Possibilities of Using Phytoenergy Systems in the Ecological Rehabilitation of Contaminated Areas of the Baikal Region

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Abstract. Recently, green technologies based on the use of the purifying potential of plants have been rapidly developing. Wetland treatment systems have been designed. Variants of phytoenergetic systems are proposed that allow integrating phytoremediation and microbial fuel cells. The article summarizes and analyzes the achievements in the field of creating and mastering phytoremediation technologies in combination with the generation of bioelectric energy and evaluates the prospects of using this technology in local treatment facilities of hotel complexes in the Baikal natural territory. The results of studies on the assessment of the phytoremediation potential of aquatic vegetation growing directly in the bays of Lake Baikal are presented, and the selection of the most promising aquatic plants for use in phytoremediation facilities is carried out. The use of hybrid technology based on plant-fuel cells should contribute to solving the problems of ecological rehabilitation of the contaminated territories of the Baikal region. In places of intense recreational load, it will be possible to create autonomous local treatment facilities operating on the generated energy itself.

1. Introduction

A huge amount of waste and pollutants from domestic, industrial and other sources eventually end up in water bodies. For two centuries, they have been developing and implementing technologies for purifying natural and waste waters from pollutants. Closed water supply systems are being tested using a variety of physicochemical and biological methods. Moreover, microorganisms and, to a lesser extent, invertebrates are used as bioagents. Only in recent decades have there been fundamental changes in this direction. Green technologies have begun to be developed in a number of countries. They use the cleansing potential of plants. Wetland treatment systems have recently been designed. Various options for phytoenergetic systems have been proposed. The latter make it possible to combine phytoremediation and microbial fuel cells (MFC). Wetland phytoenergy systems are integrated bioelectrochemical systems (BES). They stably collect electricity from the anaerobic respiration of bacteria that multiply in the rhizosphere. In CW-MFC systems, during anaerobic
respiration, electrons accumulate at the anode. It, in turn, is electrochemically associated with electron acceptors at the aerobic cathode [1]. Recently, there are many publications on plant-microbial fuel cells (PMFCs), which can be considered as new derivatives of MFC devices [2-7]. Many microorganisms can participate not only in the transformation of pollutants, but also use them as a source for the generation of bioelectricity. An innovative scientific direction of bioelectricity has appeared and various designs of MFC have been developed [15-22]. MFCs are bioelectrochemical systems that convert the chemical energy of organic waste into electricity. Many articles are published in this direction every year. Developers from China have especially succeeded in this direction [18, 19].

The aim of this work is to generalize and analyze the achievements in the field of creating and mastering phytoremediation technologies in combination with the generation of bioelectricity. The task was also to assess the prospects of using this technology in local treatment facilities of hotel complexes in the Baikal natural territory, in particular on Olkhon Island.

2. Objects and research methods
The authors analyzed the directions of development of innovations in the field of phytoremediation in combination with the generation of electricity with a retrospective of 5 years. The object of our own research was the waste water of hotel complexes located on Lake Baikal.

3. Results and discussion
At present, phytoremediation technologies are being used more and more in wastewater treatment. A number of extensive historical reviews of the use of phyto-treatment plants (FTP) have been published [8-13]. These works describe in detail the stages of development of this technology: from the first scientific research in Europe in the 1950s, in the USA in the late 1960s, prior to the creation of design guidelines for such systems [11]. The first active FTP system was put into operation in 1947 in Germany and the cleaning process was called the "root zone method" [13]. Today FTPs are successfully working in different countries, especially in countries with warm climates. In Russia, there is experience of using FTP in the Perm Territory, Tomsk Region, in the village of Shongui, Murmansk Region. The only bioplateau in the world beyond the Arctic Circle has been created here. Detailed information is presented in the monograph [14]. FTP are artificial systems designed and built for wastewater treatment. They are composed of elements similar to a natural natural landscape with integrated technical elements. FTP include: hydrobotanical sites, phyt-filtration devices, bioponds with specially selected plant species, artificial swamps, bioplate [14]. In FTP, plants: 1) absorb, accumulate and transform pollutants; 2) provide detoxification of pollutants; 3) enrich water with oxygen; 4) stimulate the activity of microorganisms.

It was proposed to create phytoenergetic systems by integrating the principles of MFC operation into them [1, 23, 24]. Artificial wetland FTP systems take advantage of the processes that occur naturally in wetlands. This allows treatment including filtration, plant adsorption, and aerobic / anaerobic degradation by microorganisms to be carried out. The reactions that take place in the wetland environment create aerobic and anaerobic zones. The latter are suitable for MFC operation. In these systems, organic compounds are oxidized with the release of protons and electrons. Electrons are transferred to the anode and transported through an external circuit to the cathode. Here, together with protons, they are used to reduce the acceptor (usually oxygen). MFC technology for treating a wide range of wastewater types [17-24] is still in its infancy and has not been fully developed for large-scale reactors. FTP technology is widely used to treat various types of wastewater from pilot to large-scale applications [9]. Today, a hybrid technology is proposed that combines the capabilities of phytoremediation and power generation on graphite and other electrodes.

