



Silver-rice husk cellulose composite for methyl orange adsorption: Kinetics, isotherm, and mechanism studies

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Abstract

Biosorbents are alternative pollutant adsorbents, usually sourced from waste biomass and requiring little or no treatment, which are less expensive than conventional adsorbents. This study investigates the potential of silver-rice husk cellulose composite (AgNPs@RHC) using cashew apple juice (*Anacardium occidentale* L.) as a

Received: August 23, 2026; Revised & Accepted: October 11, 2026; Published online: October 20, 2026

Keywords and phrases: cashew apple, *Anacardium occidentale*, cellulose, rice husk, methyl orange, adsorption, isotherm study, kinetic analysis.

reducing agent silver for nanoparticles for the adsorption of methyl orange (MO). Characterization through SEM, FTIR, and XRD analysis showed a coarse surface, detected chemical functional groups, and the metallic Ag dispersed into cellulose fibers. The composite has $\text{pH}_{\text{pzc}} = 4.87$ and was tested for MO removal via various pH levels, doses, contact times, and initial concentrations. The highest removal efficiency is observed at $\text{pH} = 4$, and it reaches 60 min before declining, indicating a saturation of active sites on the biosorbent surface. Isotherm study data fitted the Langmuir model with an affinity of K_L indicating a monolayer adsorption process. The kinetic analysis performed on the study data favored the pseudo-second-order model. Overall, AgNPs@RHC provides a low-cost, ecofriendly, and promising alternative for treating anionic dyes.

1. Introduction

Textile wastewater pollution is one of the major concerns for many governments in the world. It estimate that a significant proportion of the dyes used in the textile industry activities bypass the treatment system (Jorge et al., 2023). Consequently, textile wastewater contains hazardous and toxic chemical compounds (e.g., dyes, dispersants, heavy metals, and levelling agents) (Akter et al., 2023; Dutta et al., 2022; Jorge et al., 2023). These dye residues and other chemical toxic pollutants do not disintegrate and are discharged into the environment and threaten human health (Değermenci et al., 2019; Holliday et al., 2024). Several dye removal techniques, including filtration, coagulation, and precipitation, are used on wastewater through physicochemical techniques (Bal & Thakur, 2022; Dutta & Bhattacharjee, 2022). While these conventional methods are technically difficult to establish, they have high energy consumption, high costs and an important amount of toxic sludge (Cheng et al., 2020). Adsorption is one of the most effective methods for dye removal. It is more advantageous than other methods due to its economic nature, ease of process and ability to ensure full dye removal (Değermenci et al., 2019). Recently, various adsorbent materials have been used in an attempt to remove organic material and colour. Although active carbon is effective for removal, it is costly. Naturally abundant, agricultural waste can impact soil quality, threaten the environment and pose serious health risks when not managed properly (Srinivasan, 2026). Consequently, agricultural wastes derived from agricultural and food processing by-products have been frequently used as biosorbents for the removal (Tsoutsas et al., 2024). Several research studies using low-cost biosorbents for dye removal include corn cobs (Kouassi et al., 2023), cocoa pod shells (Koffi et al., 2025), walnut shells (Dominguez et al., 2024), cashew shells (Samiyammal et al., 2022), and oil palm shells (Mve Mfoumou et al., 2022). Agricultural residues are among the most abundant and natural sources of lignocellulosic compounds used as biosorbents (Ungureanu et al., 2023; Vasić et al., 2023). They have specific properties such as being renewable, available, mechanically strong, biocompatible, dimensionally stable, and biodegradable. Since cellulose materials are commonly used to remove dye and heavy metals from wastewater, especially from that produced by cereal farming (Da Silva Souza et al., 2025; Ivanovska et al., 2023; Nan et al., 2023). Several authors have demonstrated the negative impact of current agricultural residue management techniques, such as burning or on-site decomposition (Baloch et al., 2025; Sharma et al., 2023). In Côte d'Ivoire, such as in many developing countries, agricultural activities accounted for about 50% to 70% of the national export revenues, resulting in an important amount of agro-waste (Paul K. et al., 2020). The country produced approximately 2.38 million tons of paddy rice; however, 20% to 25% of that total represents a significant amount of cellulosic materials (Kinimo et al., 2026). Rice husk, composed of 31% to 40% cellulose and 15% to 25% hemicellulose, can be considered as an excellent candidate for cellulose extraction and biosorbent preparation. The alkali extraction process is a proven method and widely used, followed by bleaching with hydrogen peroxide or sodium chloride (Freitas et al., 2024; Gil-Guillén et al., 2024; Worku et al., 2022).

Recently, nanocomposite research has focused on the combining of nanoparticles (e.g., Ag, Cu, Au, Cd, etc.) with cellulose materials (Fato et al., 2026; Rahman et al., 2023). Cellulose favored the incorporation of the nanoparticles into its fiber matrix, as well as from the nanoscale size of the metal particles. Due to its unique properties, cellulose derived from rice husks has attracted the attention of researchers developing low-cost materials for dye removal (Chauhan et al., 2024; Tripathy et al., 2024; Wasim et al., 2022). In contrast to previous work, this study used a fruit extract as a reducing agent for silver nanoparticle synthesis. This study investigates the preparation of a hybrid material combining silver and cellulose nanocomposite. For this purpose, the adsorption capacity of the rice husk cellulose (RHC) for methyl orange (MO), an anionic dye, was determined with the adsorption process. Firstly, the physicochemical characteristics of cellulose by conventional methods were carried out through FTIR, XRD, and SEM analysis. Additionally, the influence of contact time, the dye concentration, the biosorbent dose, and pH on equilibrium, kinetic, and isotherm adsorption parameters was assessed.

