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Maize Cob-Based Adsorbent for Efficient Removal of Amoxicillin from Aqueous Systems: Isotherm Modeling, Kinetics, and Desorption Studies

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Abstract
Antibiotic pollution has emerged as a major environmental concern due to the widespread use of antibiotics, their persistence in aquatic systems, and their adverse effects on ecosystems and human health. Consequently, the development of efficient and sustainable technologies for antibiotic removal from water has become increasingly important. This study investigated the potential of raw maize cob, an abundant agricultural waste, as a low-cost adsorbent for removing amoxicillin from aqueous solutions. Amoxicillin concentrations were determined using a validated UV–Visible spectrophotometric method with satisfactory linearity, sensitivity, accuracy, and precision. FTIR and SEM analyses confirmed the involvement of surface functional groups and morphological changes during adsorption, while BET analysis revealed reductions in surface area and pore volume after adsorption. Optimum adsorption was achieved at an adsorbent dosage of 0.1 g (50.92 mg g^{-1}), pH 6 (31.34 mg g^{-1}), initial concentration of 40 mg L^{-1} (33.80 mg g^{-1}) and a contact time of 140 min (81.42 mg g-1). The adsorption kinetics followed the pseudo-second-order model (R^2 = 0.987), whereas equilibrium data were best described by the Langmuir isotherm model (R^2 = 0.913), with a maximum adsorption capacity of 46.35 mg g^{-1}. Regeneration studies showed adsorption and desorption efficiencies exceeding 96% after three cycles. The possible adsorption process was governed by hydrogen bonding, electrostatic attraction, and surface complexation, demonstrating the potential of maize cob as a sustainable adsorbent for amoxicillin-contaminated water.

Keywords: Adsorption; Adsorption kinetics; Agricultural waste; Amoxicillin; Antibiotic removal; Langmuir isotherm; Maize cob; Water treatment.

1. Introduction

The rapid advancement of the pharmaceutical industry has significantly improved global health outcomes through the development of effective therapeutic agents for the treatment of various diseases. However, the widespread production and consumption of pharmaceuticals have led to growing environmental concerns due to their continuous release into aquatic systems (Kayode-Afolayan et al., 2022; Hejna et al., 2022). A substantial proportion of administered drugs are not completely metabolized in humans and animals, resulting in their excretion through urine and feces and subsequent introduction into wastewater streams (Li et al., 2023; Georgin et al., 2023). Consequently, diverse water bodies, including surface water, groundwater, and wastewater systems, have become reservoirs of pharmaceutical contaminants, posing serious risks to aquatic ecosystems and human health (Nkoh et al., 2023).

Among these contaminants, antibiotics are of particular concern due to their potential to induce antimicrobial resistance, a major global public health challenge (Serwecińska, 2020). Amoxicillin (AMX) (Figure 1), a widely used β-lactam antibiotic with the chemical formula $C_{16}H_{19}N_3O_5S$, is commonly prescribed for the treatment of bacterial infections such as pneumonia, sinusitis, and urinary tract infections. Despite its therapeutic importance, a large fraction of the administered dose is excreted unmetabolized into the environment, contributing to its frequent detection in wastewater systems (Georgin et al., 2023). This continuous discharge has raised concerns regarding its ecological impact, particularly its role in promoting the development of antibiotic-resistant microorganisms and disrupting microbial communities (de Boer et al., 2023).

The environmental persistence of AMX is largely attributed to its complex molecular structure and physicochemical properties, including high solubility and the presence of multiple functional groups such as hydroxyl, amine, amide, and carboxyl groups (Yang et al., 2021). These characteristics enhance its interaction with aqueous media and hinder its complete removal using conventional wastewater treatment processes (Ratnasari et al., 2023). As a result, wastewater treatment plants often exhibit limited efficiency in eliminating such contaminants, especially at low concentrations, thereby contributing to their continuous release into aquatic environments.

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To address this challenge, various treatment technologies, including membrane filtration (Sharma et al., 2017), advanced oxidation processes (Pirsaheb et al., 2023; Souza et al., 2018), and photocatalytic degradation (Verma & Haritash, 2020) have been investigated for the removal of antibiotics from water systems. However, these methods are often associated with high operational costs, energy requirements, and the potential formation of secondary pollutants. In contrast, adsorption has emerged as a promising alternative due to its simplicity, cost-effectiveness, high efficiency, and adaptability. Notably, adsorption has demonstrated excellent performance in removing antibiotics even at low concentrations, making it one of the most widely studied techniques for pharmaceutical remediation (de Boer et al., 2023).

Agricultural wastes have attracted considerable interest as low-cost adsorbents for the removal of emerging contaminants from water (Eniola et al., 2023). Although maize cob has been widely investigated for the removal of dyes and heavy metals and as a precursor for activated carbon production, most studies have focused on chemically modified or thermally activated forms. In contrast, the use of unmodified maize cob for the removal of pharmaceutical contaminants remains largely underexplored. In particular, limited information is available on the adsorption of AMX, a widely used β-lactam antibiotic, onto raw maize cob biomass. Therefore, this study investigates the potential of unmodified maize cob as a sustainable and cost-effective adsorbent for AMX removal from aqueous solutions through comprehensive characterization, adsorption modelling, regeneration studies, and mechanistic evaluation. This work contributes to the development of environmentally friendly approaches for the treatment of antibiotic-contaminated water.

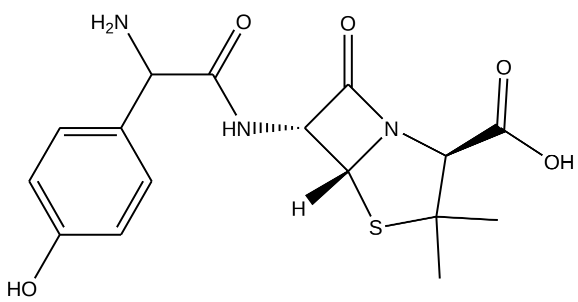

Figure 1. Structure of AMX

2. Materials and methods

2.1. Materials and Reagents

Analytical-grade AMX (≥99% purity) was obtained from Sigma Aldrich, UK. All other reagents used in this study, including hydrochloric acid (HCl) and sodium hydroxide (NaOH) for pH adjustment, were of analytical grade. Deionized water was used throughout the study for the preparation of all solutions. maize cobs (*Zea mays*) were obtained on March 2025, from Iyana Offa farm settlement in Lagelu Local Government Area of Oyo State, Nigeria.

