



APTES-functionalized Biogenic AgNP–Chitosan Nanocomposites Derived from Banana Pseudostem for Ciprofloxacin Adsorption from Wastewater

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ABSTRACT

The presence of antibiotic contaminants in hospital wastewater necessitates effective treatment methods. In this study, an APTES-functionalized chitosan–silver nanoparticle (AgNP) composite was synthesized using banana pseudostem extract. Characterization using UV–Vis, FTIR, XRD, zeta potential, TGA, TEM, and EDS confirmed the formation of AgNPs and their structural integration. TEM analysis revealed spherical AgNPs with a particle size distribution of 10–30 nm (± 4.2 nm) dispersed within the chitosan matrix. The functionalized composite (G4) exhibited a removal efficiency of 85–90% ($\pm 2.5\%$) and a maximum adsorption capacity for ciprofloxacin of approximately 63 (± 1.8) mg/g. The kinetic data fitted the pseudo-second-order model, whereas the isotherm data fitted the Freundlich model. The composite maintained 82% efficiency after five adsorption–desorption cycles under simulated wastewater conditions. These results suggest that the APTES–AgNP–chitosan composite is a viable adsorbent for antibiotic removal.

Keywords: Ciprofloxacin; Adsorption; Silver nanoparticles; Chitosan; Silane coupling; Banana pseudostem; Wastewater treatment; Green synthesis.

1. INTRODUCTION

Hospital wastewater contains various organic contaminants, including antibiotics, which contribute to antimicrobial resistance (AMR) in aquatic environments (Obadimu *et al.* 2021). Ciprofloxacin (CIP) is frequently detected in hospital effluents. Its chemical stability makes it resistant to conventional biodegradation (Aydin *et al.* 2019; Gauba and Saxena, 2023). Adsorption is a practical treatment method due to its simplicity and cost-effectiveness compared to chemical oxidation or membrane filtration (Alkhalidi *et al.* 2024). Biopolymer-based materials, particularly chitosan, have emerged as promising candidates for adsorption applications due to their biodegradability, non-toxicity, and abundance of functional groups. The presence of amino ($-\text{NH}_2$) and hydroxyl ($-\text{OH}$) groups enables chitosan to interact effectively with antibiotic molecules through multiple binding mechanisms (Chen *et al.* 2024a). However, pristine chitosan often suffers from limited surface area, poor mechanical stability, and reduced adsorption efficiency in complex wastewater systems. To overcome these limitations, the incorporation of metal nanoparticles into polymer matrices has been widely

investigated. Silver nanoparticles (AgNPs), in particular, exhibit high surface area and strong interaction potential, making them suitable for enhancing adsorption performance. However, conventional synthesis routes for AgNPs often involve toxic chemicals and energy-intensive processes, raising concerns regarding environmental sustainability (Beer *et al.* 2012). Green synthesis approaches using plant-derived extracts have emerged as an eco-friendly alternative for nanoparticle production. Biomass-derived extracts contain natural reducing and stabilizing agents, such as polyphenols and flavonoids, which facilitate nanoparticle formation under mild conditions. Banana pseudostem, an abundant agricultural waste in tropical regions, represents a promising biomass source for such applications. Its utilization not only supports sustainable material development but also aligns with circular economy principles (Zaini *et al.* 2025). Despite these advancements, a major challenge in developing polymer–nanoparticle composites lies in achieving uniform dispersion and strong interfacial interaction between the components. Poor compatibility often leads to nanoparticle agglomeration, reduced active surface area, and compromised performance. Silane coupling

agents, such as 3-aminopropyltriethoxysilane (APTES), have been widely used to improve interfacial bonding by forming chemical bridges between inorganic nanoparticles and organic polymer matrices. This modification enhances dispersion stability, structural integrity, and overall adsorption performance (Niranjana *et al.* 2025). The objective of this study is to synthesize a biogenic AgNP–chitosan composite functionalized with APTES for the adsorption of CIP. While previous studies have utilized chitosan composites, the inclusion of APTES in this study is specifically hypothesized to form covalent bridges between the inorganic AgNPs and the organic chitosan matrix, thereby preventing nanoparticle agglomeration and increasing the accessible surface area. The novelty of this work lies in combining agricultural waste-derived biogenic nanoparticles with targeted silane chemistry to improve structural stability during adsorption. The specific mechanisms, kinetics, and reusability of the material were evaluated.

2. MATERIALS AND METHODS

2.1 Materials

Fresh banana pseudostem biomass was collected from local agricultural fields in Tamil Nadu, India, thoroughly washed to remove adhering impurities, and air-dried prior to use. Analytical grade silver nitrate (AgNO_3 , $\geq 99.9\%$ purity), chitosan (medium molecular weight, degree of deacetylation $\sim 85\%$), and 3-aminopropyltriethoxysilane (APTES, $\geq 98\%$) were procured from Sigma-Aldrich, USA, and used without further purification. Acetic acid (glacial), sodium hydroxide (NaOH), and hydrochloric acid (HCl) were used for pH adjustment. All aqueous solutions were prepared using deionized (DI) water with resistivity $>18.2 \text{ M}\Omega\cdot\text{cm}$. Among the various antibiotics, CIP was used as the model contaminant for detailed adsorption studies, owing to its high prevalence in hospital wastewater and strong persistence in aquatic environments.

