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Disposal of polluted bentonite clays as a means of minimising environmental risk

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Abstract. The effective disposal of spent clay sorbents reduce the anthropogenic impact on the environment and to improve recycling technologies for highly dispersed clays. Study aimed to investigate the sorption of organic dye molecules by spent bentonite, previously saturated with chromium (III) ions, with possible subsequent utilisation of the bentonite in pigment compositions. The study was based on a comparative analysis of natural, modified and spent montmorillonite using thermogravimetric analysis, the determination of the colloidal-chemical characteristics of the dispersions, the construction of adsorption isotherms and spectrophotometric monitoring of dye concentrations. Changes in the structure, surface charge, interplanar distance, specific surface area and sorption activity of the samples were analysed. The study established that the saturation of montmorillonite with chromium (III) ions does not lead to a significant deterioration in its properties. This study demonstrated that spent bentonite retains its porous structure, active sorption sites and the ability to effectively adsorb anionic dyes over a wide range of concentrations. The study established that chromium-containing sites can enhance the fixation of dye molecules through complex formation and interaction with the functional groups of the adsorbates. The characteristics of the adsorption of anionic green, blue and black dyes have been analysed, in particular the influence of molecular structure, molecular size and spatial hindrance on adsorption. The study developed an approach for the utilisation of spent bentonite as a secondary mineral base to produce organo-mineral pigment compositions without additional chemical modification. The practical value of these

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results is determined by their potential application by specialists in environmental safety, wastewater treatment, materials science and pigment coating technologies

Keywords: sorption; spent sorbents; montmorillonite; dyes; chromium (III) ions

Introduction

Cobalt-based technologies are the most promising method for treating surface water and wastewater and are widely used in many countries. The main advantages of highly dispersed clays as sorbents are their high efficiency, availability and relatively low cost. Given this last point, the regeneration and reuse of such sorbents is often impractical; consequently, these materials are usually landfilled or incorporated into soil mixtures or building materials, provided that the spent sorbents do not contain toxic pollutants.

Review of studies shows that highly dispersed clays are widely used in various industries (building materials, nanocomposites, fillers, etc.) (Shamsuddin *et al.*, 2025). Their ease of processing, environmental friendliness and cost-effectiveness are constantly fuelling growing interest in the use of clay for the development of a wide range of products. Considerable experience has been gained in the use of natural highly dispersed clays and their modified forms for the sorption-based treatment of wastewater to remove ammonium ions, heavy metals (Ranskiy *et al.*, 2025) and organic pollutants (Alhalafi, 2026), in particular oil and petroleum products (Dong *et al.*, 2024). The main mineral in highly dispersed clays – montmorillonite – has found widespread use in fillers and multifunctional materials due to its specific colloidal-chemical properties and crystalline structure. A. Zaiets & O. Andreyeva (2024) presented the potential for using clay minerals with sorption properties in the preparation of fat and filler compositions for the treatment of semi-finished leather products. An overview of all areas of application for clay-based sorbent minerals in the leather industry is provided by A. Thomasset & S. Benayoun (2024), in which the authors examined in detail the balance between the technological advantages of traditional methods and modern environmental requirements.

The chemical composition and characteristics of the crystal structure of montmorillonite (bentonite), as determined by the ratio of aluminium- to silicon-oxygen layers, give rise to a complex set of sorption, exchange and coagulation phenomena, as well as a capacity for dispersion, which is effective when filling polar polymers, in particular R. Kryklyvyi *et al.* (2022) proposed a formulation for filling polystyrene-butadiene rubbers and noted an improvement in the physicochemical properties of the polymeric materials due to the use of bentonite. Use of montmorillonite for filling polyester premixes is also promising, as it can increase the content of the dispersed filler and improve its aggregation stability. S. Paszkiewicz *et al.* (2024) synthesised block copolymers and used both carbon-based and mineral sorbent materials as fillers.

A.A. Rahimi & F. Alihosseini (2022) proposed using a dye-saturated clay adsorbent, obtained following the treatment of dyeing effluent, as a pigment for textile printing. It is worth noting that the methods described relate to the use of native clays that were further treated with complex compounds containing heavy metals, as outlined in the review by M. Chokri *et al.* (2025), which describes the industrial application of native and modified bentonite clays in nanocomposites, water treatment, the oil and gas sector, and catalysis; whilst the question of the analogous use of spent clay-based sorbents, which contain pollutants – heavy metal ions – within their structure, remains a matter of debate. M. Malovanyy *et al.* (2021) noted that economic factors are decisive in determining the feasibility of disposing of or reusing sorbents.

