's anode enhanced the power density from 5.13 to 12.42 mW/m^2 and the COD removal efficiency from 92.1% to 94.8%.	[64]
	Single chamber MFC	Graphite felt	Co_3O_4 nanowires/ Graphite felt		75	Cr(VI) removal efficiency was 99.76%, which was achieved at an initial concentration of Cr (VI) of 21.16 mg/L.	[94]
Rice paddy field 		Graphite felt	Graphite felt		6	The power generation was dependent on the sunlight. The artificial shading prevented electricity generation. Using acetate as a supplementary substrate improved the power generation at night.	[50]
	Single chamber/ cylindrical-MFC	Graphite felt	Pt/graphite felt		~ 19	*G.Psychrophilus* and other *Geobacteraceae* strains were grown in the anode around the rice paddy roots, producing power output.	[65]
	Cylindrical MFC	Carbon felt	Carbon felt		22.2	Planting rice in MFC reduced rice grains' pollution with toxic heavy metals, i.e., Ni, Cr, Cu, and Cd.	[67]
 *Lolium perenne*	Cylindrical-MFC	Carbon felt/ Graphite granules	Carbon felt		55* mA/m^2	PMFC was used to remove chromium from soil and water achieving as high chromium removal as 99%.	[97]
 Lemna gibba	Dual chamber MFC	St.St-Mg alloy	Graphite	Glass wool	17,783	PMFC was used to remove boron from irrigation water; monoculture was more effective than polyculture. This MFC can work effectively up to 4 mg/L of boron, a very high concentration of boron , 32 mg/L, inhibited the growth of microorganism and chlorophyll production.	[76]

(*continued on next page*)

Table 3 (*continued*)

Plant type	MFC	anode	cathode	Separator	Max. power densitymW/m^2	The main remarks	Ref.
Wetland 	Dual chamber-MFC	AC/Ti-mesh	AC/Ti-mesh	-	7.432	PMFC was constructed to remove the Pb(II) from wastewater. The removal efficiency reached around 85% with an initial Pb(II) concentration of 5 mg/L.	[88]
	_	Carbon fiber brush	MnO2/Carbon felt		102	The PMFC was designed for oily wastewater treatment. This system showed oil removal efficiency of 95.7% and a COD removal rate of 75% highly.	[59]
	Up flow MFC	Granular activated carbon	Granular activated carbon	-	458.2	PMFC was fabricated to remove Cr(VI) from sewage wastewater. When the initial concentrations of Cr(VI) and COD were 60 and 500 mg/L, respectively, the removal efficiencies were 90.7% Cr(VI) and 92.5% COD.	[98]
Iris croceis 	Single chamber MFC	AC/Ti-mesh	AC/Ti-mesh	-	3.67	The removal efficiency of Zn(II) was 98.5%. Zn (II) was affected badly in the removal efficiency of PT, TN, NH_4^+-N, and COD.	[93]
lemna minor 	Air cathode PMFC	Woven carbon fiber	Woven carbon fiber	-	1.076	Cu ions uptake was enhanced by 38% by a combination of P-MFC and phytoremediation	[74]
 *Chlorella UMACC 313*	BPV	Carbon paper	Hydrogen	Cellulose	0.45	Algae-BPV device was effectively used to directly convert the sunlight to electricity and remove POME from wastewater.	[41]
	Single-chamber BPV	ITO coated glass	Pt-coated glass	-	0.289	Immobilization of algae on the anode promotes the electron transfer process and maintains the photosynthesis process's efficiency longer than suspended algae.	[40]

Note: all images of the plants/algae are from Wikipedia (https://www.wikipedia.org/).

almost treated using chemical or physiochemical techniques, but these techniques consume chemicals and/or energy [85–87]. Zhao et al. fabricated an MFC based on the wetland to remove Pb from wastewater [88]. The authors studied the effect of Pb (5 mg/L) on wastewater treatment efficiency, power generation, and the microbial community. This study revealed that the presence of Pb(II) decreased the internal resistance of the MFC and thus increased the power density from 3.873 to 7.432 mW/m^2. Still, it negatively affected the removal efficiency of NH_4^+-N as it negatively affected the microbial community diversity and species richness. The removal efficiency of Pb from wastewater reached around 85% and the microbial community was adaptated to Pb(II) with long term operation.

