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Synthesis and Characterization of Cellulose-Based Hydrogel from Durian Rind for Peat Water Purification

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Abstract: Peat water in Indonesia, abundant in swamp regions, is acidic and rich in humic substances and Fe^{2+} ions, making it unsuitable for direct use. This study explores a sustainable approach to treating peat water using hydrogel synthesized from durian rind (*Durio zibethinus*), an agricultural waste rich in cellulose. Cellulose was extracted via alkali and bleaching treatment, then crosslinked with chitosan in a NaOH/urea solvent system to form a biodegradable, porous hydrogel. The hydrogel exhibited a swelling ratio of 857% and a gel content of 98.23%, indicating high hydrophilicity and network integrity. Adsorption experiments demonstrated removal efficiencies of 98.96% for methylene blue and 25% for Fe^{2+}. The high dye removal at low concentrations suggests strong interaction between hydrogel functional groups (–OH, $–NH_2$) and organic molecules, while Fe^{2+} removal was attributed to electrostatic interaction and potential chelation. Adsorption followed pseudo-second-order kinetics, indicating chemisorption as the rate-limiting step. These results suggest that durian rind hydrogel is a promising low-cost material for organic and inorganic pollutant removal in acidic water systems. This study highlights the potential of agro-waste valorization in developing eco-friendly materials for water purification.

Keywords: Adsorption; Durian rind; Hydrogel; Peat water; Water treatment

Introduction

Access to clean and safe water remains a critical issue worldwide, particularly in tropical developing countries such as Indonesia. Despite its abundant freshwater resources, including rivers, lakes, and wetlands. Indonesia continues to face significant challenges related to water quality and distribution (Fransiska et al., 2024). In regions dominated by wetlands, peat water constitutes one of the primary surface water sources. Peat water is chemically characterized by low pH values (typically < 4.5), high concentrations of natural organic matter (NOM) such as humic and fulvic acids, and elevated levels of dissolved iron ions (Fe^{2+}). These attributes result in dark coloration, unpleasant odor, and chemical instability, rendering the water unsuitable for direct consumption without proper treatment (Islam et al., 2020; Kalsum et al., 2024; Qadafi et al., 2023). Conventional treatment methods such as coagulation–flocculation, oxidation, and ion exchange are generally costly, energy-intensive, and impractical for application in remote or decentralized areas (Ekoputri et al., 2023). Therefore, there is an urgent need for decentralized, environmentally friendly, and cost-effective water treatment technologies.

Adsorption is one of the most effective and economically viable methods for water purification, particularly for the removal of organic contaminants and heavy metals (Akhtar et al., 2024; Astuti et al., 2023;

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Satyam et al., 2024). This process operates based on interactions between pollutants and active sites on the adsorbent surface, and its performance is heavily influenced by the nature and structure of the adsorbent material. In recent years, natural adsorbents derived from agricultural and biomass waste have gained prominence due to their low cost, biodegradability, and environmental safety. Materials such as activated carbon, clay, coconut husk, and fruit peels have shown excellent potential for use in pollutant removal (Barus et al., 2022; Haskis et al., 2024; Kainth et al., 2024; Sarah, 2018; Sen, 2023; Tsoutsa et al., 2024). Among these, hydrogel-based adsorbents represent a novel advancement. Hydrogels are three-dimensional polymeric networks capable of retaining large quantities of water within their structure. Their high porosity, large surface area, and tunable functional groups make them ideal for adsorption-based water treatment applications (Darban et al., 2022; Jelita et al., 2024; Susanto et al., 2024).

The application of hydrogels synthesized from biomass is particularly appealing from a green chemistry perspective. These materials offer dual benefits: reducing agricultural waste and producing environmentally friendly adsorbents. Durian rind (*Durio zibethinus*), a lignocellulosic waste rich in cellulose and lignin, is an abundant byproduct in Southeast Asia and remains underutilized. Studies have shown its potential in adsorbing metal ions and dyes due to its fibrous structure and surface functionalities (Alaoui et al., 2023; Bakshi et al., 2025; Guan et al., 2025; Mondal et al., 2023; Rico-García et al., 2020). By converting this waste into value-added hydrogel materials, it is possible to address both waste management and water treatment challenges simultaneously.

