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Removal of Dye from Real Textile Wastewater using Sodium Alginate and Bentonite Composite

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A composite adsorbent was synthesized from Sodium Alginate (SA) and Bentonite (BT) named SA/BT to treat textile wastewater sourced from the Rooma Textile Park situated in Kanpur, Uttar Pradesh, India. The materials were evaluated through various analyses, such as Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR). Batch adsorption techniques were employed to investigate how various process variables, including adsorbent dosage, contact time, pH, and temperature influence the removal of dyes and other pollutants from textile wastewater. The physicochemical characteristics, including pH, Electrical conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Total hardness, color, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), sulfate, and chloride of textile effluents were assessed both prior to and following the treatment process. The results indicated that the SA/BT composite showed higher adsorption efficiency, highlighting its promise as a viable and eco-friendly option for the treatment of textile wastewater. This research provides important perspectives on the creation of sustainable treatment approaches to tackle water pollution issues within the textile sector.
Keywords: Sodium alginate, Bentonite, Adsorption, Textile wastewater treatment.

1. Introduction

Water is essential for life on our planet, but its quality is being increasingly threatened by various human activities, such as industrial, domestic, and agricultural practices (Akhtar et al., 2021). One of the critical issues we face today is the contamination resulting from dyes released in wastewater from sectors like textiles, tanneries, sugarcane processing, and dye production. The discharge of these effluents leads to unusual coloration in surface waters, creating considerable ecological concerns. Research indicates that textile wastewater is one of the most contaminated, primarily due to its elevated levels of harmful dyes. These pollutants significantly disrupt the ecosystem by altering pH levels, increasing Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), and raising Total Dissolved Solids (TDS), suspended solids, and organic contaminants (Astuti et al., 2020; Azari et al., 2022). In light of these challenges, numerous countries have enacted rigorous regulations aimed at reducing dye pollution. In water-scarce regions, especially in developing countries, there is a pressing necessity to implement recycling and reuse of wastewater for both industrial and agricultural purposes. This imperative has compelled the textile and dyeing sectors to investigate efficient methods for the elimination of dyes. A variety of treatment methods have been explored, including coagulation-flocculation processes, anaerobic biological treatments, catalytic wet oxidation, photochemical degradation, and advanced oxidation processes like the Fenton reaction (Tanji et al., 2020; Titchou et al., 2020). Nonetheless, these methods frequently encounter challenges stemming from elevated operational expenses and intricate technical requirements. Adsorption technology has surfaced as a viable option for wastewater treatment, due to its straightforward nature, affordability, and effectiveness in eliminating dyes from polluted water (Bener et al., 2022). This method has attracted significant interest as a cost-effective and scalable option for industrial uses. Ongoing studies aim to refine adsorption materials and methods to improve their efficiency and sustainability in tackling dye pollution issues.

Sodium alginate, a water-soluble linear polysaccharide sourced from brown algae, has attracted considerable attention owing to its excellent bioavailability and straightforward extraction process. The structure is composed of β-D-mannuronic (M) and α-L-guluronic (G) acid residues linked together by successive 1,4-linkages. This distinctive configuration enables sodium alginate to create hydrogels, especially when the sodium ions in the guluronic acid residues are replaced with divalent cations like calcium, barium, or strontium (Xie et al., 2022). The interaction of divalent cations with α-L-guluronic acid blocks promotes the development of a three-dimensional crosslinked network, thereby improving the structural integrity of the hydrogel. Sodium alginate hydrogels are well-regarded for their ability to attract water, safety for living organisms, compatibility with biological systems, and affordability, positioning them as strong contenders for use as adsorbents in water treatment (Asadi et al., 2018). The addition of bentonite, a naturally occurring smectite clay, has enhanced the mechanical properties of alginate hydrogels. Bentonite serves as a reliable adsorbent for wastewater treatment, due to its chemical and mechanical stability, large surface area, swelling characteristics, and cost-effectiveness. The presence of these characteristics enhances its capacity to effectively adsorb a diverse array of contaminants (Khaleghi et al., 2023). Recent studies emphasize the promise of hybrid alginate-bentonite composites in effectively removing dyes from wastewater. The incorporation of bentonite into alginate matrices effectively tackles challenges like inadequate shape retention, inconsistent bead sizing, insufficient mechanical strength, and high porosity. The incorporation of bentonite into alginate beads improves their structural strength and ability to adsorb effectively. The extensive surface area, remarkable swelling ability, and chemical stability of bentonite create a synergistic effect that enhances the formation of hybrid adsorbents, leading to exceptional performance in water purification applications (Zhou & Sun, 2022). These advancements highlight the promise of alginate-bentonite composites as affordable and sustainable options for treating wastewater.

