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WASTEWATER TREATMENT USING MACROPHYTES: ENVIRONMENTAL BENEFITS AND ECONOMIC FEASIBILITY

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Abstract. The study evaluated the efficiency of wastewater treatment from a poultry farm using the macrophytes *Azolla caroliniana*, *Lemna minor*, and *Eichhornia crassipes*. Wastewater samples collected from a poultry farm in the Tashkent Region were studied in 20-L bioreactors for 14 days with three replicates. The reduction in concentrations of ammonium, nitrates, phosphates, biochemical oxygen demand, chemical oxygen demand, and turbidity was compared. *Azolla* demonstrated the highest efficiency in removing nutrients, while *Eichhornia* was more effective in removing organic pollutants. The possibility of further utilization of the resulting biomass and the environmental advantages of the proposed method are also considered.

Keywords: wastewater, biotechnology, phytoremediation, *Azolla caroliniana*, *Lemna minor*, *Eichhornia crassipes*, nutrients, biofilter, green economy.

INTRODUCTION. Ensuring environmental safety, rational use of natural resources, and waste reduction are among the priority areas of state policy in the Republic of Uzbekistan. The increasing volume of wastewater and the presence of nutrients (nitrates, ammonia, and phosphorus), organic substances, heavy metal ions, chemical compounds, and pathogenic microorganisms contribute to increased hydrosphere pollution, drinking water scarcity, soil degradation, and sanitary risks when discharged into the environment. Therefore, the need for environmentally safe and innovative technologies is continuously increasing.

A number of legal frameworks have been established in the country in this area. In particular, the “Concept for Environmental Protection (2021–2030),” approved by Resolution No. PP-5863, defined tasks related to wastewater treatment, the implementation of environmentally safe technologies, and the strengthening of monitoring systems [1]. In

addition, the “Strategy for the Transition to a Green Economy until 2030,” approved by Resolution No. PP-4477, provides for waste bioconversion, the widespread implementation of environmentally friendly industrial technologies, and the reuse of natural resources [2].

Biotechnological treatment systems using microorganisms, algae, biosorbents, enzymes, and bioreactors can absorb nutrients, degrade organic substances, sorb heavy metal ions, and reduce pathogen levels. These environmentally safe and cost-effective methods make it possible to simultaneously treat wastewater and obtain water suitable for reuse as well as secondary biomass [3,4].

In particular, the application of biotechnological systems at agricultural and poultry enterprises makes it possible not only to treat wastewater but also to process the resulting biomass into biofertilizers, feed additives, and substrates for biogas production [5]. Therefore, the development of biotechnological approaches to wastewater treatment, assessment of their environmental and economic efficiency, and implementation under the conditions of Uzbekistan represent a relevant scientific and practical task.

LITERATURE REVIEW AND RESEARCH METHODOLOGY

In recent years, biological treatment technologies have become one of the most promising approaches to addressing wastewater treatment problems. Compared with conventional chemical and mechanical methods, biotechnological treatment is characterized by cost-effectiveness, environmental safety, and the potential for resource recovery. Biotechnological methods accelerate the decomposition of nutrients in water, suppress pathogenic microorganisms, promote the sorption of organic pollutants, and facilitate the complexation of heavy metal ions [6].

Biotechnology employs microorganisms, enzymes, biofilters, bioreactors, macrophytes, and adsorbents. Aerobic and anaerobic biodegradation involving microorganisms enables the extensive decomposition of organic substances in wastewater, the production of biogas, and the generation of an energy source [7]. Enzymatic treatment technologies are based on the enzymatic breakdown of proteins, lipids, and polysaccharides and reduce the need for chemical reagents [8].

Phytoremediation technologies, i.e., treatment using aquatic plants, represent a particularly accessible and effective solution for agriculture. *Eichhornia*, *Lemna minor*, *Spirodela polyrrhiza*, and *Azolla caroliniana* are capable of absorbing ammonia, nitrates, phosphates, phenols, fats, and heavy metals present in water [9]. An important advantage of macrophytes is the biological fixation of atmospheric nitrogen, which contributes to reducing nitrogen pollution in water [10,12].

The cyanobacterium *Anabaena azollae*, which lives in symbiosis with species of *Azolla*, converts atmospheric molecular nitrogen (N_2) into an ammonium form. Therefore, macrophytes not only purify contaminated water but also produce biomass suitable for subsequent reuse. This biomass can be used as biofertilizer, animal feed, or a substrate for biogas production [11]. Thus, biotechnology makes it possible to combine wastewater treatment with resource recovery within a “green economy” model. Among macrophytes, *Azolla* is of particular importance due to its symbiotic relationship with *Anabaena azollae*. According to the reported data, these microorganisms fix atmospheric N_2 , while the

concentration of ammonium nitrogen in wastewater decreases by 80–90% [12]. The rapid growth of *Azolla* also makes it an effective phytoremediator, with its biomass doubling within 3–5 days [13].