2.2. Preparation of Maize Cob-Based Adsorbent

The maize cobs were cleaned with distilled water to remove adherent dirt, sun-dried for five days, and oven-dried at 105 °C for 24 h to eliminate moisture content. The dried biomass was then crushed and sieved to obtain a uniform particle size (typically 100–250 µm). The maize cobs powder was stored in a black sealed polyethylene bag until further used.

2.3. Characterisation of Adsorbent

The prepared maize cob-based adsorbent was characterized using standard analytical techniques to determine its physicochemical properties. Fourier Transform Infrared Spectroscopy (FTIR, Spectrum Two, PerkinElmer, USA) was used to identify surface functional groups, while Scanning Electron Microscopy (SEM, JSM-IT200, JEOL Ltd., Japan) operated at an accelerating voltage of 15 kV was employed to examine surface morphology and porosity. Brunauer–Emmett–Teller (Micromeritics ASAP 2020, Micromeritics Instrument Corporation, USA) (BET) analysis was conducted to determine surface area and pore volume.

2.4 Preparation of Amoxicillin Solutions

A stock solution of amoxicillin trihydrate (1000 mg L^{-1}) was prepared by dissolving 1.0 g of the standard in 10 mL methanol and diluting to 1000 mL with deionized water. Subsequently, a 200 mg L^{-1} intermediate working solution was prepared from the stock solution and used for the adsorption experiments. Calibration standard solutions ranging from 5 to 30 mg L^{-1} were prepared by serial dilution of the working solution with deionized water. The absorbance of the prepared standards was measured using a UV–Visible spectrophotometer (UV-1800, Shimadzu Corporation, Kyoto, Japan) to construct the calibration curve for quantitative determination of amoxicillin at its maximum absorbance wavelength (λmax) of 228 nm.

2.5. Analytical Method Validation

The analytical method employed for the quantification of amoxicillin was validated in accordance with the International Council for Harmonisation (ICH) Q2(R2) guidelines to ensure its suitability, reliability, and fitness for the intended purpose. Validation parameters assessed included linearity, sensitivity, accuracy, and precision (ICH, 2024).

Linearity was evaluated using calibration standard solutions prepared within the concentration range of 5–30 mg L^{-1}. The absorbance of each standard solution was measured at 228 nm using a UV–Visible spectrophotometer, and a calibration curve was constructed by plotting absorbance against concentration. The linearity of the method was assessed from the regression equation and coefficient of determination (R^2) obtained by least-squares regression analysis. The sensitivity of the method was determined by calculating the limit of detection (LOD) and limit of quantification (LOQ) based on the standard deviation of the response (σ) and the slope of the calibration curve (S). The LOD and LOQ were calculated according to Equations (1) and (2), respectively.

$$LOD = \frac{3.3_\sigma}{S} \quad (1)$$

$$LOQ = \frac{10_\sigma}{S} \quad (2)$$

where σ is the standard deviation of the analytical response and S is the slope of the calibration curve.
The accuracy of the method was assessed through recovery experiments using the standard addition approach. Known concentrations of amoxicillin were spiked into previously analyzed samples at three concentration levels, and the resulting solutions were analyzed under identical experimental conditions. The percentage recovery was calculated using Equation (3)

$$\%Recovery = \frac{C_{found}}{C_{added}} \times 100 \quad (3)$$

where C_{found} is the experimentally determined concentration and C_{added} is the concentration of amoxicillin added to the sample.
Precision was evaluated in terms of repeatability (intra-day precision) by analyzing a standard amoxicillin solution in six replicates under identical experimental conditions. The results were expressed as percentage relative standard deviation (%RSD), calculated using Equation (4)

$$\%RSD = \frac{\text{SD}}{\bar{\text{x}}} \times 100 \quad (4)$$

where SD = standard deviation of replicate measurements and $\bar{x}$ is the mean measured concentration.

2.6. Batch Adsorption Experiments

The adsorption performance of maize cob adsorbent for the removal of AMX from aqueous solutions was evaluated through batch adsorption experiments. A calibration curve for AMX determination was established by measuring the absorbance of standard solutions (5–30 mg L^{-1}) at 228 nm using a UV–Visible spectrophotometer. The standard solutions were prepared by serial dilution of a stock AMX solution at pH 7. The concentration of AMX in aqueous samples was subsequently determined from the calibration curve (Imanipoor et al., 2020; Mosavi et al., 2023).

The effects of key operational parameters, including solution pH, adsorbent dosage, contact time, and initial AMX concentration, on the adsorption performance were systematically investigated. The solution pH was adjusted within the range of 2–10 using 0.01 M HCl and 0.01 M NaOH. Optimization studies were conducted using maize cob dosages of 0.1–0.5 g, contact times ranging from 5 to 140 min, and initial AMX concentrations of 10–400 mg L^{-1}.

Adsorption equilibrium data were analyzed using the Langmuir and the Freundlich isotherm models to elucidate the adsorption mechanism and surface characteristics of the adsorbent. Furthermore, adsorption kinetics was evaluated using pseudo-first-order, pseudo-second-order kinetics and intraparticle diffusion models based on the experimental contact-time data. All experiments were performed in triplicate, and the results are presented as mean values.
The adsorption capacity (q_e) and removal efficiency (%) of AMX onto the maize cob adsorbent were calculated using Equations (5) and (6), respectively (Mehdizadeh et al., 2022).

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (5)$$

$$\%R = \frac{(C_0 - C_e)}{C_0} \times \frac{100}{1} \quad (6)$$

where C_0 and C_e are the amoxicillin initial and the equilibrium concentrations in the solutions measured in mg/L, correspondingly. m is the mass (g) of maize cobs adsorbent while V is the volume of the solution (L).

