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BIOELECTROCHEMICAL SYSTEMS BASED ON THE ELECTROACTIVITY OF PLANTS AND MICROORGANISMS IN THE ROOT ENVIRONMENT

(review)

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Abstract

Bioelectrochemical systems (BES) based on electroactive processes in the root environment of plants and accompanying microorganisms are a new promising environmentally friendly technology for generating renewable energy. Although the possibility of practical use of bioenergy resources has already been shown in many studies, the nature of electrogenesis and the influence of external parameters on it have not been fully identified. The emergence of a potential difference in living systems is due to a complex of physicochemical processes that maintain an uneven distribution of ions at the cellular, tissue and organism levels (N. Higinbotham, 1970). In the process of plant development along the whole organism, a gradient of electrical potentials arises due to the diffusion of ions, concentration effects and differences in the intensities of biochemical processes (T.A. Tattar et al., 1976). Along with this, microorganisms of the rhizosphere are able to oxidize organic matter secreted by the roots (L. De Schamphelaire et al., 2010), while synthesizing carbon dioxide, protons and electrons. The ions and electrons formed in the course of redox reactions diffuse through the inhabited medium, leading to charge separation (B.E. Logan, 2008); as a result, a gradient of electropotentials is established, associated with differences in the concentrations of charged substances. A complex of processes for converting chemical energy from organic substances into electrical energy forms is the basis of the plant-microbial fuel cell (PMFC). The most common configuration of the PMFC device consists of an anode and cathode chambers, an ion-selective membrane (D.P. Strik et al., 2008); there are also various modifications in the form of a flat plate (M. Helder et al., 2013), a tubular configuration (R.A. Timmers et al., 2013), aimed at increasing the output electrical characteristics. One of the most important components of a BES are electrode systems. Most often carbon materials, which have high electrical conductivity, corrosion resistance, and a large specific surface area, are used. The productivity of BES depends on the composition of the root environment, the presence of potential-forming ions, and on the parameters of the light environment, the efficiency of photosynthesis. A promising option for using PMFC is their combination with significant production processes, in particular, their introduction into agricultural production. The possibility of using BES is shown on a number of cultivated and industrial plants with obtaining the following low-power energy output when growing rice — 140 mW/m^2 (N. Ueoka et al., 2016), lettuce — 54 mW/m^2 (T.E. Kuleshova et al., 2021), *Reed mannagrass* — 80 mW/m^2 (R.A. Timmers et al., 2012), *Common reed* — 42 mW/m^2 (J. Villasenor et al., 2013), cattail — 93 mW/m^2 (Y.L. Oon et al., 2016), *Common cordgrass* — 679 mW/m^2 (K. Wetser et al., 2015), etc., which have found application as food products, fuel, building materials, animal feed, etc. Prospects for the use of BES include power supply for environmental sensors (A. Schievano et al., 2017), light sources (W. Apollon et al., 2020), wireless sensor networks (E. Osorio-De-La-Rosa et al., 2021), the Internet of things (IoT) (Jayaraman P.P. et al., 2016),, phytomonitoring systems in natural conditions, greenhouses, remote areas, partial power supply of plant life support devices in artificial agroecosystems (T.E. Kuleshova et al., 2021), wastewater treatment (L. Kook et al., 2016).

Keywords: green energy, plant-microbial fuel cell, bioelectrogenesis, electroactive bacteria

Currently, the energy market is mostly occupied by fossil fuels — coal, oil and natural gas, the consumption of which leads to environmental pollution and climate change. Thereof, the use of environmentally friendly renewable natural energy resources is relevant. Solar energy, wind, geothermal heat, hydrothermal energy, biofuels are intensively used to generate electricity. However, they also have disadvantages, such as high installation costs, dependence on weather conditions and time of day, landscape transformation, and geographic localization. Against the background of these limitations, bioelectrochemical systems (BES) based on electroactive processes accompanying the vital activity of plants and surrounding rhizospheric microorganisms have the development potential.

The use of bioenergy resources for the development of a new field of "green" energy is a complex and not fully understood task that requires the integration of a wide range of knowledge in the fields of physics, electrochemistry and biology.

The purpose of this review is to analyze the existing designs of bioelectrochemical systems, describe the electrogenic and potential-forming reactions occurring in BES, and the influence of individual environmental factors on them, as well as consider the prospects for using bioenergetic devices.

