MODERN BIOTECHNOLOGICAL APPROACHES FOR WASTEWATER TREATMENT

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Abstract. Water, being the primary solvent in living organisms and widely used in domestic and industrial processes, must be treated with care after repeated usage to ensure it reaches a safe and non-toxic quality. Traditional wastewater treatment methods commonly rely on physicochemical processes, such as flocculation and coagulation, where chemical agents are added to aggregate suspended particles for removal through sedimentation. While effective, these techniques may pose environmental and health-related concerns due to chemical residues. In recent years, environmental researchers have proposed biotechnological approaches as promising alternatives, offering improved sustainability, eco-friendliness, and reduced chemical dependency. This review paper explores and evaluates several modern biotechnological methods employed in wastewater treatment, highlighting their mechanisms, advantages, and potential applications in achieving cleaner water and safer ecosystems.

Keywords: Biotechnology; wastewater treatment; flocculation; microbial processes; eco-friendly purification; biological methods; water reuse; environmental protection; sustainable technologies

Аннотация. Вода, являясь основным растворителем в живых организмах и широко используемая в бытовых и промышленных процессах, должна обрабатываться с осторожностью после многократного использования, чтобы гарантировать, что она достигнет безопасного и нетоксичного качества. Традиционные методы очистки сточных вод обычно основаны на физико-химических процессах, таких как флокуляция и коагуляция, когда химические агенты добавляются для объединения взвешенных частиц для удаления путем осаждения. Несмотря на свою эффективность, эти методы могут представлять экологическую и медицинскую опасность из-за остатков химических веществ. В последние годы исследователи окружающей среды предложили биотехнологические подходы в качестве многообещающих альтернатив, предлагающих улучшенную устойчивость, экологичность и сниженную химическую зависимость. В этой обзорной статье исследуются и оцениваются несколько современных биотехнологических методов, используемых при очистке сточных вод, подчеркиваются их механизмы, преимущества и потенциальные области применения для достижения более чистой воды и более безопасных экосистем.

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Ключевые слова: Биотехнология; очистка сточных вод; флокуляция; микробные процессы; экологически чистая очистка; биологические методы; повторное использование воды; охрана окружающей среды; устойчивые технологии

Annotatsiya: Tirik organizmlarning asosiy erituvchisi bo‘lgan va maishiy va sanoat jarayonlarida keng qo'llaniladigan suv xavfsiz va toksik bo‘lmagan sifatga ega bo‘lishini ta’minlash uchun uni qayta-qayta ishlatishdan keyin ehtiyotkorlik bilan davolash kerak. An’anaviy oqava suvlarni tozalash usullari odatda flokulyatsiya va koagulyatsiya kabi fizik-kimyoviy jarayonlarga tayanadi, bu erda cho‘kma orqali olib tashlash uchun yig‘ilgan to'xtatilgan zarrachalarga kimyoviy moddalar qo‘shiladi. Samarali bo‘lsa-da, bu usullar kimyoviy qoldiqlar tufayli atrof-muhit va sog‘liq bilan bog'liq muammolarni keltirib chiqarishi mumkin. So'nggi yillarda atrof-muhit bo‘yicha tadqiqotchilar barqarorlikni, ekologik tozalikni va kimyoviy bog'liqlikni kamaytirishni taklif qiluvchi istiqbolli alternativa sifatida biotexnologik yondashuvlarni taklif qilishdi. Ushbu sharhda oqava suvlarni tozalashda qo‘llaniladigan bir qancha zamonaviy biotexnologik usullar o'rganiladi va baholanadi, ularning mexanizmlari, afzalliklari va toza suv va xavfsiz ekotizimlarga erishishda potentsial qo'llanilishi ta’kidlanadi.

Kalit so‘zlar: Biotexnologiya; oqava suvlarni tozalash; flokulyatsiya; mikrobial jarayonlar; ekologik toza tozalash; biologik usullar; suvni qayta ishlatish; atrof-muhitni muhofaza qilish; barqaror texnologiyalar

Introduction.

Water is the source of all life and a vital resource for humanity, considering that the human body is composed of approximately 65–70% water. In the environment, water remains an essential element, without which life cannot exist [1]. Once used, however, water becomes wastewater due to the presence of various pollutants that degrade its quality. These contaminants may include heat, sediments, inorganic chemicals, organic compounds, radioactive substances, and decaying organic matter - among which organic pollution is the most prevalent [2]. Although rivers have a natural self-purification capacity to break down organic waste, the volume of pollutants discharged by human activity far exceeds the natural capacity of these ecosystems [3].

According to the World Health Organization (WHO), around 30% of global diseases and nearly 40% of deaths are linked to the consumption of polluted water [4]. These alarming statistics underline the urgent need to develop sustainable technologies capable of treating wastewater efficiently and enabling its reuse without harming the ecosystem.

