RESEARCH PAPER

OPTIMIZATION OF CELLULOSE EXTRACTION FROM AGRO INDUSTRIAL WASTE FOR EFFECTIVE ANTIBIOTIC DEGRADATION

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ABSTRACT

The present study investigated the extraction of cellulose from agro-industrial waste and its application for the removal of erythromycin from aqueous solutions. Cellulose was extracted using alkali pretreatment followed by microwave-assisted acid extraction, resulting in a maximum yield of 90%. Characterization studies using FTIR, SEM, and XRD confirmed the successful removal of non-cellulosic components, porous surface morphology, and enhanced crystallinity of the extracted cellulose. Adsorption experiments demonstrated that erythromycin removal was influenced by pH, contact time, adsorbent dosage, and initial antibiotic concentration. Maximum removal efficiency of 93.5% was achieved at pH 7, 2.0 g adsorbent dosage, and 60 min contact time. UV–Visible analysis confirmed significant reduction of erythromycin concentration with approximately 92.1% removal efficiency. Adsorption kinetics followed the pseudo-second-order model ($R^2 = 0.998$), while isotherm studies showed better agreement with the Langmuir model ($R^2 = 0.991$) and a maximum adsorption capacity of 27.6 mg/g. The findings indicate that agro-industrial waste-derived cellulose is a sustainable, low-cost, and efficient adsorbent for antibiotic-contaminated wastewater treatment.

Keywords: Cellulose; Agro-industrial waste; Erythromycin; Adsorption; Wastewater treatment.
How to cite this article: Karikalan R, Suganya C, Mohan M, Abinaya S, Akash M, Sabesh Solomon Raja S, Praveen S. Optimization of Cellulose Extraction from Agro Industrial Waste for Effective Antibiotic Degradation. Int J Drug Deliv Technol. 2026;16(63s):1372-1382. DOI: 10.25258/ijddt.16.63s.136

INTRODUCTION

The increasing discharge of pharmaceutical pollutants into the environment has become a major concern due to their persistence and potential impact on human health and ecosystems. Among these pollutants, antibiotics are frequently detected in water bodies because of their extensive use in healthcare, veterinary practices, and pharmaceutical industries [1]. The presence of antibiotic residues in wastewater contributes to the development of antimicrobial resistance and poses serious environmental challenges. Therefore, the development of sustainable and efficient methods for antibiotic removal and degradation has gained significant research attention [2,3].

Agro-industrial wastes are generated in large quantities from agricultural and food processing activities and are often discarded without proper utilization [4]. These wastes are rich in lignocellulosic biomass, particularly cellulose, which can be recovered and converted into valuable materials for environmental applications. Cellulose is a biodegradable, renewable, and environmentally friendly biopolymer with excellent adsorption properties, making it a promising material for wastewater treatment [5,6].

The extraction of cellulose from agro-industrial waste not only provides a value-added product but also supports waste management and circular bioeconomy concepts. Optimization of extraction conditions is essential to maximize cellulose yield and improve its physicochemical properties [7]. The extracted cellulose can be characterized using analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and X-Ray Diffraction (XRD) to evaluate its functional groups, surface morphology, and crystalline structure [8,9].

In recent years, cellulose-based materials have shown considerable potential in the removal and degradation of antibiotic contaminants from aqueous systems [10]. The efficiency of antibiotic degradation depends on various operational parameters, including pH, contact time, and adsorbent dosage. These factors influence the interaction between the adsorbent surface and antibiotic molecules, thereby affecting the overall removal efficiency. The degradation process can be monitored and quantified using analytical techniques such as UV–Visible Spectroscopy [11,12].

Furthermore, adsorption studies provide valuable information regarding the mechanism of antibiotic removal [13]. Adsorption kinetics help to understand the rate and pathway of adsorption, while adsorption isotherms describe the

interaction between adsorbate and adsorbent at equilibrium conditions. The reusability of the extracted cellulose is another important factor in determining its practical applicability and economic feasibility for large-scale wastewater treatment [14,15].

Therefore, the present study focuses on the extraction and optimization of cellulose from agro-industrial waste and its application in the degradation of antibiotic contaminants [16]. The extracted cellulose is characterized using FTIR, SEM, and XRD analyses, and its degradation efficiency is evaluated under different experimental conditions [17]. Adsorption behaviour and reusability studies are also carried out to assess the potential of the extracted cellulose as a sustainable and effective material for environmental remediation.

MATERIALS AND METHODS

Sample collection

Agro - waste was collected from Salem, Tamil Nadu, India. The collected material was thoroughly washed to remove dust and impurities, dried, and utilized for cellulose extraction and subsequent characterization studies.