- **Zn removal**

Zn is an abundant element on the earth as it comes in 24th of most abundant elements [89]. Zinc is an essential trace element for all living things as it is an enzyme cofactor and constituent of many proteins [90,91]. However, Zn's high concentration causes a toxic effect on all living things [89,92]. A wetland-based MFC was constructed to remove Zn(II) from wastewater achieving 98.5 % removal of Zn(II) [93]. Zn(II) significantly decreased TP's removal efficiency (total phosphorous) from 91% to 75.6%. It slightly decreased TN (total nitrogen) removal efficiencies, NH_4^+-N, and COD from 72.05%, 85.9%, and 84.94% to 68.87%, 80.4%, and 79.83%, respectively. Although Zn(II) decreased the MFC's internal resistance, the power density decreased little from 3.87 to 3.67 mW/m^2.

- **Chromium (hexavalent) removal**

Chromium is used in many industries such as leather tanning, nuclear reactors, electroplating, and pigment and steel industry [94]. Therefore, a lot of wastewater contaminated with chromium is produced. Generally, chromium exists in wastewater in two forms Cr(III), trivalent, Cr(VI), or hexavalent. A trace amount of Cr(III) is essential for human beings as it helps the human body to use protein, fat, and sugar; however Cr(VI) is highly toxic for all living things [95,96]. The removal of various chromium concentrations using P-MFC, was investigated [97]. The authors revealed that the Cr removal efficiency and the columbic efficiencies increased from 90.3% to 99% and from 2.05% to 4.12%, respectively, by increasing the chromium concentration from 9.5 to 19 mg/L. This system could be operated for a long time for Cr removal. The chromium was removed by precipitate as $Cr(OH)_3$ or by adsorbed onto the electrodes, and only a little soluble Cr(lll) remained in the P-MFC. When acetate was used as a substrate in the same MFC, its consumption was low using the plant (15–22% of that without using plants). The consumption of acetate in P-MFC might be related to the direct reduction of Cr(Vl), biomass growth, or other electron acceptors by the microorganisms (nitrate or oxygen).

Wetland-MFC was constructed to remove the Cr(VI) from wastewater [98]. Several factors were investigated, i.e., the space between the anode and cathode, hydraulic retention time (HRT), the concentration of Cr, and COD concentration. Cr(VI) highest removal efficiency of 93.4% was achieved using Cr (VI) of 40 mg/L and 10 cm electrode spacing. However, a maximum power density of 458.2 mW/m^2 was obtained using Cr (VI) and COD concentrations of 60 and 500 mg/L, respectively, achieving removal efficiencies of 90.7% Cr(VI) and 92.5% COD. Another study investigated a sediment MFC with Ipomoea Aquatica to remove Cr (VI) from wastewater [94]. Different initial concentrations of Cr(VI) (4.97, 10.29, and 21.16 mg/L) were examined, the maximum power density of 75 mW/m^2 and the highest removal efficiency of Cr(VI) of 99.76% was achieved when the initial concentration of Cr(VI) was

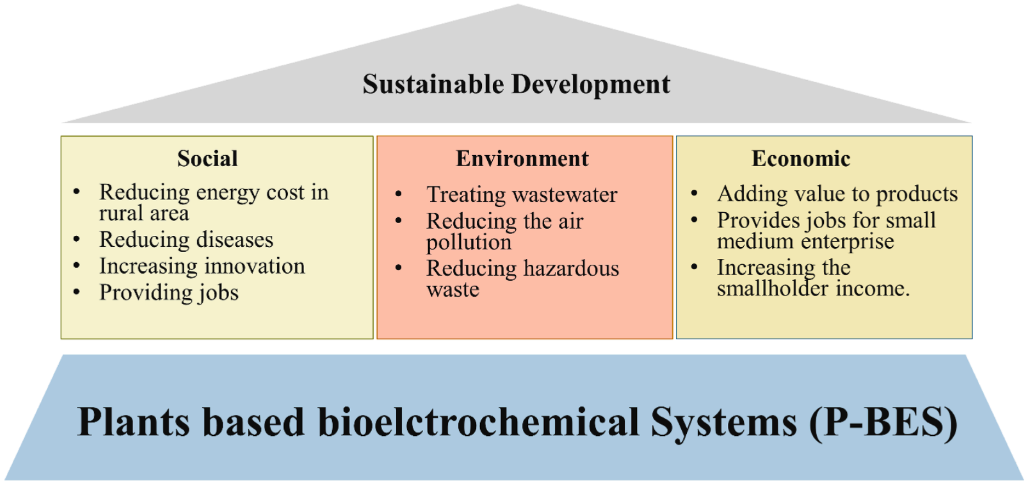


Fig. 4. Contribution of the P-BES to the three pillars of sustainable development.