Although highly dispersed clays are widely used in many sectors of the economy, the limited scope of scientific research results in a low level of utilisation of spent clay-based sorbents in the production and processing of natural and synthetic polymers, fillers and pigment sorbent bases, although many experts consider this field to be highly promising. In view of this, the industrial application of spent clay-based sorbents and the development of composite and multifunctional materials are topical and promising areas of research. The study aimed to evaluate the effectiveness of sorption-based wastewater treatment for the removal of organic dyes using spent bentonite activated with chromium (III) ions, followed by a reduction in environmental risk through its utilisation in pigment compositions.

Materials and Methods

This paper presents a comparative study of the ability of montmorillonite, modified with chromium (III) complex compounds, and spent montmorillonite that has sorbed chromium (III) ions from waste water, to subsequently adsorb anionic dyes. It also analyses possible changes in the clay structure following the sorption process. The analysis of the studies was conducted by comparing the properties of three samples.

Sample 1 (control): Natural bentonite clay with a montmorillonite content of 85%; Sample 2: Modified montmorillonite following treatment with a solution of chromium (III) sulphate complex (dosage 10.0% by mass of dry mineral, calculated as Cr_2O_3); Sample 3: Spent montmorillonite with a residual chromium (III) content of 7-8 % by mass of the dry mineral, calculated as Cr_2O_3. The sorption capacity of modified montmorillonite and the mechanism of adsorption of synthetic anionic dyes on the surface of the mineral sorbent were investigated for dispersions prepared based on samples 2 (modified montmorillonite) and 3 (spent montmorillonite).

The modification of the second sample involved the sequential treatment of bentonite from the Cherkasy deposit (85% montmorillonite content) with sodium carbonate (6.0 per cent by mass of the dry mineral) (Na^+ – MMT) and a solution of hydroxochrome complexes in the form of basic chromium sulphate $Cr_2(SO_4)\ n(OH)_{6-2n}$ (Cr_2O_3 content – 25.6%, basicity – 33%). The chromium cation content in the sample was a maximum of 10% on a Cr_2O_3 basis. As a result of the modification, montmorillonite modified with hydroxochromium complexes – Cr^{3+}-montmorillonite (Cr^{3+}-MMT) was obtained. Spent montmorillonite (sample 3) was treated with a sodium carbonate solution (6.0 % by mass of the dry mineral) to convert it into a dispersed form. The chromium cation content in the sample was a maximum of 8% on a Cr_2O_3 basis. The colloidal and rheological properties of the bentonite-based dispersions were evaluated using standard methods (Bondaryeva *et al.*, 2022). The adsorption of dyes and, before that, chromium ions for sample 3 with a stationary sorbent bed was conducted using a glass column with model solutions and a bentonite bed weighing 15-20 g (Fig. 1).

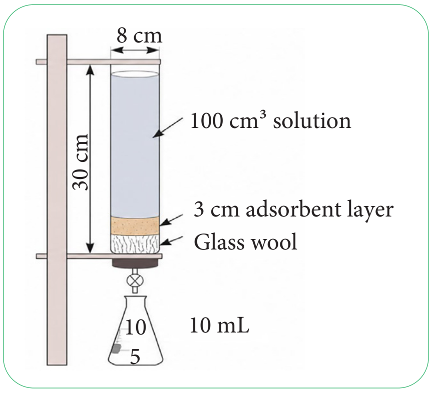


Figure 1. Schematic diagram of a fixed-bed montmorillonite adsorption system

Source: I. Andriulaityte *et al.* (2024)

Sorption of anionic dyes from the dispersions of samples 2 and 3 onto the surface of montmorillonite was investigated as follows. A 20% paste dispersion of the test sample was used, containing 0.1 g of the mineral component. To this dispersion, 100 ml each of anionic dye solutions with concentrations ranging from 2.5×10^{-5} to 1.0×10^{-3} mol/l were added. The resulting mixture was shaken periodically. The shaking duration was 24 hours. The precipitates were then separated from the liquid phase by centrifugation (8,000 rpm). The concentration of anionic dyes on the surface of montmorillonites was determined by measuring the intensity of the optical absorption spectra of the initial and equilibrium solutions in the wavelength range 570-580 nm (Ismail *et al.*, 2022). A Specord UV-V is spectrophotometer (Germany) was used. A calibration curve was employed to determine the concentration. The equilibrium concentration of the dyes was determined in the resulting solution. Anionic black, anionic dark green and anionic blue were used as dyes.