Alkali Pretreatment

Alkali pretreatment was carried out on the agro-industrial waste to facilitate cellulose extraction by removing lignin and hemicellulose. The pretreated sample was subjected to microwave-assisted extraction at 540 W for 180 seconds using 2 M sulfuric acid in a 1:25 solid-to-liquid ratio. Following extraction, the cellulose-rich fraction was separated by filtration and collected. The obtained material was thoroughly washed with distilled water until free from residual chemicals and then dried for further analysis. This pretreatment and extraction process improved the accessibility, yield, and quality of the extracted cellulose.

Determination of Cellulose Yield

The yield of cellulose extracted from agro-industrial waste was determined to evaluate the efficiency of the pretreatment and extraction processes. After completion of alkali pretreatment and microwave-assisted extraction, the obtained cellulose was thoroughly washed, dried to a constant weight, and weighed. The cellulose yield was calculated based on the initial weight of the raw material and the final weight of the extracted cellulose [18].

The cellulose yield was calculated using the following equation:

$$cellulose\ yeild\ (\%) = \frac{Weight\ of\ Extracted\ cellulose}{\text{Weight of Raw Material}} \times 100$$

pH and Solubility of Extracted Cellulose

The pH and solubility of the extracted cellulose were determined to evaluate its physicochemical properties. The pH was measured using a digital pH meter after dispersing the cellulose in distilled water. Solubility analysis was carried out in 1% acetic acid solution under constant stirring, followed by filtration to separate the insoluble fraction. The percentage solubility was calculated based on the initial sample weight and the weight of the insoluble residue. These analyses provide important information regarding the stability and application potential of the extracted cellulose.

$$\text{Solubility (\%)} = 100 - \frac{\text{Weight of Insoluble Fraction}}{\text{Initial Weight of Sample}} \times 100$$

Bulk Density, Tapped Density, Hausner Ratio and Carr's Index

The flow and compressibility properties of the extracted cellulose were evaluated by determining its bulk density, tapped density, Hausner ratio, and Carr's index. Bulk density was measured by transferring a known quantity of cellulose powder into a graduated cylinder and recording the volume occupied under loose packing conditions. Tapped density was determined after gently tapping the cylinder until a constant volume was obtained.

The Hausner ratio and Carr's index were calculated from the bulk and tapped density values to assess the flowability and compressibility of the cellulose powder. These parameters provide useful information regarding the handling, storage, and potential industrial applications of the extracted cellulose.

$$\text{Bulk Density } (\frac{\text{g}}{\text{cm}^3}) = \frac{\text{Mass of Sample}}{\text{Bulk Volume}}$$

$$\text{Hausner Ratio } = \frac{\text{Tapped Density}}{\text{Bulk Density}}$$

$$\text{Carr's Index (\%)} = \frac{\text{Tapped Density } - \text{ Bulk Density}}{\text{Tapped Density}} \times 100$$

Characterization of Extracted Cellulose

The extracted cellulose was characterized to evaluate its structural and physicochemical properties. Characterization was carried out using Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), and X-Ray Diffraction (XRD) analysis. These techniques were used to identify the functional groups, examine the surface morphology, and determine the crystallinity of the extracted cellulose.

Fourier Transform Infrared (FTIR) Spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy was performed to identify the functional groups present in the extracted cellulose and to confirm the successful removal of non-cellulosic components during the extraction process [3]. For analysis, the cellulose sample was mixed with spectroscopy-grade KBr and compressed into pellets using a hydraulic press. The prepared pellets were dried at 105°C to eliminate moisture and prevent interference during spectral analysis. FTIR spectra were recorded using an FTIR spectrophotometer over a wavenumber range of 4000–450 cm^{-1}. The obtained spectra were analyzed to identify the characteristic absorption bands corresponding to cellulose and to evaluate its structural properties.

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was performed to examine the surface morphology and structural characteristics of the extracted cellulose. The cellulose sample was mounted on a sample stub using double-sided adhesive tape and coated with a thin layer of gold to improve conductivity [3]. The coated sample was then placed in the SEM chamber and analyzed at different magnifications. The obtained micrographs were used to evaluate the surface texture, fiber arrangement, and morphological changes resulting from the cellulose extraction process.

X-Ray Diffraction (XRD) Analysis

X-Ray Diffraction (XRD) analysis was performed to evaluate the crystalline structure of the extracted cellulose. The cellulose sample was prepared in powdered form and analysed using an X-ray diffractometer with Cu-Kα radiation. The diffraction pattern was recorded over a 2θ range of 5°–70°. The obtained diffractograms were used to determine the crystallinity and structural characteristics of the extracted cellulose and to assess the effectiveness of the extraction process [3].