21.16 mg/L.

- **Ni removal**

Nickel (Ni) is used in many applications such as stainless steel industry, catalysts, rechargeable batteries, plating, and coinage [99–102]. Also, Ni is an essential trace element for living things; however, it is dangerous when it exceeds a definite amount. High Ni concentration can cause severe diseases for humans and animals [103]. Removal of Ni from various wastes is considered an obligate request. A hybrid P-MFC-phytoremediation system was examined for Ni removal [104]. Three systems were investigated, including P-MFC, phytoremediation, and combination between them. The combination of P-MFC and phytoremediation enhanced the performance of both solo processes. The hybrid system showed three times higher power output than P-MFC, and Ni ions uptake doubled compared to phytoremediation only. The increase in the power was related to the decrease in the ohmic resistance and further terminal electron acceptor. The Ni ions uptake's improvement was related to the plant's physiological change because of the electrical stimulation, charge separation, and or system polarization.

- **Cu removal**

Copper is an essential element considered as metalloenzymes that act as an electron acceptor or donner [105]. A high copper concentration negatively affects the human being, causing severe diseases also causes toxicity for the plant [105,106]. P-MFCs with two different plants named *Azolla pinnata* and *Lemna minor* were recently constructed and examined for cupper uptake [74]. The presence of copper ions decreased the internal resistance of the P-MFC and thus increased the power density from 0.00334 to 0.01782 mW/m^2 for *Azolla pinnata* based MFC and from 0.2471 to 1.0761 mW/m^2 for Lemna minor. When a hybrid system of the P-MFC and phytoremediation was used, the cupper uptake enhanced by 18% and 38% for Azolla pinnata and Lemna minor, respectively, compared to phytoremediation.

- **Oil removal**

Massive oily wastewater is discharged from oil refining, transportation, and petrochemical industries [107]. Drainage of oily wastewater harms groundwater resources, aquatic life, crop production, and human health [108]. The conventional approaches for the treatment of oily wastewater are highly energy-consuming processes [59]. A wetland-based MFC was used to treat oily wastewater, achieving a high oil removal efficiency of 95.7%, COD removal rate of 75% simultaneously with bioelectricity generation [59].

- **Nitrobenzene (NB) removal**

Nitrobenzene (NB) is found with a high concentration in industrial wastewater discharged from drugs, dyes, organic intermediates, pesticides, and explosive industries [109]. NB is considered a dangerous pollutant as it has a stable chemical structure, extremely toxic, and causes dangerous health issues [110]. The wastewater contaminated with NB is usually treated with active carbon adsorption or supercritical water oxidation. Such processes are high energy consumption, secondary pollution production, and low degradation rate [111,112]. Recently a biological method using constructed wetland was successfully used to treat wastewater contaminated with NB, achieving a high NB removal efficiency of 95% at a low NB concentration of 70 mg/L, while it reached 57% at a high NB concentration of 160 mg/L. At high NB concentration, higher removal efficiency of NB could be achieved using a large constructed wetland area, but this isn't easy [113]. An MFC was made based on a constructed wetland to treat wastewater polluted with different NB concentrations (20, 120, and 200 mg/L). Three other plant species (*Scirpus Validus, Typha Orientalis, and Iris pseudacorus)* were investigated. *Scirpus Validus* grew well even at high NB concentration (200 mg/L) while part of *Iris pseudacorus* and *Typha Orientalis* died. Another study investigated the effect of the hydraulic retention time (HRT), the distance between the anode and cathode, and the concentration ratio of NB and COD in wetland-based MFC [114]. A high NB removal rate of ~ 93% was achieved at 24 h HRT using NB to COD ratio of 1:16.