A comparative assessment of the surface structure of modified and spent bentonite samples against native clay was conducted in previous studies, described in greater detail in the paper by H. Sakalova *et al.* (2025). To determine the surface structure of the samples, a comprehensive thermal analysis was first conducted using a Q-1500 derivatograph from the "Paulik-Erdei" system, connected to a personal computer. The sample was heated in an air atmosphere to a temperature of 1,000°C. The heating rate of the sample was 5°C per minute. The mass of the enriched clay sample was 500 mg. Aluminium oxide served as the reference substance.

Results and Discussion

Preliminary thermogravimetric studies of montmorillonites were used to assess their surface structure and predict their properties in a dispersed form. The results of the comprehensive thermal analysis of samples 1, 2 and 3 are summarised in Table 1.

Table 1. Results of a comprehensive thermal analysis of montmorillonite samples

Sample	Stage	Temperature range, °C	Mass loss, %	Interpretation
Sample 1 (pure montmorillonite)	I	20-194	9.59	Release of physically bound water
	II	194-280	1.26	Removal of interlayer water
	III	280-800	3.82	Dehydroxylation
Sample 2. Mixture of montmorillonite with chromium (III) sulfate crystal hydrate	I	20-202	7.57	Physically bound water release
	II	202-306	2.01	Loss of crystallisation water
	III	306-800	7.64	Clay structure destruction
Sample 3. Spent montmorillonite with Cr^{3+} ions content (Cr_2O_3 7-8%)	I	20-190	7.50	Bound water release
	II	190-280	1.78	Interlayer water removal
	III	280-800	5.03	Chromium compound decomposition

Source: developed by the authors

Loss of the first layer of water, which is coordinatively bound to the exchange cations Ca^{2+} and Mg^{2+}, occurs in the range 20-194°C (the first stage of thermolysis). The next layer of water is lost in the range 194-280°C (the second stage of thermolysis) (Kochubei *et al.*, 2022). The intense mass loss (9.59%) observed for the pure montmorillonite sample (sample 1) in the temperature range 20-280°C corresponds to the release of residual physically bound water. In this range, the loss of interlayer water, which is coordinatively bound to the exchangeable cations of montmorillonite, is also possible. The mass loss (3.82%) of the bentonite sample in the 280-800°C range (the third stage of thermolysis) corresponds to dehydroxylation (loss of constitutional water) associated with the destruction of the structure of the clay mineral present in the sample.

Rapid loss of mass (7.57%) of sample 2 in the range 20-202°C (the first stage of thermolysis) corresponds to the release of physically bound water and part of the interlayer water. The mass loss (2.01%) of sample 2 in the 202-306°C range (the second stage of thermolysis) is associated with the release of residual interlayer water from montmorillonite and the loss of crystallisation water from $Cr_2(SO_4)_3 \cdot 6H_2O$. The mass loss (7.64%) of sample 2 in the 280-800 °C range (the third stage of thermolysis) corresponds to the destruction of the clay mineral's structure with the release of constitutional water. In this temperature range, the decomposition of chromium sulphate also occurs, resulting in the formation of volatile decomposition products (Singh *et al.*, 2021).

Similar destructive processes occurred during the heating of sample 3. The significant mass loss (7.5%) of sample 3 in the 20-190°C range (the first stage of thermolysis) corresponds to the release of physically bound water and some of the interlayer water from the bentonite. The mass loss (1.78%) of sample 3 in the 190-280°C range (the second stage of thermolysis) was primarily associated with the release of residual interlayer water from montmorillonite. The mass loss (5.03%) of sample 3 in the 280-800°C range (the third stage of thermolysis) corresponded to the destruction of the clay mineral's structure with the release of constitutional water. In this temperature range, the decomposition of chromium-containing compounds also took place, resulting in the formation of volatile decomposition products. The more significant mass loss of the spent sample 3 during the third stage of thermolysis (5.03%) compared with the natural montmorillonite sample (3.82%) indicates the presence of a certain amount of sorbed chromium (III) compounds, possibly including sulphates. The results of the thermal analysis suggest the possibility of sulphate sorption on the surface of bentonite particles, which decompose during heating, releasing gaseous products. Covering decomposition mechanism of $Cr_2(SO_4)_3$ (reaction 1) and the difference in mass loss between samples 1 and 2 during the third stage of thermolysis, a control calculation of the chromium (III) oxide content for sample number 3 (spent clay mineral) can be performed:

$$Cr_2(SO_4)_3 \cdot 6H_2O \rightarrow Cr_2O_3 + 3SO_3\uparrow + 6H_2O\uparrow. \tag{1}$$

According to stoichiometric calculations, chromium ion content, expressed as Cr_2O_3, in the spent clay sample is 7.25% (Sakalova *et al.*, 2025).