ADSORPTION STUDYS

Preparation of Erythromycin Solution

A stock solution of erythromycin (1000 mg/L) was prepared by dissolving 1 g of erythromycin in 1 L of distilled water. Working solutions of different concentrations were then prepared by diluting the stock solution with distilled water. The prepared solutions were used for evaluating the adsorption and degradation efficiency of the extracted cellulose under different experimental conditions [19].

Antibiotic Adsorption/Degradation Study

The adsorption and degradation performance of the extracted cellulose was evaluated using erythromycin solution under batch experimental conditions. Different amounts of cellulose (0.5, 1.0, 1.5, 2.0, and 2.5 g) were added to 100 mL of erythromycin solution of known concentration. The mixtures were continuously agitated at 200 rpm for 60 min at room temperature [20]. After treatment, the cellulose was separated by filtration, and the residual erythromycin concentration was determined using a UV–Visible spectrophotometer. To investigate the effects of operating parameters, adsorption experiments were conducted using erythromycin solutions of different concentrations (10, 20, 30, 40, and 50 mg/L). The influence of contact time and pH on antibiotic removal was also evaluated under optimized conditions. The percentage removal of erythromycin was calculated from the initial and final concentrations, and the optimum conditions for effective antibiotic degradation were determined [21].

Adsorption Capacity and Removal Efficiency

The adsorption capacity and removal efficiency of erythromycin were calculated using the initial and final concentrations obtained from UV–Visible spectrophotometric analysis. The equilibrium adsorption capacity (q_e) and percentage removal efficiency were determined using the following equations:

$$q_e = \frac{(C_0 - C_e)\,V}{M}$$

$$Removal\ Efficiency\ (\%) = \frac{(C_0 C_e)}{C_0} \times 100$$

Where:

q_e = Equilibrium adsorption capacity (mg/g)

C_0 = Initial erythromycin concentration (mg/L)

C_e = Equilibrium erythromycin concentration (mg/L)

V = Volume of solution (L)

M = Mass of adsorbent (g)

These calculations were used to evaluate the adsorption efficiency of the extracted cellulose under different experimental conditions.

Adsorption Kinetics Studies

Adsorption kinetics studies were conducted to investigate the rate and mechanism of erythromycin adsorption onto the extracted cellulose. The adsorption data obtained at different contact times were analyzed to understand the adsorption behaviour and determine the time required to reach equilibrium. Pseudo-first-order and pseudo-second-order kinetic models were applied to the experimental data to

evaluate the adsorption mechanism. The suitability of the kinetic models was assessed based on the correlation coefficient (R^2) values and the agreement between experimental and calculated adsorption capacities [22]. These analyses provided important information regarding the adsorption performance of the extracted cellulose.

Pseudo-First-Order Kinetic Model

The pseudo-first-order kinetic model was used to evaluate the adsorption rate of erythromycin onto the extracted cellulose. This model assumes that the rate of adsorption is proportional to the number of unoccupied adsorption sites available on the adsorbent surface. The linear form of the pseudo-first-order model is expressed as:

$$\ln(q_e - q_t) = \ln(q_e) - k_1 t$$

where q_e (mg/g) is the adsorption capacity at equilibrium, q_t (mg/g) is the adsorption capacity at time t, and k_1 (min^{-1}) is the pseudo-first-order rate constant. The values of k_1 and calculated qe were determined from the slope and intercept of the plot of $\ln(q_e - q_t)$ versus t, respectively.

Pseudo-Second-Order Kinetic Model

The pseudo-second-order kinetic model was used to evaluate the adsorption of erythromycin onto the extracted cellulose [23]. The linear form of the model is expressed as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e}$$

where q_t (mg/g) is the amount of erythromycin adsorbed at time t, q_e (mg/g) is the equilibrium adsorption capacity, and k_2 (g mg^{-1} min^{-1}) is the pseudo-second-order rate constant. The values of k_2 and q_e were obtained from the slope and intercept of the t/q_t versus t plot. The suitability of the model was evaluated using the correlation coefficient (R^2) and the agreement between experimental and calculated adsorption capacities.

ADSORPTION ISOTHERM

Langmuir Isotherm Model

The Langmuir isotherm model was used to evaluate the adsorption behaviour of erythromycin onto the extracted cellulose. This model assumes that adsorption occurs as a monolayer on a homogeneous surface containing a finite number of identical adsorption sites. It further assumes that each adsorption site can accommodate only one adsorbate molecule and that no interaction occurs between the adsorbed molecules [22].

