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Wastewater treatment systems based on plant-microbial fuel cells

Abstract. *The article presents data on the current state of using combined engineered wetlands and microbial fuel cells and on the factors that provide wastewater treatment and power generation. Wastewater treatment is one of the energy-intensive industries, with most of this energy being used to supply oxygen from the atmosphere to biological reactors to oxidize effluent organic matter. Both classical and new water purification methods, including biological post-treatment, are used to increase the degree of purification and reduce energy losses. The simplest and most effective way is soil cleaning using the technology of irrigation and filtration fields, as well as wetlands.*

Data are presented on plant-microbial fuel cells that perform wastewater treatment and are a way to generate electricity through microbiological oxidation of organic substances with oxygen. Fuel cells based on «Constructed Wetlands» sedimentary type, which received widespread use in recent years. Even though «Wetlands» have been widely used for wastewater treatment since the 70s of the last century, the modern use of Constructed Wetlands is an imitation of a swamp with aquatic plants, soil, and associated microorganisms due to the possibility of generating electricity in such systems.

Presented results of experimental plant-microbial fuel cells from plants (PMFCs) of various natures. As a result of the conducted studies of experimental systems with PMFCs, stainless steel, and graphite electrodes were selected, developing the highest potential, the optimal distance between the electrodes in the plant was determined, which was 10 cm and was established, that of plants more effective were plants of pistia, then rice and eihornia, which have a well-developed root system, the smallest indicators of the current generation were in the reed.

Keywords: *wetlands, plant-microbial fuel cells, purification, wastewater, electricity generation, microorganisms, electrode.*

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Introduction

The sharp increase in the demand for water and energy, while simultaneously increasing their scarcity, increases the likelihood of a humanitarian crisis. In the next decade, the shortage of available fresh water and the growth in energy consumption are expected to be 40% and 36%, respectively, which will require sustainable solutions to these problems. Existing wastewater treatment methods suffer from an imbalance in the work-to-energy ratio in providing treatment standards [1]. It is now generally accepted that wastewater is a renewable energy source, holding in the chemical bonds of organic matter several times more energy than is required for their purification [2].

Thus, the concepts of converting waste to energy and developing less energy-intensive wastewater management technologies have evolved and been widely researched worldwide. Developing economical and energy-neutral technologies is currently the most demanded approach [3].

Reservoirs that have received excess organic matter (for example, from sewers or runoff from cattle farms) become a “dead zone”: water blooms in them and fish and fauna die. To prevent this, it is necessary to purify water from organic contaminants. On average, developed countries annually spend up to 3% of all energy generated on such events. Conventional wastewater treatment processes consume large amounts of energy, and energy demand in these systems is expected to increase by as much as 20% over the next 15 years. The leading technologies for treating urban, agricultural, and industrial wastewater operate based on energy-intensive aerobic biological processes developed more than a century ago. Aeration accounts for 70% of the energy used in wastewater treatment [4].

The municipal wastewater treatment sector is one of the most energy-intensive industries, with most of this energy being used to supply oxygen from the atmosphere to biological reactors to oxidize the organic matter of the effluent. Wastewater treatment accounts for about 3% of the U.S. electrical load, which is approximately 110 terawatt-hours per year, or the equivalent of 9.6 million electricity consumers annually [5]. At the same time, water aeration makes up 45-75% of the cost of electricity consumption by water treatment facilities, and the purification itself and waste disposal can be up to 60% of the total operating cost. Their biological tertiary treatment is used to increase the degree of purification and reduce energy losses. The simplest and most effective way is soil cleaning using the technology of irrigation and filtration fields, as well as «wetlands».

Biological treatment methods also include plant-microbial fuel cells (PMFC), which allow minimizing energy losses by turning wastewater treatment from an energy-intensive process into a method of generating electricity. Currently, the application of   spread to environmentally friendly engineering systems [6], to generate bioelectricity from rice fields [7], wetlands [8], green roofs [9] and floating ponds [10]. In addition, there is potential for PMFC to be incorporated into agricultural land without any impact on food production [11]. Indoor plants, green roofs, and rooftop gardens can also be used in PMFC to generate bioelectricity, maintain air quality, and provide ecosystem services [12].

Among plant-microbial fuel cells, fuel cells based on “Constructed Wetlands” of sedimentary type, which have been widely used for wastewater treatment since the 70 years of the last century, have become widely used.

Constructed Wetlands (CW) imitate a swamp with aquatic plants, soil, and associated microorganisms, with a controlled environment for wastewater treatment in an aesthetic, sustainable, and economical way [13]. The ability of natural wetlands to treat wastewater was discovered as early as the 1950s [14]. The first constructed wetlands for municipal wastewater treatment were established in 1974 in Germany [5] thanks to the work of K. Seidel from the Max Planck Institute, which showed the possibility of using reeds for wastewater treatment. After that, C.W.’s popularity grew in Europe and North America. CW has traditionally been used for wastewater treatment. However, since the late 1980s, it has become more widely used to treat various types of industrial, domestic, and agricultural wastewater [15].

In wetland treatment systems, aquatic plants are the primary tool for removing heavy metals and bioremediation [16]. The first CW- MFC was constructed by A.K. Yadav [17]. Since then, several more systems have been developed and tested, such as the vertical flow system [18], horizontal subsurface flow system [19], and surface flow system with floating macrophytes [20]. They have been used in the treatment of various types of wastewaters, and some of the declared maximum power density of CW- MFC was 80 mW/m^2 [20], 35 mW/m^2 [18], 43 mW/m^2 [20] and 184.75 ± 7.50 mW/m^2 respectively [21].