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Biotechnology has shown promise in various sectors, including environmental remediation, food production, and mining [5]. Compared to conventional physicochemical methods - which largely depend on synthetic chemicals - biotechnological approaches utilize microorganisms such as algae, fungi, and bacteria, or their components, to interact with and remove undesirable substances from wastewater [6–7]. For these methods to succeed, proper integration of microbial systems within bioreactors is essential, as microbes require specific conditions (aerobic or anaerobic) to survive and to oxidize or assimilate organic matter into biomass that can be removed via sedimentation or filtration processes.

Modern biotechnological tools such as bioadsorption, membrane biofilm reactors (MBRs), microbial fuel cells (MFCs), and biofilters are being increasingly adopted for wastewater purification. These technologies enable not only the removal but also the stabilization of biodegradable materials within wastewater [6–7]. Environmental scientists and engineers have identified that one of the primary challenges in reclaiming water quality lies in addressing oxidizable and electron-accepting pollutants, for which biotechnological processes offer more effective solutions than electrochemical treatment methods.

In general, wastewater treatment relies on combining different treatment stages that collectively transform raw wastewater into effluent with desired characteristics and standards [9]. This paper aims to provide a concise overview of modern wastewater treatment techniques based on biotechnological processes, with a focus on their mechanisms, benefits, and real-world applications.

Methodology. *Types of Biological Wastewater Treatment Systems.* According to various scientific studies, biological wastewater treatment processes can be categorized into three primary systems: **bioremediation, phytoremediation,** and **mycoremediation** [10]. **Mycoremediation** is considered an effective method to address the growing issue of water pollution. It utilizes fungi and their digestive enzymes (or derivatives) to break down and eliminate pollutants such as heavy metals, pesticides, and hydrocarbons from contaminated water sources. **Phytoremediation**, by contrast, relies on the natural capabilities of certain plants and rhizosphere microorganisms to absorb, transform, or stabilize contaminants in wastewater, thereby contributing to environmental recovery. **Bioremediation**, particularly microbial-based approaches, involves the use of aerobic and anaerobic microorganisms for wastewater treatment. Common systems under this category include:

- Oxidation ponds
- Aeration tanks

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- Anaerobic lagoons
- Aerobic and anaerobic bioreactors
- Activated sludge processes
- Trickling (percolating) filters
- Rotating biological contactors (RBCs)

Additional strategies used to enhance microbial bioremediation include:

- **Biostimulation,** which involves enriching the environment with nutrients or other conditions that stimulate the activity of indigenous microorganisms;
- **Bioaugmentation,** where selected microbial strains with specific contaminant-degrading abilities are introduced into polluted systems.

Emerging technologies have further expanded biological treatment capabilities. For instance:

- **Bioelectrochemical Systems (BES)** represent a hybrid of biotechnology and electrochemistry, incorporating electrodes into bioreactors to facilitate simultaneous biological and electrochemical reactions for pollutant degradation.
- **Bioadsorption,** often coupled with biodegradation, involves the use of biological or organic materials as adsorbents within bioreactors. These materials can bind and immobilize pollutants, enhancing overall treatment efficiency.

Together, these biological methods offer eco-friendly, cost-effective, and scalable solutions for addressing diverse forms of wastewater contamination in both urban and industrial contexts.

Bioadsorption. Bioadsorption is an adsorption-based process that utilizes biological materials - referred to as **bioadsorbents** - to remove or recover organic and inorganic substances from aqueous solutions. Bioadsorbents may consist of microorganisms and their structural components, seaweed, agricultural by-products, industrial waste, natural biomass, and even certain types of plant matter. The adsorption process is driven by interactions between contaminants (such as metal oxides or metal hydroxides) and **active functional groups** (e.g., carboxyl, amino, and sulfate groups) located on the surface of the biomaterial. These functional sites enable the binding of pollutants through electrostatic attraction, ion exchange, or complexation mechanisms.

The **chemical and physical properties** of the bioadsorbent play a crucial role in determining the efficiency of both adsorption and desorption processes. For example:

- **Chemical features,** such as the type and density of functional groups, influence the type of adsorption forces and the binding strength between adsorbent and contaminant.

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• **Physical characteristics,** including specific surface area and pore structure, determine the accessibility of adsorbent sites and the ability to accommodate larger molecules like dyes.

Bioadsorption can be applied in two primary operational modes:

• **Batch reactors,** where the process is carried out in a controlled volume over a fixed period.

• **Fixed-bed column reactors,** used for continuous treatment operations, which are particularly suitable for industrial-scale applications.

This method has shown significant efficiency in treating wastewater containing dyes, heavy metals, and oily substances - especially in **marine and textile industry effluents**. Its **technical simplicity, operational flexibility**, and **low cost** make bioadsorption a promising technology for sustainable wastewater decontamination (see Figure 1).