Electrical processes in the root environment. *Plant electrogenesis.* The history of research on the electrophysiological properties of plants dates back more than a hundred years, but the mechanism of bioelectrogenesis, that is, the ability to move a charge and generate electricity [1], is still discussable. It is generally accepted that the occurrence of a potential difference in living systems is primarily due to a complex of physicochemical processes that ensure the maintenance of an uneven distribution of ions at the level of cells, tissues and the body.

The main electrical characteristic of the cell is the membrane potential, which arises primarily as a result of diffusion and the active process of ion transfer between the extracellular environment and intracellular compartments [2]. Ions K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, Cl^-, $H_2PO_4^-$, SO_4^- are most susceptible to active transport. Many other organic substances that are mobile within cells and tissues also carry charges, such as organic acids, amino acids, adenosine phosphates, etc. [3]. Potential differences between plant tissues and organs, generated as a result of electrogenic active transport, are determined by the physiological state and are divided into potentials of resting, action, damage, and flow [4]. Bioelectric potential (BEP) gradients result from the flow of metabolic reactions in the entire plant organism [3].

Thus, ion diffusion, concentration effects and the operation of ion pumps lead to the appearance of an electric current in plant organisms during their vital activity [5]. The electrogenic properties are most intense in the root environment—plant system, which is associated with the input and transport of ions in the process of mineral nutrition [6]. For example, the resting potential of cells of higher plants varies on average within 50-120 mV [7], while the bioelectric potential in the root zone can reach 700 mV [8].

Electroactive bacteria. Along with the diffusion of ions, which accompanies the vital activity of plants, the separation and movement of charges in the root-inhabited environment can be carried out by electroactive bacteria. In the process of development, rhizosphere microorganisms are able to oxidize organic substances secreted by the roots, synthesizing carbon dioxide, H^+ protons, and e^- electrons [9]. The transformation of the energy of chemical bonds of organic substances into electrical energy is the basis of a biotechnological device, a microbial fuel cell. In it, the generated electrons, under the action of the redox potential difference, move along the external circuit to the opposite electrode where they combine with protons that have migrated, for example, through an ion-selective membrane, and oxygen, forming water [10].

The transport of electrons from electrochemically active bacteria to the electrode surface can be carried out both directly in direct contact with the electrode, and with the help of electrically conductive processes (pilae) or mediators [11]. In particular, the transfer of electrons to the anode from bacteria of the species *Shewanella* and *Geobacter* is carried out both directly and using pili [12], while *Pseudomonas* secrete mediators (flavins) [13].

Currently, there are many species of bacteria [14] that are applicable in microbial fuel cells. Bacteria potentially capable of carrying out electrochemical reactions in the root environment were identified by the method of fluorescent in situ hybridization on plant roots, These are *Geobacter serreducens*, *Geobacter metallireducens*, *Geobacter grbiciae*, *Geobacter hydrogenophilus*, *Ruminococcus bromii*, *Clostridium sporosphaeroides* and *Clostridium leptum* [15]. It has been determined that *Shewanella putrefaciens* uses lactate, pyruvate, and formate as an electron donor [16], *Clostridium butyricum* and *Clostridium beijerinckii* use glucose, starch, lactate [17], *Rhodopseudomonas palustris* uses acetate, lactate, valerate, fumarate, ethanol, glycerol [18], *Geobacter serreducens* [19], *Geobacter sulfurreducens* [20] and *Geobacter metallireducens* [21] use acetate, *Rhodoferax ferrireducens* [22], *Alcaligenes faecalis*, *Enterococcus gallinarum* and *Pseudomonas aeruginosa* [23] use glucose, *Enterobacter cloacae* uses cellulose [24]. Most of the these compounds are present in the root environment as biota waste products and serve as an energy resource for electrochemically active bacteria.

Electric potential gradient in a root environment. Chemical reactions in the root environment, occurring as a result of the vital activity of plants and associated microorganisms, also serve as a source of electrons and ions [9, 25, 26]. Ions and electrons, formed in the process of redox reactions, diffuse through the root-inhabited medium, leading to charge separation. As a result, a gradient of electric potentials is established in the soil or soil substitute, associated with differences in the concentrations of charged substances [27, 28].

