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Original Research Article

Effect of Macroporous Chitosan-Tripolyphosphate Beads On COD And Turbidity Values in Sasirangan Wastewater

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Abstract

A batch system was applied to study the effect of using macroporous cross-linked chitosan–Tripolyphosphate (TPP) beads on Chemical Oxygen Demand (COD) values and turbidity in Sasirangan wastewater. The ionic cross-linking reagent sodium tripolyphosphate was used to obtain more rigid chitosan beads, and sodium bicarbonate was added as a porogen. The COD value was analyzed using the titrimetric method and the turbidity value using the turbidimetric method. This analysis was used to study the effect of dose and pH on the performance of beads in sasirangan wastewater. SEM characterization of the beads showed that $NaHCO_3$ as porogen enlarged the pores in the beads of chitosan-TPP, and FTIR characterization showed interactions among chitosan, chitosan–TPP beads, and wastewater. The results showed that higher chitosan dosages resulted in increased final COD values in sasirangan wastewater, and the higher the pH, the higher the COD value. The addition of beads reduced the turbidity value of the sasirangan wastewater, where higher doses led to greater turbidity reduction, with the optimum achieved at 400 mL/L. The pH conditions did not affect the reduction in the turbidity value where with less than 1% variation observed.

Keywords: Chemical oxygen demand (COD), chitosan-tripolyphosphate (TPP) beads, sasirangan wastewater, turbidity

1. Introduction

The textile industry is recognized as one of the major contributors to environmental pollution, particularly due to the discharge of dye-laden effluents into natural water bodies. Even at very low concentrations, textile dyes remain highly visible and can exert toxic effects on aquatic organisms, thereby disrupting ecosystems and deteriorating water quality (Nurmasari et al., 2018; Utami & Nurmasari, 2012). A notable example can be found in South Kalimantan, Indonesia, where the traditional Sasirangan textile industry generates large volumes of wastewater characterized by elevated chemical oxygen demand (COD) and turbidity as two critical indicators of organic pollution (Khair & Noraida, 2025; Nooryaneti et al., 2023). If untreated, this wastewater poses severe risks to aquatic life, destabilizes ecological balance, and limits the usability of water resources. Despite increasing awareness, Sasirangan wastewater treatment remains a challenge due to its complex pollutant composition and the absence of cost-effective, environmentally friendly treatment technologies suitable for small-scale industries. Conventional treatment methods are often inefficient or economically unfeasible for local artisans, highlighting the urgent need for alternative solutions capable of reducing COD and turbidity effectively at low cost.

Several conventional and advanced methods have been applied to textile effluents. Coagulation–flocculation is simple and effective for turbidity removal but generates large sludge volumes and struggles with soluble dyes (Bratby, 2016; Verma et al., 2012). Oxidation processes (ozone, chlorine) degrade chromophores quickly yet require high chemical inputs and may form harmful byproducts (Robinson et al., 2001). Fenton's reagent achieves strong mineralization but works only in acidic pH and produces iron sludge (Nidheesh & Gandhimathi, 2012). Advanced oxidation processes (AOPs) such as UV/H_2O_2 and O_3/UV can mineralize dyes completely, but their high energy costs and sophisticated setups make them unsuitable for small-scale Sasirangan industries (Oturan & Aaron, 2014). Compared to these, adsorption offers a low-cost, eco-friendly, and easy-to-implement option without generating hazardous byproducts or large sludge volumes.

Adsorption has therefore emerged as a promising technique for treating textile effluents due to its simplicity, efficiency, and cost-effectiveness. Among the various adsorbents studied, chitosan has garnered attention for its high adsorption capacity, non-toxicity, biodegradability, and antimicrobial properties (Khubiev et al., 2023; Ravi Kumar, 2000). However, native chitosan has limitations in acidic environments, where it tends to dissolve and lose structural integrity. To overcome this, chemical modification through ionic cross-linking with sodium – TPP has been proposed to enhance chitosan's stability and mechanical strength (Crini & Badot, 2008). Native chitosan, despite its high adsorption capacity and biodegradability, suffers from poor stability in acidic environments where it tends to dissolve and lose structural integrity. To address this limitation, ionic cross-linking with sodium – TPP has been widely applied, as it enhances the chemical stability and mechanical strength of the polymer matrix (Crini & Badot, 2008). However, this modification can also restrict the number of accessible active sites, thereby reducing overall adsorption efficiency (Nurmasari et al., 2018; Syauqiah et al., 2011; Vakili et al., 2014; Zhao et al., 2016). To mitigate this drawback, recent studies have explored the incorporation of porogens such as sodium bicarbonate ($NaHCO_3$) during bead synthesis. The decomposition of $NaHCO_3$ releases CO_2, generating interconnected macropores within the bead structure. These macropores increase the surface area and diffusion pathways, resulting in markedly enhanced porosity and adsorption performance (Ariyani, Mujiyanti, Santoso, Maulana, et al., 2021; Chiou & Li, 2003; Mi et al., 2003; Rockson-Itıveh et al., 2024).