One of the design options for the CW is shown in Figure 1. This shows the design with a horizontal wastewater supply.

CW designs are diverse, and attempts are being made to create combined CW, which includes plant-microbial fuel cells based on CW- MFC

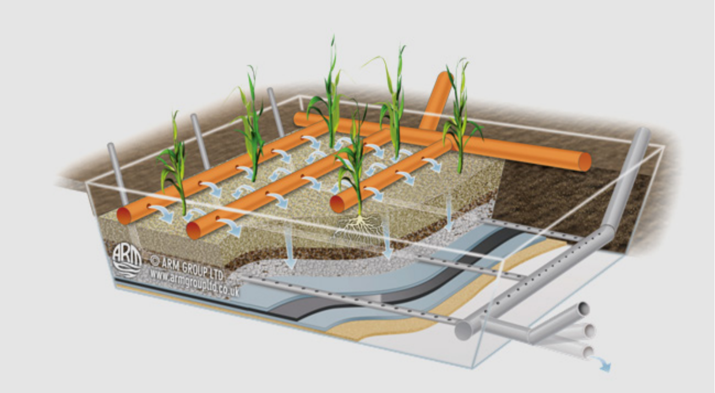

Figure 1. Diagram of a CW device.

Technology CW- PMFC allows you to generate energy continuously without causing competition for power and can work anywhere. Mild operating conditions make CW - PMFC more attractive than traditional alternative energy sources.

A typical microbial fuel cell consists of anode and cathode chambers. In the anode compartment, microorganisms oxidize organics, generating electrons and protons. Electrons flow through the electrical circuit doing work, and protons are transferred through the separator to the cathode chamber. Electrons and protons are consumed in the cathode compartment and combined with oxygen to form water.

$2\ C_6H_{12}O_6 + 6\ O_2 \rightarrow 12\ CO_2 + 24H^+ + 24e^-$ - (anode compartment)
$6O_2 + 24H^+ + 24e^- \rightarrow 12\ H_2O$ - (cathode compartment)

Chemical reactions occurring in a fuel cell are generally simple and have the following form:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 24e^-$$

Microorganisms that consume a substrate such as sugar under aerobic conditions produce carbon dioxide and water. Thus, the chemistry of the reaction is like the combustion process, where the released energy is converted directly into electrical energy.

The standard redox potential of the glucose/CO_2 pair is - 0.41 V. At the cathode side, the standard redox potential of the O_2/H_2O pair is + 0.82 V. Thus, the maximum potential difference that can be obtained between the anode and cathode in PMFC is equal to 1.23 V.

The advantages of fuel cells over other types of devices that produce energy are:

- higher efficiency;
- no moving parts and as a result, no sound pollution;
- no emissions of environmentally polluting gases such as SO_x, NO_x, CO, etc.

In contrast to the advantages, a significant disadvantage of microbial fuel cells is the low current strength, which leads to the need to connect numerous MFC into batteries, the need to use current amplifiers and converters, which ultimately increases the cost of the MFC themselves and the cost of the generated current. One of the solutions to this problem can be a combination of MFC with plants, i.e., plant-microbial fuel cells) or rhizome-microbial fuel cells within sedimentary systems [22].

According to [23] the current strength of such PMFC can reach values of 3.2 W/m^2 plant growth area. Dutch start-up Plant-e uses PMFC to generate electricity from rice fields. They promise to increase the capacity of their 100 m^2 of fuel cells to 2,800 kilowatt-hours per year [24]. MFC systems can be applied to generate electricity at the water/sediment interface in environments such as bay areas, wetlands, and rice fields. Using these systems, power generation in rice fields has been demonstrated up to ~80 mW/m^2 [25].

The ability of PMFC based on CW to produce electricity with the simultaneous processing of wastewater from livestock farms is shown. The removal efficiency was 93±1.7% chemical oxygen demand (COD); 85±5.2% for total nitrogen; 90±5.4% ammonium; 98±5.3% for total phosphorus and 99±2.9% for exchangeable phosphorus, respectively [26]. According to Zhao (2013), MFC integrated with wetlands is the most economical way to achieve both wastewater treatment and power generation goals [27].

Plants play a large role in PMFC, they provide filtration effects, nutrient absorption, and oxygen release from the roots, increasing the surface area for microorganism growth [28].

Many plant species have been researched for bioelectricity production and wastewater treatment in PMFC: this includes different types of rice [29], seaside marsh plants cordgrass and arundo cane (*Spartina anglica* and *Arundo donax*), freshwater plants evasive reed (*Arundinella anomola*), barnyard grass (*Echinochloa glabrescens*), *Pennisetum setaceum*, sucrose (*Cyprus involucratus*), ryegrass (*Lolium perenne*) [30-34], wetland plants - water hyacinth (*Echinorriea crassipes*), water morning glory (*Ipomoea aquatic*), broadleaf cattail (*Typha latifolia*), marsh calamus (*Acorus calamus*), small duckweed (*Lemna minuta*) and Indian canna (*Canna indica*) [21, 35-39].

Spartina anglica has been recognized as an ideal plant for large-scale implementation in wetland bioelectric production in the future. It provides maximum current generation and a high degree of wastewater treatment from contaminants [40]. Among floating plants, the water hyacinth (*E. crassipes*) is preferred, which is well known for its great ability to remove biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, phosphorus, organic carbon, suspended solids, phenols, pesticides, heavy metals, etc. from wastewater, also provides satisfactory current generation [41, 42].