The linear form of the Langmuir isotherm model is expressed as:

$$\frac{C_e}{q_e} = \frac{1}{q_m K_l} + \frac{C_e}{q_m}$$

where C_e (mg/L) is the equilibrium concentration of erythromycin in solution, q_e (mg/g) is the amount of erythromycin adsorbed at equilibrium, q_m (mg/g) is the maximum monolayer adsorption capacity, and K_l (L/mg) is the Langmuir adsorption constant. The values of q_m and K_l were determined from the slope and intercept of the C_e/q_e versus C_e plot. The applicability of the model was evaluated using the correlation coefficient (R^2) and the adsorption parameters obtained from the experimental data.

Freundlich Isotherm Model

The Freundlich isotherm model was applied to evaluate the adsorption behaviour of erythromycin onto the extracted cellulose [24,25]. This model assumes that adsorption occurs on a heterogeneous surface with different adsorption energies and allows for multilayer adsorption. The linear form of the Freundlich isotherm equation is expressed as:

$$\log q_e = \log K_f + \frac{1}{n} \log C_e$$

where q_e (mg/g) is the amount of erythromycin adsorbed at equilibrium, C_e (mg/L) is the equilibrium concentration of erythromycin in solution, K_f is the Freundlich adsorption constant related to adsorption capacity, and n is the adsorption intensity. The values of K_f and n were determined from the intercept and slope of the $\log q_e$ versus $\log C_e$ plot, respectively. The applicability of the model was evaluated using the correlation coefficient (R^2) and the adsorption parameters obtained from the experimental data.

RESULT AND DISCUSSION

Cellulose Yield

The cellulose yield obtained from agro-industrial waste ranged between 85% and 90% under different extraction conditions. The maximum yield of 90% was achieved under optimized extraction conditions, indicating the effectiveness of the alkali pretreatment and microwave-assisted extraction process. The high yield obtained suggests efficient removal of non-cellulosic components and successful recovery of cellulose. These results demonstrate that agro-industrial waste can serve as a promising raw material for cellulose extraction and subsequent antibiotic degradation applications [26].

CHARACTERIZATION

pH and Solubility of Extracted Cellulose

The extracted cellulose exhibited a near-neutral pH of 7.6 ± 0.1, indicating its chemical stability and suitability for environmental applications. The solubility analysis showed a solubility of 8.4% in 1% acetic acid solution, confirming that the cellulose remained largely insoluble due to its crystalline structure [10]. The low solubility and near-neutral pH suggest that the extracted cellulose possesses good structural stability and can effectively function as an adsorbent for antibiotic removal. These properties indicate its potential applicability in wastewater treatment and adsorption-based remediation processes.

Bulk Density, Tapped Density, Hausner Ratio and Carr's Index

The extracted cellulose exhibited a bulk density of 0.42 g/cm³ and a tapped density of 0.51 g/cm³, indicating moderate packing characteristics. The Hausner ratio was found to be 1.21, while the Carr's index was 17.6%. These values suggest that the extracted cellulose possesses satisfactory flowability and moderate compressibility. The observed powder characteristics indicate that the cellulose can be easily handled, stored, and utilized for adsorption applications. Overall, the results confirm the suitability of the extracted cellulose for further antibiotic removal studies [11].

FTIR Analysis

The FTIR spectrum of the extracted cellulose confirmed the presence of characteristic functional groups associated with cellulose. A broad absorption band corresponding to O–H stretching vibrations indicated the presence of hydroxyl groups, which are abundant in cellulose. Peaks attributed to C–H stretching and C–O stretching vibrations were also observed, confirming the cellulose structure **(Fig. 1)**. The reduction or absence of peaks associated with lignin and hemicellulose suggested that the alkali pretreatment and extraction process effectively removed most non-cellulosic components from the agro-industrial waste [27]. The observed FTIR profile was consistent with the characteristic spectrum of purified cellulose reported in previous studies. The FTIR results confirmed the successful extraction of cellulose and demonstrated the effectiveness of the pretreatment and extraction processes in improving cellulose purity.

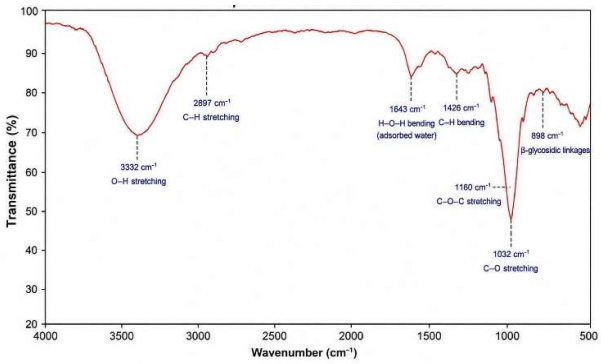

Fig. 1 FTIR Spectrum of Extracted Cellulose.