2. Material and methods

2.1. Materials

Chemical materials such as potassium hydroxide, sodium hypochlorite, glacial acetic acid, hydrochloric acid, sulfuric acid, silver nitrate, and methyl orange dye ($C_{14}H_{14}N_3NaO_3S$, molecular weight = 327.33 g mol⁻¹) (all reagents were analytical grade) from Sigma Aldrich, England, were used. The rice husks were collected from the small-scale local milling industry at a market in Korhogo, Côte d'Ivoire.

2.2. Pretreatment and extraction of cellulose from rice husk

Similarly to the described method of Kargarzadeh et al. (2017), the rice husk (*Oryza Sativa*) was thoroughly washed with water to remove dust and soil residues and dried in an oven at 50°C for 24h. After drying, the RH was milled in a grinder and the particles were sieved through 75-mesh screens. The fine fraction of RHC was placed in zipped polyethene and stored for further analysis. The milled samples were treated with 6% (v/v) of potassium hydroxide (KOH) at 80°C under continuous stirring at 500 rpm for 2h. The alkaline-treated fibre was then treated with 4% (v/v) sulphuric acid and stirred for another 2h. After filtering, the acid fibrous sample was bleached with 1.4% sodium hypochlorite (NaOCl) solution. A solution of 5% acetic acid was added dropwise to adjust the pH to 4 with continuous stirring and heated to 50°C for 3h. Finally, the sample fibres were filtered and washed with distilled water until a neutral pH was maintained and dried at 50°C for 24h. The cellulose was placed in a zipped polythene bag for chemical and microstructural analysis.

2.3. Cashew apples extract (CAE) and AgNPs preparations

The cashew apples were also collected from the Korhogo local market. The cashew apples were kept at 4°C in the lab to prevent deterioration and the proliferation of microorganisms. 500 mL of distilled water was added to increase filtration after 2 kg of CA was mixed for 1 minute in order to extract the juice. For additional analysis, the extracted juice (CAE) was stored in a refrigerator at 4°C before use. The AgNPs preparation was carried out following the method described by (Dayanidhi et al., 2020). Firstly, a freshly made AgNO₃ (5 mM) solution was mixed with 0.5 mL of CAE and microwaved for 120 seconds at 850 W in a home microwave oven. A distinctive adsorption band in UV-Vis spectroscopy at 420 nm revealed the creation of the silver nanoparticles, which were visually indicated by a color shift from pale yellow to dark brown. After centrifuging, the solution for 20 minutes at 5000 rpm, the supernatant was removed. The pellets obtained were redissolved in deionized water to remove adsorbed material on silver nanoparticle particles and washed many

times. The suspension was dried for three hours at 60°C to produce black powdered nanoparticles, which were then verified by spectroscopic examination.

2.4. Cellulose-AgNPs composite preparation

Silver nanoparticles (AgNPs) were incorporated into cellulose using the method described by Kadhim & Al-khafaji (2026) with some modifications. 1 g of cellulose was dispersed in 10 ml of a 10 mM sodium citrate solution. The mixture was placed under magnetic stirring. 10 ml of a 1 mM silver nitrate solution was slowly added to the mixture, which was then stirred for 1 hour. During this step, the Erlenmeyer flask was completely covered to prevent exposure of the mixture to light, which can cause the aggregation of AgNPs. Subsequently, the citric acid was added as a crosslinking agent to the AgNPs@RHC solution in a rate of 15% of the solid sample's total weight (Mali et al., 2018). The cellulose@AgNPs solution was centrifuged at 4000 rpm for 10 min. the supernatant was then removed, and the composite was washed three times with distilled water to remove traces of citrate and AgNO₃. The cellulose@AgNPs composite was dried at 50°C for 12 hours, then lightly ground into a powder.

2.5. Characterization of RHC and AgNPs@RHC nanocomposite

To confirm the extraction of RHC, the AgNPs synthesis using an extract of *Anacardium occidentale*, and the AgNPs@RHC formation, the UV-Vis adsorption spectra were recorded using the Shimadzu UV-1800 spectrophotometer (Shimadzu, Japan) with a quartz cell of 1.0 cm diameter in a scan range of 200 to 800 nm. The scanning electron microscopy (SEM model Joel JSM-6510/v, Japan) was used to investigate the particle size and the shape of cellulose and AgNPs-cellulose nanocomposite. The crystallinity of cellulose and the AgNPs@RHC was estimated using an X-ray diffractometer (PAN Analytical X-Pert PRO, spectral plc, Almelo, the Netherlands). The pH of the zero charge was determined by mixing 0.15 g of composite with 0.01 mol/L NaCl dissolved in 100 mL of deionized water, and then the pH of the mixture was adjusted to 2, 4, 6, 7, 8, 9, 10, 11, and 12 by adding 0.1 mol/L solutions of NaOH and HCl alternately. After 24h, the new pH was measured using HANNA pH (Rzig et al., 2021).

2.6. Adsorption test

To evaluate the adsorption capacity of the AgNPs@RHC nanocomposite prepared, methyl orange (MO) was used as a model dye. A 1000 ml stock solution was prepared by dissolving 0.1 g of MO in 1000 ml deionized water, and various appropriate concentrations were reached by dilution. The adsorption parameters, such as the medium pH (2 – 11), the contact time (1 – 120 minutes), the initial concentration (1 – 50 mg L⁻¹) of the dye, the adsorbent mass (0.05 for AgNPs@RHC, respectively), were carried out at ambient temperature (25°C) and under magnetic stirring. Once the equilibrium time was completed, each solution was filtered through Whatman paper (2.5 µm) to separate adsorbent from the dye solution. The optimal adsorption of the residual dye was measured by UV-Vis spectrophotometer at an absorbance wavelength of 465 nm (Lafi et al., 2025; Usama et al., 2025). The standard curve was used to determine the concentration of MO after sorption. The removing percentage and the amounts of MO adsorbed onto the surface of AgNPs@RHC have been calculated by the following relationships: Eq. 1 and Eq. 2, respectively.

$$\% \text{OM sorption} = \frac{(C_0 - C_e)}{C_e} \times 100 \quad (\text{Eq. 1})$$

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (\text{Eq. 2})$$

where C₀ and C_e were initial and final (equilibrium) concentrations of MO (mg/L), m (g) is a mass of adsorbent,

q_e (mg/g) is the adsorption amount per unit gram of adsorbent at equilibrium (mg/g), and V (L) is the volume of the dye solution. The values obtained for these parameters are used to plot the kinetic and adsorption isotherms, which describe the equilibrium relationship between adsorbate activity and the adsorbed quantity of MO on its surface at constant temperature.