1. Difference of soil electrical potentials during plant growth of spring barley (*Hordeum vulgare* L.) cv. Leningradskii

Electrode number	Distance from the soil surface to the electrode, mm	Days							
		0-5 (seedlings)		5-13 (tillering)		13-18 (stem extension)		18-51 (earing)	
		MVD, mV	DR, mV	MVD, mV	DR, mV	MVD, mV	DR, mV	MVD, mV	DR, mV
1	30	112	18	151	18	107	14	190	23
2	80	151	27	176	21	132	16	151	30
3	130	103	18	73	4	34	5	298	63
4	180	73	14	103	15	98	13	337	81
5	230	98	22	132	13	103	10	132	23
6	280	73	13	73	14	54	11	63	9

Note. MVD is the maximum voltage drop vs. the bottom electrode, DR is the dispersion range of values. as based on materials [30].

The formation of different mobile charge densities due to the diffusion and adsorption of their carriers [29] is an integral part of the metabolism that accompanies the functioning and development of plants and microorganisms. In an experiment comparing the gradient of electric potentials in soil, including that under spring barley (*Hordeum vulgare* L.) cv. Leningradsky [30] it was shown that the change in the potential difference along the soil profile is associated with the stage of plant and the development of root system (Table 1).

An electric potential gradient occurred both during the development of the root system in the soil or a soil substitute, and in the soil structure itself without plants, which indicates the presence of ion transport processes, for example, due to diffusion ith the water flow. Plants in a community with rhizoplane and rhizosphere microorganisms seem to trigger additional reactions, absorbing and releasing various organic and mineral compounds, and increase the intensity of processes in the soil.

Bioelectric measurements and design features. *Plant microbial fuel cell.* Based on the ability of microorganisms to act as catalysts for redox reactions involving the extracellular transfer of electrons from microbes to the electrode [31], a bioelectrochemical system has been developed called the plant-microbial fuel cell (PMFC) [32].

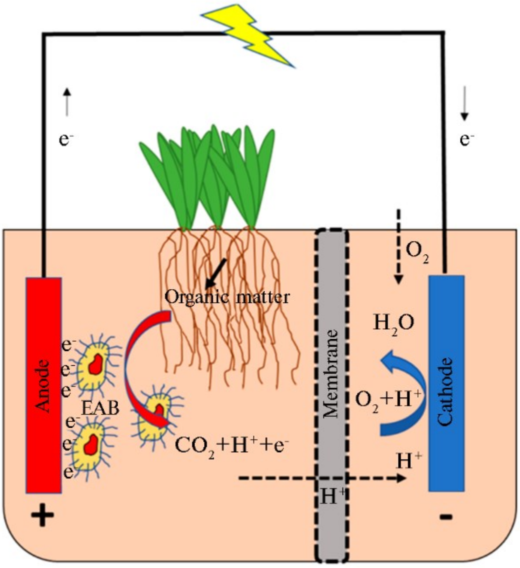

Fig. 1. Electricity generation in a plant-microbial fuel cell. Electro-active bacteria (EAB) oxidize organic matter of root exudates. As a result, carbon dioxide is formed, electrons move to the anode, and protons diffuse through the ion-exchange membrane to the cathode along the potential gradient, where water molecules are formed with the participation of electrons and oxygen molecules coming through the external circuit.

PMFC is a modification of a microbial fuel cell and, in addition to a cathode and an anode with microorganisms placed on it, includes living plants that produce rhizodeposites, the substrates for electroactive bacteria (Fig. 1). The most common configuration of the PMFC device consists of an anode chamber, an ion-selective membrane, and a cathode chamber.

In the anode chamber, microorganisms, as catalysts for the oxidation process, convert organic substances secreted by the roots according to the reaction $C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24e^- + 24H^+$. Getting to the anode, the electrons move along the external circuit to the cathode. Protons migrate through the ion-selective membrane into the cathode chamber, where, with the participation of electrons, oxygen is reduced to form water molecules [33].

Currently, the direction of PMFC is actively developing, various modifications of the device are being created, aimed at increasing the efficiency and electrical characteristics. For example, to reduce the proton transfer distance between the electrodes, a flat plate configuration has been developed: a cation exchange membrane is placed in it between closely spaced anode and cathode chambers. The power of such PMFC was 240 mW/m^2 during long-term operation for 151 days [34]. To simplify integration into the natural environment, a model was developed in which the anode and cathode are combined into a single unit in the form of a tube. The maximum output power for this option was 72 mW/m^2 [35].