This research evaluates the efficacy of sodium alginate and bentonite-based composites as adsorbents for treating textile wastewater. The study focuses on the affordability, environmental sustainability, and adaptability of these materials, supported by a detailed analysis of the physicochemical properties of wastewater and the structural characteristics of the adsorbents. Key process parameters, including adsorbent dosage, contact time, pH, and temperature, will be optimized to maximize adsorption efficiency. This comprehensive approach aims to validate sodium alginate and bentonite composites as cost-effective and sustainable solutions for removing dyes and contaminants from textile wastewater.

2. Materials and Methods

2.1. Chemical Substances

This study utilized the following chemicals: sodium alginate ($C_6H_9NaO_7$), bentonite (aluminum silicate hydrate), hydrochloric acid (HCl, 35%), calcium chloride ($CaCl_2$), and sodium hydroxide (NaOH, 98%). These were obtained from Molychem, Avra, and Sigma Aldrich located in Mumbai, India. All reagents were of analytical grade and appropriate for experimental use.

2.2. Collection of textile wastewater sample

Samples of wastewater and sludge were collected from the discharge site at Rooma Textile Park in Kanpur, Uttar Pradesh, India (26.3646° N, 80.4292° E). Kanpur serves as a prominent industrial center, producing considerable amounts of wastewater, which presents significant threats to adjacent water bodies and soil ecosystems. Samples were collected in pre-sterilized containers, transported to the laboratory, and stored at 4°C for subsequent physicochemical analysis.

2.3. Synthesis of Sodium Alginate and Bentonite Composite

The SA/BT composite was synthesized according to the method described by Vishwakarma et al. (2024). A homogeneous viscous sodium alginate solution was created by dissolving 10 g of sodium alginate in 500 mL of distilled water, with continuous stirring for a duration of 2 h. Following this, 20 g of bentonite clay was incorporated into the solution, preserving a 2:1 weight ratio of bentonite to alginate. The mixture was added dropwise using a syringe to 500 mL of a 0.5 M $CaCl_2$ aqueous solution while maintaining constant stirring to produce immobilized beads. The formation of beads resulted from the dimerization of alginate chains. The beads were immersed in the $CaCl_2$ solution for 24 h to achieve stabilization, subsequently separated via filtration, and washed twice with distilled water. The dyed solutions were processed by drying, crushing, and sieving the beads to achieve a particle size of 250 µm with a mesh sieve.

2.4. Physico-chemical analysis of untreated and treated textile wastewater sample

Physicochemical Assessment of Untreated and Treated Textile Wastewater The analyzed wastewater samples displayed a blue color, suggesting elevated dye concentration. The physicochemical parameters evaluated included pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), total hardness, color, biological oxygen demand (BOD), chemical oxygen demand (COD), sulfate, and chloride, following the standard procedures described by APHA (2005). A digital water analyzer (Systronics-361, India) was employed to assess pH, electrical conductivity (EC), and Total Dissolved Solids (TDS). BOD and COD were assessed through the 5-day dilution method and the open reflux method, respectively. Table 1 summarizes the results of the comparison between untreated and treated wastewater parameters using SA/BT.