Azolla-based bioremediation systems not only enable water purification but also allow the resulting biomass to be utilized. It can be used as a feed additive (containing 20–30% crude protein), a biofertilizer (rich in NPK), and a substrate for biogas production [14]. Thus, *Azolla*-based technologies contribute both to environmentally friendly wastewater treatment and to the production of economically valuable renewable resources.

Table 1

Comparison of Wastewater Treatment Methods [15–18]

Treatment Method	Technology Used	Advantages	Disadvantages
Mechanical Treatment	Filtration, screens, sedimentation, sand filters	Low cost, simple operation, low energy requirements	Does not remove dissolved ions (NH_4^+ , NO_3^- , PO_4^{3-})
Chemical Treatment	Coagulants (FeCl_3 , $\text{Al}_2(\text{SO}_4)_3$), flocculants, oxidizing agents (O_3 , Cl_2)	Rapid results, effective reduction of microorganisms	High cost of chemical reagents, secondary pollution
Physicochemical Treatment	Adsorption (activated carbon), ion exchange, membrane filtration (UF, NF, RO)	High treatment efficiency, removal of heavy metals and ions	High cost and energy consumption
Biological Treatment	Biodegradation by microorganisms, aerobic and anaerobic reactors, macrophytes (<i>Azolla</i> , <i>Lemna</i> , <i>Eichhornia</i>), biofilters	Environmentally friendly and cost-effective; generation of a secondary resource (biomass)	Relatively slow process; dependent on environmental conditions (temperature, pH)

Over the past 20–25 years, phytoremediation using macrophytes (aquatic plants) has become one of the fastest-growing areas of biological wastewater treatment worldwide. *Azolla*, *Lemna minor*, *Eichhornia crassipes*, *Spirodela polyrrhiza*, *Chlorella*, and *Spirulina* are used for wastewater treatment; atmospheric nitrogen fixation and the uptake of phosphorus and heavy metal ions contribute to the high efficiency of the process.

At present, phytoremediation is applied in more than 70 countries, including China, India, Brazil, Hungary, the United States, Australia, the Netherlands, Egypt, Thailand, and Indonesia.

Table 2

Global Trends in the Adoption of Phytoremediation (2000–2024) [19, 20]

Year	Number of Countries Applying Phytoremediation	Share in Wastewater Treatment (%)	Number of Scientific Publications (Scopus/Web)
2000	12	1,2	95
2005	19	2,8	210
2010	33	5,7	465
2015	48	9,4	870

Year	Number of Countries Applying Phytoremediation	Share in Wastewater Treatment (%)	Number of Scientific Publications (Scopus/Web)
2020	63	14,0	1 920
2023	71	17,3	2 870
2024	75 (forecast)	18,5	More than 3,200 (estimate)

From 2000 to 2024, the number of scientific publications on phytoremediation increased 33-fold, while the scale of its application increased 15.4-fold.

The study objects included wastewater samples from a poultry complex in the Tashkent Region and aquatic plants used for their biotechnological treatment. Three species of macrophytes were used as biocomponents: *Azolla caroliniana* was obtained from the “Algae Collection” of the Natural Sciences Research Center of the Academy of Sciences of the Republic of Uzbekistan and adapted under laboratory conditions; *Lemna minor* (common duckweed) was collected from a local water body and re-adapted in purified water; *Eichhornia crassipes* (water hyacinth) was obtained from a collection cultivated in an artificial aquaponic system and adapted to the experimental conditions. The biological characteristics of these plants, their ability to reproduce rapidly, and their potential to absorb pollutants determined their selection for the study.

The initial composition of the wastewater samples was assessed based on physicochemical and biological parameters. The pH value was determined using a pH meter. The concentration of ammonium ions (NH_4^+) was determined using the classical Nessler colorimetric method, while the concentration of nitrates (NO_3^-) was measured by UV spectrophotometry. The phosphate (PO_4^{3-}) content was determined using a colorimetric method based on the vanadate–molybdate reaction. The content of organic substances was assessed by biochemical oxygen demand (BOD) using the Winkler method and chemical oxygen demand (COD) using oxidation with potassium dichromate. Turbidity was determined using a turbidimeter by assessing the degree of light scattering by fine particles suspended in the water.