In the CW- MFC system, the potential at the cathode is 299 mV, at the anode -341 mV. In the presence of a plant, the current generation increases up to 142% [35]. Studies have shown that the presence or absence of a plant in the field between the MFC- CW poles reduce internal resistance. Thus, the internal resistance in the presence and absence of plant root systems was 217.7 Ohm and 272.9 Ohm, respectively [43].

Due to the root secretions of different plants, a different microbial community is maintained in PMFC [44, 45]. Electrogenic microorganisms play an important role in the generation of electric current. Beneficial species of bacteria that produce electricity in PMFC have been identified and include *Geobacter spp., Ruminococcaceae spp., Desulfobulbus spp., Desulfovibrio, Bacillus, Geothrix, Pseudomonas, Shewanella, Acidobacteria* [46, 47].

Among the representatives of *Bacillus*, the main electrogenerating bacteria is *Bacillus subtilis* [48]. These bacteria are classified as electrogenic, anodophilic, and exoelectrogenic based on their ability to transfer electrons to electrodes without exogenous mediators [49]. Electrogenic bacteria (EGB) can be both gram-negative and gram-positive, they have been identified as electron donors in PMFC [50]. These microbes are grouped according to their location (on the anode or cathode) or their role in electron transport. In addition, EGB and anaerobic bacteria in sediments and surface waters oxidize available organic matter and directly transfer electrons to the anode [51].

Extracellular transfer of electrons by microorganisms to the anode is carried out in three ways:

1) mediated electron transfer, for example, *Shewanella* and *Pseudomonas* release mediators (flavins) that can transfer electrons from bacteria to the anode surface [52];

2) direct electron transfer by biofilm-forming bacteria, for example, *Shewanella* and *Geobacter* species transfer electrons through cytochromes or pili [53];

3) electron transfer through nanowires, for example, *Geobacter* and *Shewanella* use conductive processes to transfer electrons to the anode [54].

Recent studies aim to enhance electricity production by PMFC and wastewater treatment from various types of pollutants. Bulgarian researchers have shown the ability of PMFC to purify wastewater from oil products. The best results were achieved with a bottom feed of water, a 3:1 mixture of sludge and peat, the use of stainless-steel electrodes, and no separator between the aerobic and anaerobic zones. The plant was cordgrass. The oil supply was 100 mg/l crude oil (total oil content 1 mg/l, COD 4690 mg/l), the system was inoculated with highly active oil-oxidizing bacteria (*Pseudomonas veronii, Azoarcus communis, Pseudomonas chlororaphis, Pseudomonas putida, Pseudomonas libanensis*), the hydraulic retention time was 14 days. With this design and mode of operation, a maximum specific power of 10.40 mW/m^2 was achieved and the degree of purification of water and oil products was more than 99% in CW with an integrated PMFC [55].

Treatment of gray wastewater with the following composition: turbidity 15.4 NTU; COD$_{total}$ - 477.8 mg O/l, COD$_r$ - 380.4 mg O/l, suspended solids - 95.9 mg/l, nitrates - 7.1 mg/l and phosphates - 19.9 mg/l in the CW-MFC system with the common reed plant showed its effectiveness in 152 days for the purification of COD 91.7%, for phosphates 56.3%. The nitrate removal efficiency was above 86.5% with a current density of 33.52 achieved mW/m^2 [56].

Spanish researchers showed that CW-MFC was more effective with open circuits than with closed circuits in wastewater treatment. In the first case, cleaning was more efficient by 18%, 15%, 31% and 25% in terms of COD, HDTV, phosphates and ammonium, respectively. The optimal external resistance turned out to be 220 Ohm from the investigated resistance range from 50 to 1000 Ohm [57].

On the other hand, experiments, conducted by Indian scientists, in open-circuit and closed-circuit modes have shown that in a closed circuit the current generated is 12-20% more than in open-circuit operation and 27-49% better in removing COD [58]. The maximum power density of 320.8 mW/m^3 and current density of 422.2 mA/m^3 were achieved with a granular graphite anode and a Pt-coated carbon cloth cathode. The plant in the system was represented by the Indian shot

When adding 1/2 of the modified Hoagland's solution to the anolyte solution and potassium ferricyanide as an interelectronic transfer mediator the maximum power of 100 W/m^2 was achieved at the cathode in PMFC with the plant *S. anglica* [59]. Adding graphene oxide to anolyte PMFC gave a maximum power of 17 - 49 mW/m^2, which was higher than the control (7.7-20 mW/m^2) [60].

The addition of compost to the PMFC substrate with rice increased the maximum power density to 23 mW/m^2 [61]. Inoculation of CW-MFC with Ipomoea water plant (*I. aquatica*) with anaerobic sludge and phosphate buffer provided a maximum specific power of 12.42 mW/m^2, which was 142% higher than that of the control CW-MFC (5.13 mW/m^2) [61]. Based on results using different levels of dissolved oxygen among CW-MFC, the Chinese authors concluded that a distance of 20 cm between the anode and cathode provides an optimal COD elimination of 94.90% at a power density of 0.15 W/m^3, 339.80 W internal resistance and Coulomb efficiency of 0.31%. In addition, COD at 200mg O/L provided greater power generation (open circuit voltage 741mV, power density 0.20 W/m^3, internal resistance 339.80W and current 0.49mA) and cleaning capacity (removal 90, 45% COD) than at higher COD values. By adding 50 mM phosphate buffer solution to synthetic wastewater, relatively high conductivity and buffering capacity were achieved, resulting in improved power generation [62].

Enrichment of PMFC with raigras (*Lolium perenne*) electrogenic bacteria from another laboratory MFC allowed to remove 99% of Cr (VI) and obtain a current in the range of 30–70 mA/m^2 using half Hoagland's solution and sodium acetate [63].