- **Salinity removal**

Saline wastewater is produced from many industries such as leather, agro-food, and petrochemicals industries [115,116]. Discharging saline wastewater without proper treatment negatively affects the ecosystem [117]. Conventional chemical or physical methods used to treat saline wastewater are expensive or result in secondary pollutions [118]. Biological treatment is preferable from the economic and environmental points of view [119]. A wetland-based MFC was designed to treat saline wastewater [120]. The salinity of the wastewater significantly enhanced the power generation by four times as the salinity increased the ionic

Table 4
The Interlinkage between P-BES and SDGs.

SDG	Contribution P-BES and SDGs	Related Target/s
SDG 1: No Poverty	Raise the income of the smallholder [126]	1.1
SDG 2: Zero Hunger	Enhance agricultural production and revenue of smallholder [127]	2.3
SDG 3: Good Health and Well-being	As reviewed in the paper, P-BES assists in boron removal, lead removal, Zn removal, chromium (hexavalent) removal, Ni removal, Cu removal, oil removal, Nitrobenzene (NB) removal, and salinity removal	3.1, 3.2,3.3,3.4, 3.9
SDG 4: Quality Education	Increase the energy was directly linked to improving the quality of education by many researchers [128]	Undetermined
SDG 5: Gender Equality	Some previous papers had linked violence against women and discrimination [129].	5.1,5.2
SDG 6: Clean Water and Sanitation	P-BES is assisting wastewater treatment, water desalination, removing boron, lead, Zn, chromium (hexavalent), Ni, Cu, oil, Nitrobenzene (NB), and salinity from the water.	6.1,6.2,6.3,6.6
SDG 7: Affordable and Clean Energy	Hence the P-BES are directly contributing to the energy sector; this SDG is positively impacted by P-BES.	7.,7.2,7.3
SDG 8: Decent Work and Economic Growth	The agricultural and energy sector have significant contributions to the GDP. In addition, the P-BES can reduce the energy footprint [130].	8.1,8.2,8.3,8.4
SDG 9: Industry, Innovation, and Infrastructure	P-BES can lower energy costs; therefore the small-scale enterprises can have more access to energy. This can be added to the contribution of P-BES in the GDP. Besides, since P-BES is a new area, more research will be needed in the future.	9.1,9.2,9.3,9.4,9.5
SDG 10: Reduced Inequality	Similar to linkage with SDG 5, there is clear evidence that increases the energy and can lead to reducing the inequality	10.1,10.3
SDG 11: Sustainable Cities and Communities	Concerning SDG 11, P-BES can support SDG 11 by: • Removing boron, lead, Zn, chromium (hexavalent), Ni, Cu, oil, Nitrobenzene (NB), and salinity • Increase energy accessibility. • Reduce energy footprint	11.6,11.7
SDG 12: Responsible Consumption and Production	P-BES decrease hazardous waste since it a sustainable source of energy, and reduce the material footprint	12.2,12.4
SDG 13: Climate Action	In general, P-BES is capable of supporting strengthen resilience against climate change	13.1
SDG 14: Life Below Water	P-BES will assist in the reeducation of land-based marine pollution	14.1
SDG 15: Life on Land	The P-BES is contributing to SDG 15 by: • Improve the sustainability of the terrestrial ecosystem • Reduce the hazards wastes	15.1
SDG 16: Peace and Justice Strong Institutions	The lack of energy has been identified as the main reason for conflict in many world regions. [131]	16.2
SDG 17: Partnerships to achieve the Goal	Because P-BES still new technology relatively it can assist in enhancing the goal partnerships	Undetermined
SDG 17: Partnerships to achieve the Goal	Because P-BES still new technology relatively this can assist in enhancing the goal partnerships	Undetermined

Table 5
List linked Targets to P-BES.