A promising way for using PMFCs is their combination with significant production processes. For example, it is possible to introduce such fuel cells into wastewater treatment systems [36] and into agricultural production.

Biocompatible electrode systems. One of the most important characteristics of the BES operation efficiency is electrode materials. In addition to high electrical performance, they must have the properties of chemical stability and biocompatibility. Most often, carbon-based materials are used as electrodes (anode and cathode) (Table 2): graphite felt, fabric, granules, rod, carbon paper, reticulated vitreous carbon [37].

2. Electrodes used in plant-microbial fuel cells (PMFC)

PMFC	Anode	Cathode	Plant species	Substrate	Output power	Reference
5 liter pots	Graphite granules	Platinum coated carbon sheet (0.4 mg/cm^2)	*Cyperus papyrus nanus* L), *Wachendorfia thyrsiflora* Burm.	Soil mix, sludge	1036±59 mW/m^3 (*Wachendorfia thyrsiflora* Burm.), 510±92 mW/m^3 (*Cyperus papyrus* L.)	[38]
Glass cylinders	Graphite granules	Graphite felt	*Glyceria maxima* Hartm.	Hoagland's solution with potassium phosphate buffer (8 mmol/l)	0.39 W/m^2	[15]
Tube-like form	Graphite felt and graphite granules	Graphite felt	*Glyceria maxima* Hartm.	Hoagland's solution rich in ammonium	10 mW/m^2 for felt, 12 mW/m^2 for granules	[35]
Flat porous plates	Three layers of graphite felt	One layer of graphite felt	*Spartina anglica* Hubbard	Nitrate-free, ammonium-rich medium for plant growth	679 mW/m^2	[39]
For growing on the roof	Graphite granules	Graphite felt	*Spartina anglica* Hubbard)	Soil mix and rainwater	88 mW/m^2	[34]

In the RMFCs based on papyrus (*Cyperus papyrus nanus* L.) and red root (*Wachendorfia thyrsiflora* Burm.), graphite granules served as the anode and a carbon sheet as the cathode. The large area of contact between the electrodes and plant roots provided in this variant and the availability of oxygen for cathodic reactions of water formation resulted in obtaining high output power values up to 1036±59 mW/m^3 [38]. In research using mannik (*Glyceria maxima* Hartm.), the influence of the electrode material on the internal resistance of the system which mainly consists of the resistances of the anode and membrane [40], was studied. Therefore, a suitable biocompatible anode electrode plays a very important role in reducing energy losses. The maximum energy production in the proposed variant of a tube-like PMFC was 10 mW/m^2 for graphite felt as an anode and 12 mW/m^2 for graphite granules [35]. The use of a biocathode, on which the reduction of oxygen is catalyzed by microorganisms, is promising. With its use, electricity generation was increased to 679 mW/m^2 in the cordgrass (*Spartina anglica* Hubbard) PMFC [39]. In real applications, such as the growing trend of growing plants on roofs, the maximum achieved power of PMFC was 88 mW/m^2 compared to 440 mW/m^2 obtained in a laboratory installation [41], which is most likely due to changes in the properties of the substrate as a result of weather conditions. Therefore, for use in natural conditions, electrode systems still need to be modified, reducing their area and resistance and increasing tolerance to external factors.

Electrical parameters. The measured characteristic, reflecting the bioelectrical activity of the root system and associated microorganisms and the course of metabolic processes in the root environment, is the electrical voltage U (V), determined by Ohm law: $U = \varepsilon - I \cdot r$. The ε parameter characterizes the electromotive force (EMF) of the BES that is due to external forces for moving charge. The product of the current strength I and the internal resistance of the system r determines the voltage drop inside the system. From this it follows that the performance of the BES and its output characteristics are highly dependent on the ability of the nutrient medium to pass an electric current. One of the most common ways to reduce the effect of internal resistance is to reduce the distance between the electrodes, that is, the gap over which the charge must be transferred

[42].

