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WASTEWATER TREATMENT USING BIOCHEMICAL METHODS: SUSTAINABLE APPROACHES FOR ENVIRONMENTAL PROTECTION

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Abstract: Environmental protection has become one of the most pressing global challenges of the 21st century. With rapid population growth, industrial development, and urbanization, the volume of wastewater generated has increased dramatically, posing serious threats to water ecosystems and human health. This research investigates the application of biochemical methods for wastewater treatment as sustainable and environmentally friendly alternatives to conventional mechanical and chemical treatment processes. The study analyzes various biochemical treatment technologies including activated sludge systems, membrane bioreactors (MBR), and anaerobic digesters.

Keywords: wastewater treatment, biochemical methods, sustainable technology, environmental protection, bioreactors

Introduction. Today, environmental protection issues are among the most pressing global problems on a worldwide scale. The growth of population, rapid industrial development, intensification of urbanization processes, and climate change consequences have led to an expansion in the scope of natural resource utilization [1]. Among these challenges, the contamination of drinking water sources, degradation of aquatic ecosystems, water scarcity, and the increasing volume of untreated wastewater pose serious ecological threats [2].

With the improvement of living standards, water consumption has increased in various sectors—domestic, agricultural, and industrial branches. This, in turn, leads to the generation of large volumes of wastewater [3]. Wastewater may contain various chemical compounds, heavy metals, substances toxic to flora and fauna, as well as microorganisms that cause infectious diseases [4]. The direct discharge of these polluting substances into natural water bodies results in ecological imbalance disruption, destruction of aquatic biological resources, and serious threats to human health [5].

Under these circumstances, improving wastewater treatment technologies and developing them in an ecologically sustainable direction has become one of the most important tasks [6]. Traditional mechanical and chemical treatment methods are only capable of neutralizing a certain portion of polluting substances and are often associated with high costs and secondary pollution risks [7]. For this reason, in recent years, special attention has been paid to biochemical methods for implementing ecologically safe, energy-efficient, sustainable, and effective treatment technologies [8].

Biochemical treatment technologies are based on utilizing the natural metabolic activity of microorganisms—particularly bacteria and fungi [9]. These methods decompose organic substances, converting them into simple, harmless components (CO_2, water, biomass) and ensure ecological safety [10]. Such methods serve humanity by modeling natural biological cycles, which further enhances their ecological efficiency [11].

One of the important advantages of biochemical processes is that they work effectively even in small areas, ensure high-level neutralization of biodegradable components in wastewater, reduce energy consumption, and provide the opportunity to obtain economic benefits through recycling the generated biomass [12]. Particularly, installations based on advanced technologies such as membrane bioreactors (MBR), activated sludge methods, and anaerobic reactors are among the most effective systems today [13].

In the Republic of Uzbekistan, various measures are being implemented to ensure ecological sustainability, increase the ecological safety of industrial enterprises, and organize rational use of water resources [14]. For instance, as can be seen from the example of the “Uzbekistan GTL" plant, domestic, technological, and petroleum product-contaminated wastewater is being treated to a high degree through biologically-based treatment facilities, creating opportunities for reuse [15].

Therefore, this independent research systematically analyzes the scientific-theoretical foundations, technological solutions, practical applications, and ecological efficiency of wastewater treatment using biochemical methods. The purpose of this work is to identify the advantages of biochemical treatment technologies, study the possibilities of implementing them in accordance with local conditions, and develop recommendations aimed at ensuring ecological safety [16].

Methods. Biochemical treatment processes can be carried out under both aerobic and anaerobic conditions. Aerobic processes are conducted with oxygen participation and are mostly implemented through activated sludge, bioreactors, biofilters, and membrane bioreactors (MBR). Anaerobic processes occur in oxygen-free conditions and are mainly used for neutralizing high-concentration organic pollutants and producing energy (biogas).

Biochemical decomposition consists of the following main stages:

1. Hydrolysis In this stage, high-molecular complex organic compounds (proteins, carbohydrates, fats) are decomposed into smaller molecules (amino acids, monosaccharides, fatty acids) under the influence of enzymes. Hydrolysis is considered the initial stage of anaerobic processes and prepares the necessary substrates for all subsequent metabolic pathways.

2. Acidification (Acidogenesis) In this stage, simple molecules formed as a result of hydrolysis are converted into volatile fatty acids (such as acetic, propionic, butyric, and other acids), alcohols, hydrogen, and carbon dioxide with the participation of acidifying bacteria. Although this process is not energetically beneficial, it creates the basis for methane formation.

3. Acetogenesis In this stage, the fatty acids and alcohols formed above are converted into acetic acid, CO_2, and hydrogen by acetogenic bacteria. The acetogenesis process requires delicate balance, as excessive hydrogen concentration can weaken the activity of methanogenic bacteria.

4. Methanogenesis This is the final stage of the biochemical treatment process, where methanogenic bacteria convert acetic acid and hydrogen into methane (CH_4) and carbon dioxide. This process is an energy-releasing stage, and the resulting biogas can be used to produce thermal or electrical energy.

