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State of the Art and Environmental Aspects of the Plant Microbial Fuel Cells Application

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Abstract: Environmental pollution is becoming ubiquitous; it has a negative impact on the ecosystem diversity and worsens the quality of human life. This review discusses the possibility of applying the Plant Microbial Fuel Cells (PMFC) technology for concurrent processes of electricity generation, purification of water and soil ecosystems from organic pollutants, in particular, from synthetic surfactants and heavy metals. The review describes the PMFC functioning mechanisms and highlights the issues of the PMFC environmental application. Generally, this work summarizes different approaches to the PMFC development and to the potential usage of such hybrid bioelectrochemical systems for the environmental protection.

Keywords: plant microbial fuel cell; electrogenic microorganisms; biofuel cells; synthetic surfactants; ecosystem cleaning; reduction of greenhouse gases; environmental protection

1. Introduction

The ubiquitous environmental pollution by various anthropogenic substances, such as heavy metals [1], petroleum products [2], medicinal preparations [3] and pesticides [4] is one of the main problems of mankind nowadays. Pollutants have a negative impact not only on the environment, but also on human life, accumulating in heterotrophic food chains and entering the human body, which leads to various diseases of the nervous system, respiratory organs, genetic abnormalities, reduces life expectancy [1]. The above-described problems are reflected in the UN Sustainable Development Goals; according to the developed programs: United Nations Environment Programme, UN-Water, the control over the global pollution of ecosystems and their restoration are of the high priority [5].

Bioremediation, a complex of purification methods using the metabolic potential of biological objects, is applied to purify soil and water ecosystems from pollutants. Thus, the introduction of microorganisms into ecosystems makes it possible to dispose of various pollutants by converting them to simpler safe substances. The principle of phytoremediation is based on the binding and accumulation of pollutants in plant vacuoles [6], it activates a complex metabolic pathway involving the antioxidant plant protection system [7]. Besides, plants and microorganisms (fungi and bacteria) interact with each other at the root level (in the rhizosphere), showing a positive synergistic effect in the elimination of pollutants such as heavy metals and organic compounds [8,9]. The disadvantages of bioremediation of soils include the low rate of toxicant biodegradation as well as the need for a thorough preliminary examination of the contaminated site to clarify the modes of biotechnological work. This requires large labor and energy costs, such as plowing and irrigation of fields, disposal of waste plants. Therefore, this technology is not widely used in developing countries and makes it unattractive in poor countries [10].

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A significant contribution to atmospheric pollution is made by heat and power stations (hereinafter referred to as CHP) operating on traditional fuel sources (coal, oil, gas), their share (Figure 1) is about 60% in global electricity generation [11]. The issue of using renewable energy sources (RES) for electric generation is relevant considering the trend programs of many developed countries towards the reduction of carbon dioxide emissions into the atmosphere and providing an access to inexpensive, reliable, sustainable and modern energy for all segments of the population [12]. These include solar panels, wind generators and biofuels [13].

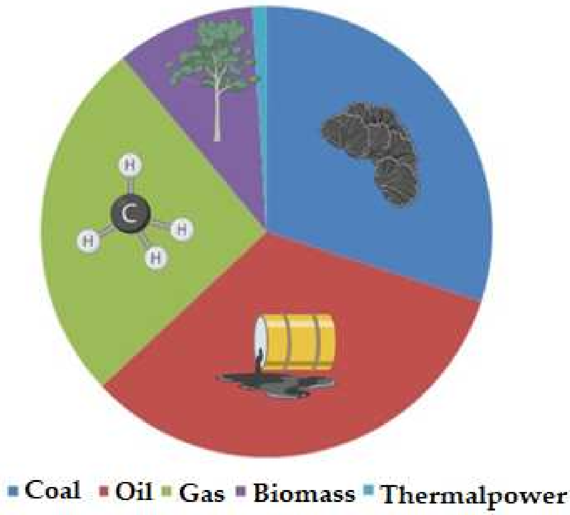

Figure 1. Global electricity generation by type of fossil fuel (according to EnerData, 2021) [14].

However, renewable energy sources have a number of disadvantages. Thus, the processes of their disposal is an extremely difficult task [15], since, for example, solar panels contain elements such as As, Cd, Hg, Pb [16], which can have a negative impact on the ecosystem and their burial is an extremely undesirable method of their disposal [17], thermal and chemical methods of solar panel recycling is not sufficiently mastered and is not characterized by a high degree of efficiency [18,19]. Dust is released during the mechanical processing of solar panels. It contains glass fiber, noise pollution is created, and rare earth elements are lost. However, 80 million tons of waste from used solar panels are expected worldwide by 2050, which will inevitably have a negative impact on the surrounding ecosystem.

The use of biofuel cells (BFC) is an effective alternative in this context, as electricity generation is carried out in the process of biocatalytic oxidation of various substrates. Despite the low power generated in the BFC system and, as a result, a long payback period, the research in the field of biofuel elements is relevant due to humanity's awareness of global environmental problems, the need to solve which reduces the role of economic levers in the development of the world community. PubMed (NCBI) points to an exponential growth of publications on the subject of "biofuel cell" in the first decade of our century, and this interest persists throughout the following years. It should be noted that biofuel elements based on microorganisms (microbial fuel cells, MFC) are a promising technology to produce bioelectricity, since they simultaneously solve the problems of contamination with anthropogenic organic waste, which can be used by microorganisms as a source of carbon and energy. A continuous and steady supply of organic substrates is required to ensure uninterrupted generation of electricity in the MFC, which cannot always be implemented in practice. A fairly new technology of plant microbial fuel cells (hereinafter referred to as PMFC) eliminates this disadvantage of MFC largely. The electricity generation is carried out by the oxidation of organic substances by microorganisms, both synthesized by plants during photosynthesis under the action of sunlight energy and produced into the environment (root exudates, root deposits, rhizo-deposition), and coming from outside, for example, from wastewater or industrial waste. Such hybrid energy technology can be used for phytomonitoring the state of plant crops, local power supply: charging

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portable devices [20], powering various low-power sensors for monitoring ambient temperature, humidity, powering camera traps in remote areas [21], as a biosensor for monitoring plant health in smart greenhouses [22] (Figure 2). It should be noted that the PMFC technology, using macrophytes, reduces the level of greenhouse gases (N_2O and CH_4) from 5.9-32.4% in terms of CO_2 [23].

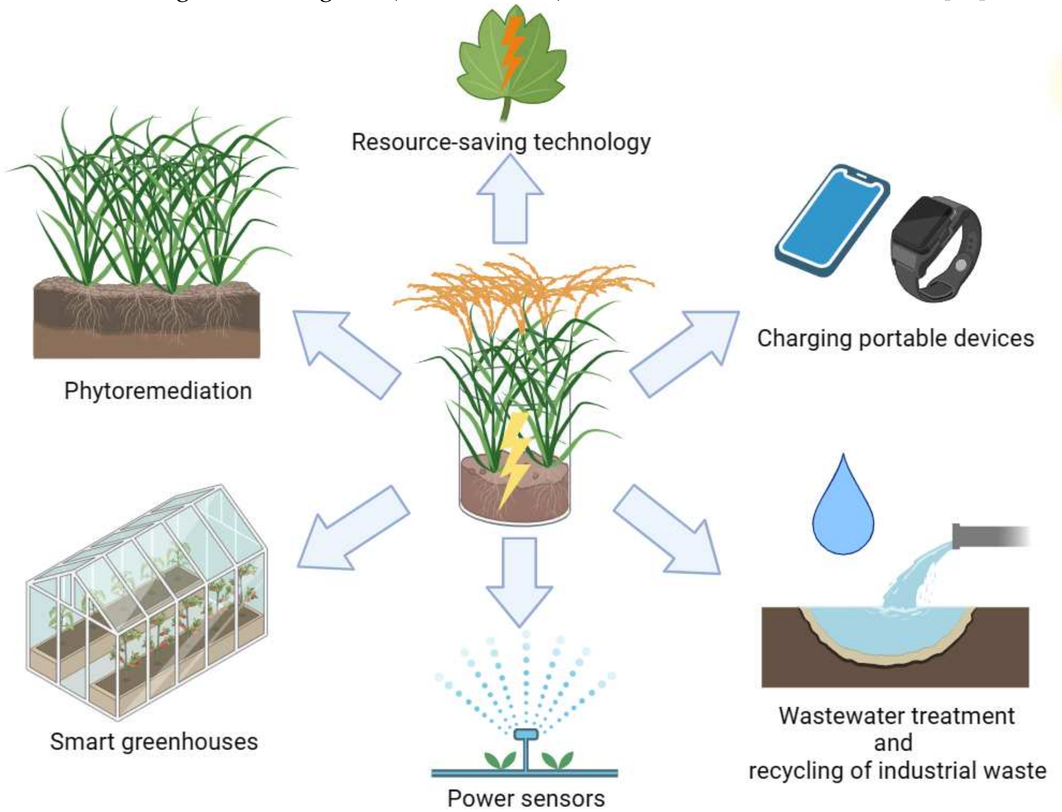

Figure 2. Possibilities of PMFC application.

