METHODS FOR REMOVING DYE SUBSTANCES FROM WASTEWATER

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Abstract. This work examines dye substances found in wastewater and their environmental hazards. It analyzes the effectiveness of major physical, chemical, and biological methods used in the treatment of dye-contaminated wastewater, including adsorption, coagulation–flocculation, oxidative technologies (Fenton process, ozonation, photocatalysis), membrane technologies, and bioremediation methods. By comparing these techniques, their advantages, limitations, and practical application possibilities are highlighted. The study provides a scientific and practical basis for restoring dye-polluted water to an environmentally safe state and implementing modern treatment technologies in industrial enterprises.

Keywords: Wastewater, Dye substances, Adsorption, Coagulation and flocculation, Photocatalysis, Fenton process, Membrane filtration, Ozonation.

Annotatsiya. Ushbu ish oqava suvlarda uchraydigan bo'yoq moddalari va ularning ekologik xavflarini o'rganadi. Unda bo'yoq bilan ifloslangan oqava suvlarni tozalashda qo'llaniladigan asosiy fizik, kimyoviy va biologik usullarning, jumladan, adsorbsiya, koagulyatsiya-flokulyatsiya, oksidlovchi texnologiyalar (Fenton jarayoni, ozonlash, fotokataliz), membrana texnologiyalari va bioremediatsiya usullarining samaradorligi tahlil qilinadi. Ushbu usullarni taqqoslash orqali ularning afzalliklari, cheklovlari va amaliy qo'llanilish imkoniyatlari ta'kidlanadi. Tadqiqot bo'yoq bilan ifloslangan suvni ekologik xavfsiz holatga qaytarish va sanoat korxonalarida zamonaviy tozalash texnologiyalarini joriy etish uchun ilmiy va amaliy asos yaratadi.

Kalit so‘zlar: Oqova suvlar, Bo'yoq moddalari, Adsorbsiya, Koagulyatsiya va flokulyatsiya, Fotokataliz, Fenton jarayoni, Membran filtratsiyasi, Ozonlash.

Аннотация. В данной работе исследуются красители, содержащиеся в сточных водах, и их экологическая опасность. Анализируется эффективность основных физических, химических и биологических методов, используемых для очистки загрязненных красителями сточных вод, включая адсорбцию, коагуляцию-флокуляцию, окислительные технологии (процесс Фентона, озонирование, фотокатализ), мембранные технологии и методы биоремедиации. Путем сравнения этих методов выявляются их преимущества, ограничения и возможности практического применения. Исследование предоставляет научную и практическую основу для восстановления экологически безопасного состояния загрязненной

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красителями воды и внедрения современных технологий очистки на промышленных предприятиях.

Ключевые слова: Сточные воды, Красители, Адсорбция, Коагуляция и флокуляция, Фотокатализ, Процесс Фентона, Мембранная фильтрация, Озонирование.

Introduction.

Water is the source of life. It has no alternative. Today, water and water-use problems have become increasingly important not only around the world but also in the Central Asian countries, standing among the major ecological issues of recent years.

As a result of rapid industrial development, large volumes of colored wastewater are generated from textile, leather-footwear, paper, food, and chemical industries. These wastewater streams contain various organic and inorganic dyes, heavy metals, surfactants, and other harmful components that pose significant threats to the environment and human health. Therefore, the efficient removal of dye substances from wastewater is one of the key directions of environmental safety.

The removal of dyes from wastewater is a crucial and complex task for both ecology and industry. This process involves chemical, physico-chemical, and biological methods, through which dyes are separated using adsorption, coagulation, membrane techniques, oxidation-reduction reactions, and microorganisms. As a result, water pollution is reduced, and the possibility of water reuse is increased.

Wastewater from the Printing and Dyeing Industry. The printing and dyeing industry consumes a large amount of water; typically, processing 1 ton of textile products requires 100–200 tons of water. About **80–90%** of this water is discharged as wastewater from printing and dyeing operations. Common management methods include recycling and safe treatment.

Recycling. Wastewater can be bleached and purified, and depending on the characteristics of the wastewater—such as printing and dyeing effluents—it can be separated, treated, and reused. The first stage can be rinsed through convection. To reduce emissions, the same water may be used for multiple purposes. Alkali recovery and reuse generally employ evaporation techniques. If the alkalinity level is high, it can be recovered through triple-effect evaporation. If the alkalinity level is low, thin-film evaporation can be used for recovery.

Recovery of Dyes. For example, Shilin dyes can be acidified to form colloidal particles and produce a precipitated resinous acid suspended in the

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remaining solution. After precipitation and filtration, these dyes can be recovered and reused.

Safe treatment can be divided into several categories: There are physical treatment methods such as precipitation and adsorption. The precipitation method mainly removes suspended solids from wastewater. The adsorption method is mainly used to remove dissolved pollutants and to decolorize wastewater.

Chemical treatment methods include neutralization, coagulation, and oxidation. The neutralization method consists of regulating the acidity and alkalinity of wastewater, and it can also reduce the chromaticity of the effluent. The coagulation method is used to remove dispersed dyes and colloidal substances from wastewater. The oxidation method involves the oxidation of reducing agents in wastewater, including the precipitation of sulfides and the treatment of reducing dyes.