3. Generated electrical power of plant-microbial fuel cells for various plants and substrates

Plant species	Substrates	Power density, mW/m^2	Reference
Chlorophytum comosum Thunberg	Soil	18	[45]
Phragmites australis Cavanilles	Glucose + sodium acetate	43	[46]
Lactuca sativa L.	Nutrient solution	54	[47]
Ipomoea aquatic L.	Anaerobic sludge and nutrient substances	55	[48]
Brassica juncea L.	Compost potting mix	70	[49]
Glyceria maxima Hartm.	Graphite granules	80	[50]
Trigonella foenumgraecum L.	Soil	80	[49]
Puccinellia distans Jacq.	Soil mixtures	84	[51]
Typha latifolia L.	Synthetic waste water	93	[52]
Sporobolus arabicus Boiss., *Cynodon dactylon* L.	Soil	120	[53]
Oryza sativa L.	Rice fields	140	[54]
Pennisétum setaceum Forsskal	Red soil	163	[55]
Elodea Michaux	Mixed culture sludge	185	[56]
Canna stuttgart L.	Marine sediment	223	[49]
B*Eichhornia crassipes* Mart.	Precipitation	225	[57]
Chrysopogon zizanioides L.	Garden soil	242	[58]
Canna indica L.	Fermented manure	320	[59]
Lemna L.	Carbon sources and drinking water	380	[60]
Sporobolus anglicus Hubbard	Soil	679	[61]

For an effective study of electrical phenomena in a living organism and their environment, the method of diverting electrical potentials must satisfy the following conditions: 1) ensure reliable electrical contact of the electrode with the object under study, 2) exclude the possibility of the occurrence of polarization potentials, 3) take into account the electrokinetic phenomena that occur in the root-inhabited environment, 4) exclude the possibility of damage to the biological object [43]. A method for measuring the potential difference generated in the system root habitat—plants that satisfies these conditions was proposed by T.E. Kuleshova et al. [44]. It is based on a non-damaging, non-invasive method of providing surface electrical contact between the root system and the electrodes. The rate of obtaining electrical energy using BES based on plants and microorganisms is characterized by units of electrical power $P = I \cdot U$ and, as a rule, is normalized to the area occupied by plants. Table 3 presents some of the obtained power values for RMTE with various configurations, plant objects and nutrient media. Despite the fact that BES are currently low-power devices, they have a number of unique properties that make it possible to provide environmentally friendly autonomous energy in a reproducible way, which has great application prospects.

The role of environmental factors. Environmental parameters are significant for vital activity of plants and the accompanying microflora, including bioelectrogenesis. The most significant factors influencing the functioning of the BES are the composition and conditions of the root and light environments.

Influence of the composition of the root environment. Based on the electrical activity of plants and rhizospheric bacteria, BES uses a variety of root habitats, including soils of agricultural, forest, and wetlands, soil substitutes, as well as sand, clay, compost, silt, salt marshes, etc. [47, 62, 63]. In this case, the state and concentrations of the components of the nutrient medium of plants (apparently, as well as the properties of the electrolyte in a galvanic cell) play a decisive role in the output electrical characteristics of the BES.

The main “fuel” oxidized by electrochemically active bacteria is rhizodeposits: about 20-40% of all photosynthesized carbon enters the root environment in various forms in the form of root exudates, metabolites, and dead plant parts [64]. Organic compounds excreted by the roots mainly include organic acids, phenols, sugars and amino acids, and macromolecular compounds such as polysaccharides and proteins [65]. Their composition depends on the plant species, carbon sequestration method, growth intensity, plant age, and environmental conditions [66].

Along with the composition of the root-inhabited medium, the mobility of ions plays a potential-forming role in charge separation. The cations H^+, H_3O^+ with 36.2 $m^2/(V \cdot s)$, NH^{4+}, K^+ with 7.6 $m^2/(V \cdot s)$, Fe^{3+} with 7 $m^2/(V \cdot s)$ and anions OH^- with 20.5 $m^2/(V \cdot s)$, Cl^- with 7.9 $m^2/(V \cdot s)$, NO^{3-} with 7.4 $m^2/(V \cdot s)$ are the most mobile [67]. In addition, the magnitude of the potential difference depends on soil moisture, including both the change in the resistance of the environment and the processes of absorption and transport of water associated with the vital activity of plants. For example, T.E. Kuleshova et al. [68] show the dependence of the electrical voltage created in the root zone on the water regime, including water-deficient conditions.