The use of an aero cathode in the system under discussion made it possible to obtain a current amplification from 0.07 V to 0.52 V and a current density of 0.005 mV/m^2 and 4.21 mV/m^2, respectively, in 75 days of CW-MFC operation [64]. The use of a system of capacitors to collect electricity has increased the performance of the CW-MFC system by almost 20% [65].

Thus, the selection of plants and their cultivation conditions, plant substrate, nutrient solutions, electrogenic microflora, electrode design and material make it possible to regulate the production and degradation processes of wastewater organic substances in promising CW-MFC systems.

Experimental part

Representatives of aquatic phytophthores in water bodies and wetlands were selected as plants for plant and microbial fuel cells. Sediment type PMFC system for plants was used (Tab.1).

Table 1. Plants grown in laboratory and their characteristics in the experimental PMFC installation: a) Pistia, b) Eichhornia, c) Reeds, d) Seeded Rice

			
a	b	c	d
a) *Pistia* (lat. *Pistia stratiotes*) is a monotypic genus of the *Aroid family* (*Araceae*), including the only perennial herbaceous floating plant species. Small, evergreen, free-floating herbs with spreading roots. The roots are numerous, pinnate, and floating, and the stem is shortened. The leaves form a rosette, floating on the surface of the water, have intercellular spaces filled with air, gray-green, sessile, obtusely wedge-shaped, with the greatest width at the end and somewhat narrowed towards the base, with a rounded anterior margin, 15-25 cm long, 8-10 cm wide.			
b) *Eichhornia* thick-legged (lat. *Eichhornia crassipes*) - water hyacinth, aquatic plant; species of the genus *Eichornia* of the family *Pontederiaceae.* An annual floating aquatic plant shoots up to 2 m in length (Figure 3). Leaves are collected in the socket. At the base of the leaf is a swelling, inside which is a porous tissue, thanks to which the plant is kept afloat. The roots are long (up to 0.5 m), and completely submerged in water. The flower is shaped like a hyacinth, it can be pink, blue or purple.			
c) *Reed* (lat. *Scirpus*) is a genus of perennial and annual coastal aquatic plants of the sedge family (Figure 4). *Reeds* grown in the laboratory. It grows up to 4 meters and, in rare cases up to 6. Tall perennial plant. The stem is cylindrical or trihedral, up to 3.5 m high. The flowers are bisexual, in spikelets collected in an umbellate, paniculate or capitate inflorescence. Grows in swampy areas.			
d) *Seeded Rice* (lat. *Oryza sativa)* is a genus of annuals and perennial herbaceous plants in cereal families. Rice stalks reach up to one and a half meters in height, its leaves are quite broad, dark green and rough along the edge. One-year rice is grown as an agricultural crop in the tropics, subtropics, and warm temperate zones. Rice is one of the oldest food crops.			

The PMFC system of sedimentary type for plants was used. The scheme is shown in Figure 2.

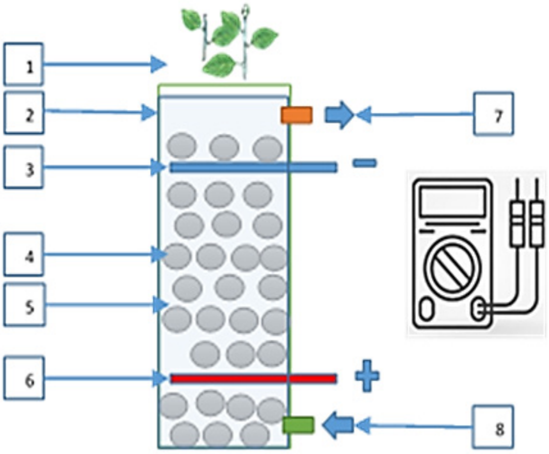

Figure 2. Scheme of the design of a sedimentary fuel cell: 1 - plants, 2 - plastic cylinder, 3 - cathode, 4 - gravel, 5 - substrate, 6 - anode, 7 - substrate output, 8 - substrate input

Membrane-free design. The electrodes included in the system close the electrical circuit. The following served as electrodes: an aluminum mesh 23.2 mm × 13.4 mm × 2.4 mm PVA (TU U00236010.001-97), carbon (graphite) electrodes with a diameter of 8.0 mm (GOST 10720-75), a graphite electrode, and a stainless steel sheet 2.0 mm, the anode is also made of the same materials.

The distance between the electrodes was 5, 10, 20 cm. Two electrodes were connected to a portable digital multimeter of the UT33C+ type (included in the State Register of Measuring Instruments of the Republic of Kazakhstan) using copper wires or through a 1000 Ohm resistance. System performance is determined by measuring open circuit voltage and short circuit current.

The plant system was installed on the Technopark NURIS Nazarbayev University premises, where the temperature fluctuated between 20-25°C and humidity was not controlled. Illumination with light from linear phytolamp of a full spectrum of 60 cm with a power of 12 W.

The imitation of the following composition (g/l) with pure substances was used as wastewater: CH_3COONa - 256.41 mg/l; NH_4Cl - 76.43 mg/l; $NaNO_3$ - 30.36; KH_2PO_4 - 14.24 mg/l; $CaCl_2$ - 14.7 mg/l; $MgCl_2$ - 20.3 mg/l and solution of microelements containing *Fe, B, Zn, Cu, Mn, Mo* in optimal quantities for the universal cultivation of almost any plants by hydroponics - 10 ml/l [21]. Synthetic wastewater was applied to the surface of each CW-MFC.