2.7. Adsorption kinetics

Adsorption of MO solutions with concentrations in the range of 10-50 mg/L on AgNPs@RHC was conducted at a time range of 1-60 min. The adsorption process explained previously was applied to investigate the kinetics of adsorption. The pseudo-first-order (PFO) and pseudo-second-order (PSO) models were applied using the following Eq. 3 and Eq. 4, respectively.

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (\text{Eq. 3})$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} \quad (\text{Eq. 4})$$

where q_e and q_t (mg/g) are the amount of MO at equilibrium and at any time t , respectively; k_1 and k_2 can be obtained by linear plot of $\ln(q_{e, \text{exp}} - q_t)$ and $\frac{t}{q_t}$ against time, respectively.

2.8. Adsorption Isotherms

The isotherm adsorption parameters were widely used to explain the interaction between the adsorbent and adsorbate of any system. It is used to understand how adsorbate molecules are distributed between the liquid and solid phase at equilibrium and to find a suitable model for design purposes. Langmuir and Freundlich models are employed to evaluate the adsorption process of MO on AgNPs@RHC. The analysis of the linear regression correlation coefficient (R^2), helps to choose the best-fit model. The different equations for each isothermal model applied are presented in Table 1.

Table 1. Equations of isothermal models used to study the adsorption process of MO on AgNPs@RHC

Isotherm model	equation	Parameters	Reference
Langmuir	$\frac{1}{q_e} = \frac{1}{q_{\max}} + \frac{1}{q_{\max} K_L} \cdot \frac{1}{C_e}$	q_e : equilibrium adsorption capacity (mg/g) $q_{\max}$: maximum monolayer adsorption capacity from Langmuir model (mg/g) K_L : Langmuir constant (L/mg) C_e : remaining concentration of the dye in the solution (mg/L)	(Mostafa et al., 2024; Saule et al., 2024)
Freundlich	$\ln q_e = \ln K_F + \frac{1}{n_F} \ln C_e$	K_F : Freundlich adsorption constant indicative of adsorption capacity (mg/g) $\frac{1}{n_F}$: heterogeneity factor C_e : remaining concentration of the dye in the solution (mg/L)	(Jahan et al., 2021)

3. Results and discussion

3.1. Rice husk (RH) extraction and green synthesis of AgNPs characterization

The rice husk was successfully extracted, and the nanocomposite AgNPs@RHC was developed. After the delignification process, about 19.7 g of cellulose was recovered from a weight of 40 g of initial dry RH, which corresponds to a yield of about 38%. This indicated that during the extraction process, 62% of lignin, hemicellulose, pectin, wax, and silica were removed from rice husk. This result is in consistency with those reported by (Hafid et al., 2021). The successful reduction of silver ions in Ag was confirmed by the change in color from light yellow to reddish brown and the displaying of the UV-Vis adsorption band at the wavelength of 432 nm (Figure 1). This result denotes that the *Anacardium occidentale* juice was efficient to reduce metallic and allows the control of nanoparticle synthesis. (Mukunthan & Balaji, 2012) reported the phytoconstituents of *A. occidentale* apple juice act as a reductor agent in the metallic ions reducing.

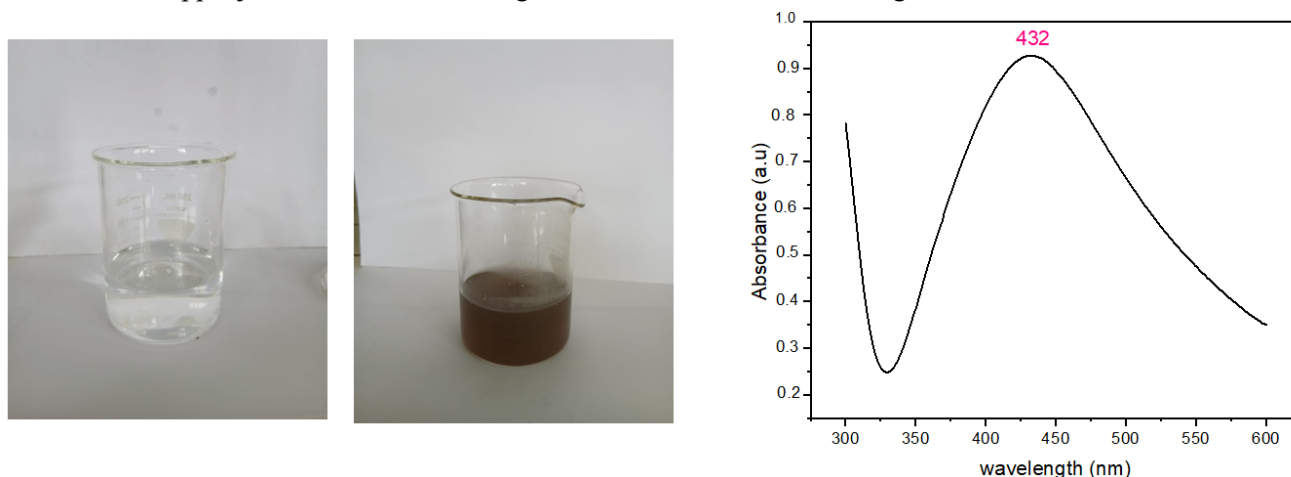


Figure 1. Absorption spectrum of silver nanoparticle synthesized with *Anacardium occidentale* extract.