Although previous studies have widely demonstrated the effectiveness of chitosan-based beads in removing dyes from textile wastewater, most evaluations have been limited to color as the primary indicator. However, as shown in Table 1, Sasirangan wastewater is also characterized by elevated COD (276.9 mg/L) and turbidity (676 NTU), both of which surpass national discharge standards and represent critical ecological risks. These parameters, which reflect organic load and suspended solids respectively, are more directly relevant to regulatory compliance and environmental sustainability. Despite their importance, limited research has systematically examined how factors such as pH and adsorbent dosage influence the ability of macroporous chitosan–TPP beads to reduce COD and turbidity. Therefore, this study seeks to address that gap, expanding the application of chitosan-based adsorbents beyond color removal toward comprehensive wastewater quality improvement.

2. Methods

This research is experimental in nature, conducted to evaluate the performance of macroporous chitosan–TPP beads in reducing turbidity and COD of Sasirangan textile wastewater. Sampling and preliminary testing were performed in the Banjarmasin region, South Kalimantan, Indonesia (approx. 3.32° S, 114.59° E; 3°19′ S, 114°35′ E). Laboratory-scale synthesis and treatment experiments were conducted at the Chemistry Laboratory, Faculty of Mathematics and Natural Sciences. Wastewater samples were collected from a reservoir of a Sasirangan fabric home industry. The samples were stored in clean, closed containers, placed in a dry and dark room to minimize changes in composition. Prior to treatment, initial COD and turbidity values were measured using a UV–Vis spectrophotometer and a turbidimeter as baseline references for comparison. The flow chart of the study is shown in Figure 1.

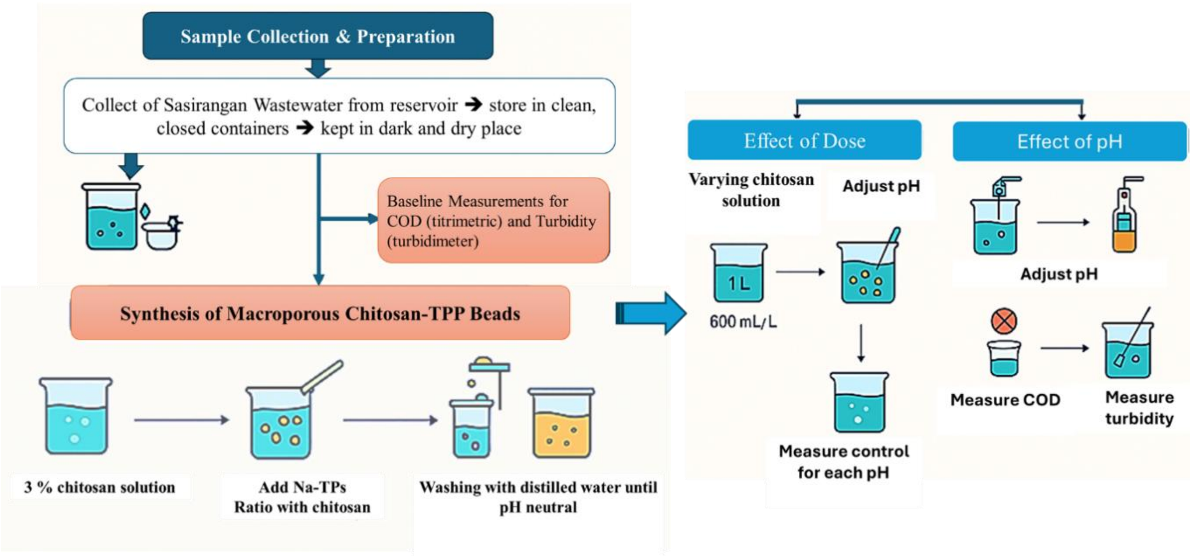


Figure 1. Flow diagram of Sasirangan wastewater treatment process: sample collection, synthesis of chitosan–TPP beads, and adsorption tests

2.1. Effect of Dose on The Ability of Beads in The Treatment of Sasirangan Wastewater

In this study, the chitosan-TPP bead synthesis procedure followed the method used in the study by Azkia et al. (2021) with several modifications. The dose of chitosan was determined based on the amount of 3% chitosan solution used to make beads for 1 liter of sasirangan wastewater, with variations of 300 ml/L, 400 ml/L, 500 ml/L, 600 ml/L. A dose of 300 ml/L of 3% chitosan solution was taken as much as 300 mL, and 0.2 grams of $NaHCO_3$ was stirred until foamy. To make beads, the chitosan solution is foamed and then soaked in a sodium-TPP solution for 24 hours. The resulting beads are then filtered and washed with distilled water until the pH becomes neutral. A total of 1 L of sasirangan liquid waste solution was prepared and added with 300 mL of chitosan-TPP beads, and the filtrate was then separated by filtering with Whatman No 42 paper. The resulting filtrate was then measured against the COD value and turbidity. The same procedure was carried out for variations in the dose of chitosan solution of 400 ml/L, 500 ml/L, and 600 ml/L. The dose of 300 mL/L was prepared with a 1:1 ratio of Na-TPP solution to chitosan solution. The negative control was prepared with one beaker containing 500 mL of sasirangan waste without adding beads.

