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Performance Evaluation of Bentonite–Nano SiO_2 as an Adsorbent in the Decolorization Process of Rhodamine B

Evaluasi Kinerja Bentonit–Nano SiO_2 sebagai Adsorben pada Proses Dekolorisasi Rhodamin B

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ABSTRACT

Among various sources of industrial water pollution, effluents from printing, dyeing, and textile processes represent one of the most significant environmental threats. These wastewaters contain numerous toxic and hazardous substances that are difficult to biodegrade. This study investigates the synthesis, characterization, and adsorption performance of a Bentonite–Nano SiO_2 composite for the removal of Rhodamine B dye from aqueous solutions. The research was conducted in two main stages: the preparation of the Bentonite–Nano SiO_2 composite and the evaluation of its adsorption performance at various adsorbent concentrations and contact times. The composite was synthesized by dispersing nano-silica (15% w/w) into bentonite using ethanol as the solvent, followed by stirring, filtration, and drying processes. Characterization using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) confirmed successful modification. Adsorption tests showed that Rhodamine B removal efficiency increased with higher adsorbent concentration, reaching optimal conditions at 0.75% (w/v) with a removal efficiency of 90.2% after a contact time of 10–15 minutes. The enhanced adsorption performance was attributed to the larger surface area, higher porosity, and increased number of active sites resulting from the incorporation of nano-silica.

Keywords: Bentonite–Nano SiO_2; adsorption; Rhodamine B; wastewater treatment

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1. INTRODUCTION

Among the various sources of industrial water pollution, printing, dyeing, and textile effluent is one of the significant environmental threats. These wastewaters are high in many toxic and hazardous substances with low susceptibility to biodegradation (Małachowska et al., 2021). Dye containing effluents, especially, impose a significantly adverse effect on human health as well as the natural environment (Kolya & Kang, 2024). Wastes of synthetic dyes such as Rhodamine B, methyl orange, Congo red, methylene blue, and tetracycline hydrochloride frequently consist of toxic chemical compounds such as nitrates, sulfur compounds, acetic acid, chromium species, and small quantities of heavy metals (e.g., arsenic, lead, mercury, cadmium, nickel, cobalt, and zinc). The persistence of such pollutants in aquatic environments, albeit at low concentrations, presents serious ecotoxicological risks, with possibilities of disrupting aquatic life and human health through bioaccumulation and water-based exposure pathways (Mohammadhosseini et al., 2022). Rhodamine B (Rh B) is highly water-soluble xanthene dye that exists in two structurally pH-dependent forms: a fluorescent open form that dominates under acid conditions, and a non-fluorescent spirolactam (closed form) that predominates in alkaline media. Rh B is environmentally persistent and resists microbial degradation, and thereby poses significant aquatic pollution. Even at trace concentrations, it can exert extreme toxicological effects on aquatic organisms, including respiratory and reproductive toxicity, tissue necrosis, and carcinogenesis. In humans, chronic exposure has been linked to mutagenic effects. Because of its toxicity and stability, it is of paramount interest to come up with better remediation technologies for Rh B-contaminated wastewaters to protect aquatic life and public health (Bashofi & Prasetyo, 2023)

The methods for treating dye-containing wastewater are generally categorized into physical processes (e.g., adsorption, ion exchange, coagulation-flocculation, membrane filtration), chemical processes (e.g., oxidation, electrochemical processes, Fenton reaction), and biological processes (e.g., natural attenuation, bioaugmentation, biostimulation, bioleaching, rhizoremediation) (Ahmad et al., 2021). Adsorption has emerged as a highly efficient and cost-effective technique for removing dyes, pigments, phenolic compounds, and other chemical contaminants from wastewater. Its effectiveness in treating high-concentration dye solutions, combined with low operational costs and simple system design, makes it an attractive option for industrial wastewater treatment. Various adsorbent materials have been developed for dye remediation, including bentonite clay, peanut husk biomass, polydopamine-based microspheres, and tin oxide (SnO_2) nanoparticles (Al-Kazragi & Al-Heetimi, 2021). Bentonite, composed of aluminum silicate minerals, has become a major focus in dye removal due to its uniform porosity, wide interlayer spacing, and non-swelling behavior (Li et al., 2024). Because of its inertness, thermal stability, and eco-friendliness, bentonite is suitable for use in catalytic processes. Its activity is often enhanced through functionalization with metals or metal oxides, where Na^+ ions have been shown to increase surface area and basal spacing (Chauhdary et al., 2022). According to (Warsono et al., 2018), Indonesian natural bentonite modified through pillaring with Al, Cu, Mn, and Ti exhibited enhanced dye removal capability: the cation exchange capacity (CEC) increased up to 125.3 meq/100 g in the HTiB modification compared to 98 meq/100 g in the raw bentonite, and the specific surface area (SSA) rose to 151.3 m^2/g in the HAlB modification compared to approximately 70.7 m^2/g in the raw bentonite. Nano-silica has emerged as one of the materials with high pozzolanic reactivity, good thermal stability, and compatibility with cementitious systems.