2.5. Adsorption Studies

Batch adsorption experiments were performed to study adsorption processes. In each experiment, 100 mL of dye-laden wastewater was introduced into a 250 mL conical flask containing a predetermined amount of SA/BT adsorbent. The flask was agitated in an orbital shaking incubator to examine the effects of parameters including pH (2 to 10), adsorbent dose (1–4 g/L), and temperature (20°C, 30°C, 40°C, and 50°C) on dye removal efficiency. Samples were collected at designated time intervals, and pollutant concentrations were analyzed according to established protocols. The effluent pH was adjusted using 0.1 N solutions of sodium hydroxide or hydrochloric acid as necessary.

Table 1 Physico-chemical characteristics of textile wastewater before and after treatment

Parameter	Sample	
	Untreated	Treated by SA/BT
pH	8.89 ± 0.02	7.22 ± 0.03
EC (mS)	6.26 ± 0.08	2.34 ± 0.06
Color	Dark bluish	Transparent
Total Hardness	1041 ± 9.5	541 ± 10.08
TDS (mg/L)	6237 ± 13.92	2618 ± 17.32
TSS (mg/L)	428 ± 5.77	148 ± 3.46
COD (mg/L)	1306 ± 6.76	186 ± 6.92
BOD (mg/L)	536 ± 7.68	77 ± 3.52
Sulfate (mg/L)	1498 ± 8.66	978 ± 8.08
Chloride (mg/L)	1583 ± 6.68	1166 ± 8.19

3. Results and discussion

3.1. Characterization of SA/BT

3.1.1. SEM

The surface morphology and properties of SA/Bnt were examined using Scanning Electron Microscopy (SEM). The material displayed a rough surface texture, characterized by discernible particles of different shapes and sizes, predominantly measuring less than 2 μm, as illustrated in Fig. 1(a and b). The observed particles exhibited a tendency to cluster, resulting in dense and irregular aggregates, probably influenced by the binding properties of alginate (Khaleghi et al., 2023).

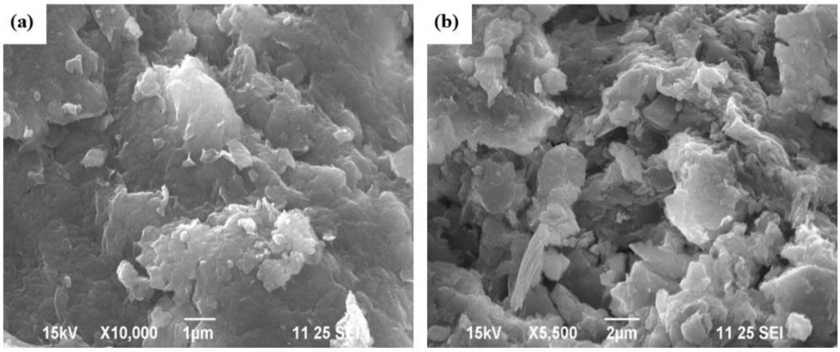

Fig. 1 SEM analysis of SA/BT.

3.1.2. FTIR

The FTIR spectra of SA/Bnt, illustrated in Fig. 2(a), reveal the surface functional groups that are inherent to the material. A clear peak observed at 3413 cm^{-1} is linked to the -OH stretching vibrations, which are associated with water molecules present in the interlayer of bentonite and alginate. Peaks at 1632 cm^{-1} were identified, indicating the asymmetric and symmetric stretching of carboxylate groups, as well as the vibrations of C=C bonds in alkenes, respectively. The band observed at 1037 cm^{-1} corresponds to C-O stretching in alcohols, whereas the structural features of bentonite are associated with Si-O-Si in-plane stretching and Si-O bending vibrations at 532 cm^{-1} (Mohammadi et al., 2014; Thakur et al., 2022).

3.1.3. XRD

The XRD pattern of SA/Bnt, illustrated in Fig. 2(b), reveals several diffraction peaks that are indicative of montmorillonite, noted at angle of 31.63°. The results substantiate the elevated levels of montmorillonite present in the composite material. The presence of additional peaks at 26.59° and 45.45° indicates quartz impurities, whereas the peak at 19.83° points to the existence of feldspars. The positively charged surface characteristics of bentonite facilitate the adsorption of alginate. The absence of alginate peaks in the diffractogram indicates that encapsulation has occurred within the bentonite layers (Wang et al., 2018).