The review [24] summarizes the evolution of the PMFC technology and discusses the basic principles associated with it, factors affecting its effectiveness, application areas, prospects, and disadvantages. The review [25] describes in detail such features of the PMFC as the basis, the function of plants and their rhyzo deposition, electrical characteristics, internal resistance, substrate kinetics, and redox reactions of the root medium, electron transport mechanisms. This work [25] also depicts the used microbial communities, capable of electrogenesis, as well as presents the most common PMFC structures and comparative analysis of their characteristics. There are highlighted the issues of the PMFC technology usage for wireless energy sensing, farming and agricultural applications of the next generation at the end of the review. However, the existing reviews pay little attention to the PMFC technology usage to solve the environmental problem of anthropogenic pollutant utilization from water and soil ecosystems along with electricity generation.

This review briefly describes the principle of the PMFC technology functioning, the influence of environmental factors on the PMFC characteristics; our emphasis is on the environmental aspect of the PMFC technology application.

2. Plant microbial fuel cells: functioning and factors affecting the electrochemical characteristics of the system

The generation of electricity depends on many factors, such as: the used types of exoelectrogenic microorganisms, the material of the electrodes and their modification, environmental factors, and the used plants. Understanding of the functioning principles and the optimal choice of microorganisms and plants makes it possible to increase the efficiency of electricity generation in the PMFC.

2.1 The principle of PMFC operation

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The principle of PMFC operation is based on two interrelated processes: the synthesis of rhizodeposits by plants and their use as a substrate by microorganisms to generate electricity (Figure 3). Complex interactions in heterogeneous polydisperse multifactorial natural systems were previously described as a computer model of chemical and microbiological production processes of plant biomass, soil microorganisms and nutrients in the rhizosphere [26].

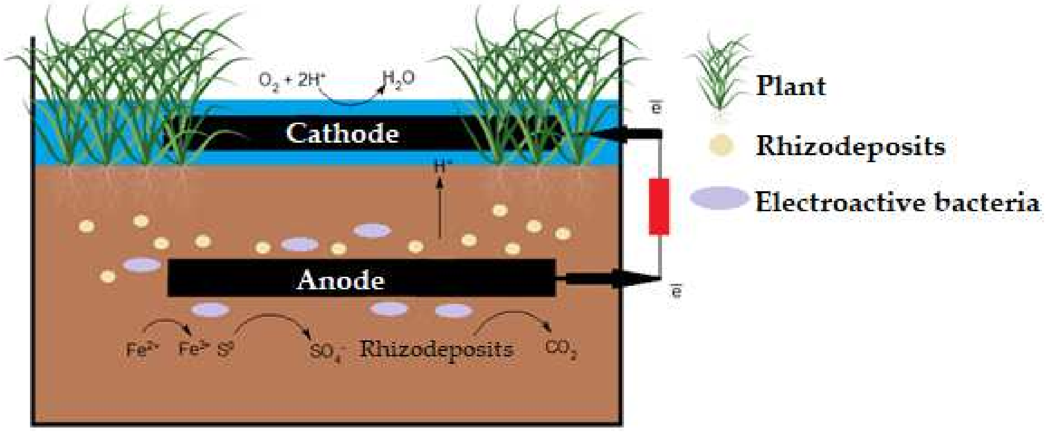

Figure 3. The scheme of the PMFC functioning.

Photosynthesis regulates the vital activity of plants, during which plants fix carbon dioxide from the atmosphere, and form carbohydrates, organic acids and amino acids, secrets - polysaccharide mucus (mucigel), lysates - materials of dead cells, gases – ethylene and carbon dioxide under the influence of sunlight energy [27]. Electrogenic microorganisms use deposits as substrates for growth and development, as well as electricity generation as a result of ongoing oxidative processes involving enzymatic systems of microorganisms. As a result, carbon dioxide is synthesized, and free charge carriers (protons and electrons) are formed. Charges need to be separated to convert chemical energy into electrical energy. The process is carried out by moving the generated electrons at the anode to the cathode through an external circuit; protons migrate through a nutrient matrix or medium from the substrate to the cathode due to the presence of a potential gradient [18], where molecular oxygen or another catalyst and water molecules are formed [28]. However, it is likely that hydroperoxyl radicals (HO_2) are formed on the cathode during the reduction process as an intermediate product [28]. Microorganisms, in turn, can enter symbiosis with plant roots, forming protective biofilms and producing antibiotics to protect plants from pathogens [30].

When choosing microorganisms, it is necessary to consider their ability to transfer electrons to the anode, which can be caused by various mechanisms: direct electron transfer through cytochromes and electron-conducting molecular saws (nanowires), with the help of electroactive compounds (mediator transfer) [31–34].

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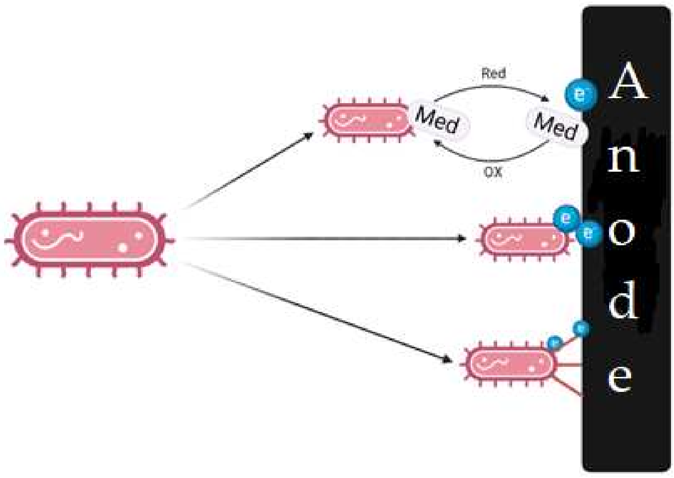

Figure 4. Various ways of electron transfer to the anode.

Direct electron transfer involves the electron transfer directly from microbes to the electrode because of physical contact between the bacterial membrane and the electrode [35]. The proposed mechanism of electron transfer occurs through cytochromes of the outer membrane or conductive pili [36]. C-type cytochromes, found on the outer surface of the bacterial membrane, are multiheme proteins stable to chemical modifications. They facilitate the electron transfer to the anode [34], which contributes to an increase in current density in bioelectric systems [37]. The electron transfer to the electrode can be carried out through electrically conductive saws [38]. Such nanowires are associated with membrane-bound cytochromes of bacteria and allow the electron transfer to an electrode that can be physically removed from microorganisms [36]. At the same time, nanowires consist of cytochromes, periplasmic proteins, and outer membrane proteins. The formation of such nanowires makes it possible to develop thicker electroactive biofilms and, consequently, higher anode characteristics [39].