Comparison of the results of thermal analysis of the three samples leads to the following conclusion:

- for samples 2 and 3, similar rheological characteristics are to be expected at low temperatures (20-190°C);
- interlayer water content, which affects the degree of clay swelling, is approximately the same for all samples;
- experiments indicate that chromium ions are more strongly bound in spent bentonite; therefore, the chromium ions in sample 3 may also act as complexing agents;
- comparative analysis of samples 2 and 3 across all the temperature ranges studied indicates that they have a similar porous structure.

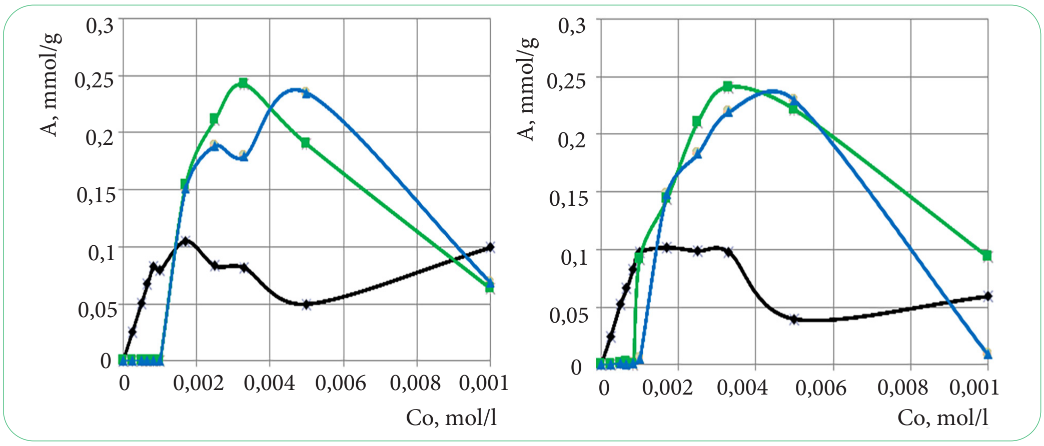
Characteristics of the sorbents in dispersed form are given in Table 2. The table presents the characteristics of samples 2 (modified bentonite) and 3 (spent bentonite), which were used for the subsequent adsorption of dyes.

Table 2. Colloidal and chemical characteristics of montmorillonite dispersions

Sample number	Base, OH/Cr	Surface charge, μC/cm²	Inter-plane distance (d_{001}), Å	Specific area (S), m²/r	pH	Specific electrical conductivity (K), 10^{-4} S/cm	Zeta potential (ζ), mW
2	1.5	1.07	16.8	280	4.9	3.70	+32.3
3	1.3	1.1	17.4	260	4.5	3.43	+30.7

Source: developed by the authors

Obtained sorbent dispersions are characterised by a high specific surface area and a positive charge on the sorption surface. The basicity values are consistent with the results of thermal analysis, which indicate similar amounts of absorbed OH groups and chromium ions on the montmorillonite surface; furthermore, the dispersions based on samples 2 and 3 have approximately the same pH and specific electrical conductivity values. Similar values for surface charge, ζ-potential, interlayer distance and specific surface area indicate that the preliminary adsorption of chromium (III) ions does not lead to a significant deterioration in the colloidal-chemical properties of the clay sorbent. The adsorption isotherms for anionic dyes on the surface of modified montmorillonite (sample 2) and spent montmorillonite (sample 3), shown in Figure 2, generally indicate a similar adsorption behaviour for the test samples.