Biological treatment methods include activated sludge, biological trickling filters, biological rotating discs, and biological contact oxidation. To improve the quality of wastewater and meet discharge standards or recycling requirements, it is often necessary to use multiple treatment methods in combination.

Wastewater in the Paper Industry: Wastewater from paper production mainly originates from the two major processes in the pulp and paper industry: pulping and papermaking. Pulping refers to extracting fibers from plant raw materials, preparing pulp, and then bleaching it. Papermaking is the process of diluting pulp, forming it into sheets, pressing, and drying it to produce paper.both processes generate large amounts of wastewater.

Textile wastewater contains a wide range of harmful chemical substances such as dyes, bleaching agents, heavy metals, surfactants, and other toxic components. If these substances are discharged into natural water bodies, they negatively affect ecosystems, degrade water quality, harm human and animal health, and lead to long-term environmental consequences. So, what is the solution to these problems?

Wastewater discharged from factories and enterprises must first be treated at their own primary (local) treatment facilities. For example, wastewater from textile factories contains hexavalent chromium, which kills microorganisms in treatment facilities, drastically reducing the efficiency of biological purification.

METHODS.

This study employed a comparative analytical methodology to evaluate the effectiveness of major physical, chemical, and biological methods for removing dye substances from wastewater. The research was conducted based on an

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extensive literature review, analysis of industrial wastewater treatment practices, and reported experimental results from recent scientific publications

The selected treatment methods included adsorption, coagulation–flocculation, advanced oxidation processes (AOPs) such as the Fenton process, ozonation, and photocatalysis, as well as membrane filtration and biological treatment methods. These techniques were analyzed under comparable conditions, focusing on parameters such as dye removal efficiency, operational complexity, environmental impact, and economic feasibility.

For adsorption studies, materials such as activated carbon and low-cost adsorbents were considered, evaluating their capacity to remove dissolved dyes from aqueous solutions. Chemical treatment methods were assessed based on their ability to destabilize and remove dye molecules through coagulation and oxidative degradation. Biological methods were analyzed in terms of biodegradation efficiency using activated sludge systems and microbial processes.

The performance of each method was evaluated using color removal efficiency (%), chemical oxygen demand (COD) reduction, and practical applicability in industrial wastewater treatment systems. The comparative results are summarized in Tables 1 and 2.

RESULTS AND DISCUSSION

The analysis demonstrated that different dye removal methods exhibit varying levels of effectiveness depending on wastewater composition, dye structure, and operational conditions. Adsorption and advanced oxidation processes showed the highest dye removal efficiencies, while biological methods were more suitable as secondary or complementary treatments.

Table 1

Comparison of Dye Removal Methods

Treatment method	Main mechanism	Dye removal efficiency (%)	Advantages	Limitations
Adsorption	Physical adsorption on porous materials	70–95	High efficiency, simple operation	Adsorbent regeneration required
Coagulation–flocculation	Charge neutralization and precipitation	60–85	Low cost, rapid treatment	Sludge generation

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Fenton process	Hydroxyl radical oxidation	80–98	Strong oxidation ability	Chemical consumption, pH control
Ozonation	Direct and indirect oxidation	75–95	No sludge formation	High energy cost
Membrane filtration	Physical separation	90–99	High-quality effluent	Membrane fouling, high cost
Biological treatment	Microbial degradation	40–70	Environmentally friendly	Slow, dye-resistant compounds

The results indicate that membrane technologies and advanced oxidation processes achieve the highest color removal efficiencies, often exceeding 90%. However, their operational costs and energy requirements may limit large-scale application. In contrast, coagulation–flocculation remains economically attractive but produces significant amounts of chemical sludge.

Table 2

Suitability of Dye Removal Methods for Industrial Application

Method	**Treatment stage**	**Cost level**	**Environmental impact**	**Recommended application**
Adsorption	Primary/tertiary	Medium	Low	Textile and printing wastewater
Coagulation–flocculation	Primary	Low	Medium	High-color industrial effluents
AOPs (Fenton, ozone, photocatalysis)	Secondary/advanced	High	Low	Toxic and non-biodegradable dyes
Membrane filtration	Advanced	High	Low	Water reuse systems
Biological treatment	Secondary	Low	Very low	Biodegradable dye wastewater

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Overall, the study confirms that no single treatment method is sufficient to completely remove dye substances from wastewater. The most effective approach involves a combined treatment system, integrating physical, chemical, and biological methods. Such hybrid systems significantly improve dye removal efficiency while reducing environmental risks and operational costs.

CONCLUSION. The removal of dye substances from wastewater is a critically important and complex task for both environmental protection and industry. This process involves chemical, physico-chemical, and biological methods, where dyes are separated through adsorption, coagulation, membrane techniques, oxidation-reduction reactions, and the use of microorganisms. As a result, water pollution is reduced, and the possibility of water reuse is created.

Currently, the most effective results are achieved when physical, chemical, and biological methods are applied in combination. The choice of technology depends on the type of dye, the degree of water pollution, economic capabilities, and environmental requirements. By modernizing industrial wastewater treatment systems, it is possible to conserve water resources and reduce harmful environmental impacts.

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