Like MFCs, PMFCs consist of anode and cathode compartments, electrodes, microorganisms and plants. The anode and cathode compartments are usually represented by a layer of coal, or carbon material, nanofiber. It is usually made by thermal treatment of organic fibers. Graphite, activated carbon granules, fibrous materials (felt, cloth, paper, foam), glassy carbon are used as electrodes.
Microorganisms and plant roots are placed in the anode space under anaerobic conditions. The cathode is located on the surface of the system. In principle, any plant can be used in PMFC. For the operation of PMFC, the flora of wetlands or humid habitats is mainly used. Cruciferous or cereals are also used. In conventional MFC, the anode is separated from the cathode by an ion-selective membrane. There is no membrane in PMFC. Separation occurs through a layer of fine gravel or soil.

Bacteria located on the anode work in PMFC. Electrogenic microorganisms use, in particular, substances secreted by plant roots, organic substances produced as a result of photosynthesis as a nutrient substrate. The latter are removed through the roots of plants. In the anode chamber, in which anaerobic conditions are always maintained, the carbon bonds of organic matter produced by plants and microorganisms are broken. When the bonds are broken, electrons are released, which enter the electrode, and then into the cathode chamber. In the cathode compartment, which maintains aerobic conditions, oxygen acts as an electron acceptor. Electrons entering the electrode bind to oxygen molecules, then oxygen is reduced to form water. When the circuit is closed, an electrical current is generated that can be diverted.

Consequently, for the implementation of the hybrid technology, it is important to select the material of the electrodes, systems for the removal of electricity, plants and microorganisms, PMFC designs. The PMFC tested such plants as Glyceria maxima, Zizania aquatica, Spartina anglica, Eichhornia crassipes, Phragmites australis and others. It has been established that the use of plants floating on the surface of water, with the supply of oxygen to their roots, as a result of the process of photosynthesis, leads to an increase in the cathodic potential of MFC. At the same time, accordingly, the generation of electricity is growing. Root secretion, when oxygen is supplied, activates rhizosphere microorganisms that transform organic pollutants.

The preferred design of the PMFC is tubular, with an anode directly between the plant roots and an oxygen-reducing biocathode inside the tube. Oxygen can be passively supplied to the cathode through the gas diffusion layer. The electrodes are placed directly in the FTP. In this case, the maximum average daily power generation was 82 mW/m².

The hybrid technology can be used in the Baikal natural area for the treatment of waste water from hotel complexes.

**Table 1.** The rate constants for the elimination of chemically and biochemically oxidizable organic substances of the household wastewater of the hotel complex by aquatic plants growing in the bays of Lake Baikal according to the integral indicators of COD, BOD₅.

| Aquatic plant               | Elimination rate constant K, day⁻¹ by COD | BOD₅ |
|----------------------------|-----------------------------------------|------|
| Nitella sp.                | 1,05                                    | 1,12 |
| Elodea canadensis          | 0,60                                    | 2,86 |
| Ceratophyllum demersum     | 0,58                                    | 2,31 |
| Myriophyllum spicatum      | 0,40                                    | 1,89 |
| Potamogeton perfoliatus   | 0,28                                    | 1,01 |
| Sparganium gramineum      | 0,10                                    | 0,23 |
| Sagittaria natans         | 0,15                                    | 0,94 |
| No plants                 | 0,01                                    | 0,07 |

We have carried out studies to assess the phyto-purifying potential of aquatic vegetation growing directly in the bays of Lake Baikal. The selection of the most promising aquatic plants for use in FTP was carried out. In model experiments, we studied the ability of aquatic plants to utilize organic matter
from the household wastewater of a hotel complex according to the integral indicators of COD and BODs. It has been established that the total process of elimination of organic matter by aquatic plants is satisfactorily described by a first-order equation. The rate constant for the elimination of organic substances is 5-50 times higher than the value of the constants of physicochemical and microbiological destruction. The highest speeds are noted for elodea, nitella (Table 1).

It has been established that enzymes such as peroxidases play a significant role in the elimination of pollutants. Additional introduction of hydrogen peroxide significantly speeds up the process of elimination of pollutants. In the studied plants, the maximum level of peroxidase was found in *Elodea canadensis*. Thus, it has been established that aquatic plants, possessing peroxidase activity in the presence of hydrogen peroxide in water and the plants themselves, are able to effectively eliminate pollutants. In this case, the process is complex: there is an accumulation and metabolic transformations with the participation of enzymes.

4. Conclusion
The use of hybrid technology based on plant-fuel cells should contribute to solving the problems of ecological rehabilitation of the contaminated territories of the Baikal region. In places of intense recreational load, it is possible to create autonomous local treatment facilities operating on their own generated energy.

The technological system for wastewater treatment contains a filtration section sequentially located from the drain, filled with limestone with Kf = 10-20 m³ / day, a filtration module filled with dunite-based material enclosed in mesh box containers, biopond with plants – macrophytes in the form of a complex of hydatophytes, hydrophytes, helophytes. The plants recommended by us are inhabited in the biopond space, such as: hydatophyte – *Potamogeton natans* L., and hydrophytes – *Potamogeton lucens* L., *Potamogeton hictinatus* L., (rooting) and *Ceratophyllum demersum* L., *Cladophora glomerata* (non-rooting algae), – *Typha angustifolia*. The plant section itself can be supplemented with tubular electrodes.

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