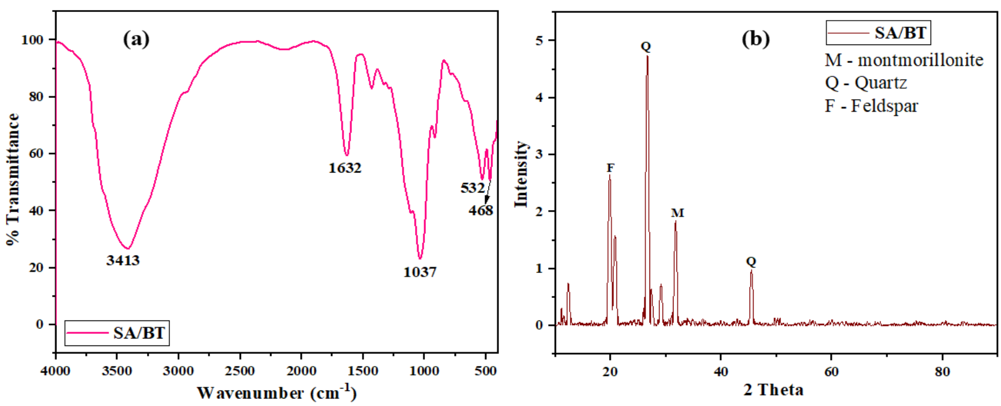

Fig. 2 (a) FTIR analysis of SA/BT and (b) XRD analysis of SA/BT.

3.2. Adsorption of Textile Dyes

3.2.1. Effect of adsorbent dosage

Adsorption of textile dyes is influenced by the dosage of the adsorbent used. The influence of SA/BT dosage on the adsorption of textile wastewater is illustrated in Fig. 3 (a). The efficiency of adsorption demonstrated a significant increase from 10% to 86% with the rise in adsorbent dosage from 1 to 4 $g \cdot L^{-1}$, which can be attributed to the enhanced availability of active surface sites. However, saturation was observed at 3 $g \cdot L^{-1}$, as the concentration of wastewater remained constant, suggesting that the adsorption capacity was limited beyond this dosage (Khalque et al., 2018).

3.2.2. Effect of contact time

The adsorption kinetics were evaluated by adding 3 g of adsorbent to 100 ml of textile wastewater under ambient temperature conditions. The findings illustrated in Fig. 3 (b) indicate a two-phase process: an initial rapid stage where 65% adsorption occurs within the first hour, succeeded by a more gradual phase as equilibrium is attained after 120 minutes. The diminished adsorption rate observed in the later stages can be attributed to the repulsive interactions between the molecules that have already adsorbed and those present in the solution, leading to a plateau at equilibrium (Malekbala et al., 2015).

3.2.3. Effect of temperature

The impact of temperature on adsorption was examined with a 3 g adsorbent dosage utilizing a water bath for temperature stabilization. The findings illustrated in Fig. 3 (c) indicate that elevated temperatures enhance adsorption efficiency, likely as a result of activating more adsorption sites and improving the retention of pollutant molecules. This suggests that temperature variations enhance the material's ability to adsorb substances (Karim et al., 2010).

3.2.4. Effect of pH

The influence of pH on adsorption was assessed with an adsorbent dosage of 3 $g \cdot L^{-1}$. The pH of the solution was modified from 2 to 10 using 0.5 M HCl and NaOH. The data illustrated in Fig. 3 (d) shows that the adsorption efficiency reached its maximum at 87% when the pH was adjusted to 8. This behavior can be attributed to diminished competition from H^+ ions at elevated pH levels, which facilitates enhanced electrostatic interactions between negatively charged adsorbent sites and dye molecules. When the pH falls below 6, the surface of the adsorbent carries a positive charge, which impedes the process of adsorption. In contrast, at elevated pH levels, the surface acquires a negative charge, which facilitates the absorption of dye molecules (Kim, 2003).