Despite its potential, limited studies have investigated the application of durian rind-derived hydrogel specifically for the treatment of peat water, which presents the dual challenge of acidic conditions and complex organic-metal mixtures. This study aims to fill that gap by synthesizing and characterizing a cellulose-based hydrogel from durian rind, crosslinked with chitosan, and evaluating its performance in removing both methylene blue (as a model organic pollutant) and Fe^{2+} (as a representative inorganic contaminant) under acidic conditions mimicking peat water. The use of chitosan, a biopolymer with amino functional groups, enhances the hydrogel's affinity toward metal ions and contributes to mechanical stability in aqueous environments (Aranaz et al., 2021; Chelu et al., 2023; Das et al., 2024; Edo et al., 2024; Gonçalves et al., 2024; Jiménez-Gómez et al., 2020; Oktavia et al., 2024; Saiyad et al., 2024; Saragih et al., 2025).

The novelty of this research lies in its development of a dual-functional, biodegradable hydrogel sourced entirely from agro-waste materials, designed specifically for the remediation of acidic peat water. Unlike conventional adsorbents that target single pollutants or rely on synthetic polymers, this study integrates waste valorization, green synthesis, and multifunctional adsorption into a unified material system. Furthermore, the hydrogel is characterized by high swelling ability, strong network integrity, and significant removal efficiencies, highlighting its promise as a cost-effective and scalable solution for water purification in peatland and remote communities.

By addressing the critical gap in low-cost, biomass-based adsorbents for complex wastewater types, this research supports broader efforts in sustainable water management, circular economy, and the implementation of environmentally responsible technologies in developing regions.

Method

This research was conducted using an experimental method to synthesize and evaluate hydrogel derived from durian rind (*Durio zibethinus*) for the adsorption of contaminants in peat water. The methodological stages include five main steps: (1) cellulose extraction, (2) hydrogel synthesis, (3) hydrogel characterization, (4) adsorption performance test in peat water, and (5) adsorption kinetics study.

Materials and Equipment

The primary materials used in this study included durian rind waste, peat water samples, chitosan, $NaClO_2$, NaOH, acetic acid, urea, HCl, H_2SO_4, HNO_3, KI, $KMnO_4$, KOH, methylene blue, and analytical reagents. The instruments included analytical balance, oven, hotplate, shaker, centrifuge, pH meter, UV-Vis spectrophotometer (Agilent Cary), FTIR spectrometer, atomic absorption spectrophotometer (Varian AA 240FS), and standard glassware.

Cellulose Extraction from Durian Rind

Cellulose was extracted following a two-step process adapted from Tawakkal et al. (2012): (1) Holocellulose Production: Durian rind powder was treated with 5% sodium chlorite ($NaClO_2$) to remove lignin via chlorination, forming holocellulose. (2) Mercerization: The holocellulose was treated with 17.5% sodium hydroxide (NaOH) at room temperature to convert it into purified cellulose. (3) FTIR Analysis: The resulting cellulose was confirmed using Fourier Transform Infrared (FTIR) spectroscopy to verify the removal of lignin and the presence of cellulose-specific functional groups.

Hydrogel Synthesis

The hydrogel was synthesized according to the procedure by Pakdel et al. (2018) with slight modification: (a) The extracted cellulose was mixed with chitosan in a 7:3 ratio. (b) The polymer blend was dissolved in a NaOH/urea/water solution with a volume ratio of 7:11:81 and stirred for 1 hour at room temperature. (c) The mixture was then cooled to −13°C for 1 hour to facilitate pre-gelation. (d) The resulting composite solution was sequentially treated with 250 mL of 2 M acetic acid, hydrochloric acid (HCl), and sulfuric acid (H_2SO_4). (e) The formed hydrogel was immersed in the coagulation media for 2 hours, followed by thorough washing with deionized water until neutral pH was achieved. (f) The final hydrogel was stored in deionized water prior to characterization and testing.

Hydrogel Characterization

Hydrogel properties were characterized based on: Methylene Blue Adsorption to estimate active surface area.

Adsorption Testing in Peat Water

a) Peat water samples were collected from Jl. Sepakat II, Pontianak.
b) A permanganate index calibration curve was created by diluting peat water samples (30×–70×) and measuring absorbance at 254 nm using UV-Vis spectrophotometry.
c) Adsorption tests were carried out to evaluate the ability of the hydrogel to reduce organic content and iron (Fe^{2+}) concentrations in the peat water.