Some microorganisms are not capable of direct electron transfer to the electrode surface in bioelectric systems due to the absence either of appropriate mechanisms or contact with the electrode surface. Electronic transport mediators are used in these cases: they are compounds capable of reversible oxidation-reduction processes. The mediator receives electrons from bacterial cells, and then transfers the electrons to the anode in bioelectric systems [40]. The oxidized form re-initiates the next transfer cycle. Mediators can be either endogenous (compounds produced by microorganisms) or exogenous (compounds added from the outside). Riboflavins [41], phenazines [42–44], pyocyanins [45], quinones [46] are distinguished among endogenous media. It should be noted that the use of a mediator increases the current density by growing the electron transfer rate [42,47]

The focus is on natural ecosystems when choosing microorganisms for the PMFC system. Thus, bacteria inhabit the environment in the rhizosphere, they are anaerobes that produce protons, carbon dioxide and can transfer electrons to the anode during the oxidation of organic compounds. Table №1 presents the description of some rhizospheric bacteria.

Table 1. Rhizospheric microorganisms capable of direct extracellular electron transfer.

Microorganism	Description	Consumable substrates	References
Desulfobulbus sp.	Obligate anaerobes capable of oxidizing sulfur to sulfate using an anode as an electron acceptor	Acetate, Propionate, butyrate, lactate, pyruvate	[35,48,49]
Geobacter sp.	Anaerobic metal-reducing bacteria. Fe (III) and Mn (IV) are used as electron acceptors. They can transmit	Benzoate, p-cresol, trichloroethane, benzene, lactate, acetate, starch	[50]

	electrons using pili – filamentous protein formations.		
Geothrix fermentans	Anaerobic metal reducers, Fe (III) is used as an electron acceptor. They are capable of forming extracellular mediators of the quinone series and riboflavin, which makes it possible to transfer electrons to the electrode more efficiently	Acetate, Propionate, lactate, fumarate	[51,52]
Rhodoferax ferrireducens	Facultative metal reducing anaerobe with a wide temperature range of growth. Fe (III), Mn (IV), nitrate, fumarate and oxygen can be used as electron acceptors	Acetate, lactate, propionate, pyruvate, malate, succinate, benzoate	[53]
Shewanella sp.	Facultative anaerobic bacteria using Fe (III) and Mp (IV) as electron acceptors are capable of producing flavins that act as electronic transfer mediators	Lactate, formate	[54,55]
Clostridium butyricum *C. beijerinckii*	Obligate anaerobes can use an anode as an electron acceptor. Hydrogen, which is able to oxidize at the anode, is produced during the enzymatic fermentation of substrates.	Glucose, starch, sucrose, lactate	[56]

The basic property of microorganisms that allows to use them in bioelectric systems [57–59] is their ability to produce electroactive compounds, as well as to use the anode as an electron acceptor. Moreover, the use of inorganic anions as an electron acceptor makes it possible to reduce the salinity of treated wastewater [60,61], for example, when using sulfate-reducing bacteria that are capable of assimilatory reduction of sulfates to sulfides [62].

PGPR (Plant Growth-Promoting Rhizobacteria) bacteria, which promote plant growth, play an important role in maintaining the vital activity of plants, and are used for the development of PMFC. Such microorganisms include, for example, bacteria of the species *Bacillus thuringiensis*, which are involved in nitrogen fixation processes, sulfur and phosphorus exchanges, and the synthesis of plant growth stimulants [63]. Bacteria of the genus *Pseudomonas sp.* can be also considered as PGPR group bacteria [64]. Some species of the *Pseudomonas sp.* are capable of surfactant destruction [65,66], they can form biofilms on the surface of the anode and secrete compounds of the phenase-new series [67]. These compounds play an important role both in protecting plants from pathogen infection [68] and stimulating the growth of shoots [69]. Besides, phenazines act as mediators of electronic transport between bacteria and the electrode [70]. Bacteria of the family *Ruminococcaceae spp.* are not electroactive, but are capable of utilizing cellulose (35-50% of the dry plant weight), while producing organic substrates, which are additionally used by electroactive microorganisms as electron donors [71]. Therefore, the use of PGPR group bacteria can be used in PMFC systems to stimulate plant growth and protection, which theoretically can have a beneficial effect on electricity generation.

2.2. Electrodes in PMFC

It is important to choose the right electrode material for efficient generation of electrical energy when creating PMFC along with biological components [72]. Generally, the electrode material should have high electrical conductivity, electrochemical stability, porosity, and biocompatibility [73]. Metals (zinc [74], stainless steel [75], platinum [76]), carbon materials [77] are usually used as electrodes in bioelectrochemical systems. Despite the high electrical conductivity of metals in comparison with carbon materials, the use of stainless steel, for example, increases the period of microorganism adaptation on the metal anode surface [77]. It causes a decrease in current generation

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at the initial stage of the PMFC operation, which is explained by the lower biocompatibility of stainless steel to microorganisms. Moreover, metals are subject to corrosion processes [75] and have a high cost, thus limiting their use in the PMFC development.

The use of carbon electrodes obtained from organic food waste is one of the promising directions in the PMFC development. In [78], the authors present information on the use of carbon got from the husk of the plant *Trapa natans* (water nut), which is a fruit crop widespread in Asia. The waste of the *Trapa natans* plant amounts to about 3,400 tons per year [79], therefore, the company Guantain Black Gold has developed a method for producing carbon felt based on the husk of the *Trapa natans* plant by oxygen-free carbonation at high temperatures. According to the obtained data, carbon felt based on the husk of *Trapa natans* had a more porous surface in comparison with graphite felt, greater hydrophilicity due to the presence of oxygen-containing groups. Using a vegetable fiber let obtain a higher power in comparison of applying a graphite fiber (55 mW/m^2 and 22 mW/m^2, respectively) [78].

The geometric area of the electrodes affects the output of electricity – the larger the area, the more contact there is for electroactive microorganisms, which leads to an increase in current density [80]. In turn, graphite electrodes (felt/fiber) have a developed surface that promotes the adhesion of microorganisms and the sorption of organic compounds, this material is not subject to corrosion, therefore it is promising for the creation of PMFC [81]. The addition of granular graphite or activated carbon to the surface of the anode improves the adsorption of organic compounds and increases the specific surface area for colonization by bacteria.

Various methods of modifying the electrodes of bioelectrochemical systems have been increasingly used to rise the electricity generation recently [82–84]. However, most publications describe the modification only for microbial fuel cell (MFC) electrodes. Nevertheless, the work [85] describes a modification of the PMFC cathode consisting of a steel mesh with a cell size of 1 mm. Cathode modification was carried out by crosslinking chitosan with glyoxal with the addition of Fe_3O_4 magnetic nanoparticles. Then, solutions of salts of various divalent metals were added to the suspension of magnetic particles, which imparted a porous structure to the chitosan-based catalyst, which increased the potential by rising the efficiency of the cathode reaction of oxygen to water. The specific power of PMFC [86] was from 86 mW/m^2 (control) to 1298 mW/m^2 due to cathode modification.

Thus, the choice of electrode material is the key element determining the efficiency of the entire PMFC system. Existing materials can be modified to reduce their internal resistance to increase current output and power.

2.3. Application of proton exchange membranes in PMFC system

One of the components of bioelectrochemical systems for power generation is a proton exchange membrane, which allows to improve charge segregation and power performance [87]. The most preferred proton exchange membrane is Nafion, but its use in BES significantly (by 40%) increases the cost of the device [88]. Thus, the search for new membranes that will have a lower cost and provide high stability and efficiency of the BES is currently underway.

In [89], modified Nafion 117proton exchange membranes were tested. The modification included treatment of the membrane with solutions of polyvinylidene difluoride (PVDF) and sulfonated PVDF with the addition of silicon oxide (SiO_2). The third modification involved the polymerisation of Nafion membrane in methyl methacrylate (MMA) solution with the addition of sodium sulphite as an initiator. According to the results obtained, all three methods increase the power generation parameters in MFC systems. The highest increase in current density from 0.81 mA/m^2 to 18.82 mA/m^2 was demonstrated by the modification of Nafion with MMA.