3.2. Characterization of the RHC and AgNPs-RHC nanocomposite

3.2.1. FTIR analysis

The Fourier Transformed Infrared (FTIR) method is used to determine surface functional groups, and the FTIR spectra are displayed in Figure 2. The peak band at 3333 cm^{-1} is characteristic of O-H strain vibration contained in phenols like those present in lignin, pectin, and cellulose. Another intense peak at 2890 cm^{-1} band interval, representing the C-H bond from aliphatic groups, at 1600 cm^{-1} band interval, the peaks are the carbonyl C=O and aromatic C=C ring strains. The characteristic bands of cellulose appear at 1360 cm^{-1} and 1031 cm^{-1} and were assigned to the C-O ring stretching modes and the β -1,4 glycosidic linkage (C-O-C) stretching modes between the glucose ring of the cellulose chain, respectively. Thus, the FTIR analysis revealed the presence of cellulose, and the treatments employed are efficient for cellulose extraction and reduced significantly other non-cellulosic components (Lai et al., 2022; Sharma et al., 2023). In addition, the peak at 1629 cm^{-1} was assigned to the reduction of Ag^+ ion to Ag^0 by *Anacardium occidentale* extract, and the peak band at 1315 cm^{-1} is characteristic of N-H stretch vibration as well as reported in many studies (Malik et al., 2022; Mukunthan & Balaji, 2012). Similarly, the band around 1040 cm^{-1} was attributed to N-H and C-N (amines) stretch vibration. It is evident that the FTIR spectra indicate the deposition of AgNPs on the cellulose surface.

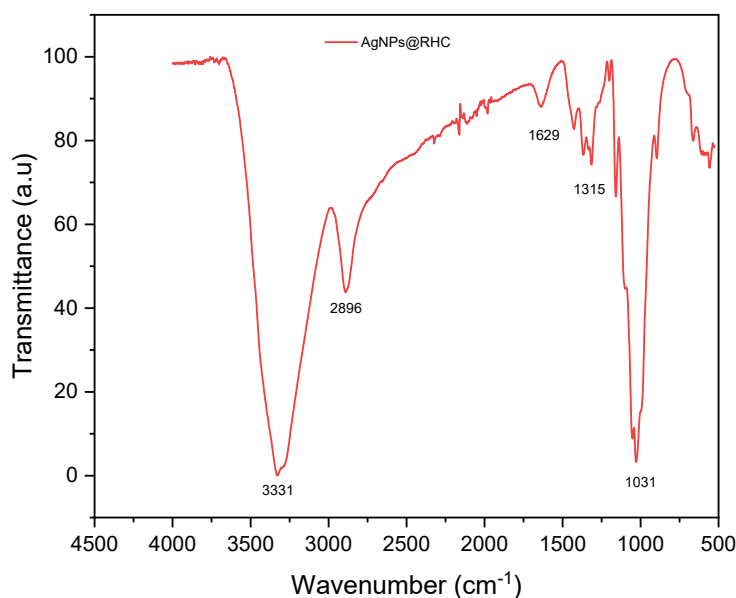


Figure 2. FTIR spectra of RHC and composite AgNPs@RHC.

3.2.2. XRD pattern analysis

Figure 3 depicted the diffractogram of AgNPs@RHC obtained through XRD measurements. Characteristic peaks appear at $2\theta = 15.8^\circ$, 22.63° , 27.99° , 32.63° , 35.09° , and 46.52° , which correspond to the lattice planes (100), (111), (200), (210), and (220), respectively (Al-Raimi et al., 2025; Khan et al., 2023). These peaks can be assigned to the diffraction from metallic silver and confirm the deposition of AgNPs on the cellulose matrix. Alteration of the XRD pattern may be due to biological reductor involved in the silver ions reduction to metallic silver and the synthesis conditions as well as reported by (Ciftci, 2024). In addition, the successfully incorporation of Ag on cellulose (AgNPs@RHC) was marked by the broad peak observed at lower angles, indicating an embedded amorphous (100) of cellulose and crystalline structure of Ag (111), (200), and (220). Thus, the XRD pattern confirms the formation of both elements contributing to the nanocomposite AgNPs@RHC.

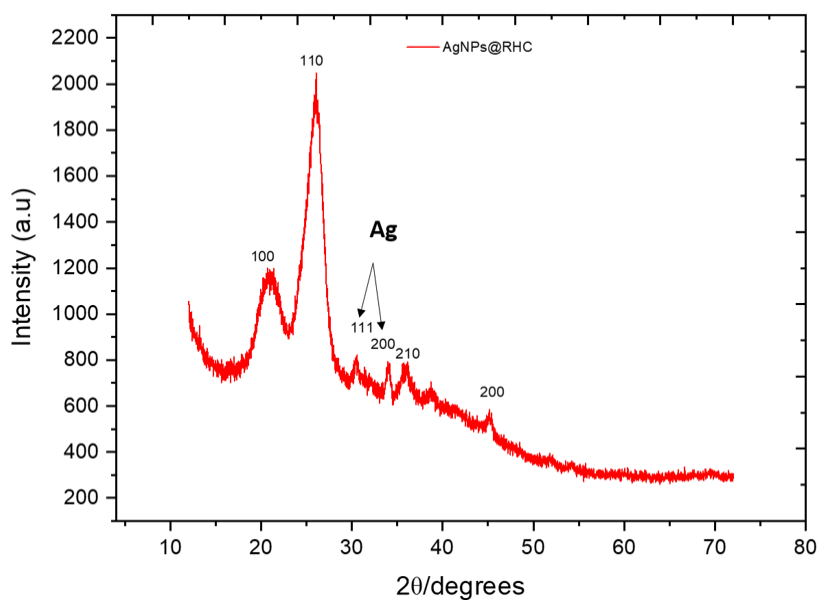


Figure 3. XRD pattern of the composite AgNPs@RHC.