All systems were operated under laboratory conditions at room temperature of 20°C. Daily water loss due to evapotranspiration and sampling in the CW-MFC ranged from 1 to 5%. The evaporated water was replenished daily with fresh synthetic wastewater. As a filler, gravel from dense rocks with a fraction of 20-40 mm was used according to GOST 8267-93.

COD measurement was carried out according to GOST 31859-2012 *“Water. Method for determining the chemical oxygen demand»* on the device *Expert 003* (Spectrophotometer with a thermoreactor). The apparatus was calibrated with solutions of a standard sample of chemical oxygen demand GSO 7552-99. The device has the function of built-in construction of a calibration curve and automatic determination of the COD value.

The current voltage characteristics were measured using a *Fluke 8808A* multimeter. Standard sample of chemical oxygen demand GSO 7552-99). The Devard method calculates ammonium and nitrate nitrogen according to GOST 30181.4-94. Determination of phosphates according to GOST 18309-2014 ‘*Water. Methods for the determination of phosphorus-containing substances”.*

Statistical results were processed using the software package «*Statistica 6.0*» with standard deviation ±1 for voltage (in mV) and *Microsoft Excel 97*. Measurements were made in three parallel.

As part of the creation of model PMFCs in CW, a series of experiments were carried out to generate electricity using various installations containing the following plant species: pistia *(Pistia stratiote)*, eichhornia *(Eichhornia crassipes)*, reed *(Scirpus)*, seed *(Oryza sativa)*.

For the production of plants, planting material has been purchased and in laboratory conditions a hydroponic plant for 150 litres of water, with a constant flow of water and illumination with full spectrum LED phytolamps has been created (Figure 3).

Figure 3. Hydroponic installation for growing aquatic plants

Cultivated crops were established in experimental PMTE. Experimental PMFC was based on a PVC pipe (polyvinyl chloride) with a diameter of 150.0 mm and a thickness of 2.0 mm (GOST 32413-2013), and the installation height is 37 cm. The working volume of PMFC was 6 liters (Figure 4).

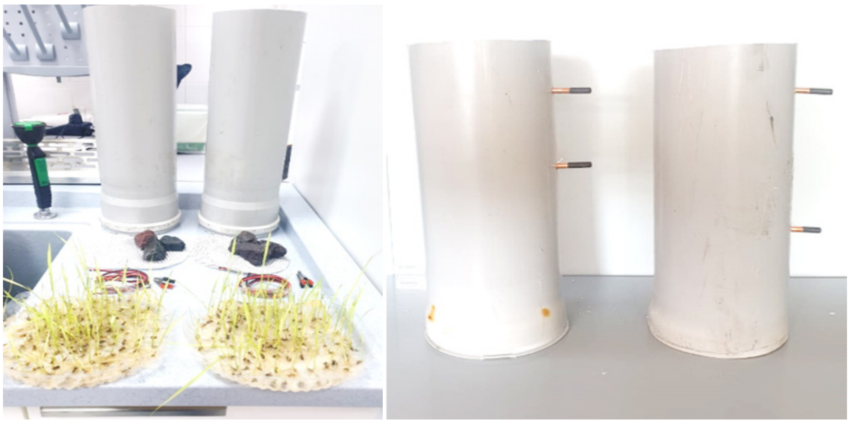

Figure 4. Experimental PMFC

When cultivating plants on experimental setups, the roots and the oxidized substrate are under aerobic conditions, aerated with air or pure oxygen in the PMFC cathode chamber. In turn, the lower compartment of the PMFC contains an anode, where anaerobic conditions are created (Figure 4).

The proposed PMFC does not have a proton-selective membrane in its design. At the anode, microorganisms assimilate organic substances from water, while free protons diffuse to the cathode, where they were oxidized by oxygen to water. A solution of synthetic wastewater was used as a substrate [21]. The wastewater solution was supplied from the bottom valve at a rate of 6 l/day, so the volume is updated in 24 hours.

The initial analysis of the chemical composition of synthetic wastewater showed: COD 210.4 ± 60.9 mg O_2/l, NH_4^+ - (N) = 19.7 ± 1.6 mg/l and NO_3^-- (N) = 4.78 ± 1.5 mg/l, while 70% to 82% TN is NH_4^+- N.

Indicators of voltage, current strength and potential difference were determined daily using a multimeter. Positive indicators of electrogenic activity were obtained during cultivation for 50-100 hours, the maximum indicators were achieved on days 10-15 (Figure 5).

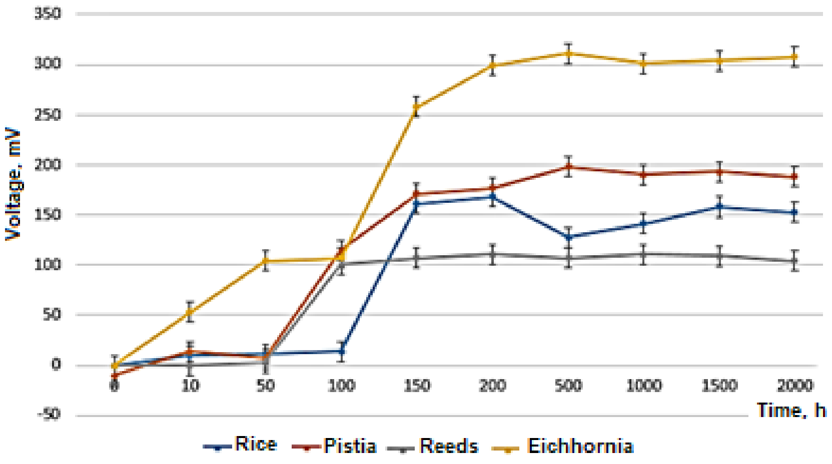

Figure 5. Dynamics of electrogenic activity of PMFC with various plants

As part of the study, high electrogenic activity was shown by installations with a graphite electrode, where the maximum voltage indicator was reached at the level of 512 mV, with a cultivation duration of 74 days using *Pistia stratiote* with a current strength of 1.61 mA (Table 2).