A B

Figure 2. Adsorption isotherms for anionic dyes on the surface of modified montmorillonite (A) and spent montmorillonite (B)

Note: –■– anionic green dye; –▲– anionic blue dye; –×– anionic black dye

Source: developed by the authors

The results obtained can also be compared with those of A.F. Nabhani *et al.* (2024), who investigated the effectiveness of natural bentonite in removing dyes from real textile effluent. The authors found that the maximum dye removal efficiency was 91.25% at an initial wastewater concentration of 10%, a sorbent mass of 20 g and a contact time of 60 minutes. It was also shown that increasing the amount of bentonite helps to reduce the concentration of dyes in the aqueous phase; however, it may reduce the specific adsorption capacity due to particle aggregation and a reduction in the available sorbent surface area. In this case, maintaining a high specific surface area and the positive charge of the spent montmorillonite dispersions is also a substantial condition for the effective fixation of anionic dyes.

A comparison of the adsorption of different dyes (Fig. 2) indicates that maximum adsorption occurs when the anionic green dye with the highest molecular weight is used in both cases. The greatest increase in adsorption is observed for the high-molecular-weight anionic green and the low-molecular-weight blue dye, whilst the smallest increase is observed for the higher-molecular-weight anionic black. The reduction in the adsorption capacity of the anionic black solutions is most likely due to the premature aggregation of their molecules into micelles. Consequently, the spatial (steric) factor becomes critical during the penetration of such associates into the slit-like microporous structure of Cr^{3+}-montmorillonite, which leads to minimal adsorption values. Similar steric hindrances in micellar systems, as compared to molecular ones, are described by A.H. Jawad *et al.* (2022). The results of these studies on the sorption of methylene blue are very similar to the adsorption curves shown in Figure 2.

According to the results of thermogravimetric analysis (Table 1), the spent montmorillonite exhibits mass losses in the first and second stages of thermolysis that are similar to those of the modified sample, indicating a comparable content of physically bound and interlayer water. This is consistent with the similar values of the d001 interplanar spacing and confirms the preservation of swelling properties and the accessibility of the interlayer space to dye molecules. Furthermore, the slightly larger interplanar spacing in sample 3 (17.4 Å) may facilitate the penetration of dye molecules into the inner layers of the structure and their additional fixation. The results of the analysis of the colloid-chemical properties of the dispersions are consistent with the data reported by A. Bondaryeva *et al.* (2021) for dispersions based on pure bentonite modified with heavy metal sulphates. A. Bondaryeva *et al.* (2021) proposed a method for preparing pigments used for coating natural and synthetic polymers. Study noted that the use of montmorillonite, the surface of which is modified with ions of various metals (chromium, copper, cadmium, etc.), reduces pigment consumption when used in coating compositions.

The relationship between the structural composition of dye molecules and their adsorption capacity on montmorillonite is evident from the adsorption isotherms of the anionic dark green and anionic black dyes. Although they have similar molecular weights and structures, these compounds differ in their auxochromic substituents (-OH versus -NH_2). The phenolic moieties of anionic dark green confer weakly acidic (more electronegative) characteristics, whilst the amino groups of the benzene ring in anionic black give rise to weakly basic (electronegative) properties. This factor alone explains the greater affinity of the mineral montmorillonite for the anionic dark green compound (Fig. 2). In contrast, the role of sulphate groups in the adsorption process is practically identical across the entire series of compounds due to their equal abundance. At the same time, an increase in the number of sulphate groups in the adsorbate structure usually significantly inhibits sorption, as lateral electrostatic repulsion is enhanced in the adsorption zone. N. Palic *et al.* (2025), in their study of the sorption of pharmaceuticals and pesticides, also note that the influence of the natural aqueous matrix reduces sorption efficiency by no more than 10%; the authors consider it appropriate to agree with this statement in the present case as well. Therefore, the influence of the aqueous component of the dispersion on sorption was not considered separately.

Addressing results of similar studies, in particular by M. Debnath *et al.* (2025), devoted to the optimisation of Congo red azo dye removal using Bent/Fe nanoparticles, it is possible to note that electrostatic and specific surface interactions between the adsorbed particles are decisive in the fixation of anionic dyes on clay sorbents. Accordingly, in addition to aggregation and spatial hindrance, the intermolecular repulsive forces – which increase as the surface becomes coated – can cause a non-linear profile of adsorption isotherms with extrema (maxima and minima). The appearance of these regions depends on the balance between repulsion and specific retention. At the same time, the presence of aromatic rings may provide such a strong bond with the mineral matrix that sorption remains positive even when the ionogenic groups and the surface carry the same charge. In addition to classical van der Waals forces, there is a high probability of specific interactions occurring between the π-electron clouds of the aromatic dye nuclei and the positively charged chromium polycations on the surface of Cr^{3+}-montmorillonite.