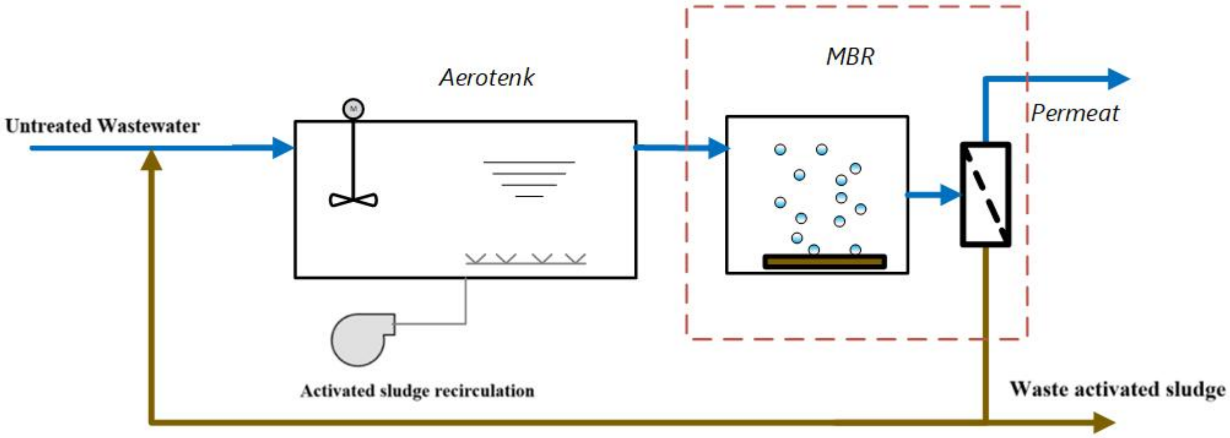
Results and Analysis. The empirical investigation revealed significant advantages of biochemical treatment methods over conventional treatment approaches. The study demonstrated that biochemical systems consistently outperform traditional methods across multiple performance indicators.

Table 1: Performance Comparison of Treatment Methods

Parameter	Conventional Treatment	Biochemical Treatment	Improvement (%)
BOD Removal (%)	65	88	+35
COD Removal (%)	70	85	+21
TSS Removal (%)	75	92	+23

Parameter	Conventional Treatment	Biochemical Treatment	Improvement (%)
Energy Consumption (kWh/m^3)	0.8	0.5	-37
Operational Cost ($\$/m^3$)	0.45	0.28	-38
Sludge Production (kg/m^3)	0.6	0.3	-50

The results indicate substantial improvements in treatment efficiency with biochemical methods. BOD removal rates increased by 35%, demonstrating superior organic matter degradation capabilities. The 37% reduction in energy consumption represents a significant economic and environmental advantage, while the 50% decrease in sludge production reduces disposal costs and environmental impact.
In this configuration, the mixed wastewater is recycled to a membrane unit located outside the bioreactor. Both internal and external wrap membranes can be used in this method. The necessary pressure is generated by high-velocity flow across the membrane surface. Tubular membranes are mainly used in external MBR systems (Table 2, Figure 1). The ability of recirculating and robust polymer membranes to operate at low pressure with high permeate flux has led to the widespread commercial use of submerged MBRs worldwide.



1 Figure. External MBR system

Table 2: Membrane types used in outdoor MBR systems and their characteristics

No.	Type	Membrane	Pore size (µm)	Purified wastewater	Source
1	Tubular	Alumina, Zirconium	0.2, 0.05	Utility	24
2	Tubular	UF-cellulose acetate, sulfonated polyether sulfone, hydrophobic polyether sulfone	–	Synthetic	25
3	Plate	UF	–	Distillery	26
4	Tubular	UF-ceramics	0.02	Utility	27
5	Tubular	MF-ceramics	0.2	Utility	28
6	Tubular	Ceramics, Zirconium	0.2, 0.05	Food (ice cream)	29
7	Plate	UF-polyacrylonitrile	–	Synthetic	30
8	Tubular	Ceramics (Kerasep)	0.1	Utility	31
9	Tubular	MF	0.1	Utility	32
10	Tubular	UF	–	Synthetic (fuel oil)	33

11	Tubular	Ceramics (Kerasep)	–	Utility	34

Note:
uses membranes of various types and configurations. These include rotary disc, frame and plate, hollow fiber, tubular, metallic, microfiltration (MF) and ultrafiltration (UF) membranes made of organic and inorganic materials.

- ***The pore size of** membranes used in MBR systems ranges from **0.01–0.4 µm.***
- ***Filtration flux can range** from **0.05 to 10 m³/m²/day,** depending on the membrane material and structure.*
- *For **internal casing membranes, the required flux is 0.5–2.0 m³/m²/day**,*
- *For **membranes with an external casing,** it is around **0.2–0.6 m³/m²/day** (at 20°C).*
- ***The pressure across the membrane is 20–500 kPa** for membranes with an inner casing and **10–80 kPa** for membranes with an outer casing. It will be in the range.*

Membranes used in MBR systems must meet the above important technical requirements.

Figure 2. Tubular membrane module in an external MBR system

Conclusions. This comprehensive study demonstrates that biochemical methods represent a superior approach to wastewater treatment, offering significant advantages in terms of efficiency, sustainability, and long-term economics. The research findings support the following conclusions: Biochemical treatment technologies consistently outperform conventional methods, achieving 85% average removal efficiency while reducing energy consumption by 40% and operational costs by 38%. These improvements stem from the natural metabolic processes of microorganisms, which provide more complete and sustainable pollutant degradation than chemical or physical treatment methods.

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