Table 2. Indicators of electrogenic activity of experimental models of PMFC

Plants	Model PMFC	Number of days	Max mV	Max mA
Pistia	graphite rod, 10 cm	74	512±1	1.61
Eichhornia	graphite rod, 10 cm	74	198±1	0.14
Rice	graphite rod, 10 cm	74	168±1	0.15±1
Reed	graphite rod, 10 cm	74	111±1	0.8

The electrical parameters of PMFC were studied depending on the design and material of the electrodes. The design parameters of the studied PMFC included various distances between the electrodes (100-200 mm), various plants (*Pistia, Eichhornia, Scirpus, Oryza sativa*), various shapes and sizes of electrodes (classic graphite electrode, graphite rod electrode 8 mm), as well as an aluminium mesh.

On average, between different electrode designs, no significant differences were observed between the specific power and strength of the studied PMFC experimental setups (Table 3).

Table 3. Indicators of electrogenic activity of experimental PMFC

No. p / p	Plants	PMFC design	Number of days	Voltage, mV	Current strength, mA
1	Rice	Sample 1, stainless steel metal, 10 cm.	74	405±1	0.15
2	Rice	Sample 2, stainless steel metal, 20 cm.	74	220±1	0.15
3	Rice	Sample 3, alum. grid, 10 cm.	83	443±1	1.38
4	Rice	Sample 4, alum. mesh, 20 cm.	83	222±1	1.10
5	Rice	Sample 5, graphite rod, 10 cm.	61	468±1	1.11
6	Rice	Sample 6, graphite rod, 20 cm.	61	222±1	1.17
7	Rice	Sample 7, graphite rod, 5 cm.	15	228±1	1.56
8	Pistia	Sample 8, stainless steel metal, 20 cm.	74	431±1	1.00
9	Pistia	Sample 9, alum. grid, 10 cm.	83	478±1	1.11
10	Pistia	Sample 10, alum. mesh, 20 cm.	83	408.4±1	1.05
11	Pistia	Sample 11, graphite rod, 10 cm.	61	447±1	1.27
12	Pistia	Sample 12, graphite rod, 20 cm.	61	88±1	0.58
13	Pistia	Sample 13, graphite rod, 20 cm.	15	180±1	1.58
14	Reed	Sample 14, stainless steel metal, 10 cm.	74	311±1	0.88
15	Reed	Sample 15, stainless steel metal, 20 cm.	74	180±1	0.58
16	Reed	Sample 16, alum. grid, 10 cm.	83	444±1	0.53
17	Reed	Sample 17, alum. mesh, 20 cm.	83	428±1	0.71
18	Reed	Sample 18, graphite rod, 10 cm.	61	401±1	0.25
19	Reed	Sample 19, graphite rod, 20 cm.	61	103±1	0.21
20	Eichhornia	Sample 20, stainless steel metal, 10 cm.	74	358±1	1.41
21	Eichhornia	Sample 21, stainless steel metal, 20 cm.	74	301±1	1.15
22	Eichhornia	Sample 22, aluminium grid, 10 cm.	83	468±1	0.75
23	Eichhornia	Sample 23, aluminium mesh, 20 cm.	83	388±1	0.38
24	Eichhornia	Sample 24, graphite rod, 10 cm.	61	408±1	0.97
25	Eichhornia	Sample 25, graphite rod, 20 cm.	61	255±1	0.57
26	Eichhornia	Sample 26, graphite rod, 5 cm.	15	270±1	0.44

However, it is important to note that PMFC. containing stainless steel electrodes achieved the highest voltage values of 607 mV. At the same time, graphite installations started up most quickly and produced current, in turn, aluminium mesh electrodes also showed a high potential with a maximum of 468 mV.

Of the presented in Table 3 indicators of electrogenic activity, the optimal distance between the electrodes in the setup was determined, which was 10 cm. The highest potential was developed by electrodes made of stainless steel and graphite. Of the plants, pistia plants show the greatest efficiency, then seed and eichhornia, the lowest indicators of the current generation were in reed.

Table 4. Power indicators of experimental PMFC

No. p / p	Experience variant	Open loop measurements		Measurements through resistance, 989 Ohm		Power, Wt
		Voltage, mV	Current strength, mA	Voltage, mV	Current strength, mA	
1	Sample 1	405	0.15	180	0.18	32.4
2	Sample 2	220	0.15	87	0.08	6.96
3	Sample 3	443	1.38	258	0.2	51.6
4	Sample 4	222	1.1	98	0.09	8.82
5	**Sample 5**	**468**	**1.11**	**314**	**0.35**	**109.9**
6	Sample 6	222	1.17	100	0.1	10
7	Sample 7	228	1.56	147	0.14	20.58
8	**Sample 8**	**431**	**1**	**305**	**0.3**	**91.5**
9	**Sample 9**	**478**	**1.11**	**323**	**0.35**	**113.05**
10	Sample 10	408.4	1.05	178	0.18	32.04
11	Sample 11	447	1.27	205	0.2	41
12	Sample 12	88	0.58	14	0.01	0.14
13	Sample 13	180	1.58	120	0.12	14.4
14	Sample 14	311	0.88	179	0.18	32.22
15	Sample 15	180	0.58	77	0.08	6.16
16	Sample 16	444	0.53	286	0.29	82.94
17	Sample 17	428	0.71	270	0.27	72.9
18	Sample 18	401	0.25	174	0.17	29.58
19	Sample 19	103	0.21	68	0.06	4.08
20	Sample 20	358	1.41	220	0.22	48.4
21	Sample 21	301	1.15	208	0.21	43.68
22	Sample 22	468	0.75	300	0.3	90
23	Sample 23	388	0.38	217	0.21	45.57
24	Sample 24	408	0.97	304	0.3	91.2
25	Sample 25	255	0.57	186	0.18	33.48
26	Sample 26	270	0.44	113	0.11	12.43