Following the adsorption mechanism, it should also be noted that the presence on the surface of Cr^{3+}-montmorillonite of chromium oligocations with strong complex-forming ability allows the formation of complex compounds between them and the functional groups of dyes (for example, $-SO_3H^+$), which act as ligands. The latter may enter the inner coordination sphere of hydroxychrome cations, penetrating quite deeply into the interlayer space of montmorillonite. Since thermal analysis indicated a higher probability of chromium complex formation in the deeper layers of the clay for sample 3, this may well explain the wider range of maximum adsorption values for spent montmorillonite. A similar relationship between maximum adsorption values and the presence of heavy metal complexes not only on the clay surface has been identified in studies by A.A. Rahimi & F. Alihosseini (2022).

The adsorption isotherms (Fig. 2) demonstrate that spent montmorillonite is practically on a par with the modified sorbent in terms of its ability to adsorb anionic dyes. This confirms the conclusion of the thermal analysis regarding the preservation of the porous structure and active sorption sites following prior saturation with chromium (III) ions. Furthermore, the slightly higher d001 values and the presence of strongly bound chromium complexes in sample 3, as shown in Table 1, may account for the broadening of the concentration range for effective adsorption and the enhanced interaction between the functional groups of the dyes and the sorbent surface. Thus, the results in Table 1 and Table 2 consistently correspond to the nature of the isotherms shown in Figure 2 and confirm the feasibility of using spent bentonite as a fully-fledged base to produce pigment compositions.

The study established that the preliminary saturation of montmorillonite with chromium (III) ions not only does not reduce its sorption capacity for anionic dyes, but may also contribute to the additional fixation of dyes through complex formation with chromium-containing centres. This paves the way to produce stable organo-mineral pigments based on spent sorbents without the need for additional chemical modification. R. Kryklyvyi *et al.* (2022) investigated the use of spent bentonite in the filling of polymer materials and noted the influence of such a filler on the formation of the functional properties of elastomeric blends. In this context, the results obtained indicate that spent montmorillonite, following the sorption of chromium (III) ions and anionic dyes, can be regarded not only as a sorbent but also as a functional mineral component for the subsequent formation of polymer-mineral or pigment composites. The study confirmed that the interaction between the organic dye and the inorganic clay matrix improves the characteristics of the final material. Such pigments will exhibit enhanced thermal stability, resistance to ultraviolet radiation and chemical influences.

Conclusions

Use of spent montmorillonite in multifunctional materials as a base for the sorption of anionic dyes and for pigment production contributes to significant resource savings and enhances the environmental sustainability of industrial processes. The similar mass loss observed for montmorillonite samples in the temperature range 20-190°C (corresponding to the release of physically bound and partial interlayer water) indicates that spent montmorillonite (sample 3) and modified montmorillonite (sample 2) may exhibit similar rheological properties, swelling capacity and porosity under appropriate processing conditions. It is reasonable to predict that the stronger fixation of chromium ions observed in spent bentonite may enhance the dye adsorption effect, as this would involve more than just surface processes. The high efficiency of sorption and precipitation of anionic dyes (dark green, black and blue) on the surface of montmorillonite, resulting in the formation of an excess monolayer, has been demonstrated; this serves as the basis for the subsequent synthesis of pigment concentrates for polymer-mineral coatings.

Dispersions based on spent montmorillonite ensure high dye adsorption across a wide range of concentrations and better fixation of dye molecules, as chromium complexes are formed in the deeper layers of the clay. Despite prior saturation with the pollutant, namely the chromium (III) ion, spent bentonite retains high adsorption activity towards anionic dyes, as confirmed by the nature of the adsorption isotherms. This allows the spent sorbent to be regarded not as waste, but as a secondary raw material to produce pigment compositions, thereby implementing the principles of the circular economy and minimising the environmental risks associated with its disposal. Due to similar colloidal and chemical properties of dispersions based on modified and spent bentonites, alongside maximum adsorption values, spent bentonite can be used in to produce pigment concentrates without significant changes to the production procedures for pigments and colouring compositions. Prospects for further research include an in-depth study of the potential for using spent clay-based sorbents in various technological processes and in assessing their long-term environmental and practical potential.

