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PROSPECTS OF USING NATURAL BASALTIC TUFF IN WASTEWATER TREATMENT TECHNOLOGIES FOR ORGANIC POLLUTANT REMOVAL

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ABSTRACT

This study investigates the prospects of using natural basaltic tuff (Rivne oblast, Ukraine), an industrial waste from basalt quarries, as an adsorbent for wastewater remediation from organic pollutants. The chemical composition of the evaluated basaltic tuff sample was verified using classical silicate chemical analysis. The adsorption capacity of the material was examined under static (batch) conditions using model organic dyes: cationic (Methylene Blue) and anionic (Congo Red). It was established that at the natural pH value (~6), the material efficiently removes contaminants from the aquatic environment, demonstrating a removal efficiency of 97% for Methylene Blue and 68% for Congo Red. The obtained results confirm the high prospects of utilizing quarry waste to develop effective eco-friendly sorption materials.

Keywords: basaltic tuff, aluminosilicate matrix, wastewater treatment, organic dyes, adsorption.

INTRODUCTION

The remediation of aquatic and atmospheric environments contaminated with hazardous anthropogenic pollutants remains a critical challenge for modern ecology and environmental engineering. Among various treatment methods, adsorption technologies are highly regarded due to their technical simplicity, flexibility, and high execution efficiency.

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In recent years, significant research focus has shifted toward natural porous minerals, particularly volcanic tuffs where zeolites constitute the dominant mineral phase, offering an abundant, eco-friendly, and cost-effective alternative to expensive synthetic adsorption materials.

Owing to their unique aluminosilicate framework, macro- and mesoporous networks, and structural stability, natural volcanic tuffs have demonstrated high versatility across diverse environmental remediation fields. In atmospheric purification, raw and modified tuffs are actively investigated for the immobilization of hazardous gases. For instance, a study [1] investigated the ability of volcanic tuff from a Romanian deposit to remove ammonia (NH₃) from the air. In another work [2], the authors explored the possibility of using volcanic tuff with various diamine functionalizers for CO₂ adsorption from the air. This indicates the feasibility of targeted chemical modifications of the volcanic tuff surface to enhance its selectivity toward specific gas phases.

Beyond gas separation, the robust silicate skeleton of volcanic tuff serves as an excellent foundational matrix or precursor for synthesis of advanced functional materials aimed at water treatment. Natural volcanic tuff has been successfully utilized as a primary raw material to manufacture stable geopolymer frameworks specifically designed for the efficient adsorption of heavy metal ions, such as Zn²⁺ from aqueous phases [3].

In the context of liquid-phase purification, the removal of complex organic macromolecules, particularly synthetic textile colorants, is of paramount importance due to their high stability and resistance to natural biodegradation. The potential of tuff-based systems in this area is highlighted by the successful application of natural zeolitic volcanic tuff from Romania for the efficient batch adsorption of Basic Blue 41 textile dye from contaminated water [4].

However, while the adsorbent properties of classic volcanic tuffs towards ionic species are relatively well-documented, the technological prospects of utilizing natural basaltic tuff complexes – which feature lower silica contents and distinct transition metal oxide profiles – for organic pollutant remediation require deeper insight. Therefore, evaluating the correlation between the specific elemental composition of local volcanic matrices and their adsorption capacity toward organic structures opens highly promising prospects for developing next-generation water-purification materials derived from industrial wastes, such as the abundant by-products generated during basalt mining.

1. MATERIALS AND METHODS

The object of research in this study was natural basaltic tuff (Rivne oblast, Ukraine), which is an industrial waste from basalt quarries. The raw material was mechanically crushed, sieved to the target fraction, and dried at 105 °C to a constant mass.

The quantitative chemical profile and major oxide composition (SiO₂, Al₂O₃, Fe₂O₃, TiO₂, CaO, MgO) of the prepared basaltic tuff sample were validated using classical chemical analysis (silicate analysis of rocks).