Result and Discussion

Cellulose Extraction and Purification

The transformation of durian rind into purified cellulose involves two key chemical steps: holocellulose production and mercerization. Holocellulose production was carried out using the chlorination method. In this stage, a 5% $NaClO_2$ solution was used. The resulting product was a white-colored holocellulose. The addition of $NaClO_2$ to the sample aimed to remove the lignin content still present in the durian rind. The transformation of durian rind into holocellulose is shown in Figure 1.

Following delignification, holocellulose obtained from durian rind was subjected to mercerization using 17.5% sodium hydroxide (NaOH). This alkaline treatment plays a crucial role in transforming cellulose I—the native crystalline form of cellulose—into cellulose II, a polymorph characterized by a more disordered structure with enhanced amorphous regions. Such structural modification not only increases the reactivity of cellulose but also improves its accessibility for subsequent chemical functionalization. During mercerization, NaOH disrupts the linkages between hemicellulose and lignin, effectively isolating cellulose chains with high crystallinity and purity (Du et al., 2025; Tawakkal et al., 2012).

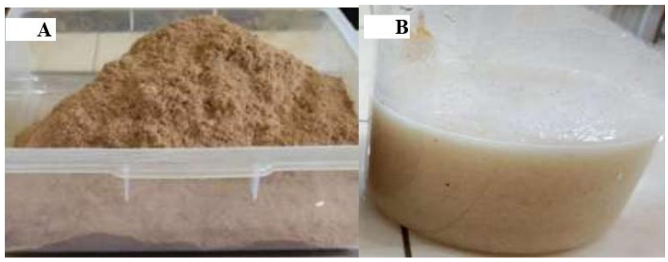

Figure 1. (A) Durian rind powder; (B) Holocellulose

The process facilitates exposure of hydroxyl groups at the C2, C3, and C6 positions of the glucose units, which are pivotal for hydrogen bonding and subsequent crosslinking during hydrogel formation (Ahmed, 2015). The regenerated cellulose fibers resulting from this treatment exhibited typical morphological features—fibrous texture, white coloration, and enhanced mechanical strength—confirming successful transformation. These features indicate improved hydrophilicity and potential adsorption efficiency. The resulting cellulose product post-mercerization is illustrated in Figure 2.

Figure 2. Regenerated cellulose obtained after mercerization

FTIR Confirmation of Functional Group Alterations

The resulting cellulose was then characterized using Fourier Transform Infrared (FTIR) Spectroscopy. The FTIR analysis results are presented in Figure 3.

FTIR analysis confirms successful cellulose isolation. The broad absorption at ~3441 cm^{-1} is attributed to O–H stretching vibrations, indicative of extensive hydrogen bonding—a prerequisite for hydrogel formation. The absence of aromatic C=C stretching bands (1500–1600 cm^{-1}) confirms effective lignin removal. Moreover, the β-glycosidic bond peak at 894 cm^{-1} validates the polysaccharide backbone structure (Hong et al., 2024). This structural profile aligns with other cellulose sources used in hydrogel-based adsorbents, including sugarcane bagasse and corn husk (Zhu et al., 2023).

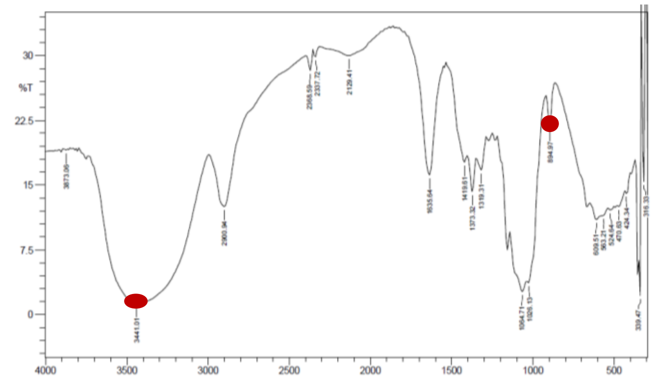

Figure 3. FTIR Spectrum

Hydrogel Network Formation and Structural Chemistry

Hydrogels are formed via physical or chemical crosslinking of hydrophilic polymers to produce a three-dimensional matrix capable of retaining large volumes of water. In this study, cellulose is crosslinked using chitosan and a NaOH/urea solvent system. Chitosan introduces amine functionalities (-NH_2) that can participate in hydrogen bonding or chelation, enhancing adsorption capacity for heavy metals and dyes (Tran et al., 2018). The synthesis results confirmed the successful formation of the hydrogel, characterized by its gel-like consistency in the hydrated state and a cotton-like appearance when dried. The images of both wet and dry hydrogel are shown in Figure 4.