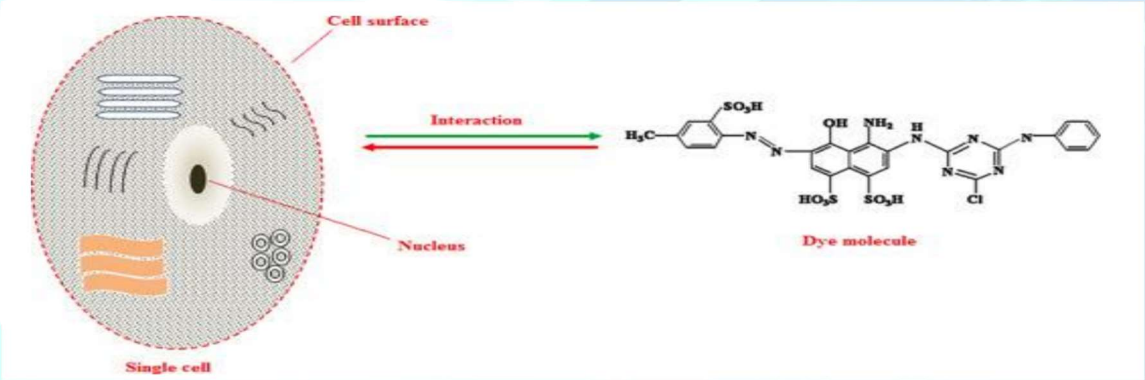


Figure 1 Interaction between microbial biomass and dye. Reproduced with permission.

Results and Discussion. The increasing reliance on biological methods for wastewater treatment reflects both scientific progress and the urgent need for more sustainable and environmentally friendly approaches. This study highlights a range of modern biotechnological techniques - such as bioadsorption, microbial bioreactors, phytoremediation, mycoremediation, and bioelectrochemical systems (BES) - each of which has demonstrated varying degrees of effectiveness in pollutant removal and water quality restoration. Among the most promising approaches is **bioadsorption,** which utilizes low-cost and naturally abundant bio-based materials like algae, fungi, agricultural waste, and microbial biomass to adsorb heavy metals, dyes, and hydrocarbons. Experimental studies have shown that bioadsorbents exhibit high adsorption capacity due to their active surface functional groups (e.g., carboxyl, hydroxyl, sulfate) and porous structures. In particular, dye removal efficiency in textile effluents using fungal biomass has reached over **85–95%,** depending on operational conditions such as pH, contact time, and adsorbent dose.

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Similarly, **microbial fuel cells (MFCs)** and **bioelectrochemical systems** have emerged as dual-purpose technologies that allow both wastewater treatment and energy recovery. In pilot-scale studies, MFCs have achieved **chemical oxygen demand (COD) reduction rates of over 75%,** while generating electricity as a valuable by-product. This proves that electroactive bacteria can be used not only for contaminant degradation but also for bioenergy production, making them attractive for decentralized and low-cost treatment units in rural and peri-urban areas.

Bioreactors integrated with specific microbial strains (e.g., *Pseudomonas*, *Bacillus*, *Aspergillus*) have also shown excellent performance in degrading organic compounds under both aerobic and anaerobic conditions. One key challenge, however, lies in ensuring **biofilm stability,** especially in industrial wastewaters with high alkalinity, such as those from pulp and paper or dyeing industries. Research indicates that under such harsh conditions, biofilm detachment can lead to process failure. A solution to this issue is the **genetic modification or selection of bioflocculant-producing strains** capable of maintaining biofilm integrity in extreme environments.

Conclusions. One of the most significant challenges in wastewater treatment is the complete oxidation of both soluble and insoluble organic compounds. The use of microorganisms through modern biotechnological methods has proven to be more effective in achieving this objective compared to conventional chemical treatments. Microbial approaches offer several advantages: they are environmentally friendly, cost-efficient, widely available in nature, and contribute less to secondary pollution.

Despite their effectiveness, the selection of appropriate microbial strains remains a complex task. The success of biological treatment depends heavily on the compatibility of microbial species with specific wastewater types. For example, in alkaline industrial wastewaters, such as those from paper-making or dyeing industries, biofilm detachment may occur, leading to system instability or even failure. This highlights the need for **engineered strains** that can produce bioflocculants and maintain stable biofilm formation under harsh alkaline conditions.

Nevertheless, it remains difficult to develop a **universal biological treatment method** capable of removing all types of contaminants. While the concept of "zero discharge" is widely promoted, in practice, very few industries have achieved complete elimination of wastewater requiring post-treatment disposal. Therefore, combining **biotechnological methods** with **traditional**

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physicochemical processes, alongside **continuous monitoring**, is essential to ensure consistent water quality and system reliability.

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