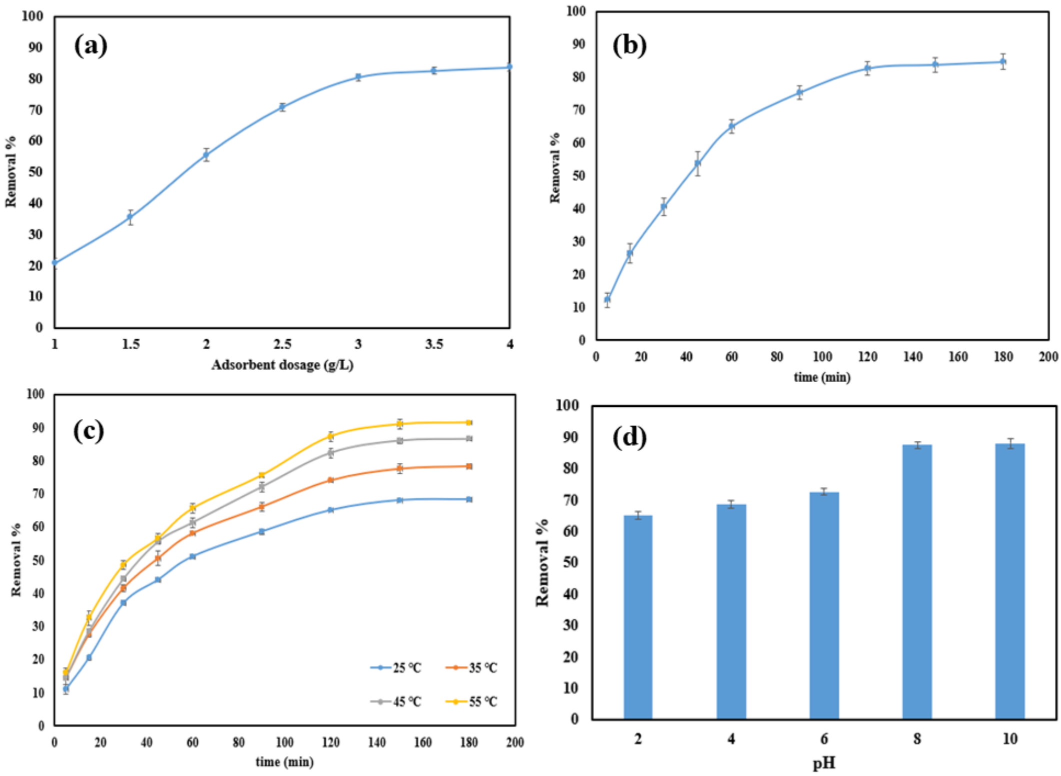

Fig. 3 (a) Effect of SA/BT dosage, (b) Effect of contact time for wastewater treatment, (c) Effect of pH on wastewater treatment, and (d) Effect of temperature on wastewater treatment.

4. Conclusion

The adsorption experiments employing sodium alginate-bentonite (SA/BT) as an adsorbent showed its efficacy in the treatment of textile wastewaters. The impact of essential parameters such as adsorbent dosage, contact time, pH, and temperature was thoroughly examined. The findings indicated that the decrease in organic compounds within the wastewater was enhanced with extended contact durations, identifying an optimal contact time of 180 minutes. In a similar manner, the efficiency of removing dyes and other pollutants increased with greater dosages of the adsorbent, reaching an optimal level at 3 g/L. The research indicated that the adsorption process exhibited a dependency on pH levels, with an optimal pH of 8, significantly improving the removal efficiency. Furthermore, elevated temperatures (50°C) showed a marginal enhancement in pollutant removal in contrast to lower temperatures (20°C), suggesting a beneficial effect of thermal conditions. The results clearly demonstrated that the SA/BT composite might serve as an effective and dependable adsorbent for treating wastewater generated by the textile industry, presenting a viable and sustainable approach to reducing water pollution.

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