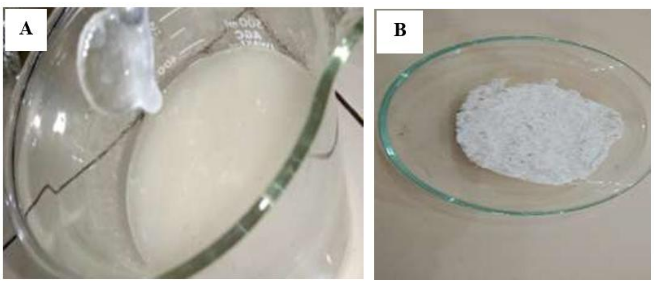

Figure 4. (A) Wet hydrogel; (B) Dry hydrogel

Swelling Behavior and Crosslinking Degree: Mechanistic Insight

The hydrogel exhibited a swelling ratio of 857%, indicating a high affinity for water molecules. From a chemical standpoint, this is a direct function of the polymer's hydrophilic groups and network porosity. Swelling occurs due to osmotic pressure between polymer chains and the external medium, counteracted by the elastic retractive force of the crosslinked network. The degree of swelling is inversely proportional to the crosslinking density—an optimal balance between mechanical stability and sorption capacity is necessary for practical applications (Chang et al., 2010).

The crosslinking degree of 98.23% suggests a highly interconnected network, potentially improving the hydrogel's mechanical resistance and reusability. Crosslinking also governs the diffusion of pollutants into the gel, making it a crucial design parameter in adsorbent materials (Alaoui et al., 2023).

Adsorption Mechanisms for Organic and Inorganic Pollutants

Dye Removal (Methylene Blue)

The adsorption performance of the durian rind-based hydrogel was systematically evaluated based on its ability to remove methylene blue (MB) from aqueous solutions. The residual concentration of MB was determined using UV-Vis spectrophotometry at a wavelength of 664 nm. As presented in Table 1, the hydrogel exhibited an impressive adsorption efficiency, with an average removal rate of 98.23% across initial MB concentrations ranging from 25 to 500 ppm.

The highest removal efficiency was observed at an initial concentration of 25 ppm, achieving 99.24%, while the lowest was recorded at 200 ppm with a still considerable value of 97.26%. These consistently high adsorption values suggest that the hydrogel possesses a strong affinity toward MB, regardless of concentration fluctuations. The standard calibration curve is shown in Figure 5, while detailed adsorption data are compiled in Table 1.

The influence of hydrogel dosage on adsorption capacity was further explored and is depicted in Figure 5. A positive correlation was observed between the mass of hydrogel and its adsorption efficiency. The maximum removal of 98.96% was achieved at a hydrogel dose of 1.0 g. This indicates that higher dosages provide a greater number of active binding sites, thereby facilitating more extensive adsorption interactions (Zhu et al., 2023).

The remarkable adsorption capacity can be attributed to the hydrogel's porous structure and the presence of surface functional groups, notably hydroxyl (–OH) and carboxyl (–COOH) (Du et al., 2025). These moieties play a critical role in facilitating hydrogen bonding, electrostatic interactions, and van der Waals forces between the hydrogel matrix and the cationic MB molecules. This observation aligns with findings by Hong et al. (2024), who reported that cellulose-based hydrogels derived from agricultural waste exhibit strong adsorption capacity for synthetic dyes due to their surface chemistry and hydrophilic nature.