3.2.3. SEM analysis

The SEM images of RHC and AgNPs@RHC are displayed in Figure 4. The surface of the pristine cellulose appears fibrous and heterogeneous. But it also presents an ordered structure, which is characteristic of cellulose. This heterogeneity can cause some inconsistencies in adsorption results. The AgNPs were randomly dispersed in the cellulose fiber network, which is consistent with previous study conclusions (Jenkhongkarn & Phisalaphong, 2023; Madivoli et al., 2022; Subha et al., 2022).

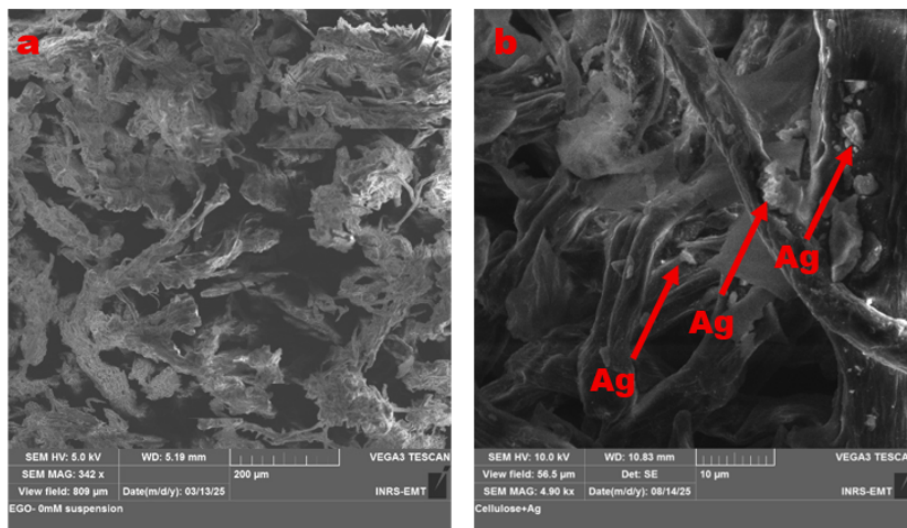


Figure 4. SEM image of the composite AgNPs@RHC.

3.2.4. Point of zero charge (pH_{pzc})

The rice husk cellulose coated with AgNPSpHpzc was depicted in Figure 5.

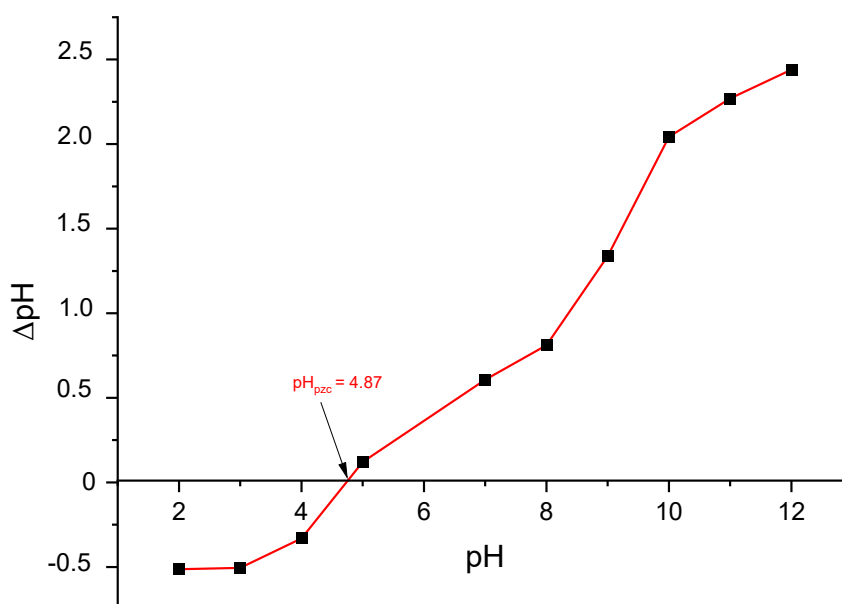


Figure 5. Point of zero charge of AgNPs@RHC.

The point of zero charge is used to examine the adsorbent surface charge (Al-Raimi et al., 2025). Thus, the surface was charged positively when $pH < pH_{pzc}$ and negative when $pH > pH_{pzc}$ and zero when $pH = pH_{pzc}$. The point of zero charge value for AgNPs@RHC at ΔpH equals zero reading is 4.87. This result means

that when the pH is less than 4.87, the biosorbent surface is positively charged or negatively charged and when the pH is above 4.87, the surface is negatively charged (Rzig et al., 2021). As MO is an anionic dye, a pH value below 5 would be expected to promote its adsorption onto the AgNPs@RHC. Our pH_{pzc} was close to the previously published research on silver nanoparticles coated with cellulose (Al-Raimi et al., 2025; Holliday et al., 2024).