In [90], a proton exchange membrane based on agar and polyvinyl alcohol (PVA) with the addition of vermiculite nanoparticles was tested. According to the results obtained, the proton exchange properties of the tested membranes were of 216% higher than of the commercial Nafion membrane. In addition, the MFC current density increases (from 605 mA/m^2 to 1515 mA/m^2) when agar and PVA-based membranes were used. Low cost and environmental safety in combination with increased efficiency of MFC energy generation allow the use of agar and PVA-based membranes as an alternative to expensive Nafion membranes.

Ceramic membranes based on clay, bentonite, coal ash, Na_2CO_3, Na_2SiO_3 and H_3BO_3 were considered in the [91]. The use of hybrid ceramic membranes with the addition of different compounds contributes to the increase of PMFC power density by 78% (up to 22.38 mW/m^2) compared to the control (100% clay membrane). There was a decrease in internal resistance from 346 Ω (control) to 234 Ω. The addition of bentonite, coal ash, Na_2CO_3, Na_2SiO_3 and H_3BO_3 improved the membrane cation transport, reducing oxygen diffusion to the anode chamber. The membrane demonstrated high stability during 6 months of PMFC operation. In addition, the ceramic membrane is significantly cheaper than Nafion membrane.

Thus, one of the important aspects of PMFC operation, power increase and internal resistance reduction is the use of proton exchange membranes. At the same time for commercialisation of PMFC systems, it is necessary to take into account the cost of production of such membranes and the expenses associated with the complication of the design when using membranes.

2.3. The influence of environmental factors on the electricity generation in the PMFC

Metabolic activity of exoelectrogenic microorganisms, which play an important role in the BES functioning and the electricity generation, depends on the temperature, pH and the rate of organic substrates receipt. Thus, the work [92] has shown that when the air temperature rises to 30 °C, the voltage of the bioelectrochemical system increases from 100 to 150 mV, which may be due to an increase in the metabolic rate of exoelectrogenic microorganisms. The pH value affects the development of microorganisms. pH 6-9 is mostly suitable for the functioning of the BES [93]. The power decreases to 158 mW/m^2 at a pH value of 6.0 for the MFC system [94], while the power value is 600 mW/m^2 at a pH of 8.0. Inhibition of the metabolic activity of exoelectrogenic microorganisms is observed with a decrease in pH, which contributes to a decrease in the BES power [95].

Periodic watering is necessary for the normal functioning of plants, since soil moisture affects the generated potential in the PMFC system. The article [96] states that in the absence of irrigation, the soil dries up, which leads to a two-fold decrease in the PMFC potential, but after watering (60-70% of the soil moisture capacity), the potential is restored. Thus, energy generation changes depending on the time of day [97]. An increase in electrogenic activity is observed after sunrise due to the launch of photosynthesis processes, the peak of which is observed from 14 to 15 hours. Depending on the system under study, the open circuit potential is 600-700 mV at the specified time. Then, the photosynthetic activity of plants decreases at nightfall, which leads to a decrease in electricity generation to 300-400 mV.

The rate of photosynthesis is affected by the concentration of carbon dioxide in the atmosphere [98]. The trend towards carbon dioxide emissions increases every year and is 390 ppmv, according to the latest data (mass fractions of a percent per volume), which is 30% more than the CO_2 concentration in the early twentieth century [99]. Increasing CO_2 concentration and climate warming significantly affect plant growth [100]. Work [101], using agricultural plants (*Saccharum officinarum* and *Sorghum bicolor*), shows that the rate of photosynthesis grows significantly with an increase in the CO_2 concentration, which in theory can have a positive effect on the power produced by PMFC. It should be noted that plants with C_3 and C_4 types of photosynthesis react differently to an increase in the carbon-acid gas concentration. C_4 plants attach CO_2 to phosphoenolpyruvate [96], resulting in the formation of oxalic acid containing 4 carbon atoms. The photosynthesis efficiency of C_4 plants is significantly higher, since the C_4 pathway is an extra pump that supplies additional portions of CO_2, increasing its concentration in the plant, since the CO_2 concentration in the assimilation chamber is lower than in air, which is a limiting factor of photosynthesis.

It should be noted that the countries with warm climate and high solar insolation, as well as the "green roofs" cities, have the greatest potential for the PMFC technology implementation to reduce the concentration of carbon dioxide in the air [102].

3. PMFC technology to utilize anthropogenic pollutants in aquatic and soil ecosystems

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3.1. PMFC to purify water and soil ecosystems from organic compounds and biogenic elements

Wastewater discharges, containing organic and biogenic (nitrogen, phosphorus, carbon) elements in concentrations above MRL (maximum residue limit), significantly affect the ecological balance of aquatic ecosystems. There begin the eutrophication and rapid development of microbiota, it entails a decrease in the dissolved oxygen concentration, causing a decrease in biological diversity [103]. Additionally, the current active use of oil has a negative impact on ecosystems that have been polluted by its spills during production and transportation. Sludge formed during oil production is discharged into specialized ponds, which "age" under the influence of the environment. So, oxidation of some components, tarring, and evaporation of light fractions occur. These processes lead to an increased stability of oil sludge to the purification; therefore, their disposal is one of the most difficult tasks at present [104].

Bioremediation, based on the pollutant biodegradation by microorganisms and plants during their vital activity, is one of the most effective methods of wastewater and soil treatment of organic pollutants. It is used for wastewater treatment and processing of biodegradable solid household waste to form biogas [105,106]. As it was noted, the PMFC technology is promising in the simultaneous processes of generating electricity [21] and recycling various pollutants [107]. Table 2 summarizes the information on the developed PMFC for the disposal of anthropogenic pollutants and their purification.

Table 2. PMFC characteristics for soil and wastewater treatment from organic compounds.

Plants	**Microorganisms**	**Electrode material**	**Organic compound/ rate**	**Purification rate, %**	**Max. output**	**Ref.**
Spartina sp	*Pseudomonas veronii* *Ps. chlororaphis* *Ps. putida* *Ps. libanensis* *Azoarcus communis*	Cathode – stainless steel Anode - stainless steel	Oil	99.6	11.56 mW/m^2	[108]
Aglaonema commutatum	Active sludge	Cathode – carbon felt Anode – carbon felt	Oil PAC	Up to 82.3 Up to 45.5	382 mV 377 mV	[109]
Steviare baudiana	Soil extraction	Cathode – stainless steel Anode – carbon felt	Urea	No data	132 mW/m^2	[110]
Ozyra sp	Soil extraction	Cathode – carbon felt Anode – carbon felt	Compost	No data	39.2 mW/m^2	[111]
Fimbristylis ferruginea	Association DC5 (*Firmicutes* *Proteobacteria* *Bacteroidota* *Desulfobacterota*	Cathode – glassy carbon fiber Anode – glassy carbon fiber	Textile wastewater	Up to 97.3	Up to 197.9 mW/m^2	[112]

	Actinibacteriota *Verrucomicrobiot)* Soil extraction					
Canna generalis, Chrysopogon zizanioides, Cyperus papyrus Hymenachne grumosa Equisetum hyemale	Wastewater bacteria	Cathode – graphite Anode - graphite	BOD_5 COD	71 74	0.93 mW/m²	[113]
Chlorella vulgaris	Anaerobic sludge	Cathode – carbon felt Anode – carbon felt	COD Nitrates Phosphates	65.3 66.6 95.6	3.64 mW/m²	[114]
Canna indica		Cathode – carbon felt A – carbon felt	COD Nitrates Phosphates	57.2 59.8 88.8	22.76 mW/m²	
Schoenoplectus californicus	Sludge	Cathode – activated carbon Anode – activated carbon	COD Nitrogen	Up to 87 Up to 98	8.6 mW/m²	[115]
Canna indica	Anaerobic sludge	Cathode – stainless steel, activated carbon Anode – stainless steel, activated carbon	Tetracycline	99.66	Up to 124.89 mW/m²	[116]
			Sulfatotoxal	100		
Canna indica	Soil extraction	Cathode – graphite plate Anode – graphite rod	Sodium dodecyl benzene sulfonate	Up to 56.8%	4.01 mW/m²	[117]

The authors [108] used *Pseudomonas*, *Azoarcus communis* oil destructor bacteria to clean the soil from oil pollution. The addition of bacteria in the PMFC system contributed to better purification of wastewater and soils from hydrocarbons. The maximum specific power (11.56 mW/m²) was obtained in a system where *Spartina sp* was used as a plant. It was almost 5 times higher compared to the control system without plants, the value of which reached about 2 mW/m². Generally, power increase (7.5 mW/m² and 9.71 mW/m², respectively) appeared because of the use of *Typha latifolia* (broadleaf cattail) and *Phragmites* (common reed) plants due to the formation of rhizodeposites that could be consumed by microorganisms. The internal resistance of the studied systems ranged from 200 Ω to 400 Ω.