SEM Analysis

The SEM images revealed significant morphological changes in the extracted cellulose compared to the raw agro-industrial waste. The extracted cellulose exhibited a rough, fibrous, and porous surface structure, indicating the effective removal of lignin and hemicellulose during the pretreatment process **(Fig. 2)**. The presence of well-defined cellulose fibers confirmed the successful extraction of cellulose. The increased surface roughness and porosity observed in the SEM images may enhance the adsorption capacity of the extracted cellulose by providing a larger surface area and more active sites for interaction with antibiotic molecules. These findings suggest that the extracted cellulose possesses suitable morphological characteristics for potential application in antibiotic removal from wastewater [28].

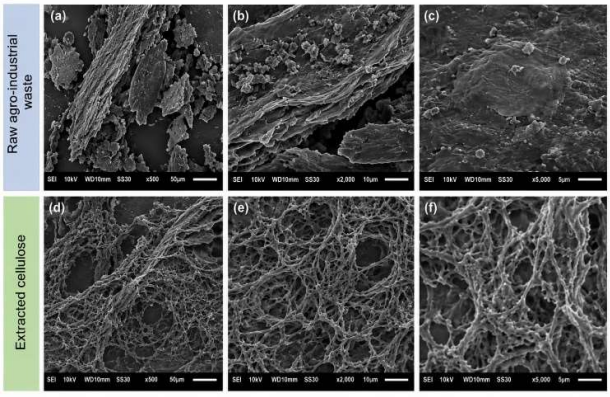

Fig. 2 SEM image of extracted cellulose from agro-industrial waste.

XRD Analysis

The XRD pattern of the extracted cellulose exhibited characteristic diffraction peaks corresponding to the crystalline regions of cellulose **(Fig. 3)**. The presence of distinct peaks confirmed the successful extraction of cellulose

from the agro-industrial waste. A noticeable increase in crystallinity was observed compared to the raw material, indicating the removal of amorphous components such as lignin and hemicellulose during the pretreatment and extraction processes. The enhanced crystallinity suggests improved structural organization of cellulose fibers, which may contribute to better adsorption performance and stability. These findings confirm the effectiveness of the extraction process in obtaining cellulose with desirable crystalline properties for potential wastewater treatment applications [29].

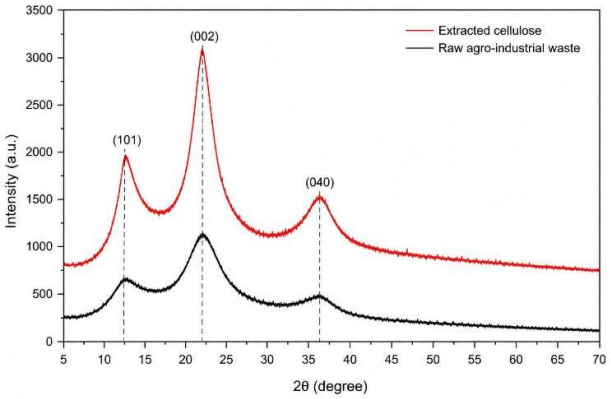

Fig. 3 XRD patterns of raw agro-industrial waste and extracted cellulose.

ANTIBIOTIC ADSORPTION

Effect of Adsorbent Dose on Adsorption

The adsorption efficiency of erythromycin increased with increasing cellulose dosage from 0.5 to 2.0 g. This improvement was due to the greater availability of active adsorption sites on the cellulose surface **(Fig. 4)**. Maximum removal efficiency was observed at 2.0 g of adsorbent. A further increase to 2.5 g resulted in only a slight improvement, indicating saturation of the available adsorption sites. Therefore, 2.0 g was selected as the optimum adsorbent dosage for subsequent experiments. The results demonstrate that the extracted cellulose is an effective adsorbent for erythromycin removal from aqueous solutions [30].

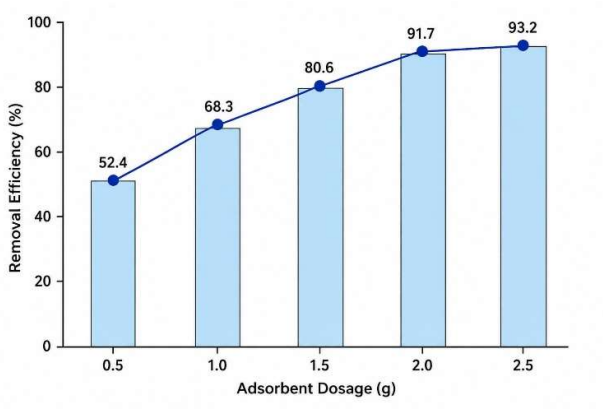

Fig. 4 Effect of initial erythromycin concentration on the removal efficiency of extracted cellulose.