3.3. Adsorption study

3.3.1. Effect of pH

The interaction between the biosorbent and the adsorbate compound usually depend on the pH level, which affects the protonation of the functional groups on the surface of the biosorbent and the ionization of the dye (Enache et al., 2023; Gaur et al., 2024). Figure 6 illustrates the OM elimination at different pH levels of the solution. The AgNPs@RHC dye removal is highly noticeable at different pH with the highest level recorded at pH 4. This pH is less than the zero's charge point, which is 4.87 (Wasilewska et al., 2025). Above of 4, the competition between the anionic dye and hydroxyl ions (OH^-) decrease the adsorption of MO onto AgNPs@RHC (El-Fattah et al., 2024)

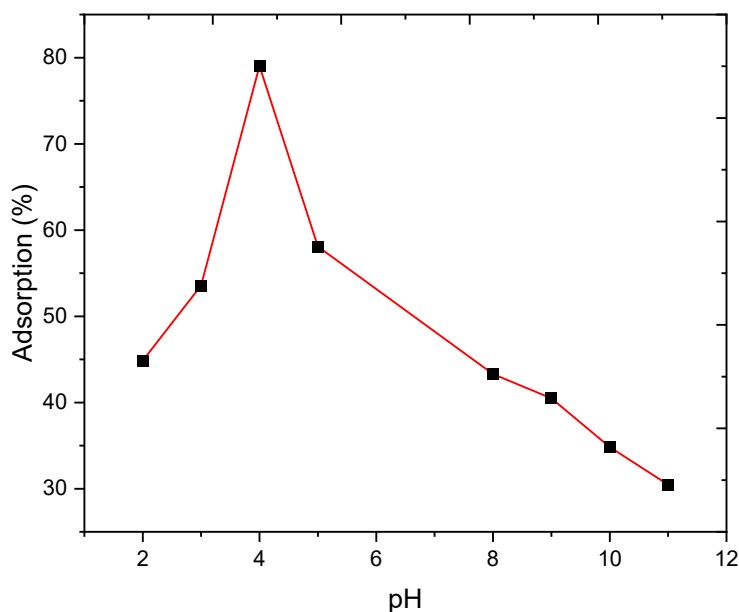


Figure 6. Effect of pH on OM removing using AgNPs@RHC biosorbent.

3.3.2. Effect of AgNPs@RHC dose

The biosorbent dose is an important parameter in the efficiency of the adsorption process; it defines the ratio of the biosorbent amount to the quantity of adsorbate the system can adsorb. In this study, the effect of AgNPs@RHC was assessed through a variable dosage ranging from 0.01 to 1 g/10 mL. As can be seen in Figure 7, increasing the dosage to 0.3 g resulted in the removal efficiency of 74.1% of MO, indicating a significant improvement in the performance with the increasing of the amount of biosorbent. This improvement can be attributed to the increased availability of active surface areas and adsorption sites, facilitating more effective dye adsorption when the concentration remains constant. However, the increase in the biosorbent amount led to a decrease in the equilibrium capacity (q_e). It can see that q_e decreased from 14.0 mg/g to 0.18 mg/g as the amount of AgNPs@RHC increased. This trend could be explained by the increased mass of the biosorbent at a constant initial concentration of the adsorbate leading to an aggregation of the active sites at higher

concentrations, which limits the accessibility of the biosorbent reactive surface, resulting in a decline in the adsorption capacity (Basha et al., 2022; Poornachandhra et al., 2023; Villabona-Ortíz et al., 2022). Figure 7 also shows that, despite the increase in the amount of AgNPs@RHC while the dye concentration was maintained constant, the q_e of MO remains constant. This can be explained by the increasing of the active sites, resulting in an available unsaturated surface. Similar behavior has been reported in literature, which confirms the competition between dye molecules in the excess amount of biosorbent and the possibility of biosorbent aggregation (Poornachandhra et al., 2023).

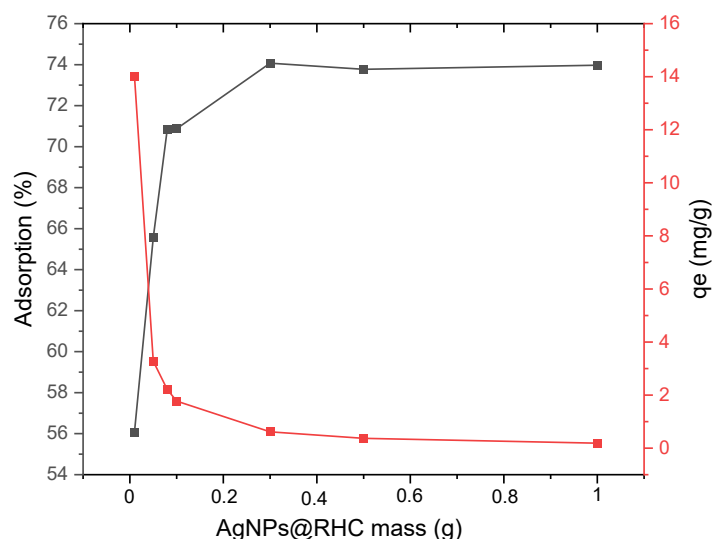


Figure 7. Effect of AgNPs@RHC amount on the adsorption capacity and the MO removal efficiency ($C_0 = 10$ mg/L, $V = 25$ mL, $pH = 4.0$, $t = 60$ min $T = 298$ K).

3.3.3. Effect of contact time

The adsorption of MO onto AgNPs@RHC biosorbent can be better by examining the contact time, which remains a crucial parameter in the application of biosorbent. An efficient biosorbent is usually defined not only by its high adsorption capacity but also its ability to enable a fast adsorption process. The contact time for the adsorption of Mo dye on AgNPs@RHC is displayed in Figure 8. The results demonstrate that the adsorption percentage and the q_e peaks at 60 min remains almost constant until 120 min. The initial rise within the first 60 min is due to the availability an active site on the biosorbent at the start. After this period the surface becomes saturated; therefore, the adsorption remains constant. Initially, the dye molecule filled rapidly the adsorption active sites, which are available, reaching equilibrium within 60 min. Villabona-Ortiz et al. (2022) found that the wheat raw straw cellulose/CTAC reached equilibrium time for the removal of Congo Red (CR) in 120 min. Similarly, Al-Raimi et al. (2022) reported that peanut shell cellulose/Ag nanocomposite for methylene blue (MB) and safranin O (SO) optimal equilibrium time was reached in 45 min. All these studies showed constant adsorption capacity if the contact time was extended. Conversely, it noted a slightly decreasing adsorption, indicating that the equilibrium observed in 60 min was reversed. This phenomenon suggests a desorption of some adsorbate molecules occurred after the equilibrium time. This behavior result may be due to the weakness of the binding from biosorbent and dye molecules into the solution. Similarly, (Aljeddani et al., 2023) reported this trend in the removal of CV dye using peanut shell cellulose coated with silver nanoparticles after the equilibrium time.