Low solubility of petroleum products is one of the problems of effective purification from them. Surface-active substances (surfactants) are additionally introduced into the PMFC systems to increase the bioavailability of the hydrophobic substrate for oil-oxidizing bacteria and, therefore, to increase the degree of biodegradation of oil pollution. It allows to increase the voltage from 184.9 to 377.2 mV [109]. Besides, the introduction of an additional carbon source available to microorganisms, for example, glucose, contributes to an increase in the system voltage from 184.9 mV to 325 mV [108]. Biosurfactants should be used instead of using synthetic surfactants (surfactants). Biosurfactants can increase the bioavailability of hydrocarbon substrates, to change the hydrophobic properties and permeability of micro-organisms' membranes [117]. Moreover, oil-resistant plants should be used to clean the soil from oil in the PMFC systems. They can release a high amount of root exudates. It follows that the further directions in the development of new soil and wastewater treatment systems may consist in the selection of effective bacteria-oil destructors.

PMFC systems can be used for the disposal of organic animal waste. The work [110] uses the plant stevia honey and urine samples of livestock (goats, cows, and sheep). It is noted that the addition of urine stimulates plant growth and significantly increases the current density of the device. The control sample has fixed the current density about 10 mA/m^2, and this indicator has reached a value of 930 mA/m^2 with the addition of cow urine. Thus, it is noted that the use of cattle urine is a good tool aimed at increasing the PMFC characteristics.

Wastewater treatment uses the technology of microbial associations enrichment with bacteria that are isolated from contaminated soils. For example, the authors [112] have used an association of microorganisms, designating it as DC5. They are capable of oxidizing textile dyes, which can potentially act as a mediator of electronic transport, thus contributing to an increase in electricity generation during their biodegradation [119]. The addition of the DC5 association to the PMFC contributes to an increase in the maximum specific power from 177.3 mW/m^2 to 197.94 mW/m^2. This approach makes it possible to improve wastewater treatment from electroactive dyes and at the same time to increase the electricity generation in PMFC systems.

A plant microbial fuel cell is a promising system for wastewater treatment. Thus, the work [108] uses a reactor for anaerobic purification, where wastewater enters the PMFC. A significant decrease in suspended compounds is observed after two-stage purification. The treated wastewater, taken from the PMFC, has a BOD_5 index lower than the initial one by 71%, the COD index decreases by 74%.

The plants used can influence the efficiency of purification and generation of electricity in the PMFC. The review [114] has studied the effectiveness of wastewater treatment using the *Canna indica* plant (Indian cane) and single-celled algae *Chlorella vulgaris*. The system based on the *C. indica* plant has a higher voltage (771 mV and 452 mV respectively). The internal resistance for a system with a plant is about 100 Ω, with chlorella algae – 335 Ω. At the same time, the paper notes that *C. vulgaris* can decompose the organic compounds, indicating a mix-trophic type of nutrition that provides better purification from organic compounds. Whereas *C. indica* has an autotrophic type of power supply, and the degradation of organic compounds occurs at the anode when electroactive microorganisms are introduced into the system, contributing to a higher voltage output and specific power of the system.

The work [116] has investigated the possibility of removing two antibiotics, tetracecline and sulfamexosol, from wastewater in the PMFC system. According to the obtained data, the greatest degree of removal is achieved during the first day of the PMFC operation. The removal efficiency has reached 99%. It has been shown that both antibiotics can accumulate in insignificant amounts in electrode compartments, which is due to the electrosorption [120]. It occurs because of the formation of a double electric layer (DEL) on the surface of cathodes and anodes, while tetracecline and sulfamexosol do not accumulate in plants. In systems with *C. indicia*, the specific power is on average 55% higher than in systems without plants. The resulting power density is 124.89 mW/m^2, and the internal resistance ranges from 600 Ω to 800 Ω for all systems. Generally, the conducted research testifies to the prospects of PMFC systems for the removal of pharmaceutical preparations in wastewater.

Canna indica plant-based PMFC system was described in [117], which was used to remove sodium dodecyl beznesulfonate (SDBS) from a model wastewater mixture. According to the results, the removal efficiency of SDBS was 56.8%, and power values of 4.01 mW/m^2 and voltage of 230 mV with a resistance of about 200 Ω were achieved at SDBS concentration of 5 mg/L. It should be noted that increasing the SDBS concentration had a negative effect on the PMFC systems, reducing the power and increasing the internal resistance.

Thus, PMFC can be used for wastewater treatment, which may contain not only biogenic elements, but also antibiotics and petroleum hydrocarbons, including PAHs. At the same time, note should be maid towards the selection of the optimal composition of the microorganism association to reduce the time of their adaptation to pollutants and higher electricity generation. It bears emphasis that there are fluctuations in the internal resistance of various systems (from 100 Ω to 800 Ω), which is associated with different designs, the distance between the anode and cathode, the electrical conductivity of the electrolytes used. High internal resistance negatively affects the power output of the BES [121].

3.2. PMFC application for removal of heavy metals from soil and aquatic ecosystems

Soil pollution with heavy metals (HM) poses a threat to the environment and agriculture [122]. Heavy metals negatively affect agricultural crops, reducing their yield. Phytoremediation methods are used to clean soils from heavy metals, the principle of which is based on biosorption and HM accumulation by various plant components. The removal rate of heavy metals from soils is about 35% of the initial HM concentration during the soil phytoremediation [123]. Microorganisms are also able to reduce concentrations of HM ions by forming chelated complex compounds with them, which is due to the production of siderophores, organic acids and extracellular polymeric substances [124]. However, as it has been shown earlier, bio-remediation has not become widespread in poor countries due to its relatively high cost [10]. Therefore, the use of PMFC technology can become a compromise solution in poor countries not only because of the purification of contaminated soils from HM, but also due to the generation of environmentally friendly electricity [125]. Table No. 3 presents the parameters of some well-known PMFC systems used for soil purification from heavy metals.

Table 3. PMFC used for soil purification from heavy metals.

Plant	Microorganism	Electrode material	Metal	Purification rate, %	Max.generation	Ref.
Lolium perenne	*Proteobacteria Bacteroidetes Firmicutes*	Anode – graphite granules, carbon felt Cathode – carbon felt	$Cr_2O_7^{2-}$	90-99	55 mA/m^2	[126]
Oryza sativa L.	*Alphaproteobacteria Anaerolineae Clostridia Deltaproteobacteria Gammaproteobacteria Actinobacteria*	Anode – carbon felt Cathode – carbon felt	As (V)	25.2-41.8	22.2 mW/m^2	[127]

Oryza rufipogon *Typha orientalis*	*Bacteroidia* *Bacilli* *Thermoleophilia* *Nocardioides* *Anaerolinea* *Geobacter* *Tumebacillus* *Azospirillum* *Bacillus*	Anode – carbon felt Cathode – carbon felt	Cd (II)	Up to 31.7 Up to 30.2	351 mV 137 mV	[128]
Eichhornia crassipes	No data	Anode – graphite rod Cathode – graphite rod	Ni (II)	Up to ~10	0.86 mW/m²	[129]
Oryza sativa L	*Proteobacteria* *Firmicutes* *Actinobacteria* *Chroroflexi*	Anode – carbon felt Cathode – carbon felt	Cd Cu Cr Ni	35.1 32.8 56.9 21.3	22.2 mW/m²	[130]
Cyperus alternifolius *Cyperu smalaccensi s*	River sludge	Anode – carbon felt Cathode – carbon felt	As Zn Cd	6.7 7.3 38.5	10.74 mW/m²	[131]

Raygrass has been used to remove $Cr_2O_7^{2-}$ in the PMFC system [126]. According to the results, the removal efficiency can reach 99% under various conditions. At the same time, most of the reduced to Cr (III) precipitates in the form of $Cr(OH)_3$. Meanwhile, an increase in the concentration of $Cr_2O_7^{2-}$ from 9 mg/dm³ to 19 mg/dm³ increases the current density by about two times (up to 55 mA/m²).