The particle size of nano-silica is smaller than that of ordinary cement particles, allowing for better dispersion, higher surface area, and stronger interactions with other

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components in composite matrices. These properties make nano-silica highly beneficial not only for improving the mechanical strength and durability of construction materials but also for facilitating adsorption and catalytic reactions in environmental remediation processes (Singh et al., 2020). The bentonite–nano silica composite is expected to enhance adsorption performance through increased surface reactivity, additional active sites, and improved pore structure. In this study, the adsorption performance of the bentonite–nano SiO_2 composite will be evaluated for the decolorization of Rhodamine B from wastewater. The research focuses on the effect of bentonite modified with silica on dye decolorization efficiency.

2. MATERIALS AND METHODS

2.1. Materials

The materials employed in this study included bleaching earth (BE) of the bentonite type (Indonesian brand), nano SiO_2 (Merck), Rhodamine B (Merck) as a model dye for wastewater simulation, and 95% ethanol (Merck) used as a solvent for the modification process.

2.2. Methods

This research was carried out in two main stages. The first stage was the preparation of the bentonite–nano SiO_2 composite material, and the second stage was the adsorption process, in which the prepared composite was used for the decolorization of Rhodamine B dye solution.

2.3. Preparation of BE-nano SiO_2

To prepare the BE–nano SiO_2 composite, 50 g of BE was blended with nano-SiO_2 at a concentration of 15% (w/w of BE) using 50 mL of 95% ethanol as the solvent. The mixture was continuously stirred for 3 hours at 70 °C to facilitate the modification process. The resulting BE–SiO_2 composite was then filtered and dried in an oven at 100 °C for 5 hours (Yahya et al., 2024).

The modified bentonite was subsequently characterized using SEM and FTIR analyses. The surface morphology of the bentonite–nano SiO_2 composite was examined using a scanning electron microscope (JSM-6510LV, JEOL Ltd., Tokyo, Japan) operated at 20 kV under a magnification of 3000×. Meanwhile, the crystallinity of the particles was analyzed using an X-ray diffractometer (MAXima_X XRD-7000, Shimadzu, Japan). Furthermore, the functional groups of the material were identified using Fourier Transform Infrared (FTIR) spectroscopy (PerkinElmer Spotlight 200, PerkinElmer Inc., Waltham, MA, USA).

2.4. Adsorption Process

The adsorption process was carried out by preparing a 1 ppm Rhodamine B solution as a simulated dye wastewater. Adsorption was then conducted using various concentrations of bentonite–nano SiO_2 adsorbent (0.10%, 0.25%, 0.50%, 0.75%, and 1% w/v) to determine the effect of adsorbent concentration on decolorization performance. The adsorption process was performed under continuous stirring for 30 minutes, after which the mixture was separated by centrifugation.

The optimum adsorbent concentration obtained from this stage was subsequently used to investigate the effect of contact time on adsorption efficiency, with contact times of 5, 10, 15, and 30 minutes. The residual concentration of Rhodamine B after adsorption was measured using a UV-Vis spectrophotometer.

3. RESULTS AND DISCUSSION

3.1. Performance Evaluation of Bentonite–Nano SiO_2 in Rhodamine B Adsorption

The adsorption performance of Bentonite–Nano SiO_2 in removing Rhodamine B dye was investigated by analyzing two major factors: adsorbent concentration and adsorption time.

Adsorption is a surface phenomenon influenced by both the amount of adsorbent available and the contact duration between the adsorbent and adsorbate (Huda et al., 2025). Rhodamine B, being a cationic dye, tends to interact electrostatically with negatively charged surfaces, such as those present in bentonite-based composites. The modification of bentonite with nano-silica is expected to enhance its surface area and improve its adsorption efficiency due to increased active sites and surface reactivity.