According to Table 4, sample No. 9 has the highest power, which consists of stainless steel electrodes located at a distance of 10 cm using pistia (*Pistia stratiote)* as a plant element.

Samples No. 5 seed *(Oryza sativa)*, graphite rod 10 cm), and No. 8 pistia (*Pistia stratiote)*, stainless steel, 20 cm) also showed high power.

The effectiveness of PMFC in the process of purification of polluted water with organo-mineral pollutants was carried out on experimental sedimentary-type PMFC installations with these planted plants and with the addition of the drug «*KazBioRem-EM*» at a dose of 109 CFU/cm^3. Synthetic wastewater was used as dirty water. The results of the experiment were presented in Table 5.

Table 5. Results of measurements of current-voltage characteristics and chemical composition of solutions

No.	Experience Variant	Voltage, mV	Current strength, μA	COD, mgO/dm^3	NO^{3-}, mg/dm^3	NH$_4^+$, mg/dm^3	PO$_4^{3-}$, mg/dm^3	NO$_2^-$, mg/dm^3
1	Initial	8.0	0	210.4	4.78	19.7	3.69	1.51
2	Sample 1	405±1	0.15	18.1	0.87	0.85	0.98	0.17
3	Sample 2	220±1	0.15	22.4	0.79	1.26	1.67	0.32
4	Sample 3	443±1	1.38	15.0	0.98	1.01	1.50	0.21
5	Sample 4	222±1	1.10	19.0	0.59	0.82	1.55	0.47
6	Sample 5	468±1	1.11	12.5	0.88	1.94	0.89	0.28
7	Sample 6	222±1	1.17	18.6	0.95	1.33	0.53	0.40
8	Sample 7	228±1	1.56	17.9	0.42	0.99	0.24	0.26
9	Sample 8	431±1	1.00	17.2	0.84	1.28	0.12	0.22
10	Sample 9	478±1	1.11	19.3	0.55	1.08	0.25	0.31
11	Sample 10	408.4±1	1.05	20.4	0.57	1.36	0.58	0.48
12	Sample 11	447±1	1.27	25.6	0.86	2.01	0.75	0.12
13	Sample 12	88±1	0.58	43.9	1.02	5.22	0.36	0.35
14	Sample 13	180±1	1.58	39.5	0.73	2.36	0.51	0.14
15	Sample 14	311±1	0.88	27.3	0.48	1.56	0.89	0.24
16	Sample 15	180±1	0.58	48.1	0.72	1.88	0.82	0.29
17	Sample 16	444±1	0.53	12.7	0.85	3.05	1.08	0.52
18	Sample 17	428±1	0.71	11.0	0.28	1.56	1.68	0.39
19	Sample 18	401±1	0.25	13.8	0.86	1.22	1.05	0.70
20	Sample 19	103±1	0.21	32.0	0.49	1.63	1.56	0.62
21	Sample 20	358±1	1.41	19.2	0.96	1.58	0.78	0.28
22	Sample 21	301±1	1.15	23.2	0.78	1.99	0.36	0.14
23	Sample 22	468±1	0.75	15.4	0.52	1.24	1.52	0.19
24	Sample 23	388±1	0.38	28.0	0.63	2.08	0.48	0.74
25	Sample 24	408±1	0.97	15.2	0.48	1.89	0.75	0.85
26	Sample 25	255±1	0.57	29.4	0.85	1.75	0.58	0.28
27	Sample 26	270±1	0.44	29.7	0.76	2.33	0.74	0.26

As can be seen from Table 5, almost all experiments show a significant decrease of 5 times or more in nitrate, nitrite and ion phosphate. Residual ion concentrations (5-0.1 mg/l) appear to be due to the inability of plants to absorb them due to the low ion force of the solution. It should be noted that ammonium, nitrite, and nitrate ions were interconnected because *Nitrosomonas*, *Nitrosococcus* and *Nitrosospira* oxidize ammonium to nitrite ions. Nitrite oxidation to nitrate is produced by nitrate bacteria of the soil genus *Nitrobacter* and aqueous genera *Nitrospira*, *Nitrococcus*, *Nitrospina*. Nitrate ions and phosphate ions were absorbed by plants.

The organic compound content in water is characterized by the COD parameter. It should be taken into account that organic compounds in water were breeding ground for microorganisms, due to their activity organic matter is reduced in water, and at the same time bacteria are organic compounds that are fixed when determining COD In the original solution, the COD was 210 mg/l after testing, dropping to 29-10 mg/l (almost 7-10 times). The decrease of carbon in water is due to its removal in the form of carbon dioxide, formed by the «breathing» of microorganisms.