The adsorption capacity of the basaltic tuff was investigated using a cationic dye (Methylene Blue) and an anionic dye (Congo Red) as model contaminants. Adsorption experiments were carried out under static (batch) conditions at room temperature. The initial concentration of the dyes was 10 mg/L, and the solution pH was maintained at natural water (~ 6). The solid-to-liquid phase ratio was fixed at 0.1 g of sorbent per 50 mL of solution. The contact time was 3 hours. The equilibrium

concentration of the dyes was determined using a UV-Vis spectrophotometer at a wavelength of 665 nm (Methylene Blue) and 498 nm (Congo Red). The dye removal efficiency (R , %) was calculated using the following Eq.1:

$$R = \frac{C_{in} - C_{eq}}{C_{in}} \cdot 100\% \quad (1)$$

where: C_{in} and C_{eq} are representing the initial and equilibrium dyes concentrations (mg/L).

2. RESULTS AND DISCUSSION

The obtained data highlights a low silica content (SiO_2 – 48.00 %) alongside a substantial concentration of aluminium oxide (Al_2O_3 – 13.92 %) which establishes a standard aluminosilicate framework. A key distinguishing feature of this specific mineral matrix is the remarkably high iron accumulation (Fe_2O_3 – 14.11 %) combined with notable amounts of magnesium (MgO – 6.35 %), calcium (CaO – 2.70 %), and titanium (TiO_2 – 1.94 %).

The calculated adsorption capacity under the investigated conditions reached 4.85 mg/g for Methylene Blue and 3.40 mg/g for Congo Red. The maximum removal efficiency toward the cationic Methylene Blue (97 %) is driven by strong electrostatic attraction between the dye cations and the negatively charged deprotonated silanol ($\equiv\text{Si-OH}$) groups of the aluminosilicate matrix at $\text{pH} \sim 6$. Concurrently, the competitive removal of the anionic Congo Red (68 %) is achieved despite electrostatic repulsion barriers. This specific behavior is attributed to the high content of Fe_2O_3 , which form localized positive surface complexes and act as active coordination sites for donor-acceptor interactions with the sulfonate groups of the anionic dye.

CONCLUSIONS

Quantitative silicate analysis confirmed that the investigated quarry waste is a natural basaltic tuff with a stable aluminosilicate framework characterized by a low silica content (SiO_2 – 48.00%) and a remarkably high iron oxide accumulation (Fe_2O_3 – 14.11%).

The raw mineral matrix demonstrated high prospective efficiency in removing organic contaminants under batch conditions, achieving a 97% removal rate for the cationic Methylene Blue and a competitive 68% for the anionic Congo Red at $\text{pH} \sim 6$.

Thus, utilizing basaltic quarry waste offers a promising, eco-friendly approach to remediating multi-component aquatic systems. While justifying deeper systematic research, practical implementation will require a comprehensive evaluation of its adsorption kinetics, isotherm models, sorbent regeneration, and efficiency in real, complex wastewater systems.

CONFLICTS OF INTEREST. The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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DATA AVAILABILITY. The manuscript does not have associated data.

USE OF ARTIFICIAL INTELLIGENCE. The authors confirm that no generative AI tools were used for scientific data fabrication or manipulation.

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**ПЕРСПЕКТИВИ ВИКОРИСТАННЯ ПРИРОДНОГО БАЗАЛЬТОВОГО ТУФУ В
ТЕХНОЛОГІЯХ ОЧИЩЕННЯ СТІЧНИХ ВОД ВІД ОРГАНІЧНИХ ЗАБРУДНЮВАЧІВ**

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Анотація

У роботі досліджено перспективи використання природного базальтового туфу (Рівненська область, Україна), що є промисловим відходом базальтових кар'єрів, як адсорбенту для очищення стічних вод від органічних забруднювачів. Проведено вивчення хімічного складу досліджуваного зразка базальтового туфу методами класичного хімічного аналізу. Адсорбційну здатність матеріалу вивчали в статичних умовах на прикладі модельних органічних барвників: катіонного (Метиленового Блакитного) та аніонного (Конго Червоного). Встановлено, що при природному значенні рН (~6) матеріал якісно вилучає забруднювачі з водного середовища, демонструючи ступінь очищення 97 % для Метиленового Блакитного та 68 % для Конго Червоного. Отримані результати підтверджують високу перспективність утилізації кар'єрних відходів для створення ефективних сорбційних матеріалів екологічного призначення.

Ключові слова: базальтовий туф, алюмосилікатна матриця, очищення стічних вод, органічні барвники, адсорбція