Goal 1. No poverty	Goal 9. Industry, innovation, and infrastructure
1.1 End extreme poverty	9.1 Develop resilient infrastructure
Goal 2. Zero hunger	9.2 Promote inclusive and sustainable industrialization
2.3 Double agriculture productivity	9.3 Increase access to financial services
Goal 3. Good health and well-being	9.4 Resource-efficient and clean technology-based industrial retrofit
3.1 Reduce maternal mortality	9.5 Enhance R&D for industrial sectors
3.2 End preventable young children deaths	Goal 10. Reduced inequalities
3.3 End epidemics of diseases	10.1 Income growth of bottom 40% population
3.4 Reduce pre-mature mortality from non-communicable diseases	10.3 Eliminate discrimination
3.9 Reduce deaths/illnesses from pollution	Goal 11. Sustainable cities and communities
Goal 5. Gender equality	11.6 Reduce urban environmental impacts
5.1 End gender discrimination	11.7 Universal access to green and public spaces
5.2 Eliminate women violence	Goal 12. Responsible consumption and production
Goal 6. Clean water and sanitation	12.2 Sustainable resource use
6.1 Universal access to safe drinking water	12.4 Sound management of chemicals and wastes
6.2 Universal access to sanitation and hygiene	Goal 13. Climate action
6.3 Improve water quality	13.1 Strengthen resilience to climate change
6.6 Protect water-related ecosystems	Goal 14. Life below water
Goal 7. Affordable and clean energy	14.1 Reduce marine pollution
7.1 Universal access to energy	Goal 15. Life on land
7.2 Increase renewable energy	15.1 Sustainable use of terrestrial and inland freshwater
7.3 Double energy efficiency	Goal 16. Peace, justice, and strong institution
Goal 8. Decent work and economic growth	16.1 Reduce violence
8.1 Sustain inclusive economic growth	
8.2 Improve economic productivity	
8.3 Create decent work	
8.4 Improve resource efficiency	

strength, thus decreased the internal resistance. It is also found that salinity had a little effect on the TP and COD removal efficiencies, while it had a high negative impact on the TN and NH_4^+-N removal efficiencies. Table 3 summarized the different plants or algae used in the anode of P-BES.

4. Contribution of plant-based bioelectrochemical systems (P-BES) to the SDG

The three pillars of sustainable development are economic, environmental, and social. The SDGs were developed to ensure a balance between these three pillars, as summarized in the P-BES case in Fig. 4. The complete analysis of the direct contribution of the P-BES in achieving the SDGs is presented in Table 4 (The related Targets are shown in Table 5). As can be seen from Table 4 that the P-BES is contributing positively to all SDGs. The main contribution is on SDG 1 (No Poverty), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action). The P-BES significant contribution is energy and wastewater treatment, which directly contributes to SDG 7 (Affordable and Clean Energy) and SDG 6 (Clean Water and Sanitation).

Fig. 5 shows the research collaboration within the P-BES area based on the papers published in the last five years. This collaboration is directly supporting SDG 17 (Partnerships to achieve the Goal). From Fig. 5, it can be noticed that most of the research was done in the USA