The influence of lighting conditions. It is known that light plays an important role in the formation of bioelectric potentials. For example, when the light is turned on, there is a sharp drop in the BEP of the leaf surface, and then a quick jump [69]. If one part of the leaf is illuminated and the other part is shaded, then the potential difference will vary from 50 to 100 mV [70]. This variation in metabolic potentials is associated primarily with differences in the intensity of biochemical processes in different parts of the plant.

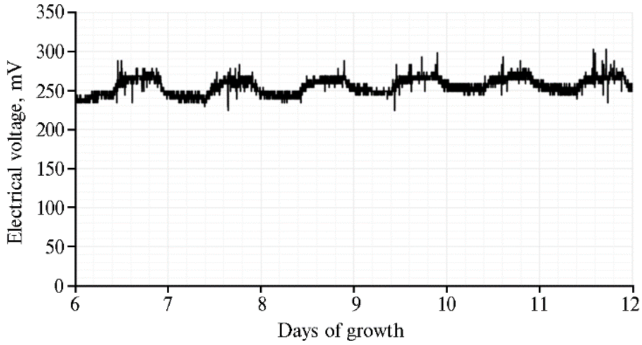

Fig. 2. Electrical voltage changes in a plant-microbial fuel cell based on *Chlorophytum comosum* Thunberg under 12-hour light and dark periods.

A change in the potential difference in response to light exposure is also noted during electroactive reactions in the root environment. It is shown that when the dark stage changes to the light one, the voltage in the root zone gradually increases by 10-15% and then evenly decreases (Fig. 2), this semi-diurnal dynamics can be described by a polynomial of the second degree. Parabolic voltage changes during the light stage of photosynthesis and stationary generation during its dark regime are most likely related to the intensity of transport of water, mineral and organic substances, depending on the formed light conditions. It is also known that the electrical resistance of the leaf surface depends both on the temperature and moisture content of the tissue, and on the mobility and concentration of ions in the tissue medium: the leaf resistance increases with wilting and decreases with watering to its original value [71].

Therefore, environmental factors play a significant role in the formation and course of bioelectric processes. A correlation was shown [72] between the dynamics of light transmission by a leaf plate and the potential difference in the root environment-plant system, which indicates the possible conversion of light energy by plant leaves into electric current in the rhizosphere.

BES application. *BES combined with plant production.* PMFC is a renewable energy source that can simultaneously produce bioelectricity and biomass in an environmentally friendly, sustainable and efficient manner [28]. The use of hybrid technology, which makes it possible to produce plant products and generate electricity by activating oxidative processes in the rhizosphere, is an innovative direction with the prospect of application in the field of autonomous automated agricultural production. The possibility of obtaining low-power energy using BES when growing plants has already been shown on some cultivated and industrial plants, including rice [73], lettuce [47], manna [15], reeds [74], goz [75], used as food, fuel, building materials, and animal feed.

BES universal device proposed by T.E. Kuleshova et al. [76] and suitable for growing vegetable crops (greens, tomatoes, cucumbers), based on thin-layer panoponic technology [77]. In such PMFC, electrode systems are placed in the cultivation tank perpendicular to the growth of the root system, thereby ensuring that the surface contact of the roots with the electrically conductive material does not damage the plants [44]. It is assumed that the formation of a gradient of electrical potentials in the BES is a consequence of the movement of ions along the root system and concentration effects, and the occurrence of EMF between the electrodes is ensured by the vital activity of plants and the electrical activity of the microbial community surrounding the root system.

The PMFC technology makes it possible to produce "green" energy almost everywhere where plants grow, and is applicable both in the natural environment and for growing crops in open ground and greenhouses, in phytotechnical complexes and regulated agroecosystems, which is especially important for areas geographically isolated from the unified power system. The agro-technological energy complex based on BES is able to provide not only environmentally friendly energy, but also high-quality plant products.

Biobatteries in the environment. Biobatteries are environmentally friendly integrated bioelectrochemical systems that convert chemical energy into electricity from or with the help of bioresources. Unlike conventional batteries which cause pollution [78], biobatteries are considered a sustainable and renewable source of energy. However, life cycle assessment (LCA) of these systems before and after their implementation is still a challenge [79] and depends on the types of material used in the fabrication of the structure.

Biobatteries include anode and cathode electrode systems and can use various biochemical energy sources [80-84].

Biobatteries have already been tested in various plant species and under varying environmental conditions [85]. In particular, plants of the cactus family (*Opuntia* Miller) which carry out CAM photosynthesis and are applicable in arid conditions, were used [86].