Effect of pH on Adsorption

The pH of the solution significantly influenced the adsorption of erythromycin by the extracted cellulose. The removal efficiency increased from 58.4% at pH 3 to 74.8% at pH 5 and reached a maximum of 92.3% at pH 7 **(Fig. 5)**. The lower adsorption observed under acidic conditions may be attributed to the competition between hydrogen ions and erythromycin molecules for the available adsorption sites on the cellulose surface. A slight decrease in removal efficiency was observed at alkaline pH values, with removal efficiencies of 86.7% at pH 9 and 79.5% at pH 11. This reduction may be due to changes in the surface charge of cellulose and the ionization behaviour of erythromycin, which affect the adsorption process [31]. Overall, neutral pH showed the highest adsorption performance, indicating that pH 7 is the optimum condition for erythromycin removal using the extracted cellulose.

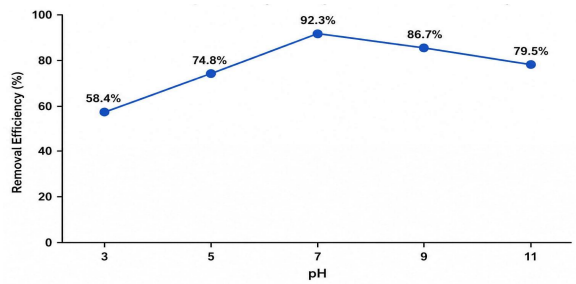

Fig. 5 Effect of pH on the removal efficiency of erythromycin using extracted cellulose.

Effect of Contact Time on Adsorption

The effect of contact time on the adsorption of erythromycin by the extracted cellulose was investigated over a period of 15–90 min. The adsorption efficiency increased rapidly during the initial stages of the experiment, rising from 45.6% at 15 min to 68.9% at 30 min and 84.7% at 45 min **(Fig. 6)**.

This rapid adsorption can be attributed to the availability of many active sites on the cellulose surface [32]. The contact time increased, the adsorption rate gradually slowed and reached a maximum removal efficiency of 93.5% at 60 min. Beyond this period, only a negligible increase in adsorption was observed, with removal efficiencies of 94.1% and 94.3% at 75 and 90 min, respectively. This indicates that adsorption equilibrium was achieved within 60 min due to the saturation of available adsorption sites. Therefore, 60 min was selected as the optimum contact time for subsequent adsorption experiments.

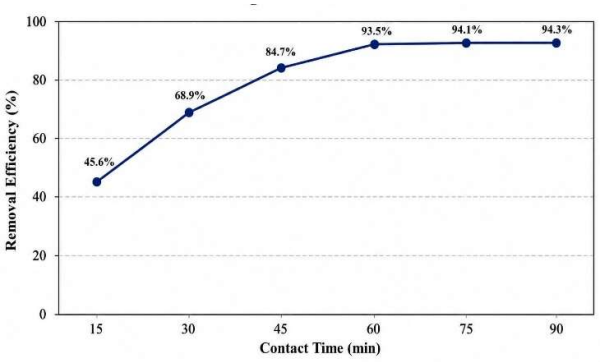

Fig. 6 Effect of contact time on the removal efficiency of erythromycin using extracted cellulose from agro-industrial waste.

Effect of Initial Concentration on Adsorption

The effect of initial erythromycin concentration on adsorption was evaluated in the range of 10–50 mg/L. The adsorption capacity increased with increasing antibiotic concentration, while the removal efficiency showed a slight decrease **(Fig. 7)**. The removal efficiency decreased from 94.2% at 10 mg/L to 85.6% at 50 mg/L due to the saturation of available adsorption sites on the cellulose surface. Despite the reduction in percentage removal at higher concentrations, the extracted cellulose exhibited effective adsorption performance over the entire concentration range, demonstrating its potential for erythromycin removal from wastewater [33].

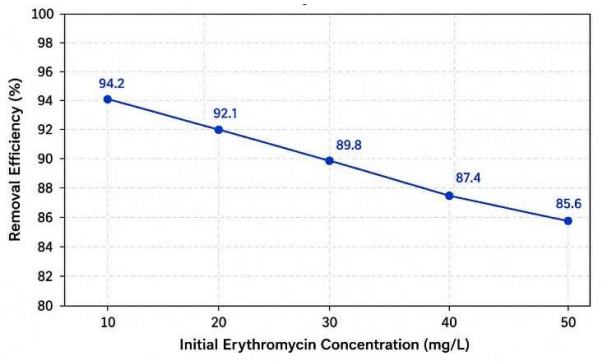

Fig. 7 Effect of initial erythromycin concentration on the removal efficiency of extracted cellulose.