3.1.1. Effect of Adsorbent Concentration

The performance evaluation of bentonite–nano SiO_2 with varying adsorbent concentrations was carried out to determine the effect of nano SiO_2 addition on the adsorption capability of bentonite in the bleaching process. The variation in concentration aimed to identify the optimum composition that provides the highest adsorption efficiency for the decolorization of Rhodamine B. The performance results of bentonite–nano SiO_2 with different concentrations are presented in **Figure 1**.

Figure 1 shows the effect of Bentonite–Nano SiO_2 adsorbent concentration on the residual Rhodamine B concentration and adsorption percentage. At an adsorbent concentration of 0.1% (w/v), Bentonite–Nano SiO_2 reduced the Rhodamine B concentration from 1 ppm to 0.177 ppm, with an adsorption percentage of 82.29%. Increasing the adsorbent concentration to 0.75% (w/v) further decreased the Rhodamine B concentration to 0.11 ppm, while a higher concentration of 1.0% (w/v) resulted in only a small additional reduction, reaching 0.09 ppm. These results indicate that at higher adsorbent concentrations, the adsorption efficiency tends to approach saturation because most dye molecules have already been adsorbed (Legarto et al., 2019). This observation is consistent with the study by (Eleraky, 2022), which reported that increasing the bentonite dosage in methylene blue adsorption enhanced dye removal efficiency until a stable level was reached. Therefore, an adsorbent concentration of 0.75% (w/v) can be considered the optimum condition, achieving an adsorption percentage of 88.98%.

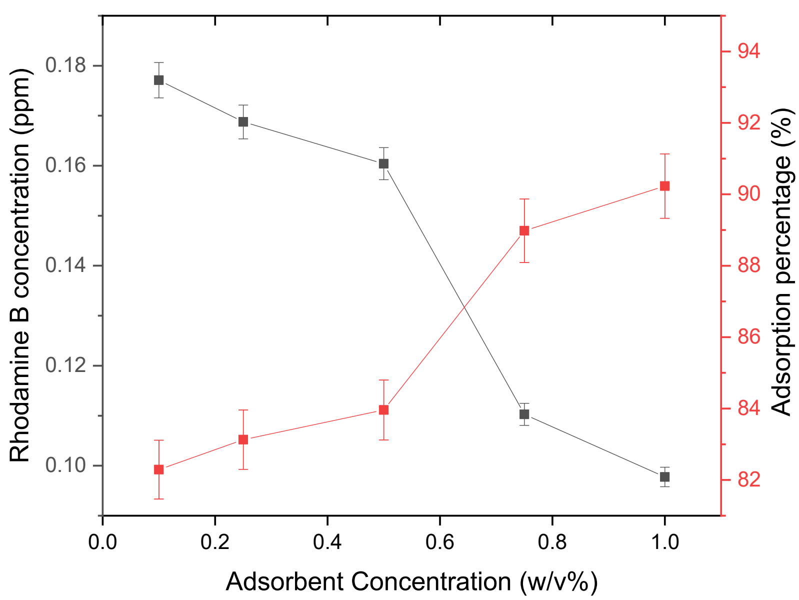

Figure 1. Evaluation of Bentonite–Nano SiO_2 Performance at Different Concentrations

3.1.2. Effect of Adsorption Time

The duration of contact between the adsorbent and dye molecules plays a crucial role in determining adsorption efficiency, as it governs the extent of interaction between the dye and the active sites on the adsorbent surface (Haleem et al., 2023). The effect of contact time on the adsorption process can be observed in **Figure 2**.

Figure 2 shows the effect of contact time on the adsorption of Rhodamine B. The residual Rhodamine B concentration decreased significantly during the first 10–15 minutes, indicating that most of the adsorption occurred at the initial stage. At this stage, the adsorption percentage reached approximately 90%, with a residual Rhodamine B concentration of 0.099 ppm, which suggests a rapid interaction between dye molecules and the active sites on the adsorbent surface. After this period, the adsorption process became stable up to 30 minutes, as indicated by only a slight change in the residual Rhodamine B concentration. This behavior indicates that most of the available active sites had been occupied and the system was approaching adsorption equilibrium. A similar trend has been reported in studies using bentonite or kaolin–bentonite composites, where the adsorption rate increased sharply in the early minutes and then remained nearly constant, confirming that equilibrium had been reached (He et al., 2022).