2.2. Effect of pH on the Ability of Beads in the Treatment of Sasirangan Wastewater

The optimum dose of chitosan solution was obtained from the procedure above. Used to study the effect of wastewater pH on the ability of beads in the treatment of sasirangan wastewater, (the same procedure is performed with the determination of the effect of the dose) A total of 500 mL. The initial pH of the waste solution was set to pH 3, then contacted with beads by stirring for 5 minutes and allowed to stand. Beads and the filtrate were then separated by filtering with Whatman No 42 paper. The resulting filtrate was then measured for COD and turbidity values. The same procedure was carried out for variations in the initial pH of the wastewater, namely pH 5, pH 7, and pH 9. The negative control was also prepared with four beakers containing 500 mL of sasirangan wastewater without adding beads with settings of pH 3, pH 5, pH 7, and pH 9.

3. Result and Discussion

3.1. Initial Characterization of Sasirangan Wastewater

The Sasirangan wastewater analyzed contained a COD of 276.9 mg/L and turbidity of 676 NTU, both far exceeding Indonesian discharge standards (Ministry of Environment Regulation No. 5/2014). Elevated COD reflects a high organic load that can deplete dissolved oxygen, trigger anaerobic decomposition, and foster microbial proliferation (Nunes et al., 2022). Likewise, high turbidity disrupts photosynthetic activity by limiting light penetration (Sahoo & Anandhi, 2023). These baseline values highlight the urgent need for effective, low-cost treatment technologies applicable to small-scale industries. In the earlier work, Ariyani et al., 2023 evaluated the ability of chitosan–epichlorohydrin beads to reduce TDS and dye content. Building on that foundation, this study directs attention to different but equally critical parameters: COD and turbidity, by employing chitosan–TPP macropore beads (Ariyani et al., 2023).

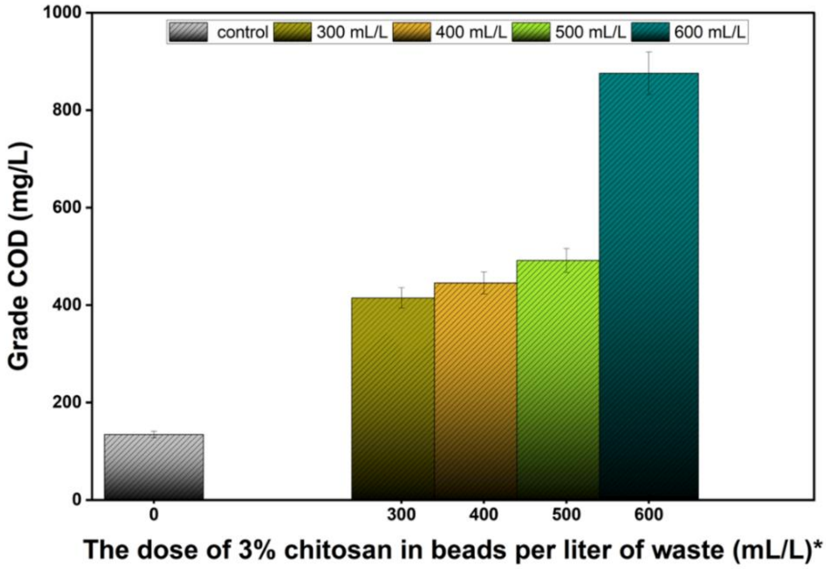
Table 1. The results of the analysis of COD and turbidity of the Sasirangan wastewater samples

No.	Parameter	Methode	Score
1	COD	Titrimetri	276,9 mg/L
2	Turbidity	Turbidimeter	676 NTU

COD reflects the overall organic load, encompassing both biodegradable and recalcitrant compounds, while turbidity represents suspended solids and dye particulates. These indicators are directly related to ecological impacts and are particularly relevant for small-scale textile industries, where cost-effective treatment remains a challenge. Thus, this study expands the scope of previous research by targeting more realistic indicators of wastewater quality.