2.7. Adsorption Isotherm Studies

Equilibrium data obtained from batch experiments were analyzed using commonly applied, Langmuir and Freundlich adsorption isotherm models. The Langmuir model assumes monolayer adsorption of pollutants on a homogeneous surface, whereas the Freundlich model describes multilayer adsorption of contaminants on heterogeneous surfaces. Temkin isotherm assumes that the heat of adsorption decreases linearly with increasing surface coverage due to interactions between the adsorbate and the adsorbent. The mathematical expression of Langmuir and Freundlich isotherm was given in Equations (7) and (8) respectively (Ogunneye et al., 2025).

$$\frac{c_e}{q_e} = \frac{1}{q_{max}k_L} + \frac{c_e}{q_{max}} \quad (7)$$

$$lnq_e = lnk_f + \frac{1}{n}lnc_e \quad (8)$$

where, c_e , q_e , and q_{max} are the equilibrium concentration (mg/L), the equilibrium, and maximum adsorption capacity (mg/g) respectively; KL (L/mg) is the Langmuir constant, calculated from the plot between $\frac{c_e}{q_e}$ and c_e ; KF (L/mg) is the Freundlich constant calculated from the plot between lnq_e and lnc_e. The n parameter indicates adsorption intensity and favorability; if n = 1, the amoxicillin adsorption onto maize cobs adsorbent is linear, n < 1, the adsorption is Poor or unfavourable but if it is 1<n<10, it indicates good and favourable adsorption behavior.

2.8. Adsorption kinetics

Kinetic studies were conducted to determine the rate and mechanism of adsorption. Experimental data obtained from contact time were analyzed using Pseudo-first-order (PFO), Pseudo-second-order (PSO) kinetic and intraparticle diffusion models. These models help to identify whether the adsorption process is controlled by physical adsorption, chemisorption, or diffusion mechanisms. The mathematical expressions for PFO, PSO and intraparticle diffusion model were given in Equations (9), (10) and (11) respectively.

$$log(q_e - q_t) = logq_e - k_1 t \quad (9)$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (10)$$

$$q_t = k_\alpha t^{0.5} + C \quad (11)$$

where q_t (mg/g), and q_e (mg/g) are the amount of adsorbate adsorbed at time (t) and equilibrium, respectively. k_1 (1/min) and k_2 (g/mg_min) are the rate constants of the PFO and PSO, respectively. k_α = intraparticle diffusion rate constant (mg g^{-1} $min^{-1/2}$), and C = intercept related to boundary layer thickness.

2.9. Desorption and Regeneration Studies

Desorption and regeneration studies were conducted to evaluate the reusability and stability of the maize cob-based adsorbent following adsorption of amoxicillin. The desorption and reusability experiments were performed using 70% ethanol. Briefly, a known quantity of the exhausted maize cobs adsorbent was transferred into 50 mL of the 70% ethanol solution and agitated in a mechanical shaker at 150 rpm for 60 min at room temperature. After desorption, the adsorbent was recovered by filtration, thoroughly rinsed with deionized water, and oven-dried at 60 °C prior to reuse. The concentration of desorbed amoxicillin was determined using a UV–Visible spectrophotometer at 228 nm. Equation (12) was used to obtain desorption percentage.

$$\%D = \frac{C_d}{C_\alpha} \times \frac{100}{1} \quad (12)$$

Regeneration experiments were subsequently conducted over three adsorption–desorption cycles to evaluate the recyclability and economic feasibility of the adsorbent for sustainable water treatment applications.

3.0. Results and discussion

3.1. Validation of the UV–Visible Spectrophotometric Method for Amoxicillin Determination

The analytical result for the sensitivity, calibration curve and percentage recovery for the analysed Amoxicillin using UV–Visible spectrophotometric method is presented in Table 1. The validation results demonstrated that the method was suitable for the determination of AMX in aqueous solutions. The calibration curve exhibited good linearity over the concentration range of 5–30 mg L^{-1}, with a regression equation of y = 0.0349x + 0.1122 and a coefficient of determination (R^2) of 0.9917. The method showed high sensitivity, with LOD and LOQ values of 0.00246 mg L^{-1} and 0.019 mg L^{-1}, respectively, indicating its capability to detect and quantify low concentrations of amoxicillin. Similar validation procedures have been reported for the determination of amoxicillin and other pharmaceutical compounds using UV–Visible spectrophotometry (Shailesh et al., 2017; Hamdy et al., 2026). The recovery values ranged from 95.62 to 99.84%, with a mean recovery of 97.43%, confirming the accuracy of the method. Furthermore, the precision of the method was satisfactory, as evidenced by a low relative standard deviation (%RSD) of 2.42%. Overall, the obtained validation parameters indicate that the analytical method is reliable, accurate, sensitive, and precise for monitoring amoxicillin concentrations during the adsorption experiments (Shailesh et al., 2017).

Table 1: Analytical validation parameters for the determination of amoxicillin using UV–Visible spectrophotometry technique

Parameter	Value
Linear range (mg L^{-1})	5–30
Regression equation	y = 0.0349x + 0.1122
Correlation coefficient (R^2)	0.9917
LOD (mg L^{-1})	0.00246
LOQ (mg L^{-1})	0.019
Recovery at low concentration (%)	95.62-99.84
Mean recovery (%)	97.43
Precision (%RSD)	2.42

3.2. FTIR Analysis

The FTIR spectra of the raw maize cob adsorbent and AMX-loaded maize cob adsorbent are presented in Figure 2. The spectrum of the raw adsorbent exhibited characteristic functional groups associated with lignocellulosic biomass. The broad band observed at 3359.4 cm^{-1} was assigned to O–H stretching vibrations of hydroxyl groups present in cellulose, hemicellulose, and lignin. Following adsorption, this band shifted to 3242.8 cm^{-1}, indicating the involvement of hydroxyl groups in the adsorption process through hydrogen-bonding interactions with AMX molecules. Similar observations have been reported for biomass-based adsorbents used in the removal of pharmaceutical contaminants (Nayak et al., 2023; Vu et al., 2025).

The band at 2850.3 cm^{-1} corresponded to aliphatic C–H stretching vibrations, while the peaks at 1528.2 and 1687.7 cm^{-1} were attributed to N–H and C=O functional groups, respectively. After adsorption, these bands shifted to 1523.4 cm^{-1}, suggesting interactions between the AMX molecules and the active sites of the maize cob adsorbent. Likewise, the C–O stretching band at 1367.9 cm^{-1} shifted to 1424.2 cm^{-1} after adsorption, further confirming the participation of oxygen-containing functional groups in the adsorption mechanism.