The study [127] has tried to reduce the absorption of soap by rice culture *Ozyra sativa L.* (seeded rice), since the rice consumption is one of the main routes of arsenic entry into the human body. The results show that the use of PMFC technology reduces the arsenic accumulation in rice by up to 67.9% due to the obstruction of As (III) migration to the plant roots. The output power equals 22.2 mW/m².

The article [128] illustrates the PMFC development based on *Ozyra rufipogon* (wild rice) and *Typha orientalis* (oriental cattail) to remove cadmium from the soil. It is shown that cadmium absorption is carried out mainly by plant roots. The addition of biochar has contributed to the better removal of cadmium from the soil. The use of PMFC reduces the cadmium mobility by binding to carbonates, iron oxides and organic compounds. When the PMFC operates in the closed-circuit mode, it is noted that the percentage ratio of the Cd^{2+} exchange fraction is significantly lower than when the PMFC operates in the open circuit mode. It is caused by bioelectrochemical processes. Additionally, higher values of the generated voltage are observed (350 mV vs. 137 mV) when using rice. At the same time, the voltage has decreased from 400 mV to 150 mV in the control system (without Cd (II)) with cattail by 112, and the voltage has increased to 400 mV in the system with rice by the end of the experiment. Such a feature may be due to the different composition of the rhizodeposits.

The study [130] has used seeded rice exploiting such HM as Cd, Cr-, Cu and Ni. It shows that a decrease in the concentration of HM in PMFC (compared with the control rate) is possible to be achieved during the experiment. The authors note that the removal of such heavy metals as Cu is probably due to the transition under the action of an electric field of Cu to the cathode region, where they react with oxygen and precipitate in the oxide form. Besides, bacterial biofilms can absorb Cu through the cell membrane. Similar mechanisms of reduced mobility are observed for Cr and Ni. The maximum current is 1.20 mA, while the fluctuations of this value have been caused by a change in the oxygen volume into the anode compartment from the rice roots. The generated capacity of 22.2 MW/m^2 allows to conclude that the PMFC system can be applied for soil purification from some heavy metals in their joint presence.

The above data prove that the soil purification from heavy metals in PMFC systems is practically not inferior to phytoremediation. In some cases, a decrease in the mobility of some HM [131] can be detected because of their conversion into poorly soluble compounds due to the course of bioelectrochemical processes in PMFC systems.

Thus, the use of PMFC technology to combat soil pollution still needs further study, since the processes and mechanisms that occur should be considered separately for various heavy metals and plants. The use of PMFC, according to the research, is promising due to the economic effect that is caused by electricity generation and low cost phytor-mediation technologies [132].

4. Further development of PMFC for the ecosystem purification from surfactants

4.1. Ways of surfactant entry into surface waters as an actual pollutant and potential substrate for microorganisms in the PMFC system

Synthetic surfactants (hereinafter surfactants) are widely used in various industries (Figure 4) as detergents, wetting agents, emulsifiers, and foaming agents [133].

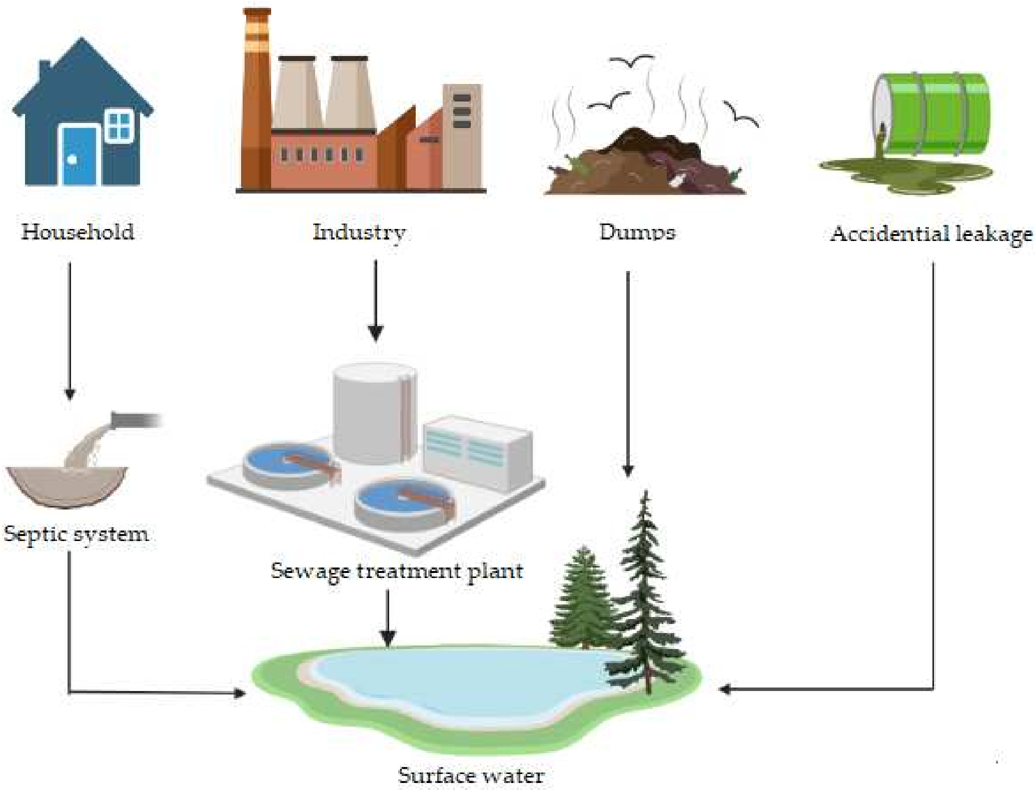

Figure 4. Inflow of surfactants into aquatic ecosystems.

The world production of surfactants is constantly increasing [134] and currently amounts to about 15 million tons per year, while about 90% of the produced surfactants are in the anionic form [135]. Many surfactants are synthetic and are used daily in large quantities by industry and households, throwing about 60% of surfactants into the water [134]. The negative impact of surfactants on the environment is ignored because of the large scale of production and use [133]. Therefore, currently there are a great number of studies focusing on the ways of the surfactant disposal in wastewater, including the development of approaches to decentralized treatment methods [136,137]. However, it should be noted that there is currently very poor data on the treatment of wastewater from surfactants using the PMFC system [117].

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The toxic effect of surfactants on bacteria is caused by the damage of the cell membrane as a result of the interaction with their lipid components and proteins [138]. The presence of surfactants in methane tanks suppresses the activity of methanogen bacteria [139].

The toxicity of synthetic surfactants towards the plants depends on the concentration, contaminant type and test object type. For example, the effect of sodium dodecyl sulfate on *Lemna minor* duckweed depends on the concentration. The selected surfactant has stimulated the growth rate at low concentrations, but it has demonstrated noticeable inhibition at higher concentrations [140]. The work shows that the concentration enlargement of anionic surfactants and organic compounds increases the biomass of phytoplankton in the seas [141]. Surfactant mixtures, used for oil extraction, have shown a pronounced toxic effect on *Atherinops affinis* (silver smelt) and *Macrocystis pyrifera* (giant algae) [142].

Acute toxicity tests, that have been conducted with the help of aquatic biota, show that the values of the negative effects from pollutants vary between different species and under different environmental conditions. Generally, surfactants have a negative effect on aquatic biota at concentrations ranging from 0.35 mg/dm3 (freshwater microalgae *S. subspicatus*) [143] and up to 76.14 mg/dm^3 (crustaceans *D. magna*) [142].