3.2. Effect of Chitosan Dosage on COD Values

Figure 2 illustrates the effect of chitosan–TPP bead dosage on COD values in Sasirangan wastewater. Unexpectedly, a progressive COD increase was observed with higher bead dosages. Rather than sequestering organic pollutants, the beads likely contributed additional oxidizable matter. This anomaly can be explained by partial bead disintegration during agitation and competitive interactions in wastewater. Ionic cross-linking between chitosan and TPP is relatively weak, and under treatment conditions fragments of the polymer can leach into solution. These fragments, containing hydroxyl and amine groups, are readily oxidized by potassium dichromate in COD titrimetric analysis, resulting in inflated COD values (Khubiev et al., 2023). Interestingly, COD values in the untreated control decreased slightly, possibly due to self-coagulation and sedimentation of suspended solids. This contrast highlights that without stabilizing modifications, the application of chitosan–TPP beads may exacerbate organic load rather than reduce it. Similar challenges have been documented in other weakly stabilized polysaccharide-based adsorbents (Rockson-Itiveh et al., 2024). Therefore, future strategies should prioritize enhancing bead structural integrity through dual cross-linking, incorporation of stabilizing fillers (e.g., silica, biochar), or immobilization in fixed matrices to ensure long-term stability and effective COD removal.



Desc: * chitosan dose = volume of chitosan solution used to make beads per 1 liter of sample

Figure 2. Effect of chitosan dose (3% chitosan in beads per liter of waste, mL/L) on COD values

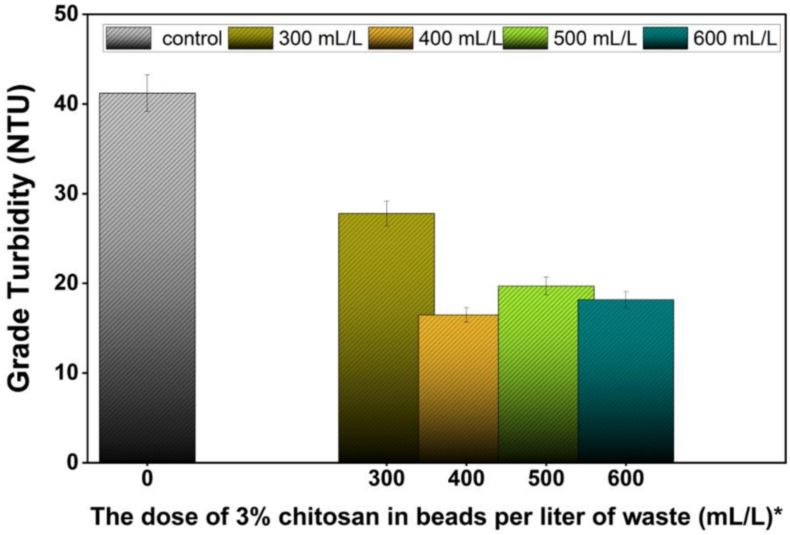
3.3. Mechanistic Insight: Chitosan Oxidation and Bead Stability

The behavior of chitosan in aqueous environments is highly pH-dependent. In acidic media, the amine groups of chitosan are protonated ($-NH_2 \rightarrow -NH_3^+$), enhancing its solubility but also promoting stronger electrostatic interactions with TPP ions (Kurniasih et al., 2011). However, under neutral or basic pH, these groups deprotonate, weakening the ionic cross-links and promoting chitosan release.The dissolution of chitosan from beads under varying pH conditions is discussed further in Section 3.5, directly contributes to elevated COD values, as the released polymer is readily oxidized. Thus, the integrity of chitosan-TPP beads is not solely a function of cross-linking efficiency but also of environmental pH and hydrodynamic conditions.

This finding calls for further research on bead reinforcement strategies, including dual cross-linking or hybrid composite formulations (e.g., chitosan–biochar or chitosan–silica composites), to ensure mechanical and chemical stability during application.

3.4. Effect of Chitosan Dosage on Turbidity Reduction

Unlike COD, the turbidity of Sasirangan wastewater significantly decreased with increasing chitosan bead dosage, as presented in Figure 3. The most substantial reduction occurred at 400 mL/L dosage, beyond which improvements plateaued. All treated samples met the turbidity standard (<50 NTU), indicating effective removal of suspended solids.



Desc: * chitosan dose = volume of chitosan solution used to make beads per 1 liter of sample

Figure 3. Effect of chitosan dose (3% chitosan in beads per liter of waste, mL/L) on turbidity values

The turbidity removal mechanism is likely dominated by a combination of physical entrapment, adsorption, and charge neutralization. The nature of cationic chitosan under acidic to neutral pH allows electrostatic interactions with negatively charged particles, while the porous bead structure enhanced by $NaHCO_3$ as a porogen facilitates the capture of colloids and dyes (Ariyani, Mujiyanti, Santoso, Irawati, et al., 2021; Chiou & Li, 2003). The large surface area offered by the macropores promotes bridging and floc formation, which subsequently settles or is filtered out.

However, diminishing returns beyond 400 mL/L suggest that adsorption sites reach saturation, and excess beads may hinder optimal mixing or contribute to re-dispersion of solids. This behavior aligns with Langmuir-type adsorption kinetics, wherein monolayer coverage limits further uptake once equilibrium is reached.