UV–Visible Spectrophotometric Analysis

UV–Visible spectrophotometric analysis confirmed the successful removal of erythromycin by the extracted cellulose [34]. The untreated erythromycin solution showed a characteristic absorbance peak at 285 nm, whereas a significant reduction in absorbance intensity was observed after treatment **(Fig. 8)**. The absorbance decreased from 1.245 to 0.098, corresponding to a removal efficiency of approximately 92.1%. The reduction in absorbance indicates the effective adsorption and degradation of erythromycin by the cellulose adsorbent. These results demonstrate the potential of extracted cellulose for the treatment of antibiotic-contaminated wastewater.

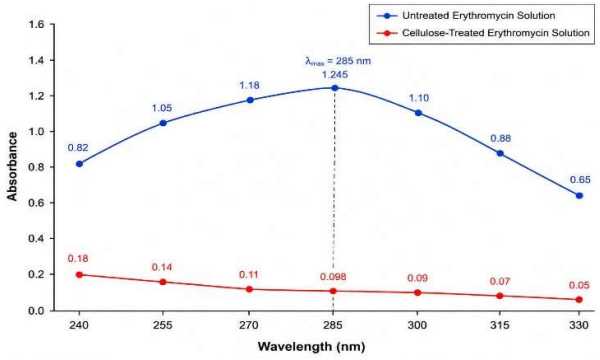

Fig. 8 UV–Visible spectra of erythromycin solution before and after treatment with extracted cellulose.

ADSORPTION STUDIES

Pseudo-First-Order Kinetic Model

The pseudo-first-order kinetic model was applied to analyze the adsorption of erythromycin onto the extracted cellulose. The model showed a correlation coefficient (R^2 = 0.942), indicating a moderate fit to the experimental data **(Fig. 9)**. The calculated adsorption capacity (21.8 mg/g) was lower than the experimental value (24.3 mg/g), suggesting that the model could not accurately describe the overall adsorption process [35]. These results indicate that erythromycin adsorption onto the extracted cellulose was not predominantly governed by a pseudo-first-order mechanism.

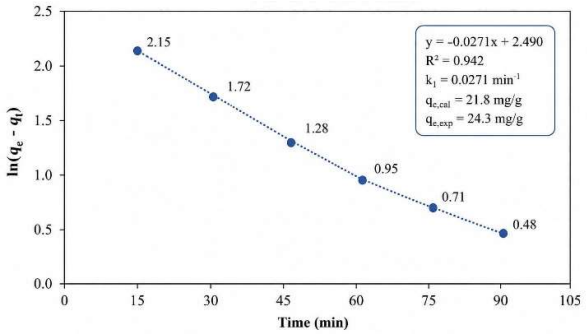

Fig. 9 Pseudo-first-order kinetic plot for erythromycin adsorption onto extracted cellulose.

Pseudo-Second-Order Kinetic Model

The pseudo-second-order kinetic model was applied to describe the adsorption of erythromycin onto the extracted cellulose. The linear plot of t/qt versus t showed an excellent fit to the experimental data with a high correlation coefficient ($R^2 = 0.998$). The calculated equilibrium adsorption capacity (q_e, cal = 24.1 mg/g) was very close to the experimental value (q_e, exp = 24.3 mg/g), indicating good agreement between the model and the adsorption data **(Fig. 10)**. The higher R^2 value and close agreement between the calculated and experimental adsorption capacities suggest that the pseudo-second-order model better describes the adsorption process than the pseudo-first-order model [36]. These results indicate that chemisorption may be the dominant mechanism involved in erythromycin adsorption onto the extracted cellulose.

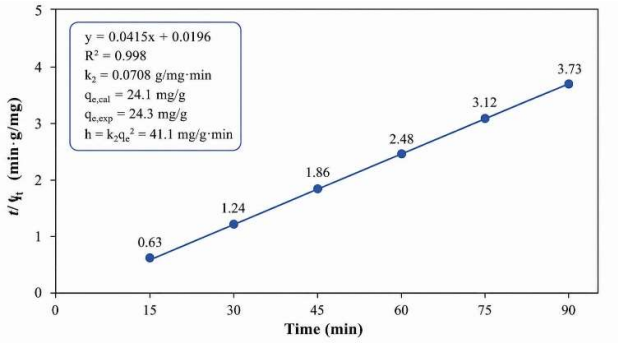

Fig. 10 Pseudo-second-order kinetic plot for erythromycin adsorption onto extracted cellulose.