The entry of surfactants with wastewater into natural reservoirs can have a negative impact on the cultivation of aquaculture in natural conditions. For example, the review [143] had investigated the influence of anionic and cationic surfactants on survival, behavioral features, and viscera pathology of African catfish *Clarias gariepinus*, used as a test object. Anionic surfactants had the greatest negative effect (linear alkylbeznosulfonate was used as a model toxicant). Behavioral characteristics of the test object included excessive mucus secretion, chaotic movement, and anger. The lethal concentration of LAS (linear alkylbenzosulfonate) equaled 10.57 mg/dm^3. The gill injuries were caused by constant contact of this organ with the environment and surfactants [146,147].

It should be noted that a "secondary" effect of surfactants on the environment, for example, the spread of HM to a wider area and an increase in the solubility of toxic organic compounds, makes it relevant to develop and improve methods for wastewater treatment from surfactants [133].

4.2. Microorganisms-destructors of surfactants

The surfactant adsorption onto solid carriers: activated carbon, zeolites, nanomaterials is one of the methods of their disposal from water [139]. Biological wastewater treatment from surfactants, when activated sludge is used, provides 95-98% efficiency [148,149]. Microorganisms use surfactants as a carbon source, while biodegradation occurs along the pathways of ω-oxidation, β-oxidation, α-oxidation, and oxidation of the benzene ring (if it is presented in surfactants) [150]. The bacteria that can oxidize surfactants include *Azotobacter sp.*, *Bacillus sp.*, *Pseudomonas sp.*, *Citrobacter sp.*, *Acinetobacter sp.*, *Klebsiella sp*. and *Serratia sp*. [138,151]. Therefore, the selection of microorganisms that can simultaneously reduce the concentration of surfactants and have exoelectrogenicity is an urgent task in the PMFC development to purify the wastewater from surfactants.

It should be noted that linear alkylbenzosulfonates are the most widely used anionic surfactants and are often added to cleaning and detergents [147]. The biodegradation pathway of linear alkylbenzosulfonates (LAS) [153] involves degradation of a linear alkyl chain, a sulfonate group, and a benzene ring. The breakdown of the alkyl chain begins with the oxidation of the terminal methyl group (ω-oxidation) through the formation of a hydroxy group, then with the formation of an aldehyde group. Oxidation ends after the formation of a carboxyl group. The reactions are catalyzed by the enzyme alkanmonooxygenase and two dehydrogenases [154]. Then the carbonic acid, which is formed as a result of ω-oxidation, undergoes β-oxidation

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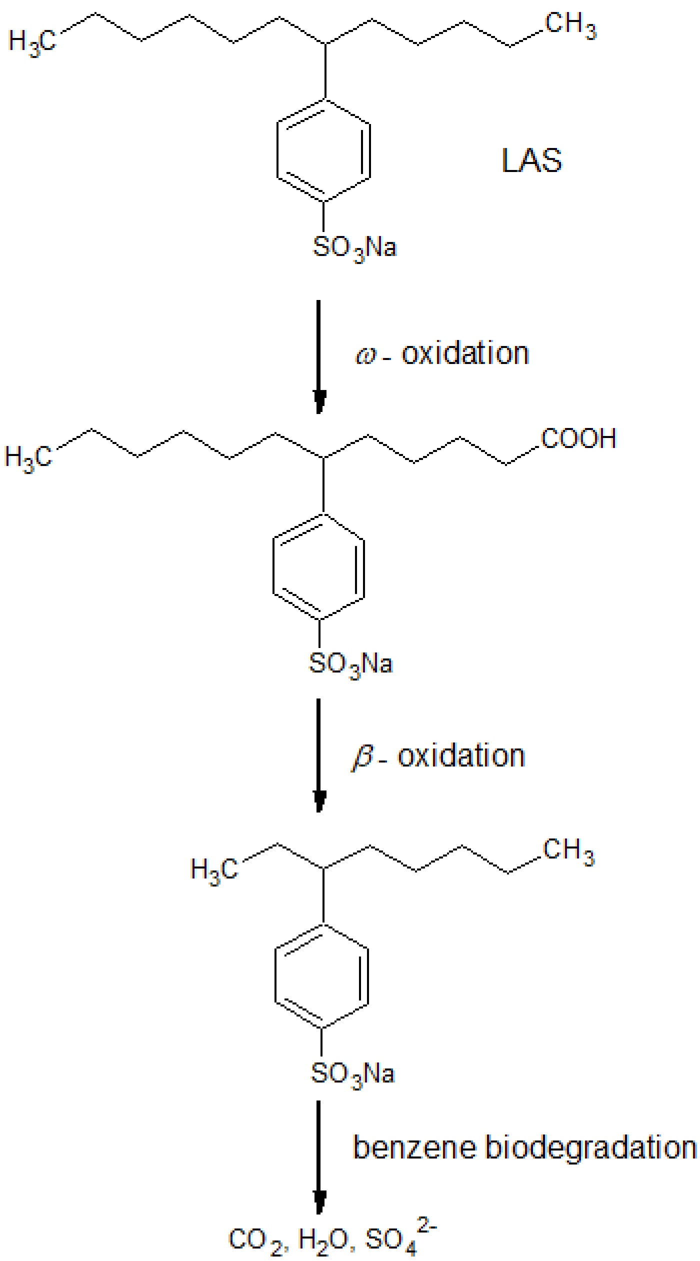

Figure 5. Scheme of biodegradation of LAS.

The second stage of alkyl sulfate biodegradation is the removal of the sulfonate group, which can take place by three mechanisms [148]: hydroxyative desulfonation, monooxygenase catalysis under acid conditions and reductive desulfonation (Figure 6).

$$\text{A. } RSO_3H + H_2O \longrightarrow ROH + 2H^+ + SO_3^{2-}$$

$$\text{B. } RSO_3H + O_2 + 2NADH \longrightarrow ROH + H_2O + SO_3^{2-} + 2NAD^+$$

$$\text{C. } RSO_3H + NADH + 2H^+ \longrightarrow ROH + 2NAD^+ + H_2SO_3$$

Figure 6. Ways of desulfonation. A – hydroxyative desulphonation, B – monooxygenase catalysis under acid conditions, C – reductive desulphonation.

Sulfite, which is oxidized to sulfate in the environment, is the decay product regardless of the mechanism.

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These processes occur under aerobic conditions, but anaerobic processes are realized in the anode compartment under the PMFC conditions. It should be noted that, anionic surfactants diffusion into the anode space cannot be excluded while the wastewater treatment [155]. At the same time, anionic surfactants, depending on their structure, have different degrees of biodegradation [156,157]. The sulfonate biodegradation is initiated by aerobic or microaerophilic microorganisms, the released metabolites can decompose anaerobically. For example, alkylbeznosulfonate (ABS) desulfurization is largely performed only in the presence of oxygen. The intermediate products formation of anaerobic ABS decomposition has been confirmed by laboratory studies that lasted for 165 days, while the efficiency of biodegradation has amounted 79% [158]. Linear alkyl sulfates are also decomposable under anaerobic conditions with concentrations of 20-50 mg/dm^3. A concentration increase has an inhibitory effect on the biodegradation of linear anionic surfactants [159].

Microorganisms of Citrobacter braakii can be used for wastewater treatment from surfactants [160]. These bacteria show a high rate of decomposition of many anionic surfactants in concentrations up to 500 mg/dm^3. Bacteria of the genus Pseudomonas sp. are widely found in natural reservoirs that are contaminated with surfactants [67,161]. Studies of isolates recovered from reservoirs contaminated with surfactants show that bacteria of this genus are capable of sodium dodecyl sulfate (SDS) biodegradation at a concentration of 1 g/dm^3, while the destruction efficiency is up to 97.2% [67] for 12 hours of the experiment. Therefore, Pseudmonas bacteria can be recommended to be used in PMFC while wastewater treatment from surfactants. The study [146] shows that the alkylbenzosulfonate (ABS) biodegradation can be improved by using a consortium of microorganisms Pantoea agglomerans and Serratia odorifera due to metabiosis, which occurs because of one of the microorganisms by the decomposition of the benzene ring. Almost complete removal of LAS is observed in 72 hours under aeration conditions (250 rpm) and at a temperature of 37 ° C in a neutral environment.