3.5. Effect of pH on COD Values

Figure 4 illustrates the effect of initial pH on COD values after treatment with chitosan–TPP beads. A clear trend was observed: COD values increased progressively as pH rose. At acidic conditions (pH 3–5), protonation of amino groups ($-NH_2 \rightarrow -NH_3^+$) facilitated stronger ionic cross-linking with TPP, enhancing bead stability and minimizing dissolution. Conversely, under neutral and alkaline conditions, deprotonation weakened electrostatic bonds, causing bead swelling, matrix disruption, and leaching of chitosan fragments (Figure 5–7). These fragments, rich in hydroxyl and amine groups, are readily oxidized during dichromate titration, artificially inflating COD readings (Khubiev et al., 2023). Interestingly, at pH 3, COD reduction was only 1.01%, confirming that although acidic conditions prevent bead disintegration, the beads themselves lack sufficient capacity to reduce organic loads significantly. This highlights a fundamental limitation of ionic cross-linking systems, which are highly sensitive to pH. Similar findings have been reported in polysaccharide-based adsorbents under alkaline environments (Rockson-Itiveh et al., 2024). For practical applications, treatment under acidic pH is necessary, but to achieve effective COD removal, chitosan–TPP beads must be further reinforced—such as through dual cross-linking, incorporation of inorganic fillers, or coupling with biological/oxidative post-treatment.

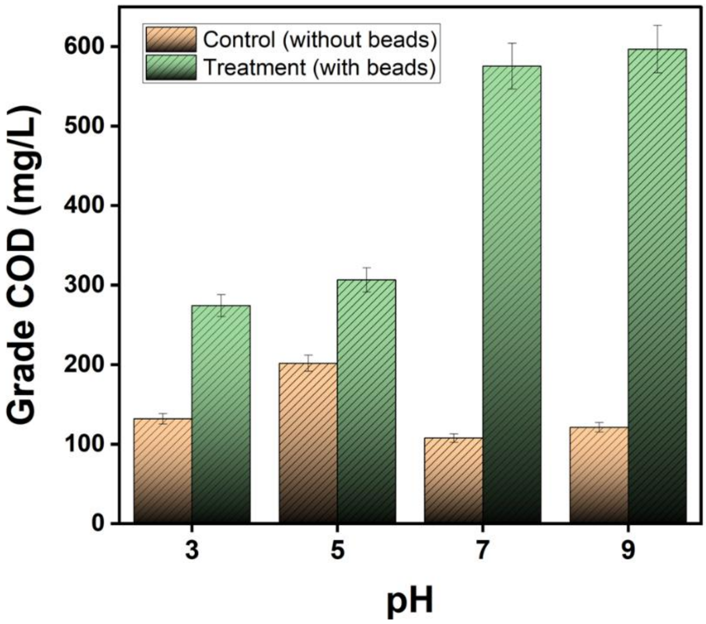


Figure 4. Effect of pH on the performance of macroporous beads in reducing COD values

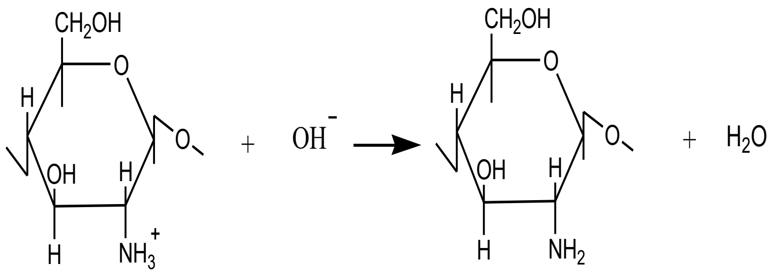


Figure 5. Deprotonation reaction beads of chitosan-TPP

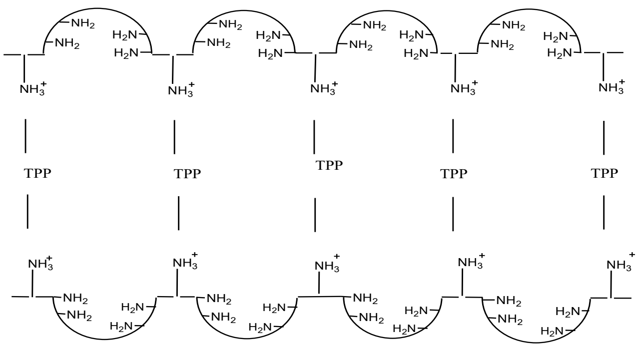


Figure 6. The shape loop of chitosan-TPP molecules due to cross-binding with TPP at basic pH

The alkaline conditions of cross-links between chitosan and TPP ions are less so that they are more easily released into the waste than under acidic conditions as presented in Figure 7. The COD value only decreased at pH 3 but not large, only 1.01%, because at acidic pH, the cross-link density between chitosan and TPP ions can be maintained so that it is not easily released into the waste. Under acidic conditions, the $-NH_2$ of chitosan will be protonated to $-NH_3^+$ causing the cross-linking interaction between the $-NH_3^+$ of chitosan and the TPP ion to become more dense. Based on the results of this study, beads are less effective in reducing the COD value in the Sasirangan wastewater treatment. In contrast, the strong electrostatic interaction between protonated amines ($-NH_3^+$) and TPP ions under acidic pH results in tighter cross-linking and a more robust bead structure. This configuration restricts the release of chitosan into the surrounding medium, contributing to better COD control.