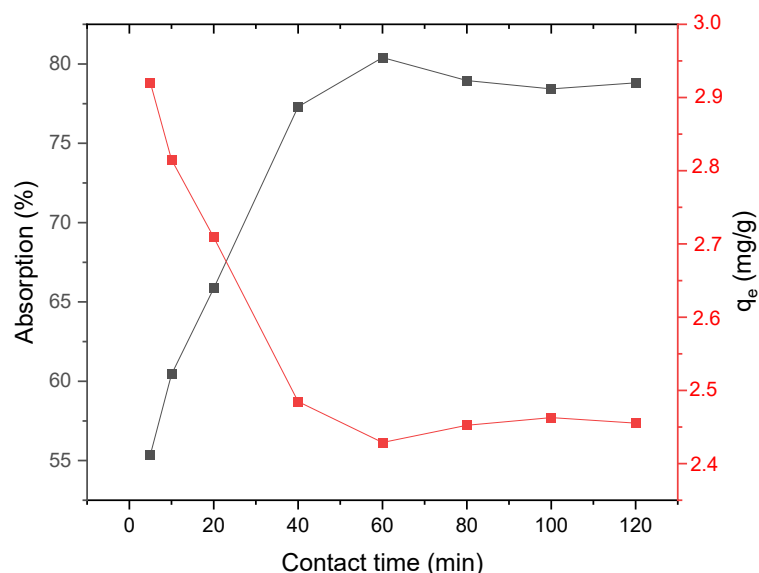


Figure 8. Effect of contact time of the MO adsorption capacity and adsorption efficiency removal of MO onto AgNPs@RHC ($C_0 = 10$ mg/L, $m = 30$ mg, $V = 25$ mL pH = 4.0, $T = 298$ K).

3.3.4. Effect of initial concentration of dye

The initial dye concentration has a determining parameter in the adsorption process. Therefore, the impact of initial concentration was assessed by varying the concentration of MO (5, 10, 15, 20, 30, 40, and 50 mg/L) on their adsorption onto AgNPs@RHC. The results are displayed in Figure 9.

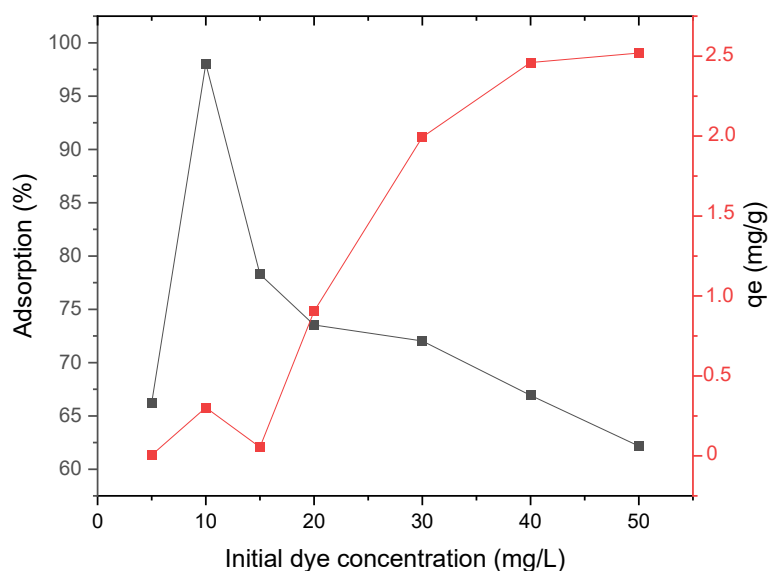


Figure 9. Effect of initial dye concentration on the adsorption capacity and adsorption efficiency of MO onto AgNPs@RHC.

As initial dye concentration increased from 5 to 10 mg/L, the adsorption of MO rose from 66.2% to 98.0%, and afterwards it decreased from 98.0% to 62.2%. It is assumed that the active site increased with the dye concentration, and they became saturated when more dye molecules were present, leading to the diminution of the removal efficiency. However, the adsorption percentage may increase as the concentration gradient rises as a response to an increase in the concentration of the dye in the solution (Al-Ghouti & Al-Absi, 2020; Aljeddani et al., 2023; Rápó & Tonk, 2021). Similarly, peanut husk cellulose-Ag for crystal violet (CV) showed that the removal of CV increased from 5.0 to 15 mg/L. Furthermore, sugarcane bagasse cellulose showed the highest

removal capacity of crystal violet and methylene blue at 40.0 mg/L but the lowest adsorption capacity at 200 mg/L (Salah-omer et al., 2022). Overall, the adsorption capacity (q_e) increased as the initial dye concentration increased significantly from 5 to 50 mg/L, is consistent with mass transfer and accumulation of available active sites. Previous studies confirm these trends and highlight the dye amount influence on adsorption efficiency (Meas et al., 2024; Shimizu et al., 2022).