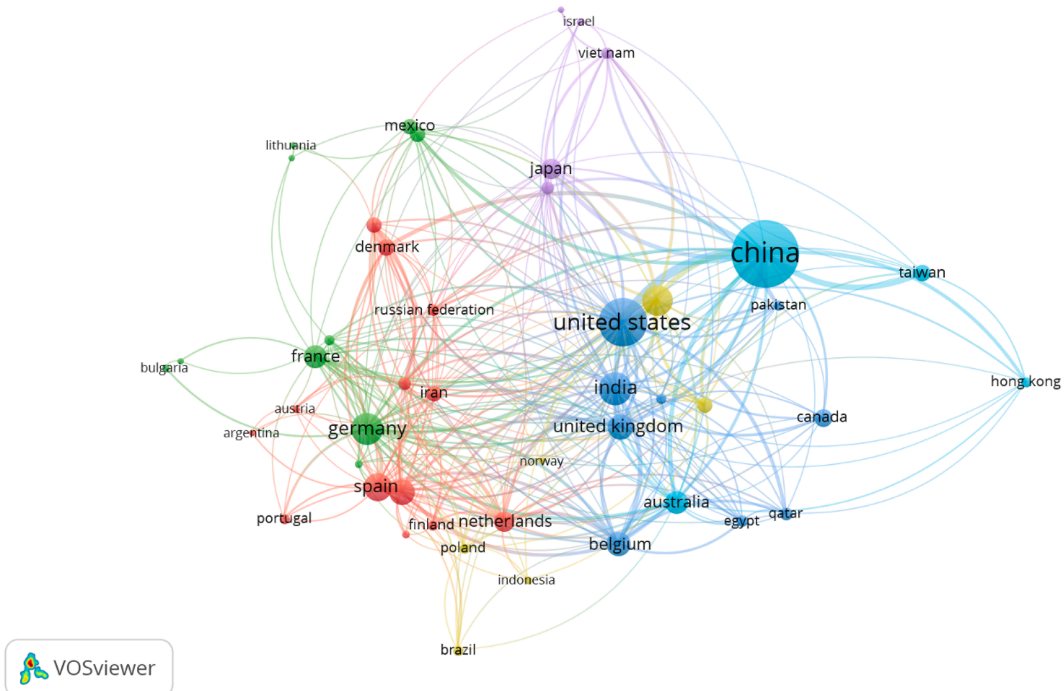


Fig. 5. Research collaboration network of P-BES during last five years.

and China. VOSviewer was used to extract the results [132]. VOSviewer uses artificial intelligence and text mining to generate this figure.

Fig. 6 shows the general relationship between the most related SDGs to P-BES, i.e., SDG 7 (Affordable and Clean Energy) and SDG 6 (Clean Water and Sanitation) in China. An open-source tool, namely SDG Interlinkages [133] was used. China was selected because the highest P-BES research came from China, as shown in Fig. 5. Fig. 6 shows the general linkage without looking to a specific industry. As it can be noticed from the figure that SDG 6 and SDG 7 have positive and negative contributions to other SDGs. As an example, there is a synergy relationship between SDG 7 and SDG 3 (Good Health and Well-being). This relationship happened mainly due to the linear relationship between energy availability growth and economic development, which improve the quality of life [134]. By contrast, this energy growth triggered many health issues. This explains the trade-off relation between SDG 7 and SDG 3 [135]. On the other hand, it can be noticed that increasing renewable energy, which is linked to Target 7.2 "substantially increase the share of renewable energy in the global energy mix", it does not always have a synergy (positive) relationship with other SDGs. The appearance of the Targets 6.3 and 6.4 separately from the other related SDGs indicated that there is no relation between them and the other targets based on the used methodology [133]. However, this might not be the case in another region.

5. Challenges and motivations

Choosing plants in BESs broadly depends on the availability of the plants, application, and weather. It is important to realize how the density of the plants and installation position will affect the system's performance. The power output from P-BES still very low; therefore, more work has to be done to optimize the cell configuration, the distance between the electrodes, and investigating cheap cathode catalysts such as nitrogen-doped graphene and other nano carbonaceous materials, i.e., carbon nanotube, carbon nanofiber,….etc. High and steady power output is also a critical request to transfer P-BES to the application stage. Furthermore, proper selection of electrode materials with high surface area, good electrical conductivity, biocompatible, inexpensive, and have high chemical and physical stabilities is an important target to realize the commercial application of P-BES. Plants that sustain the severe environmental condition with richly root biomass are also highly recommended. More work should be accomplished to study P-BESs under long-term operation, comprising how the electrode material changed over time, and how the temperature difference during the day or season to season affects the rhizosphere activity microorganisms. More research should be done to study the deterioration rate of P-BES with and without hybridization with phytoremediation. Properties and vitality also identify the environmental impacts of such systems.

6. Conclusions

In P-BESs systems, the soil's microorganisms around the plant roots use the plant's root exudates to generate bioelectricity. The P-BES performance depends on the type of plant, type and intensity of the light, temperature, type of microorganisms, the configuration of the system, and the electrode material. This system could generate electricity simultaneously with pollutants removal. The implementation of P-BES in sediment, rice paddy, and phytoremediation was thoroughly discussed. The power generation, COD removal, and pollutant removal are higher in the planted MFC than the unplanted ones or phytoremediation only. Artificial intelligence using VOS viewer was also used to determine the SDGs of the P-BESs. Accordingly, more than 3000 papers were published in the last five years in the plant-based BESs, demonstrating that P-BESs are considered a favorable renewable energy source that can help realize the SDGs. P-BES is one of the promising methods that can help in achieving the SDGs. The P-BES can contribute positively to SDGs, particularly SDG 7 (Affordable and Clean Energy), SDG 1 (No Poverty), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). One of the main contributions of P-BES into SDGs, besides a source of renewable energy, is providing a new source of income for smallholders. Providing this income is enormous benefits for eradicating extreme poverty, SDG 1 (No Poverty). The other significant role of P-BES in SDGs is cleaning hazardous materials and removing the wastes, SDG 15 (Life on Land).