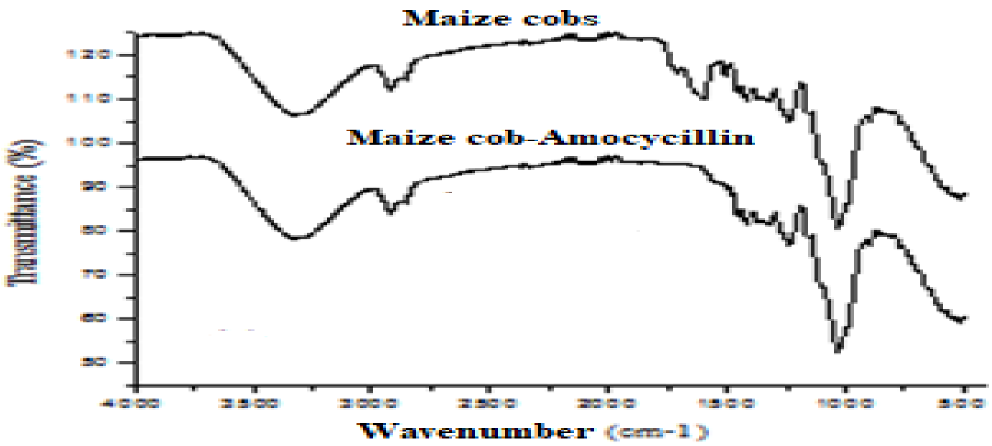

Figure 2: FTIR spectra of raw maize cob adsorbent and amoxicillin-loaded maize cob adsorbent showing the involvement of surface functional groups in the adsorption process

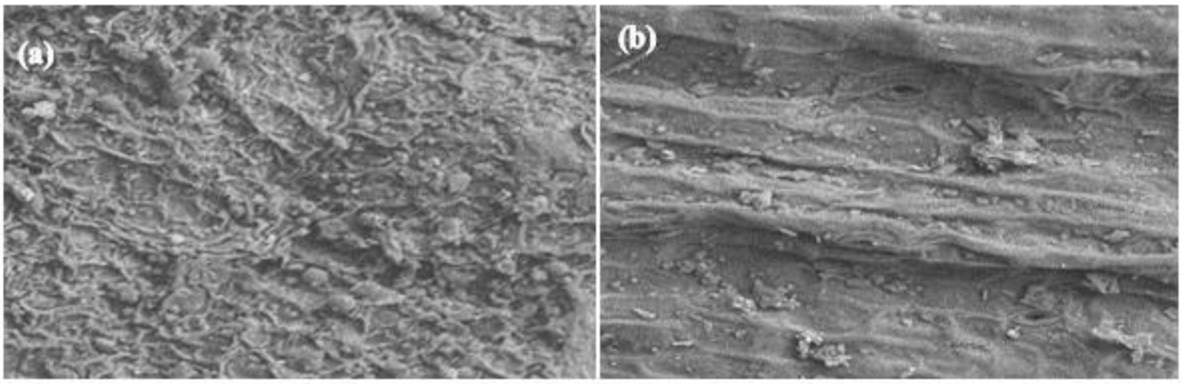

Figure 3: SEM micrographs of maize cob adsorbent before (a) and after (b) adsorption of amoxicillin

The observed shifts in the O–H, N–H, C=O, and C–O bands suggest that hydrogen bonding, electrostatic interactions, and surface complexation may have contributed to the adsorption of amoxicillin onto the maize cob surface. These findings corroborate recent studies demonstrating that oxygenated functional groups play a critical role in the adsorption of antibiotics onto lignocellulosic biomass adsorbents (Jatoi et al., 2023; Işıtan, 2025).

3.3. SEM Analysis

The surface morphology of the maize cob adsorbent before and after AMX adsorption was examined using scanning electron microscopy (SEM), and the micrographs are presented in Figure 3. The raw maize cob adsorbent exhibited a rough, irregular, and heterogeneous surface with numerous grooves, cavities, and fibrous structures, which are characteristic features of lignocellulosic biomass. Such surface irregularities provide abundant active sites and facilitate the diffusion and adsorption of contaminant molecules (Thabede et al., 2023). Following AMX adsorption, noticeable changes in surface morphology were observed. The adsorbent surface appeared relatively smoother and more compact, with partial coverage of the grooves and cavities by adsorbed AMX molecules. The reduction in surface roughness and the presence of deposited materials on the adsorbent surface suggest the occupation of available adsorption sites and successful attachment of amoxicillin onto the maize cob matrix (Abbas & Trari, 2024; Salih et al., 2022).

3.4. BET Surface Area and Pore Structure Analysis

The textural properties of the maize cob adsorbent before and after amoxicillin adsorption were evaluated using BET analysis, and the results are presented in Table 2. The BET analysis shows a marked decrease in surface area from 7.82 to 4.64 m^2/g after amoxicillin adsorption, indicating effective occupation of active sites and partial pore blocking by adsorbate molecules. A slight reduction in pore volume (0.20 to 0.19 cm^3/g) further confirms that adsorption occurred within both external surfaces and internal pore structures. The decrease in pore diameter from 2.5 to 1.9 nm suggests pore filling within the mesoporous region without structural collapse of the maize cob, confirming that the adsorbent maintains its integrity after adsorption. The moderate surface area observed is typical of raw lignocellulosic biomass, where natural porosity is limited by cellulose, hemicellulose, and lignin matrices. Similar BET ranges have been reported for agricultural wastes such as corncob and maize-based materials, which generally exhibit low-to-moderate surface areas prior to activation (Lugo-Arias et al., 2025). Compared to chemically activated biomass adsorbents, which often exceed several hundred m²/g (Abbas & Trari, 2024), the present material shows lower surface development but still demonstrates effective adsorption performance due to inherent porosity and surface functional groups.