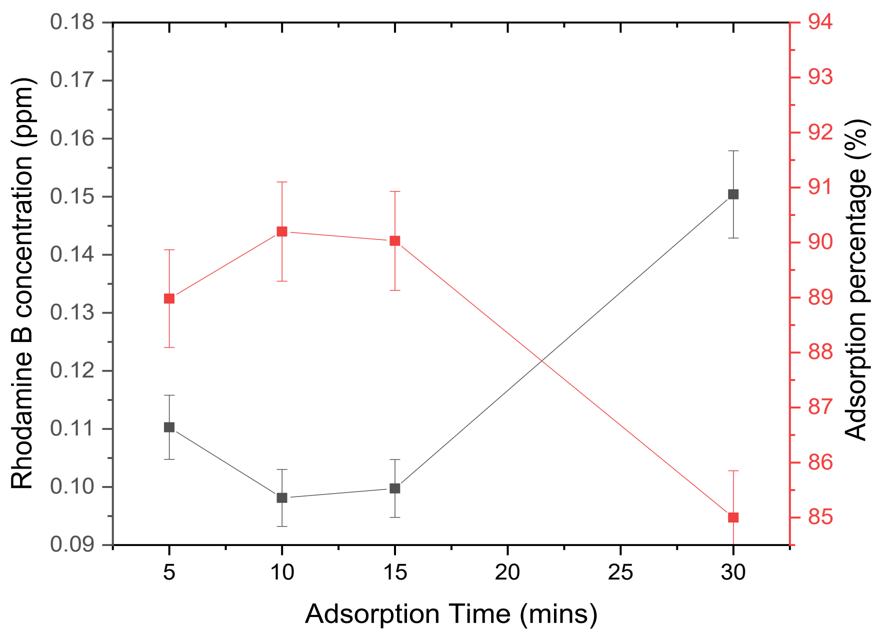

Figure 2. Evaluation of Adsorption Time

3.1.3. Bentonite–Nano SiO_2 Characterization

Characterization of the Bentonite–Nano SiO_2 composite was conducted using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) to understand its morphological and structural changes after modification. SEM provides insight into the surface morphology and particle distribution, while FTIR identifies functional groups and chemical bonds present in the material. Comparing unmodified bentonite with Bentonite–Nano SiO_2 helps determine the success of the modification process and the interaction between silica nanoparticles and bentonite layers (Pereira et al., 2015). The results of the characterization using SEM can be seen in **Figure 3**.

Figure 3 presents the surface morphology analysis obtained using Scanning Electron Microscopy (SEM), which reveals distinct differences between unmodified bentonite and the Bentonite–Nano SiO_2 composite. The unmodified bentonite (Figure A) exhibits relatively compact and irregularly shaped particles with visible agglomeration among particles. This morphological characteristic indicates low porosity and a limited number of active sites on the surface, which can directly reduce the adsorption efficiency toward dye molecules (Frida et al., 2022). In contrast, the Bentonite–Nano SiO_2 composite (Figure B) shows a rougher surface texture with more numerous and uniformly distributed pores. This observation suggests that the nano-silica particles were successfully dispersed and firmly attached to the bentonite layers. The incorporation of nanosized silica into the bentonite structure is known to promote interlayer intercalation and basal spacing expansion, resulting in an increased specific surface area and a greater number of active sites for adsorption (Rind et al., 2023).

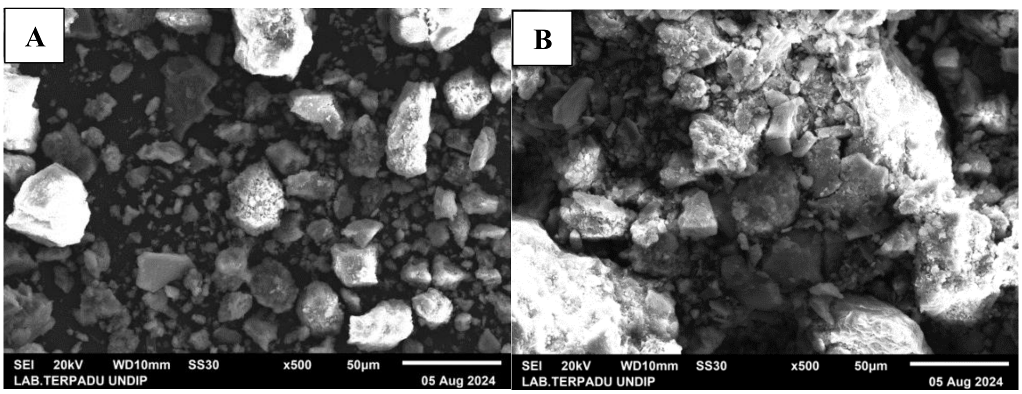

Figure 3. SEM Results A) Unmodified Bentonite and B) Bentonite–Nano SiO_2 Composite