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Conflict of Interest

None.

References

[1] Alhalafi, Z.H. (2026). Photocatalytic efficiency of bentonite-TQD via recycling and photodegradation of organic pollutants and industrial wastewater. *Arabian Journal of Chemistry*, 19, article number 11252025. doi: 10.25259/AJC_1125_2025.

[2] Andriulaityte, I., Valentukeviciene, M., & Zurauskiene, R. (2024). Research on the reusability of bentonite waste materials for residual chlorine removal. *Materials*, 17(22), article number 5647. doi: 10.3390/ma17225647.

[3] Bondaryeva, A., Zhaldak, M., Mokrousova, O., & Okhmat, O. (2022). Nanopigments for leather finishing coating. In *ICAMS 2022 – 9th international conference on advanced materials and systems* (pp. 37-42). Bucharest: National Research and Development Institute for Textiles and Leather. doi: 10.24264/icams-2022.I.4.

[4] Bondaryeva, A., Mokrousova, O., & Okhmat, O. (2021). Hybrid pigments based on montmorillonite and anionic dyes for leather finishing. *Solid State Phenomena*, 320, 198-203. doi: 10.4028/www.scientific.net/SSP.320.198.

[5] Chokri, M., *et al*. (2025). Progress in bentonite clay modification and enhancing properties to industrial applications: A review. *Materials Chemistry and Physics*, 337, article number 130486. doi: 10.1016/j.matchemphys.2025.130486.

[6] Debnath, M., Barman, M.P., Basak, D., Borah, D., & Saikia, H. (2025). Optimizing Congo red dye removal using sodium borohydride-reduced Bent/Fe NPs and bentonite in aqueous solutions. *Current Indian Science*, 3(1). doi: 10.2174/012210299X370390250429053029.

[7] Dong, Y., Abbasi, A., Mohammadnejad, S., Nasrollahzadeh, M., Sheibani, R., & Otadi, M. (2024). Recent progresses in bentonite/lignin or polysaccharide composites for sustainable water treatment. *International Journal of Biological Macromolecules*, 278(3), article number 134747. doi: 10.1016/j.ijbiomac.2024.134747.

[8] Ismail, M., Khan, M.A., & Khan, S.A. (2022). Effective removal of reactive and direct dyes from colored wastewater using modified bentonite nanocomposites. *Water*, 14(22), article number 3604. doi: 10.3390/w14223604.

[9] Jawad, A.H., Saber, S.E.M., Abdulhameed, A.S., Farhan, A., ALOthman, Z.A., & Wilson, L.D. (2022). Characterization and applicability of the natural Iraqi bentonite clay for toxic cationic dye removal: Adsorption kinetic and isotherm study. *Journal of King Saud University – Science*, 35(5), article number 102630. doi: 10.1016/j.jksus.2023.102630.

[10] Kochubei, V., Yaremchuk, Y., Malovanyy, M., Yaholnyk, S., & Lutek, W. (2022). Studies of adsorption capacity of montmorillonite-enriched clay from the Khmelnytskyi Region. *Key Engineering Materials*, 925, 143-149. doi: 10.4028/p-i713sy.

[11] Kryklyvyi, R., Sakalova, H., Petrushka, K., & Luchyt, L. (2022). Use of clay sorptive materials in the synthesis of polymer materials. *Environmental Problems*, 7(1), 18-22. doi: 10.23939/ep2022.01.018.

[12] Malovanyy, M., Blazhko, O., Sakalova, H., & Vasylinych, T. (2021). Ecological aspects of clay sorption materials usage in leather and fur production technologies. *Materials Science Forum*, 1038, 276-281. doi: 10.4028/www.scientific.net/MSF.1038.276.

[13] Nabhani, A.F., Zahidah, Z., Herawati, H., & Zulti, F. (2024). Assessment of natural bentonite efficacy for dye removal in textile wastewater treatment: Implication for mitigating River Citarum pollution. *Journal of Limnology and Water Resources*, 31(1), 4-15. doi: 10.55981/limnotek.2024.4848.

[14] Palic, N., Vukcevic, M., Maletic, M., Mirkovic, M., Ristic, M., Peric-Grujic, A., & Trivunac, K. (2025). Amino-starch derivates for adsorption of specific pharmaceuticals and pesticides in contaminated water: Examination in both spiked and real water samples. *Journal of the Serbian Chemical Society*, 90(5), 693-707. doi: 10.2298/JSC240919007P.