Table 2: BET Surface Characteristics of Maize Cob Adsorbent before and after Amoxicillin Adsorption

Parameter	Before adsorption	After adsorption
SBET (m²/g)	7.82	4.64
Pore volume (cm³/g)	0.20	0.19
Pore diameter (nm)	2.5	1.9

3.5. Optimisation of Effective Parameters for Amoxicillin Adsorption by Maize cobs

3.5.1. Effect of pH

The adsorption of amoxicillin was strongly influenced by solution pH (Figure 4a). The adsorption capacity increased from 17.5 mg g^{-1} at pH 2 to a maximum value of 31.5 mg g^{-1} at pH 6 (31.34 mg g^{-1}**)**, after which it gradually decreased to 25.8 mg g^{-1} at pH 10. The optimum adsorption at pH 6 can be attributed to favourable electrostatic interactions between the ionizable functional groups of AMX and the oxygen-containing functional groups identified on the maize cob surface by FTIR analysis. At lower pH values, excess H^+ ions compete with amoxicillin molecules for available adsorption sites, while at higher pH values, changes in AMX speciation and increased electrostatic repulsion may reduce adsorption efficiency. Similar optimum pH values ranging from 5 to 7 have been reported for the adsorption of amoxicillin and other antibiotics using lignocellulosic biomass-derived adsorbents and biochars (Adu-Poku et al., 2024; Georgin et al. 2023; Mosavi et al., 2023)

3.5.2. Effect of Adsorbent Dosage

The effect of adsorbent dosage on the adsorption capacity of amoxicillin is presented in Figure 4(b). The adsorption capacity decreased from 51.8 to 25.8 mg g^{-1} as the maize cob dosage increased from 0.1 to 0.5 g, with the highest adsorption capacity obtained at 0.1 g. This decrease may be attributed to particle aggregation and the underutilization of available adsorption sites at higher dosages, resulting in a reduction in the amount of amoxicillin adsorbed per unit mass of adsorbent. Similar observations have been widely reported for biomass-based adsorbents used in antibiotic removal, where increasing adsorbent dosage enhances the number of available binding sites but decreases adsorption capacity due to site overlap and unsaturated adsorption sites (Ajala et al., 2023).

3.5.3. Effect of Contact Time

The effect of contact time on amoxicillin adsorption is shown in Figure 4(c). The adsorption capacity increased rapidly during the first 120 min, reaching 78.8 mg g^{-1}, and subsequently approached equilibrium at approximately 140 min with a maximum adsorption capacity of 81.42 mg g^{-1}. Beyond this period, only marginal changes were observed, indicating saturation of the available adsorption sites. The rapid initial adsorption phase can be attributed to the abundance of vacant active sites on the adsorbent surface, whereas the slower adsorption rate observed at longer contact times is associated with progressive occupation of these sites and increased resistance to mass transfer. Comparable equilibrium times ranging from 120 to 180 min have been reported for the adsorption of amoxicillin and other pharmaceutical contaminants onto biomass-derived adsorbents, indicating that the present adsorbent exhibits competitive adsorption kinetics (Amaku & Mtunzi, 2025; Jellali et al., 2024; Ajala et al., 2023).

3.5.4 Effect of Initial Amoxicillin Concentration

The effect of initial amoxicillin concentration on the adsorption performance of maize cob was investigated over the concentration range of 10–100 mg L^{-1} (Figure 4(d)). The adsorption capacity (q_e) increased markedly from 6.0 mg g^{-1} at 10 mg L^{-1} to a maximum of 34.0 mg g^{-1} at 30 mg L^{-1}. This increase can be attributed to the higher concentration gradient between the solution and adsorbent surface, which enhanced the mass transfer driving force and promoted the diffusion of amoxicillin molecules to available adsorption sites. Beyond 30 mg L^{-1}, the adsorption capacity remained nearly constant (33.80 mg g^{-1}), indicating saturation of the available active sites on the adsorbent surface. At these higher concentrations, the number of amoxicillin molecules exceeded the available adsorption sites, resulting in no significant increase in adsorption capacity. The plateau observed suggests the attainment of adsorption equilibrium and the existence of a finite number of active sites on the maize cob adsorbent. Similar trends have been reported for amoxicillin adsorption onto biochars, activated carbons, and other lignocellulosic adsorbents, where adsorption capacity increases with increasing initial concentration until surface saturation is reached (Mohammed et al., 2024). These findings demonstrate the strong affinity of maize cob for amoxicillin and highlight its potential as an effective, low-cost adsorbent for pharmaceutical wastewater treatment.

3.6. Adsorption Isotherm Studies

The equilibrium adsorption data were analyzed using Langmuir and Freundlich isotherm models to elucidate the adsorption behaviour of AMX onto maize cob. The calculated isotherm parameters are presented in Table 3. As revealed in Figure 5(a), the Langmuir model provided a better fit to the experimental data (R^2 = 0.913) than the Freundlich model (R^2 = 0.829), indicating that adsorption predominantly occurred through monolayer coverage on a relatively homogeneous adsorbent surface. The maximum monolayer adsorption capacity (qmax) predicted by the Langmuir model was 46.35 mg g^{-1}, demonstrating the appreciable affinity of maize cob toward amoxicillin molecules. The Langmuir affinity constant (KL) was 0.0531 L mg^{-1}, further confirming favorable

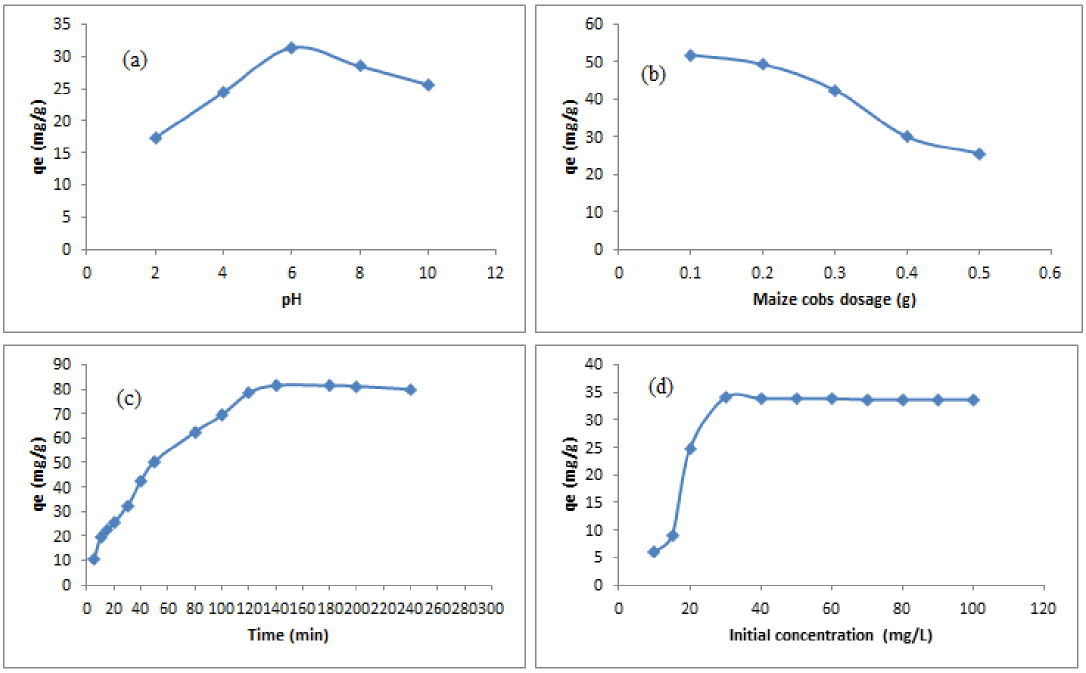

Figure 4: Optimization of adsorption parameters for amoxicillin removal using maize cob adsorbent, showing the effects of (a) solution pH, (b) adsorbent dosage, (c) contact time, and (d) Initial AMX concentration on the adsorption capacity (qe)