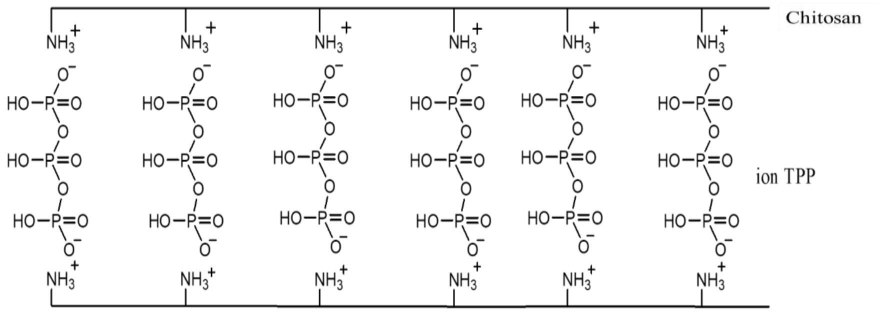


Figure 7. Cross-bond interaction between chitosan and TPP ions in acid solution.

3.6. Effect of pH on Turbidity Reduction

Figure 8 illustrates the influence of initial pH (3, 5, 7, and 9) on the turbidity removal efficiency of chitosan–TPP beads. Interestingly, unlike COD, turbidity reduction was largely unaffected by pH variation. Across all conditions, turbidity decreased significantly, reaching values below the regulatory discharge standard (<50 NTU). This suggests that the dominant mechanisms for turbidity removal—namely, physical entrapment of suspended solids, flocculation, and adsorption within macroporous structures—are relatively insensitive to changes in surface charge (Annabi et al., 2010). The addition of $NaHCO_3$ as a porogen generated interconnected macropores that enhance bead porosity, enabling efficient capture of colloidal particles regardless of protonation state. This observation is consistent with previous reports showing that structural features, rather than electrostatic interactions, govern turbidity reduction (Ibrahim, 2013). The robustness of performance across a wide pH range provides a practical advantage, as many small-scale textile producers cannot afford continuous pH adjustment. However, while turbidity removal was highly effective, the contrast with COD behavior underscores a critical limitation: the beads are efficient for particulate matter but inadequate for dissolved organics. This emphasizes the need for hybrid treatment systems, where chitosan–TPP beads serve as a pre-treatment for turbidity, followed by biological or oxidative processes for COD reduction.

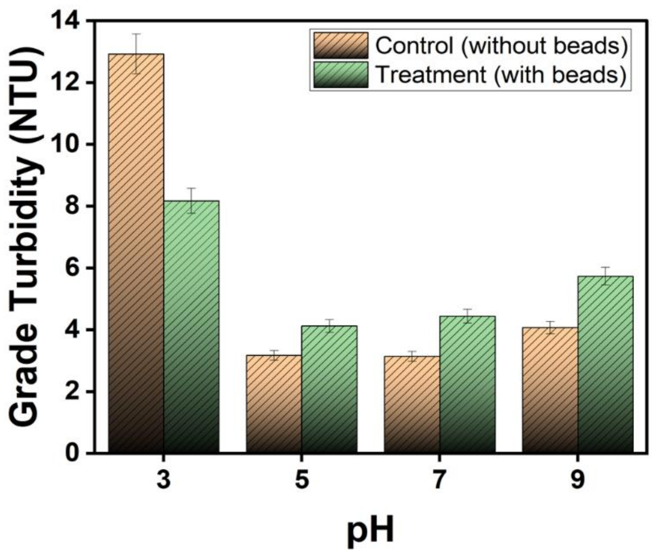


Figure 8. Effect of pH on the performance of macroporous beads in reducing turbidity values

3.7. Scanning Electron Microscopy (SEM) Analysis: Morphological Insights

SEM analysis (Figure 9) provided critical insights into the morphological differences between beads synthesized with and without $NaHCO_3$. Beads without porogen appeared smooth and dense, offering limited surface area and pore accessibility. In contrast, beads prepared with $NaHCO_3$ displayed rough, irregular textures with interconnected macropores, resulting from CO_2 release during bicarbonate decomposition (Anggraeny et al., 2014). These macropores play a central role in facilitating turbidity removal, as they increase active surface area, enhance mass transfer, and enable physical entrapment of suspended solids and dye aggregates. The strong performance observed across all pH ranges for turbidity reduction (Figure 8) can therefore be directly attributed to the structural porosity revealed in SEM images.