Thus, as a result of water purification by PMFC systems, plants such as rice, pistia, and eihornia showed good results, due to the well-developed root system of these plants. It should be noted that these plants in nature live in symbiosis with microorganisms living on the surface of the roots

Conclusion

A review of the current literature suggests that the concepts of waste-to-energy conversion and the development of less energy-intensive wastewater management technologies have been developed and extensively researched worldwide. The development of economical and energy-neutral technologies is currently the most demanded approach. One such technology is the use of systems Constructed Wetlands, which generate electricity from certain plants and microorganisms along with wastewater treatment. The selection of plants and their cultivation conditions, plant substrate, nutrient solutions, electrogenic microflora, electrode design and material make it possible to regulate wastewater organic matter's production and degradation processes in advanced CW-MFC systems.

The conducted research on plant-microbial fuel cell systems resulted in the selection of electrodes made of stainless steel and graphite, which exhibited the highest potential, the determination of the optimal distance between the electrodes in the setup (10 cm), and it was established that among the investigated plants the Pistia (*Pistia stratiote)* proved to be the most efficient in generating electricity.

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Өсімдік-микробтық отын элементтеріне негізделген ағынды суларды тазарту жүйелері

Аңдатпа. Мақалада біріктірілген жасанды сулы-батпақты жерлер және микробтық отын элементтерін пайдалану мәселесінің ағымдағы жағдайы және ағынды суларды тазарту мен электр энергиясын өндіруді қамтамасыз ететін факторлар туралы деректер келтірілген. Ағынды суларды тазарту көп энергияны қажет ететін салалардың бірі болып табылады, бұл энергияның көп бөлігі ағынды сулардағы органикалық заттарды тотықтыруға қажет оттекті биологиялық реакторларға атмосферадан беру үшін пайдаланылады. Суды тазартудың классикалық және заманауи әдістері қарастырылады, оның ішінде тазарту дәрежесін арттыру және энергия шығынын азайту үшін қолданылатын, биологиялық қайта тазарту. Ең қарапайым және тиімді әдіс – сүзу және егістерді суару технологиясын, сондай-ақ сулы-батпақты алқаптарды (ветландтарды) қолдану арқылы топырақты тазалау.

Шөгінді типтегі «Constructed Wetlands» негізінде жасалған өсімдікті-микробтық отын элементтері туралы деректер соңғы жылдары кеңінен қолданылуда. «Ветландтар» өткен ғасырдың 70-жылдарынан бастап ағынды суларды тазарту үшін кеңінен пайдаланылғанына қарамастан, қазіргі уақытта су өсімдіктері, топырақ және олармен байланысты микроорганизмдері бар сулы-батпақты жерді имитациялау болып табылатын «Constructed Wetlands» жүйелерін олардың электр энергиясын өндіру мүмкіндігімен ерекшеленеді.

Ұсынылған зерттеу нәтижелері эксперименттік өсімдік-микробтық отын элеметтерін құрастыруда табиғаты әртүрлі өсімдіктерді пайдалануға негізделген. Зерттеулер нәтижесінде шөгінді типті ӨМОЭ құрастыруда ең жоғары потенциалды көрсететін тот баспайтын болаттан және графиттен жасалған электродтар таңдалды, қондырғыдағы электродтар арасындағы оңтайлы қашықтық 10 см болатыны анықталды және өсімдіктер арасында тамыр жүйесі жақсы дамыған пистия, күріш және эйхнория өсімдіктерінің тиімдірек екендігі нақтыланды. Ең төменгі тоқты генерациялау көрсеткіштері қамыста болды.

Түйін сөздер: өсімдік-микробтық отын элементі, сулы-батпақты жерлер, тазарту, ағынды сулар, электр энергиясын өндіру, микроағзалар, электрод.

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Системы очистки сточных вод на основе растительно-микробных топливных элементов

Аннотация. В статье приведены данные по современному состоянию вопроса использования комбинированных конструированных болотных угодий и микробных топливных элементов и о факторах, обеспечивающих очистку сточных вод и генерацию тока. Очистка сточных вод является одним из энергоемких производств, и большая часть этой энергии используется для подачи кислорода из атмосферы в биологические реакторы для окисления органических веществ в сточных водах.

Рассмотрены как классические, так и новые методы очистки воды, в том числе биологическая доочистка, которая используется для повышения степени очистки и снижения потерь энергии. Наиболее простым и эффективным способом служит почвенная очистка по технологии полей орошения и фильтрации, а также ветланды. Представлены данные о растительно-микробных топливных элементах, которые совершают очистку сточных вод и представляют собой способ получения электроэнергии за счет микробиологического окисления органических веществ кислородом.

Охарактеризованы топливные элементы на основе «Constructed Wetlands» осадочного типа, которые получили широкое применение в последнее время. Несмотря на то, что «Ветланды» широко используются для очистки сточных вод с 70-х годов прошлого столетия, современное использование Constructed Wetlands (CW) – это имитация болота с водными растениями, почвой и связанными с ними микроорганизмами, обусловлено возможностью генерации электроэнергии в таких системах.

Представлены результаты исследования экспериментальных растительно-микробных топливных элементов из растений различной природы. В результате проведенных исследований экспериментальных систем с РМТЭ были подобраны электроды из нержавеющей стали и графита, развивающие наиболее высокий потенциал, определено оптимальное расстояние между электродами в установке, которое составило 10 см и установлено, что из растений более эффективными являются растения пистия, затем рис и эйхорния, которые обладают хорошо развитой корневой системой, наименьшие показатели генерации тока были у камыша

Ключевые слова: растительно-микробный топливный элемент, болотные угодья, очистка, сточные воды, генерация электроэнергии, микроорганизмы, электрод.

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