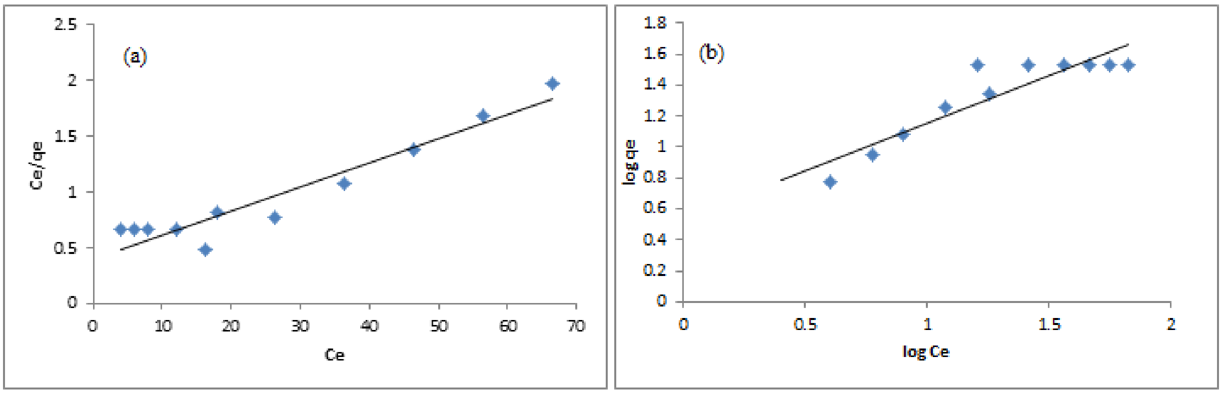

Figure 5: Linearized adsorption isotherm models for amoxicillin adsorption onto maize cob adsorbent: (a) Langmuir isotherm plot (C_e/q_e versus C_e) and (b) Freundlich isotherm plot (log q_e versus log C_e)

interactions between the adsorbent and adsorbate. In addition, the dimensionless separation factor (RL) was 0.158, which falls within the favourable adsorption range ($0 < RL < 1$).

The Freundlich model (Figure 5(b)) yielded a KF value of 3.51 and an adsorption intensity (n) of 1.64. Since n exceeded unity, the adsorption process can be considered favorable and indicative of strong adsorbate–adsorbent interactions. However, the lower R^2 value obtained for the Freundlich model suggests that surface heterogeneity played a less significant role than monolayer adsorption under the investigated conditions.

As shown in Table 3. the q_{max} capacity obtained for maize cob in the present study (46.35 mg g^{-1}) compares favourably with several low-cost and unmodified biosorbents reported in the literature (Table 4). For example, untreated *Spirogyra* biomass exhibited a maximum adsorption capacity of 21.68 mg g^{-1} for amoxicillin, while unmodified coconut shell activated carbon showed a capacity of 22.43 mg g^{-1}. Although the adsorption capacity was lower than that reported for raw *Arundo donax* biomass (75.8 mg g^{-1}), the maize cob adsorbent demonstrated appreciable adsorption performance without any chemical activation or surface modification. The favourable adsorption capacity observed in this study can be attributed to the abundance of hydroxyl, carbonyl, and ether functional groups present in the lignocellulosic structure of maize cob, which facilitate hydrogen bonding and electrostatic interactions with amoxicillin molecules

Table 3: Isotherm Parameters for the Adsorption of Amoxicillin onto Maize Cob Adsorbent

Isotherm Model	Parameter	Value
Langmuir	qmax (mg g^{-1})	46.35
	KL (L mg^{-1})	0.0531
	RL	0.158
	R^2	0.913
Freundlich	KF [(mg g^{-1})(L mg^{-1})$^{1/n}$]	3.51
	n	1.64
	1/n	0.610
	R^2	0.829

Table 4: Comparison of the maximum adsorption capacities of maize cob and other adsorbents reported for pharmaceutical removal.

Adsorbent	Adsorbate	q_{max} (mg g^{-1})	References
Maize cob (this study)	Amoxicillin	46.35	The present study
Raw *Arundo donax* biomass	Amoxicillin	75.8	Chayid & Ahmed, 2015
Spirogyra biomass	Amoxicillin	21.68	Kumar and Kumar, 2025
Agricultural soil	Amoxicillin	0.023	KIES et al., 2020)
Unmodified coconut shell activated carbon	Amoxicillin	22.43	Zhao et al., 2024
pretreated waste *Streptomyces fradiae* biomass	Tetracycline	38.61	Kirova et al., 2021
The phosphorous-doped microporous carbonous material (PPhA)	sulfamethoxazole, carbamazepine, ketoprofen, naproxen, diclofenac and ibuprofen	17.19, 17.69, 19.27, 17.66, 21.11 and 23.33	Sekulic et al., 2019
pumice stone	Tetracycline	20.02	Guler & Sarioglu, 2014
orange peels	Diclofenac	37.0	Jmai et al., 2025
Maize cobs	Ibuprofen	42.30	Thabede et al., 2023
Raw rice husk	Levofloxacin	2.47	Atta et al., 2023

3.7. Adsorption Kinetics

The adsorption kinetics of AMX onto maize cob adsorbent was investigated using pseudo-first-order, pseudo-second-order, and intraparticle diffusion models. The kinetic parameters obtained from the linearized models are summarized in Table 5.

The pseudo-first-order model (Figure 6(a)) yielded a relatively low coefficient of determination (R^2 = 0.724), indicating poor agreement between the experimental data and the model assumptions. In addition, the calculated equilibrium adsorption capacity differed considerably from the experimental value, suggesting that the adsorption process could not be adequately described by a first-order mechanism.