These findings demonstrate that nano-silica particles function as structural reinforcements that prevent bentonite particle agglomeration, maintain dispersion stability, and strengthen interlayer bonding through Si–O–Si and Si–O–Al interactions (Gustave et al., 2022). This result is consistent with the study by Suzuki et al. (2024), who reported that bentonite modified with nano-silica exhibited a more open porous morphology and an enhanced adsorption capacity for methylene blue dye, achieving up to an 85% improvement compared to raw bentonite (Suzuki, 2024). FTIR spectra further confirm the successful modification of bentonite with nano-silica. Both samples show characteristic absorption peaks around 1000–1100 cm^{-1}, corresponding to Si–O–Si stretching vibrations typical of silicate structures. However, the intensity of this peak increases in Bentonite–Nano SiO_2, indicating the incorporation of additional Si–O bonds from nano-silica. The broad band near 3400 cm^{-1} corresponds to O–H stretching vibrations from hydroxyl groups and interlayer water, while the peak around 1630 cm^{-1} represents the bending of adsorbed water molecules. The presence of these peaks in both materials confirms that the bentonite structure is maintained after modification, but the increased Si–O–Si signal demonstrates the chemical interaction between bentonite and nano-silica (Perez et al., 2022).

The combination of SEM and FTIR analyses confirms that the modification process effectively enhances the physicochemical properties of bentonite. The addition of nano-silica increases surface roughness and porosity, while strengthening the silicate framework through additional Si–O–Si bonds. These structural improvements contribute to better adsorption performance by providing more active sites and stronger surface interactions with adsorbates such as Rhodamine B. Therefore, Bentonite–Nano SiO_2 can be considered a promising adsorbent material for wastewater treatment applications due to its enhanced surface characteristics and chemical stability (Suzuki, 2024).

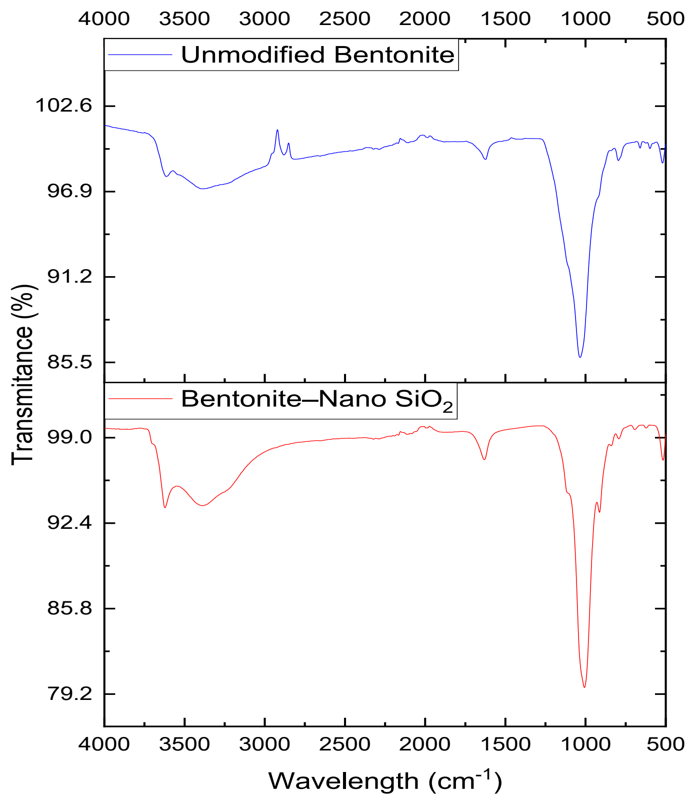

Figure 4. FTIR Spectra of Unmodified Bentonite and Bentonite–Nano SiO_2 Composite

4. CONCLUSIONS

he modification of bentonite with nano-silica (SiO_2) effectively enhanced its adsorption capacity and surface properties. The optimal adsorption of Rhodamine B was achieved at a concentration of 0.75% (w/v) and a contact time of 10–15 minutes, with an efficiency of about 90%. SEM and FTIR analyses confirmed successful modification, showing increased surface roughness, porosity, and the formation of additional Si–O–Si bonds. These improvements provide more active sites and stronger interactions with dye molecules. Therefore, Bentonite–Nano SiO_2 demonstrates strong potential as an efficient and eco-friendly adsorbent for wastewater treatment applications.

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