The review [162] has investigated the ability of nonionic surfactants to biodegradation using five strains (A, B, C, D, E) of bacteria identified as Pseudomonas fluorescens. It is important to note that the efficiency of the Triton X-100 biodegradation is influenced by nitrogen sources in the form of ammonium sulfate and potassium nitrate. As a rule, an increase in nitrogen concentration leads to an improvement in the nonionic surfactants biodegradation used in the work. For example, a 90% degree of Triton X-100 removal from the culture medium with concentrations of 5000 mg/dm^3 is observed at the concentration of ammonium sulfate 1600 mg/dm^3 for strain D in 36 hours. Besides, the addition of extra nitrogen source increases the specific growth rate of microorganisms when growing on Triton X-100.

Thus, the selection of microorganisms capable of surfactants biodegradation is an important task necessary for the normal PMFC functioning. At the same time, more attention should be paid to the selection of microorganisms that are capable of surfactants biodegradation under anodic conditions. Moreover, surfactant destructor microorganisms are recommended to be used in the cathode space for biodegradation of these pollutants under aerobic conditions, which provides faster wastewater treatment from surfactants.

4.3. Bioelectric systems based on microorganisms for wastewater treatment from surfactants

Several works on MFC have demonstrated the combination of wastewater treatment from surfactants and electricity generation [163–165]. The MFC operation principle is based on the conversion of organic substrates into electrical energy due to the enzymatic systems of bacteria.

The paper [166] describes the anaerobic decomposition of linear ABS at a concentration of 60 ppm (60 mg/dm^3) under anaerobic conditions in the MFC system. The efficiency of ABS removal is 57% of the initial concentration. Genomic sequencing has allowed to discover that Pseudomonas zhaodongensis bacteria predominates in the biofilm at the anode. It's worth noting, that the efficiency of purification decreases with an increase in the ABS concentration. Therefore, additional wastewater treatment from surfactants may be required before its use in MFC.

The study [163] has investigated the effect of sodium dodecyl sulfate (SDS) on the anode biofilm and power generation in MFC using sludge collected from a septic tank. The study results show that

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SDS inhibits the metabolic activity of microorganisms even in small concentrations (from 10 to 40 mg/dm^3), and negatively affects the formation of biofilm on the anode surface. As a result, the power of the device significantly decreases (by 66%) compared to the control. It has been found that the anode biofilm consists of bacteria of the genus Pseudomonas, Citrobacter, Treponema, Acinetobacter, which are capable of synthetic surfactant destruction. Nevertheless, the efficiency of SDS separation is more than 70% in 12 hours, and the generated power is from 10.8 mW/m^2 in the presence of 41.1 mg/dm^3 of SDS.

The work [167] presents a MFC system with a modified photocathode. Cathode modification has been carried out using TiO_2, which is a photocapalyzer. The principle of its operation is the absorption of UV radiation and the release of electrons, which enter redox reactions with oxygen or water vapor, forming strong oxidants. It contributes to the additional decomposition of organic pollutants and increases the efficiency of wastewater treatment [167]. The generated power density of the device is 0.73 mW/m^3 with the retention time of the model wastewater in the system for 12 hours, and the efficiency of removing the model anionic surfactants in the form of SDS is 88.6%.

A biosensor for determining linear ABS in water using MFC technology is described in [165]. The operation principle is to add different concentrations of linear ABS with subsequent registration of the signal in the form of amperage. The linear range of detectable system contents is from 10 to 120 mg/dm^3. At the same time, the efficiency of removing linear ABS under anaerobic conditions is 90% for 96 hours of MFC operation, and the maximum power density is 75 mW/m^3.

Thus, MFC demonstrates the possibility of removing surfactants in bioelectric systems. At the same time, the purification efficiency can reach up to 90% at relatively small concentrations, which do not lead to inhibition of the enzymatic systems of microorganisms and do not reduce the generated power of the devices.

4.5. Integration of PMFC into hydrobotanical sites for wastewater treatment from surfactants as a prospect for further development of bioelectric systems

The PMFC design features, organized according to the "constructured-wetland" technology, can replace artificial wetlands, which have been used for more than 50 years [168] and are intended for wastewater treatment: household [169], wastewater from fisheries farms [170], municipal-domestic wastewater from small settlements [171]. After wastewater treatment, their reuse is possible [171,172].

The artificial constructed wetlands (CW) operation principle is based on natural wastewater treatment processes, when plants macrophytes and microorganisms are used, while purification is carried out under controlled conditions [168]. Wastewater can be purified from biogenic elements, heavy metals, organic pollutants, including surfactants in such systems.

There is a well-known work on the use of CW laboratory models for the removal of synthetic surfactants from the wastewater of car washes [173]. The results show that the efficiency of SDS removing (the main component of the detergent in this study) is 90% when loading 75 dm^3/m^2 when using CW with the Phragmites australis plant.

The work [174] has investigated the removal degree of SDS, polyethylene glycol (PEG) and trimethylamine (TMA) using the plant Phragmites australis. The results show that the greatest removal degree of the selected model toxicants occurs within 7 days, and then sorption is significantly reduced. Besides, the plants show signs of chronic toxicity over a long period of time. The toxicants have been found to accumulate in various plant components, which makes them unsuitable for use as feed for cattle. The removal degree of SDS is 35% in 35 days.

The integration of PMFC into hydro-mechanical sites is a promising area of scientific research [175]. The use of PMFC makes it possible to achieve more efficient (by 30-50%) wastewater treatment compared to comon CW [176]. It is necessary to solve a number of problems to scale PMFC systems in the future: high internal resistance [176,178], selection of the optimal association of microorganisms to reduce competition between them [178], as well as biofouling of the cathode, which worsens the diffusion of oxygen to its surface [179,180]. It is essential to focus on improving the efficiency of wastewater treatment systems and generating electricity, which is achieved with a detailed examination of bioelectrochemical processes that occur in BES systems.

5. Conclusion

The study of the application possibilities and the development of effective PMFC technologies is relevant in creating new renewable energy sources and is important for solving environmental problems. The PMFC system has autonomy and is able to purify soil and wastewater ecosystems from a wide range of organic and inorganic compounds due to the influence of plants and microorganisms on each other. Thus, the review shows that the efficiency of soil purification from heavy metals with the help of PMFC is on average about 30%, from oil – 90%. The reduction of such indicators as BOD and COD for wastewater is from 71% and 52%, respectively. A decrease in biogenic elements in the form of phosphates and nitrates is observed when the PMFC is exploited. Purified water can be reused for household needs. The electricity generated by PMFC is ecologically clean and can be used to power and charge low-power devices. Besides, the system can be used as a bio-sensor for monitoring the plant condition. Decentralized electricity generation and the low cost of manufacturing PMFC can be used in developing countries, and the generation of electricity in wetlands can become another application of PMFC.

The problems of operation, which include high resistance and low power, can be solved by careful choice of the material for the anode and cathode manufacturing, by modifying the electrodes in order both to improve their electroconductive properties and to increase the electron transfer rate. Moreover, it is proposed to focus on plants with C_4 – type photosynthesis, which is more efficient compared to C_3 – photosynthesis. More attention should be paid to the selection of the most effective exoelectrogenic types of bacteria to increase the PMFC system power.

The review examines studies on biological wastewater treatment from synthetic surfactants. Bacteria of the genus *Pseudomonas sp*. are promising bacteria capable of biodegradation, most popular for household purposes of the group of anionic surfactants. Some species of these bacteria are capable of producing compounds of the phenazine series. They have been previously used in MFC. Therefore, this genus of bacteria is potential for their use in the PMFC system, which will combine wastewater treatment from surfactants and electricity generation.

Thus, the possibility of wastewater treatment using the PMFC technology with its reuse for household purposes, reduction of greenhouse gases, low amount of waste during operation favorably distinguishes it from traditional alternative sources of electricity, despite the low power output.

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