In contrast, the pseudo-second-order model (Figure 6(b)) provided an excellent fit to the experimental data with a high coefficient of determination (R^2 = 0.987). The superior fitting performance of this model indicates that the adsorption rate was primarily controlled by interactions between amoxicillin molecules and the active sites present on the maize cob surface. Similar kinetic behaviour has been widely reported for the adsorption of antibiotics onto lignocellulosic biomass-derived adsorbents, where the pseudo-second-order model frequently provides the best description of the adsorption process.

The intraparticle diffusion model (Figure 6(c)) produced an intermediate correlation coefficient (R^2 = 0.899), indicating that pore diffusion contributed to the adsorption process but was not the sole rate-limiting step. Furthermore, the intercept value (C = 6.33 mg g^{-1}) was greater than zero, suggesting the presence of boundary-layer effects and confirming that intraparticle diffusion was accompanied by external mass-transfer processes. Overall, the kinetic results

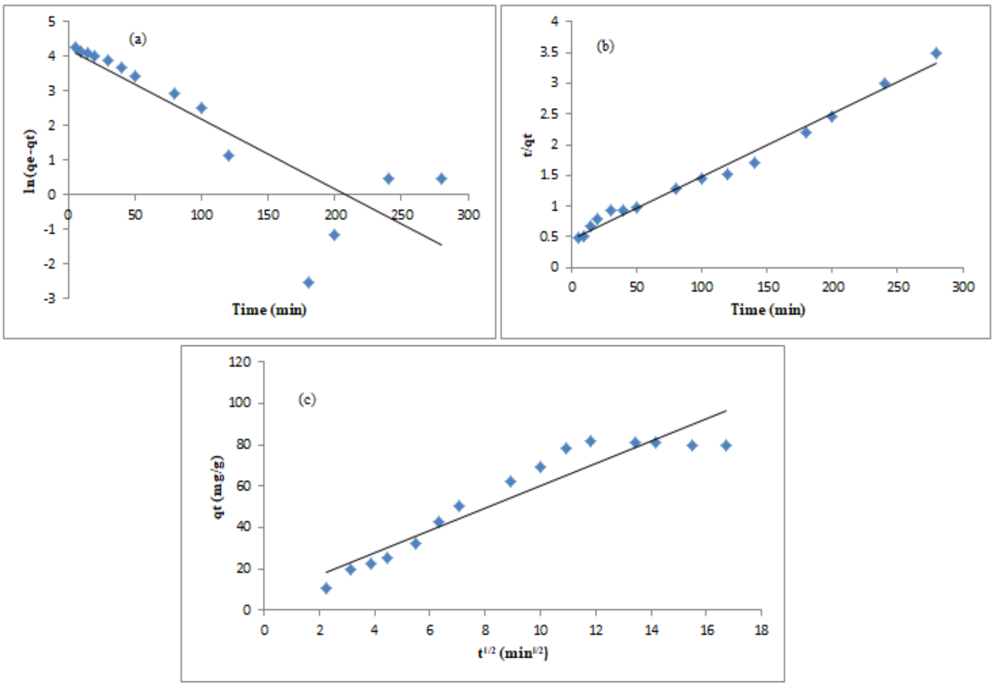

Figure 6: Linearized kinetic models for amoxicillin adsorption onto maize cob adsorbent: (a) pseudo-first-order, (b) pseudo-second-order, and (c) intraparticle diffusion plots.

Table 5: Kinetic Model Parameters for Amoxicillin Adsorption onto Maize Cob

Model	q_e(exp) (mg g^{-1})	q_e(calc) (mg g^{-1})	Rate Constant	R^2
Pseudo-first-order	81.42	67.97	$k_1 = 0.0203$ min^{-1}	0.724
Pseudo-second-order	81.42	83.33	$k_2 = 2.23 \times 10^{-4}$ g mg^{-1} min^{-1}	0.987
Intraparticle diffusion	–	–	$k\_id = 5.386$ mg g^{-1} $min^{-1/2}$ C = 6.327 mg g^{-1}	0.899

demonstrate that the adsorption of amoxicillin onto maize cob adsorbent is best described by the pseudo-second-order model, while both surface adsorption and intraparticle diffusion contribute to the overall adsorption mechanism.

3.8. Desorption and Reusability

The reusability of an adsorbent is a critical parameter in assessing the economic feasibility and practical applicability of an adsorption process. An effective adsorbent should maintain high adsorption performance over multiple adsorption–desorption cycles with minimal loss of efficiency. In the present study, the adsorption efficiency of maize cob adsorbent decreased slightly from 98.46% in the first cycle to 96.76% after the third cycle, while the desorption efficiency declined from 97.96% to 96.44% over the same period (Figure 7). The mean adsorption and desorption efficiencies were 97.72% and 97.34%, respectively.

The observed reductions correspond to adsorption and desorption losses of only 1.73% and 1.55%, respectively, after three consecutive cycles. The minimal decline in performance suggests that the adsorbent retained most of its active adsorption sites and structural integrity throughout the regeneration process. These findings demonstrate the excellent stability, regeneration capability, and reusability of the maize cob adsorbent, highlighting its potential for repeated application in the removal of amoxicillin from contaminated water. Similar retention of adsorption efficiency after successive regeneration cycles has been reported for biomass-derived adsorbents employed in the removal of pharmaceutical contaminants from aqueous media (Mosavi et al., 2023).

3.9. Suggested Mechanism of Amoxicillin Adsorption

Figure 8 showed the mechanism of adsorption of amoxicillin unto maize cobs adsorbent. The FTIR analysis revealed significant shifts in the O–H, C=O, N–H, and C–O absorption bands after adsorption, indicating the involvement of hydroxyl, carbonyl, and ether functional groups in the adsorption process. These spectral changes suggest the formation of hydrogen bonds and surface complexes between the functional groups of maize cob and the amoxicillin molecules.