However, the same porosity may also act as a weakness. Enlarged cavities reduce mechanical stability and render the matrix more susceptible to fragmentation during mixing or at alkaline pH. These fragments contribute additional oxidizable organics, consistent with the elevated COD values observed in Figures 2 and 4. Thus, SEM results not only validate the mechanism behind efficient turbidity removal but also explain the paradoxical increase in COD. This underscores the importance of balancing porosity and stability when designing chitosan-based adsorbents for real wastewater applications.

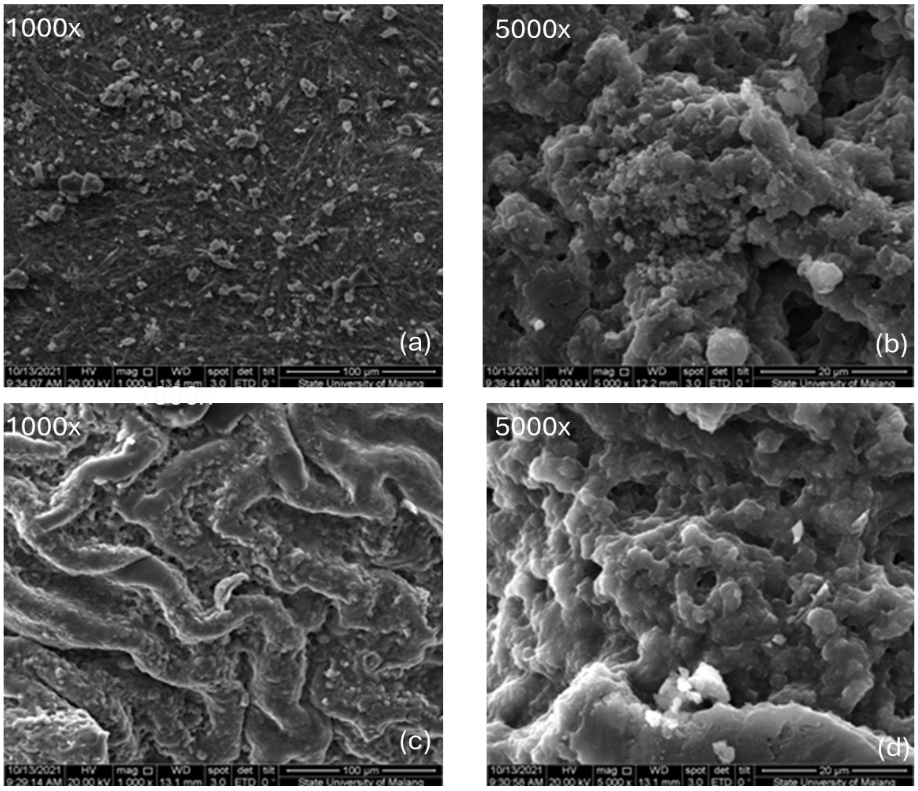


Figure 9. SEM Chitosan-TPP beads : (a) without $NaHCO_3$, magnification 1000x, (b) without $NaHCO_3$, magnification 5000x, (c) with $NaHCO_3$, magnification 1000x and (d) with $NaHCO_3$, magnification 5000x

3.8. Fourier Transform Infrared Spectroscopy (FTIR) Analysis: Chemical Interaction Evidence

FTIR analysis (Figure 10; Table 2) provided further evidence of adsorption mechanisms. Compared to spectra of pristine beads, those exposed to Sasirangan wastewater exhibited several distinct changes. A new absorption peak at 1606 cm^{-1} corresponded to azo groups (-N=N-), confirming that dye molecules from the wastewater were successfully adsorbed onto the chitosan–TPP surface. Additionally, shifts in the OH/NH stretching regions (3317–3624 cm^{-1}) suggested strong hydrogen bonding and electrostatic interactions between bead functional groups and polar groups of organic contaminants.

Aliphatic C–H vibrations and C–O–C stretching shifts also indicated Van der Waals and ionic interactions with dye and organic molecules (Vakili et al., 2014; Zhao et al., 2016).

These findings highlight the dual functionality of the beads: physical entrapment via macropores (validated by SEM) and chemical adsorption via surface functional groups. This synergy explains the efficient turbidity removal observed across all pH values. However, the persistence of elevated COD values suggests that while dyes were bound, soluble chitosan fragments released into solution also contributed to the oxidizable organic load. Thus, FTIR results complement COD–turbidity findings, emphasizing both the strengths (effective dye adsorption) and limitations (polymer leaching) of the chitosan–TPP bead system.