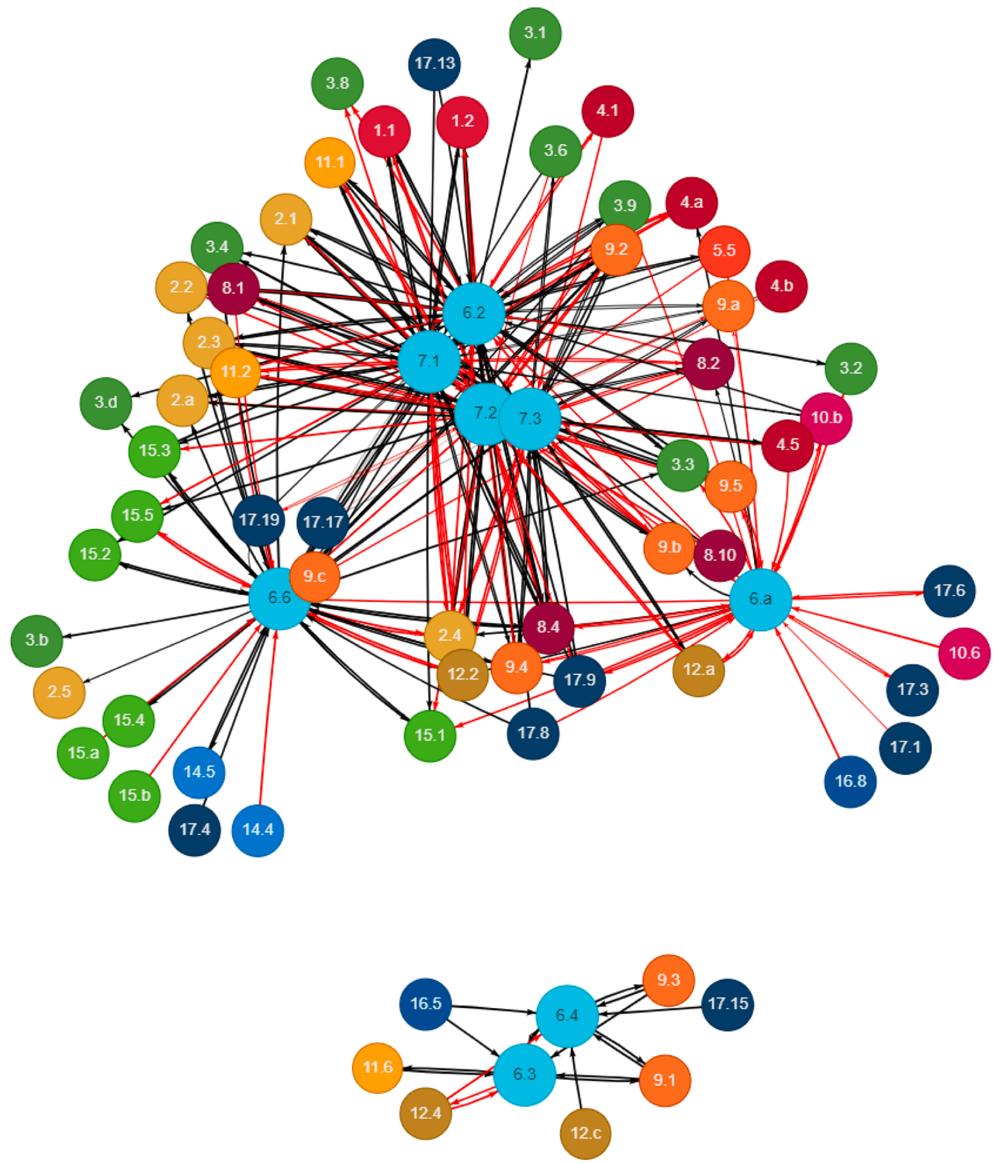


Fig. 6. The interrelationship of SDG 6 and SDG 7 with all the rest SDGs in China. Black arrows show a positive relationship. Red arrows indicate a negative relationship.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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