In the biobattery based on a vertically integrated ceramic tube containing graphite felt as the anode material and zinc foil as the cathode, the maximum power density achieved with *Opuntia albicarpa* Scheinvar was 103.6 mW/m^2 under long-term operation conditions. The addition of ammonium nitrate ($150\ mg \cdot l^{-1} \cdot week^{-1}$) to the *Opuntia joconostle* (Weber ex Diguet) biobattery resulted in an increase in energy yield from 40 to 500 mW/m^3 [87]. The developed biobatteries were effectively used to power LEDs and digital clocks, ensuring their autonomous operation for a week [85]. The use of plants with CAM photosynthesis in BES is promising for areas with limited resources and in semi-arid territories. However, this requires large-scale studies.

Phytomonitoring and power supply of sensors. BES can perform a dual function, acting as a biosensor for phytomonitoring and providing power to environmental sensors. In the work of D. Brunelli et al. [88] PMFC has been used to track the physiological state of plants and monitor light intensity and soil moisture. The energy from the PMFC was accumulated on a supercapacitor and then used to send a signal from the sensors with an interval of 15 min.

The developed wireless sensor networks (WSN) and the Internet of things

(IoT) are of priority importance for the tasks of smart farming, continuous monitoring of the state and needs of plants [89], especially for use in areas remote from power grids. PMFCs can provide an environmentally friendly option for powering these systems. At present, the problem of low-power and intermittent energy production using BES is solved by integrating supercapacitors [90]. E. Osorio-De-La-Rosa et al. [91] demonstrated the launch of an IoT-based sensor. The cell was capable of generating 3.5 mW/cm^2 with an output voltage 0.5 V which is sufficient for batteryless operation of the sensor assembly for temperature data collection and cloud storage.

Thus, BES can be used to create low-power, unattended renewable energy sources that can partially support the vital activity of plants by supplying power to light sources, pumps, sensors for plant and environmental parameters. It can also be used in scientific research and in crop production as a biosensor for setting up growing technologies and phytomonitoring.

Wastewater treatment based on BES. The introduction of BES is also rapidly developing in the field of wastewater treatment. Compared to traditional technologies, BES are more cost-effective and sustainable, as they have the advantage of renewable bioenergy resources [92]. Various possibilities of their application are being studied, in particular, the use of electrochemically active microorganisms for the removal of organic substances and heavy metals is considered promising. BES can work productively for the oxidation of organic substances in the anode chamber, especially in relation to municipal and industrial wastewater with high chemical oxygen demand, such as brewing, food and textile [93-96]. Organic waste can also act as an electron donor for microorganisms in the reduction of heavy metals. The work of Y.V. Nancharaiah et al. [97] gives information on the reduction of Ag(I), Au(III), Co(III), Cr(VI), Cu(II), Hg(II), Se(IV) or V(V) ions in the BES cathode chamber. The recovery efficiency of Cr(VI) in the work of H. Yu et al. [98] reached 99.93%.

As a result of microbial processes in BES, nitrogen removal is also possible [99]. For example, N. Yang et al. [100] showed high removal efficiency of NH^{4+}-N (99%) and total nitrogen (TN, 99%) in BES with upflow in which microbial metabolism was enhanced to carry out simultaneous nitrification, denitrification and other bioelectrochemical reactions.

So, bioelectrochemical systems based on electroactive processes in the root environment of plants and associated microorganisms are a new promising environmentally friendly technology for generating renewable energy. The performance of bioelectrochemical systems (BES) depends on a number of factors, including genetically determined physiological characteristics of plants and their state during development, the composition and activity of the microbial community, the parameters of the root environment, environmental factors, the design of the bioreactor, the type and location of electrode systems. Despite the low output power, plant-microbial energy devices have their own niche application both in the present and in the future, providing power to environmental sensors, light sources, wireless sensor networks, the Internet of things, phytomonitoring systems in natural conditions and protected ground, remote areas, partial power supply of plant life support devices in artificial agroecosystems. Generation of “green” energy can be accompanied by the production of vegetable raw materials and wastewater treatment. Further development prospects lie in the creation of multifunctional electrical circuits that take into account the properties of the root environment and plants in order to increase the efficiency of the system and the amount of generated electricity.

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