Table 1. Adsorption of Methylene Blue by 0.1 g of Hydrogel

Initial Concentration (Co) [ppm]	Absorbance after Immersion (A)	Equilibrium Concentration (Ce) [ppm]	Adsorbed Amount (Co - Ce) [ppm]	Removal Efficiency [%]
25	0.043	0.189	24.811	99.24
50	0.177	0.904	49.096	98.19
100	0.192	0.985	99.015	99.02
200	1.033	5.475	194.525	97.26
500	0.487	12.798	487.202	97.44
				Average: 98.23

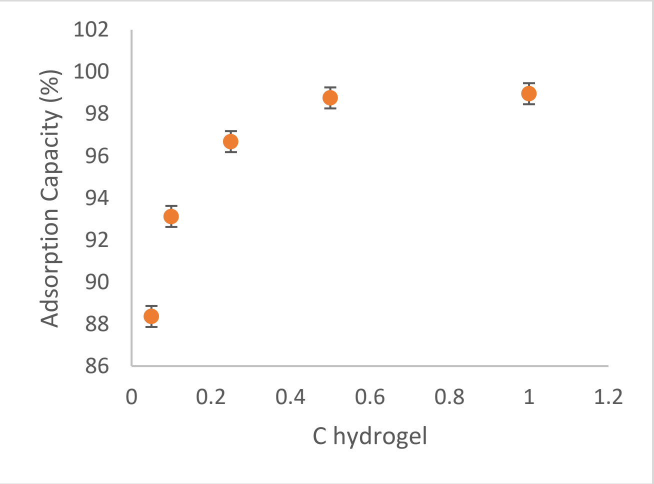

Figure 5. Adsorption capacity of durian rind-based hydrogel at varying concentrations of methylene blue

In addition, prior studies have emphasized the potential of bio-based hydrogels in enhancing adsorption processes. According to Visan et al. (2025), the integration of natural biomass materials into hydrogel matrices significantly increases the surface area and availability of active adsorption sites, resulting in superior dye removal efficiency.

Collectively, these findings underscore the efficacy of durian rind-based hydrogel as a sustainable and high-performance adsorbent. Its outstanding removal capacity for methylene blue positions it as a promising candidate for the development of eco-friendly, nature-based water treatment technologies, particularly for remediating dye-laden wastewater and peat-influenced waters.

Iron (Fe^{2+}) Ion Adsorption

Fe^{2+} ions in peat water pose significant challenges due to their solubility and ability to complex with humic substances. The hydrogel adsorbs 25% of Fe^{2+}, primarily through chelation with oxygen and nitrogen donor atoms present in cellulose and chitosan. The presence of amino and hydroxyl functional groups facilitates complex formation, supported by ligand field stabilization theory (Chelu et al., 2023; George et al., 2024; Qadafi et al., 2023; Zavarzina et al., 2021).

Although the Fe^{2+} removal is lower than dye adsorption, this is consistent with other unmodified biomass hydrogels. Future enhancements could include surface functionalization with chelating agents (e.g., EDTA) or incorporation of nanoparticles (e.g., Fe_3O_4) to improve metal binding capacity (Dutta et al., 2021; Geng et al., 2012; Zhou et al., 2019).

Conclusion

The cellulose-based hydrogel synthesized from durian rind represents a highly promising biopolymer-based adsorbent for the removal of a broad spectrum of waterborne pollutants. Its three-dimensional hydrophilic network, enriched with hydroxyl and amine functional groups, facilitates extensive hydrogen bonding and coordination interactions, resulting in outstanding removal efficiency for organic dyes (up to 98.96%) and moderate chelation of Fe^{2+} ions (25%). These findings are consistent with established adsorption and swelling mechanisms in hydrogel systems, wherein functional group availability and matrix porosity govern contaminant uptake. Given its bio-based origin and demonstrated performance, this hydrogel has significant potential for scalable application in peat water treatment. Future enhancements through targeted functionalization—such as the incorporation of specific chelating ligands or nanocomposite reinforcements—could further transform this material into a versatile, high-efficiency adsorbent for integrated and sustainable water purification technologies.

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Author Contributions

Conceptualization, R.F.; methodology, R. F., D. I, T.K.; formal analysis, R. F.; investigation, R. F., D. I., T. K.; resources, R. F., D.I., T.K.; data curation, R. F; writing—original draft preparation, R.F; writing—review and editing, R.F., and D.I., T.K.: visualization.

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Conflicts of Interest

The authors declare no conflict of interest.

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