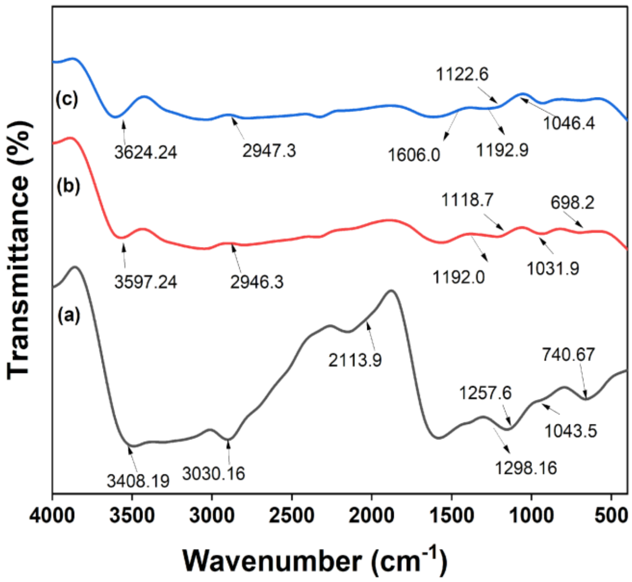


Figure 10. Spectra FTIR chitosan (a), beads chitosan (b), beads+waste (c)

Table 2. Identification of each functional group in the infrared spectrum of chitosan, beads chitosan-TPP beads, and beads chitosan-TPP with waste

Chitosan (cm^{-1})	Beads chitosan-TPP (cm^{-1})	Beads chitosan-TPP + waste (cm^{-1})	Identity
740.67	698.23		Stretching vibration 1,4-
898.83			glycosidic
1043.49	1031.92	1046.,41	C-O-C Vibration
1257.59	1118.71	1122.57	Symmetric stretching
1298.16	1192.01	1195.87	vibration C-O
		1224.80	
	2113.98		Vibration C-H aromatic
	2237.43		
		1606,01	-N=N-
3030.16	2946.30	2889.37	Aliphatic C -H
3089.98		2947.23	Vibration
3317.56	3597.24	3624.24	O-H vibration overlap
3408.19			N-H vibration

3.9. Synthesis of Findings and Implications for Practice

The study of chitosan–TPP (tripolyphosphate) macroporous beads in the treatment of textile wastewater reveals significant insights regarding their efficacy and limitations in managing the complex nature of textile effluents. Notably, these beads demonstrated remarkable performance in turbidity removal, achieving reductions from 676 NTU to below 50 NTU, translating to an efficiency exceeding 95% at an optimal dosage of 400 mL/L. Such performance underscores the effectiveness of physical mechanisms including flocculation and chemical adsorption, reinforced by the porosity induced from the incorporation of sodium bicarbonate ($NaHCO_3$), which enhanced active surface areas and diffusion pathways essential for effective contaminant capture (Wahba, 2017).

Further analysis using scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) confirmed the dual mechanisms at play, illustrating both physical entrapment of dye molecules and the presence of organic functional groups indicative of chemical interactions. However, the performance regarding chemical oxygen demand (COD) was paradoxically counterproductive; increases in COD at higher dosages and alkaline pH levels suggest instability in the chitosan bead structure leading to the leaching of oxidizable fragments, ultimately complicating treatment outcomes (Zhang et al., 2024). This indicates a critical challenge within polysaccharide-based adsorbents, the enhancement of porosity and adsorptive capacity may concurrently compromise structural integrity, necessitating careful optimization in their application.

Practically, the effectiveness of chitosan–TPP beads suggests their potential as a pre-treatment step within decentralized textile wastewater management systems, primarily aimed at rapid turbidity and color reduction. This method could complement subsequent biological or advanced oxidation treatments targeting dissolved organics, thereby improving overall treatment efficacy. Previous studies have highlighted similar incongruities in treatment efficiencies and structural stability when utilizing polysaccharide-based solutions, emphasizing the necessity for strategic reinforcements, such as dual cross-linking. Ultimately, for chitosan–TPP beads to transition into practical applications, enhancements such as immobilization within fixed matrices or the integration with biochar or silica may be critical to mitigate issues related to polymer leaching while delivering sustained performance in low-cost and eco-friendly textile waste management solutions.

4. Conclusion

The application of macroporous chitosan–TPP beads in Sasirangan wastewater treatment demonstrated contrasting outcomes: while the beads effectively reduced turbidity, they contributed to an increase in COD. At an optimal dose of 400 mL/L, turbidity was reduced from 676 NTU to 29.3 NTU 676 NTU to 29.3 NTU, achieving a 95.7% removal efficiency and meeting discharge standards. However, COD values increased with higher bead dosages and rising pH, reaching up to 366.5 mg/L at pH 9, which was approximately 32% higher than the initial COD of 276.9 mg/L. This increase is attributed to the dissolution of chitosan fragments into the solution due to weakened cross-linking under alkaline conditions, which contributed additional oxidizable organic matter. Despite this limitation, pH variation had minimal effect on turbidity removal, suggesting that flocculation and physical entrapment dominated the process. SEM analysis confirmed the role of $NaHCO_3$ in enhancing bead porosity, while FTIR spectra revealed the successful adsorption of dyes and organic compounds through interactions with functional groups in the chitosan matrix. Overall, although chitosan–TPP beads show promise for turbidity reduction in textile effluents, their use for COD removal requires further optimization to improve structural stability and minimize organic leaching.

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