Langmuir Isotherm Model

The Langmuir isotherm model was applied to evaluate the adsorption behavior of erythromycin onto the extracted cellulose. The linear plot of C_e/q_e versus C_e showed a good correlation with the experimental data, with a correlation coefficient of $R^2 = 0.991$. The maximum monolayer adsorption capacity (q_m) was found to be 27.6 mg/g, indicating a high adsorption potential of the extracted cellulose toward erythromycin. The high R^2 value suggests that the adsorption process follows the Langmuir isotherm model and occurs predominantly as monolayer adsorption on a homogeneous surface **(Fig. 11)**. The results indicate that the adsorption sites on the cellulose surface were uniformly distributed and possessed similar adsorption energies. The Langmuir isotherm analysis confirmed the effective adsorption of erythromycin onto the extracted cellulose and demonstrated its suitability as an adsorbent for antibiotic removal from aqueous solutions [37,38].

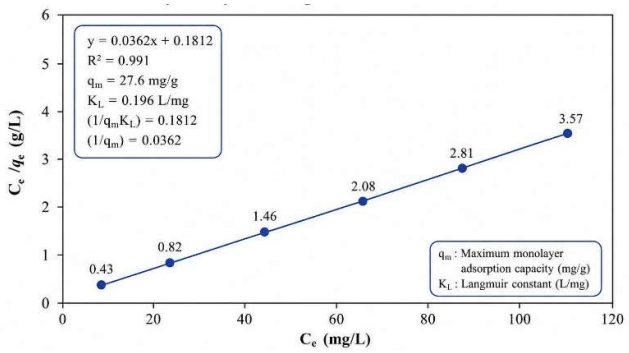

Fig. 11 Langmuir isotherm plot (C_e/q_e versus C_e) for erythromycin adsorption onto extracted cellulose.

Freundlich Isotherm Model

The Freundlich isotherm model was applied to evaluate the adsorption behavior of erythromycin onto the extracted cellulose. The linear plot of log qe versus log C_e showed a good fit to the experimental data with a correlation coefficient of $R^2 = 0.976$. The Freundlich constant (K_f) was determined to be 8.42 mg/g, indicating a favorable adsorption capacity of the extracted cellulose. The adsorption intensity (n = 2.31) was greater than 1, suggesting that the adsorption process was favorable and predominantly physical in nature. The good agreement between the experimental data and the Freundlich model **(Fig. 12)** indicates the presence of heterogeneous adsorption sites on the cellulose surface [39,40]. These results demonstrate that the extracted cellulose possesses effective adsorption characteristics and can efficiently remove erythromycin from aqueous solutions over a wide concentration range.

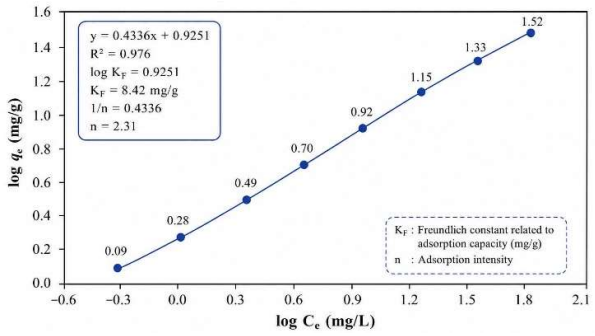

Fig. 12 Freundlich isotherm plot (log q_e versus log C_e) for erythromycin adsorption onto extracted cellulose.

CONCLUSION

Cellulose extracted from agro-industrial waste demonstrated excellent potential for the removal of erythromycin from aqueous solutions. The optimized extraction process achieved a high cellulose yield of 90%, indicating efficient recovery of cellulose from biomass. Characterization studies revealed a near-neutral pH (7.6 ± 0.1), low solubility (8.4%), and favorable flow properties, while FTIR, SEM, and XRD analyses confirmed the successful removal of non-cellulosic components, enhanced surface porosity, and increased crystallinity. Adsorption experiments showed that erythromycin removal was strongly influenced by operational parameters, with a maximum removal efficiency of 93.5% achieved at pH 7, an adsorbent dosage of 2.0 g, and a contact time of 60 min. UV–Visible analysis further confirmed antibiotic removal, showing a significant reduction in absorbance from 1.245 to 0.098 (92.1% removal). Kinetic studies demonstrated that adsorption followed the pseudo-second-order model (R^2 = 0.998), while the Langmuir isotherm model (R^2 = 0.991) showed the best fit with a maximum adsorption capacity of 27.6 mg/g. These findings highlight the potential of agro-industrial waste-derived cellulose as a sustainable, low-cost, and highly efficient adsorbent for antibiotic-contaminated wastewater treatment and environmental remediation.

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