[15] Paszkiewicz, S., Walkowiak, K., & Barczewski, M. (2024). Biobased polymer nanocomposites prepared by in situ polymerization: Comparison between carbon and mineral nanofillers. *Journal of Materials Science*, 59(30), 13805-13823. doi: 10.1007/s10853-024-10025-8.

[16] Rahimi, A.A., & Alihosseini, F. (2022). Application of dye saturated clay adsorbent from dyeing wastewater treatment as an industrial pigment for textile printing. *Journal of Chemical Technology & Biotechnology*, 97(11), 3120-3129. doi: 10.1002/jctb.7183.

[17] Ranskiy, A.P., Gordienko, O.A., Didenko, N.O., Titov, T.S., & Sydoruk, T.I. (2025). Synthesis of thioamide complex compounds of copper (II) and study of their mutual transformations. *Journal of Chemistry and Technologies*, 33(2), 352-362. doi: 10.15421/jchemtech.v33i2.321442.

[18] Sakalova, H., Malovanyy, M., Kochubei, V., Boiko, R., & Vasylinych, T. (2025). Determination of utilization directions for spent bentonite sorbents. *Pollack Periodica*. doi: 10.1556/606.2025.01396.

[19] Shamsuddin, R., Almohamadi, H., Siyal, A.A., & Ghumman, A.S.M. (2025). Charge properties, characteristics and applications of bentonite: A concise review. *Semarak Engineering Journal*, 11(1), 68-83. doi: 10.37934/sej.11.1.6883.

[20] Singh, R., Patanjali, P., Chopra, I., & Mandal, A. (2021). Organobentonite as an efficient and reusable adsorbent for cationic dyes removal from aqueous solution. *Journal of Scientific & Industrial Research*, 80(1), 80-86.

[21] Thomasset, A., & Benayoun, S. (2024). Review: Leather sustainability, an industrial ecology in process. *Journal of Industrial Ecology*, 28(6), 1842-1856. doi: 10.1111/jiec.13547.

[22] Zaiets, A., & Andreyeva, O. (2024). Evaluation of the efficiency of liquid leather finishing using polymers and modified fats. In *The 10th international conference on advanced materials and systems (ICAMS 2024)* (pp. 289-296). Bucharest: National Research and Development Institute for Textiles and Leather. doi: 10.2478/9788367405805.

Утилізація насичених полютантами бентонітових глин як спосіб мінімізації екологічного ризику

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Анотація. Ефективна утилізація відпрацьованих глинистих сорбентів допомагає зменшити техногенне навантаження на довкілля і вдосконалити технології повторного використання (Recycling) високодисперсних глин. Мета роботи полягала у дослідженні сорбційного поглинання молекул органічних барвників відпрацьованим бентонітом, попередньо насиченим іонами хрому (III), з можливістю подальшої утилізації бентоніту у складі пігментних композицій. Дослідження ґрунтувалося на порівняльному аналізі природного, модифікованого та відпрацьованого монтморилоніту із застосуванням термогравіметричного аналізу, визначення колоїдно-хімічних характеристик дисперсій, побудови ізотерм адсорбції та спектрофотометричного контролю концентрації барвників. Проаналізовано зміни структури, поверхневого заряду, міжплощинної відстані, питомої площі поверхні та сорбційної активності зразків. Встановлено, що насичення монтморилоніту іонами хрому (III) не призводить до суттєвого погіршення його властивостей. Доведено, що відпрацьований бентоніт зберігає пористу структуру, активні центри сорбції та здатність ефективно поглинати аніонні барвники у широкому інтервалі концентрацій. Встановлено, що хромовмісні центри можуть посилювати фіксацію молекул барвників за рахунок комплексоутворення та взаємодії з функціональними групами адсорбатів. Проаналізовано особливості адсорбції аніонного зеленого, синього та чорного барвників, зокрема вплив молекулярної будови, розміру молекул і просторових перешкод на поглинання. Розроблено підхід до утилізації відпрацьованого бентоніту як вторинної мінеральної основи для одержання органо-мінеральних пігментних композицій без додаткової хімічної модифікації. Практична цінність результатів полягає у можливості їх використання фахівцями з екологічної безпеки, очищення стічних вод, матеріалознавства та технологій пігментних покриттів

Ключові слова: сорбція; відпрацьовані сорбенти; монтморилоніт; барвники; іони хрому (III)