3.4. Adsorption kinetic

The pseudo-first-order and the pseudo-second-order were used to analyze the adsorption kinetics of the MO on AgNPs@RHC to determine the mechanism and the rate of the adsorption process (Chinthalapudi et al., 2021). The kinetic parameters were calculated to determine the applicable models, and the results were consigned in Table 2. The correlation coefficient (R^2), which indicates the relationship between two variables, was calculated. It can see that the correlation coefficient (R^2) of the pseudo-second-order kinetic model was higher than that of the pseudo-first-order kinetic model. The q_e values calculated from the pseudo-second-order kinetic model were also close to the experimental data. Thus, pseudo-second-order kinetic is more appropriate to define the adsorption process (Hamden et al., 2025). This relatively good fit may suggest that the adsorption process is more consistent with surface-controlled interactions than with simple diffusion; however, this interpretation remains preliminary, as the present data do not provide direct experimental evidence to confirm the underlying adsorption mechanism. Previous research reported pseudo-second-order in the dye adsorption on cellulose (Aljeddani et al., 2023; Hamden et al., 2025).

Table 2. Calculated parameter of pseudo-first order, pseudo-second order, kinetic model constant and correlation coefficients.

Dye	q_e , exp (mg/g)	Pseudo-first-order			Pseudo-second-order		
		q_e , cal (mg/g)	k_1 (min^{-1})	R^2	q_e , cal (mg/g)	k_2 (g/mg min^{-1})	R^2
MO	3.586504	1.2119124	0.0138	0.8927	3.6390102	0.1241411	0.9957

3.5. Adsorption isotherms

Langmuir and Freundlich isotherm models were used to investigate the adsorption of MO on AgNPs@RHC. The Langmuir model explains single-layer homogeneous adsorption on a surface, while the Freundlich equation describes heterogeneous surface energies changing linked to adsorption temperature (Holliday et al., 2024). Table 3 presents the isotherm parameters obtained in this study. The Langmuir isotherm outlines the best fitting model of MO adsorption process on the biosorbent, as indicated the higher linear correlation coefficient ($R^2 = 0.9563$). This result may be consistent with monolayer adsorption on the relatively homogeneous surface with energetically similar active sites, although further evidence would be needed to confirm this mechanism. Similar results were reported by previous research on anionic dye adsorption onto nanocomposites.

Table 3. Adsorption isotherms parameters for the adsorption of MO on AgNPs@RHC

Dye	Langmuir			Freundlich		
	q_m	K_L	R^2	K_F	$1/n_F$	R^2
MO	50.838841	0.0207972	0.9563	0.3167951	0.6490556	0.8842

3.6. Adsorption mechanism

As FTIR spectra analysis showed the cellulose composite structure contains diverse chemical function groups as well as a benzene ring, carbonyl, and hydroxyl. The probable reaction mechanism involves the interaction of the hydroxyl groups present in the cellulose structure with MO. Holliday et al. (2024) reported the existence of positive correlation between hydrogen bonds in azo dyes, the cellulose surface, and the number of available sites to the dye-cellulose interaction energy (Nazir et al., 2023). Finally, interaction due to opposite charges of the dye and the active sites of AgNPs@RHC. Other researchers' works confirm the electrostatic attraction on cellulose composite (Al-Raimi et al., 2025; Wang et al., 2016). Figure 10 illustrates the Mo adsorption onto AgNPs@RHC.

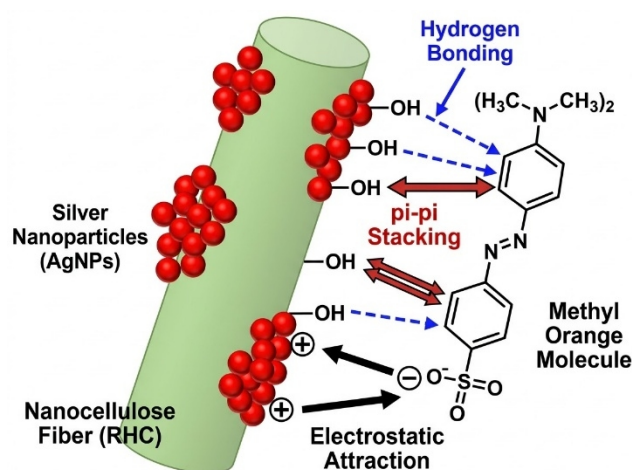


Figure 10. Schematic illustration of MO adsorption onto AgNPs@RHC.

Conclusion

The composite AgNPs@RHC was synthesized using a simple, plant-assisted method and demonstrated excellent performance in removing of MO. Structural analyses confirmed successful Ag deposition within cellulose network and effective delignification through alkaline treatment. FTIR spectra after composite elaboration showed that the polymer backbone remained intact with minimum modification. SEM images displayed Ag particles dispersed into cellulose fibers. The XRD confirmed the metallic Ag deposition onto cellulose. Electrokinetic studies ($\text{pH}_{\text{pzc}} = 4.87$) explain strong adsorption before neutral and alkaline conditions through electrostatic attraction to anionic dyes. The adsorption process is rapid, with the equilibrium time reached within 60 min, and was best described by the Langmuir model, indicating a monolayer adsorption and suggesting that the electrostatic interactions. The adsorption process follows pseudo-second-order kinetics, which is consistent with physical interactions involving electrostatic forces and hydrogen bonds. Overall, AgNPs@RHC are promising, ecofriendly biosorbents for dye-contaminated wastewater, with future research suggested to evaluate real effluents and long-term operational stability.

Funding

The authors declare that no funds were received during the preparation of this manuscript.

Conflicts of interest

The authors declare no conflicts interest.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Author contributions: Conceptualization, K.C.K and T.P.F., Methodology, K.C.K and C.C., Validation, K.C.K., K.P.D.A.N., and I.S., Formal Analysis, K.C.K and T.P.F. Investigation, K.C.K., T.P.F. and N.L.B.K., Data curation, K.C.K., K.P.D.A.N., Writing-original draft preparation, K.C.K and C.C, Writing-review and editing, K.C.K., B.H.G.D., A.S; and A.T.

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