The SEM micrographs further confirmed adsorption through the noticeable coverage of the adsorbent surface after amoxicillin uptake, indicating the

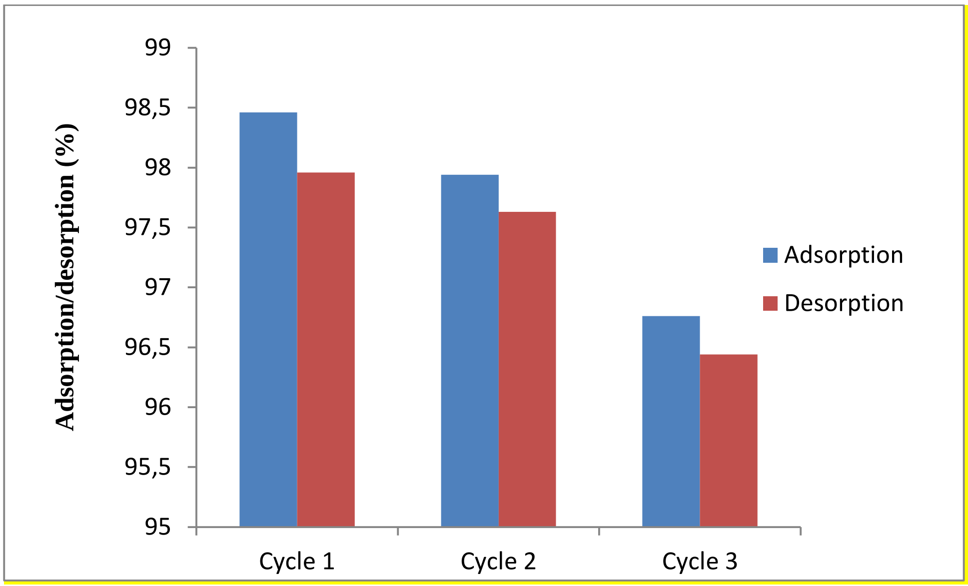

Figure 7: Adsorption and desorption efficiencies of maize cob adsorbent during successive regeneration cycles for amoxicillin removal.

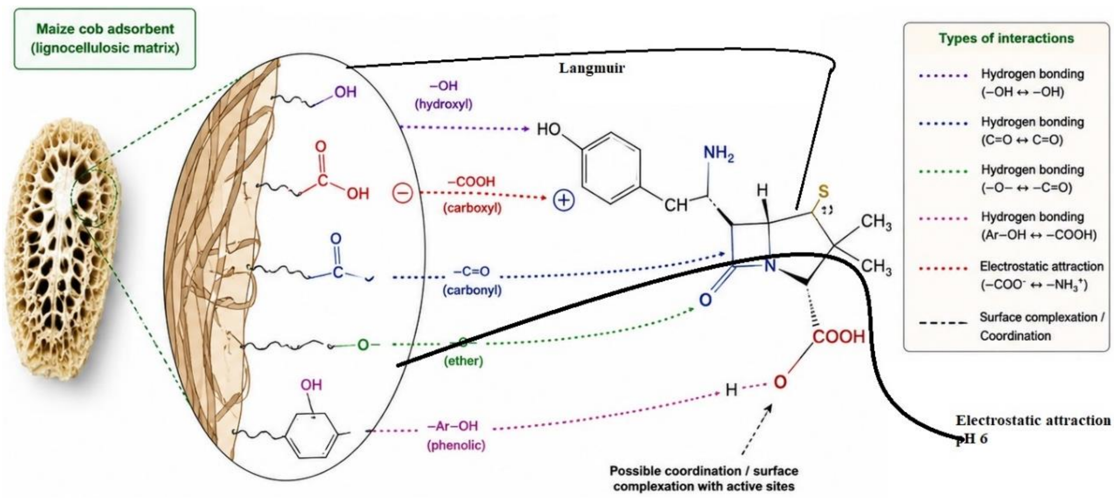

Figure 8: Proposed mechanism for the adsorption of amoxicillin onto maize cob adsorbent through hydrogen bonding, electrostatic interactions, and surface complexation involving hydroxyl, carbonyl, and ether functional groups present on the lignocellulosic matrix.

occupation of available adsorption sites. In addition, the adsorption kinetics were best described by the pseudo-second-order model (R^2 = 0.987), suggesting that surface interactions played a dominant role in controlling the adsorption process.

The equilibrium data were better fitted by the Langmuir isotherm model (R^2 = 0.913) than the Freundlich model (R^2 = 0.829), indicating that adsorption occurred predominantly through monolayer coverage on relatively homogeneous adsorption sites. The favourable Langmuir separation factor (RL = 0.158) and Freundlich intensity parameter (n = 1.64) further confirmed the strong affinity of amoxicillin for the maize cob surface.

Considering these findings, the adsorption of amoxicillin onto maize cobs is proposed to occur primarily through hydrogen bonding between the hydroxyl, amino, and carbonyl groups of amoxicillin and the oxygen-containing functional groups of the lignocellulosic matrix. Electrostatic attraction and surface complexation may also contribute to adsorption, particularly at the optimum pH of 6. The predominance of the Langmuir model suggests that these interactions result in the formation of a stable monolayer of amoxicillin molecules on the adsorbent surface.

4. Conclusion

This study demonstrated the potential of maize cob, an abundant agricultural waste, as an efficient and sustainable adsorbent for the removal of amoxicillin from aqueous solutions. Characterization studies revealed the presence of -OH, -CO, and R-O-R' functional groups on the adsorbent surface, while SEM analysis confirmed notable morphological changes after adsorption, indicating successful uptake of amoxicillin. The adsorption process was significantly influenced by operational parameters, with optimum conditions achieved at a maize cob dosage of 0.1 g, solution pH of 6, and a contact time of 150 min.

The adsorption kinetics were best described by the PSO model ($R^2 = 0.987$), suggesting that surface interactions played a dominant role in the adsorption process. Equilibrium data were more adequately fitted by the Langmuir isotherm model ($R^2 = 0.913$) than the Freundlich model ($R^2 = 0.829$), indicating favourable monolayer adsorption on relatively homogeneous adsorption sites, with a maximum adsorption capacity of 46.35 mg g^{-1}. The favourable Langmuir separation factor (RL = 0.158) and Freundlich intensity parameter (n = 1.64) further confirmed the strong affinity of amoxicillin for the maize cob surface.

Desorption and regeneration studies demonstrated excellent reusability of the adsorbent, with mean adsorption and desorption efficiencies of 97.72% and 97.34%, respectively, and only minimal losses in performance after three consecutive adsorption–desorption cycles.

This study highlight maize cob as a low-cost, environmentally benign, and reusable adsorbent with considerable potential for the remediation of amoxicillin-contaminated water.

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