All analyses were performed under laboratory conditions in compliance with sanitary requirements. Each measurement was repeated at least three times, and mean values were calculated. The results were processed using statistical methods, and measurement uncertainty was estimated to be within $\pm 5\%$. The initial analyses revealed high concentrations of nutrients in the wastewater and confirmed the need for biological treatment.

Table 3

Adaptation conditions for aquatic plants

№	Parameter	Value
1	Temperature	$25 \pm 2^\circ\text{C}$
2	Light intensity	2500–3000 lx
3	Relative humidity	70–80 %
4	NPK in the aquatic medium	5 mg/L

All plants were adapted for 3–5 days under the specified conditions. The initial biomass was evenly distributed over the water surface at the following amounts: *Azolla* — 0.5 kg/m², *Lemna* — 0.3 kg/m², *Eichhornia* — 0.4 kg/m².

Wastewater treatment was carried out in artificial biobasins with a volume of 20 L.

Table 4

Experimental variants

№	Variant	Brief Description
V0	Control	Wastewater without plants
V1	<i>Azolla</i>	Wastewater + <i>Azolla caroliniana</i>
V2	<i>Lemna</i>	Wastewater + <i>Lemna minor</i>
V3	<i>Eichhornia</i>	Wastewater + <i>Eichhornia crassipes</i>
V4	Mixture	Wastewater + a mixture of <i>Azolla</i> , <i>Lemna</i> , and <i>Eichhornia</i>

Each variant was conducted in triplicate (n = 3). The duration of the experiment was 14 days.

RESULTS AND DISCUSSION

The results showed that the efficiency of biological treatment of poultry wastewater using macrophytes varied considerably depending on the plant species. During the 14-day experiment, the ability of *Azolla caroliniana*, *Lemna minor*, and *Eichhornia crassipes* to reduce the concentrations of major pollutants (NH₄⁺, NO₃⁻, PO₄³⁻), BOD and COD values, as well as turbidity, was compared.

Overall, *Azolla caroliniana* demonstrated the highest efficiency in the uptake of nutrients (N and P) from wastewater. This is associated with the symbiotic cyanobacterium *Anabaena azollae* present in the plant tissues and the assimilation of nitrogen compounds. *Lemna minor* showed good results mainly in the uptake of nitrates and organic substances, while *Eichhornia crassipes* exhibited a high potential for reducing BOD and COD due to its well-developed root system, which ensures intensive biosorption of dissolved organic substances.

Table 5

Comparative removal efficiency of major pollutants (%)

Parameter	<i>Azolla</i> (%)	<i>Lemna</i> (%)	<i>Eichhornia</i> (%)
Ammonium (NH ₄ ⁺)	81–85	68–72	58–65
Nitrate (NO ₃ ⁻)	80–82	73–76	61–67
Phosphate (PO ₄ ³⁻)	78–80	65–69	57–62
BOD	75–80	62–70	78–84
COD	74–79	60–68	80–86
Turbidity	76–82	70–75	65–72

The results show that *Azolla caroliniana* has the highest capacity for removing nutrient pollutants, particularly nitrogen and phosphorus compounds. *Eichhornia crassipes* is more effective in reducing chemical oxygen demand (COD) and removing organic substances. *Lemna minor* showed intermediate results and, as a biofilter, contributes to comprehensive wastewater treatment.

CONCLUSION

The conducted studies showed that biotechnological treatment of poultry wastewater using the macrophytes *Azolla caroliniana*, *Lemna minor*, and *Eichhornia crassipes* represents a “green technology” with high environmental and economic efficiency. *Azolla* provided the highest removal of nutrients (NH_4^+ , NO_3^- , PO_4^{3-}), *Eichhornia* contributed to the removal of organic pollutants and the reduction of BOD and COD, while *Lemna* functioned as a stable biofilter in the integrated treatment system. The application of macrophytes reduced pollutant concentrations by 60–90%; the natural character of the process did not require additional energy consumption.

A major advantage of biological phytoremediation is a 70–85% reduction in operating costs and an 80–95% reduction in energy consumption. As a result, the cost of treating 1 m³ of water amounts to 300–600 UZS, which is 4–8 times lower than that of chemical, aeration, and membrane treatment methods. Processing the resulting biomass into feed, biofertilizer, and a substrate for biogas production also makes it possible to obtain additional products of economic value.

Thus, biotechnological wastewater treatment using macrophytes under the conditions of Uzbekistan represents an environmentally sustainable, energy-efficient, and economically beneficial solution. Its widespread implementation at small and medium-sized industrial enterprises is considered appropriate.

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