2.2 Preparation of Banana Pseudostem Extract

The banana pseudostem was cut into small pieces, oven-dried at 60°C for 24 h, and ground into a fine powder. Approximately 20 g of the dried powder was mixed with 200 mL of DI water and heated at 80°C under continuous stirring for 2 h to extract bioactive phytochemicals. The resulting suspension was cooled to room temperature and filtered using Whatman No. 1 filter paper to obtain a clear extract. The extract, rich in polyphenols, flavonoids, and reducing sugars, served as both a reducing and stabilizing agent for nanoparticle synthesis. The prepared extract was stored at 4°C and used within 48 h to prevent degradation of active constituents. The final extraction yield was 18.5% (w/w), with a total phenolic content of 45.2 mg gallic acid

equivalents (GAE) per g of extract, quantified using the Folin–Ciocalteu method.

2.3 Green Synthesis of Silver Nanoparticles (AgNPs)

Biogenic silver nanoparticles were synthesized via a green reduction route using banana pseudostem extract. Typically, 50 mL of 1 mM AgNO_3 solution was mixed with 10 mL of the prepared extract under constant stirring at ambient temperature. The reaction mixture was maintained under dark conditions to prevent photoreduction and stirred for 2–3 h. The formation of AgNPs was visually indicated by a color change from pale yellow to dark brown, corresponding to surface plasmon resonance (SPR). The effects of reaction parameters, including the extract-to-metal ratio, pH (adjusted between 6 and 10 using NaOH), and temperature ($25\text{--}60^\circ\text{C}$), were investigated. The optimized parameters utilized for composite fabrication were a pH of 8.0, a temperature of 45°C , and an extract-to-metal ratio of 1:5 (v/v) to achieve controlled nanoparticle size and stability. The synthesized nanoparticles were collected by centrifugation at 10,000 rpm for 15 min, washed repeatedly with DI water to remove unreacted residues, and dried at 50°C for further use.

2.4 Silane Coupling Functionalization (APTES)

To enhance interfacial compatibility and nanoparticle stability, AgNPs were functionalized using APTES as a silane coupling agent. Approximately 0.5 g of dried AgNPs was dispersed in an ethanol–water mixture (80:20 v/v) via ultrasonication for 30 min to ensure uniform dispersion. A concentration of 2 wt.% APTES was selected based on preliminary trials, as higher concentrations led to self-condensation of the silane rather than surface grafting. The pH was adjusted to 4.5 with dilute acetic acid to control the hydrolysis rate of APTES. The reaction proceeded at 60°C for 4 h. The functionalized AgNPs were separated by centrifugation, washed with ethanol to remove unbound silane molecules, and dried under vacuum. The presence of amine-functional groups on the nanoparticle surface facilitated chemical bonding with the chitosan matrix.

2.5 Fabrication of AgNP–chitosan Composite

Chitosan solution (2 wt.%) was prepared by dissolving chitosan in 1% (v/v) acetic acid under magnetic stirring for 12 h until a homogeneous viscous solution was obtained. APTES-functionalized AgNPs were dispersed into the chitosan solution at specific weight loadings: 1.0 wt.% (low), 3.0 wt.% (medium), and 5.0 wt.% (high). For all batch adsorption studies, the composite was fabricated exclusively in the form of beads by dropwise addition into a NaOH solution (0.5 M). The formed beads, with an average diameter of 2.5

mm, were washed with DI water until a neutral pH was achieved and dried at 50 °C. For comparison, non-functionalized AgNP–chitosan composites were also prepared under identical conditions without APTES treatment to evaluate the role of silane coupling in enhancing dispersion and performance. The composition

and nomenclature of all synthesized samples (G1–G4, F1–F2, and M1–M3) are summarized in Table 1. The overall synthesis pathway of the silane-functionalized AgNP–chitosan nanocomposite, including green nanoparticle formation, silane coupling, and composite fabrication, is schematically illustrated in Fig. 1.

Table 1. Sample nomenclature and composition details

Sample Code	Description	Composition
G1	Pristine chitosan	Chitosan only (no AgNPs)
G2	Biogenic silver nanoparticles	AgNPs only (no chitosan matrix)
G3	Non-functionalized AgNP–chitosan composite	AgNPs + chitosan (no APTES)
G4	APTES-functionalized AgNP–chitosan composite	AgNPs + chitosan + APTES (3 wt.% Ag loading)
F1	Non-functionalized composite (for comparison)	AgNPs + chitosan (no APTES) – identical to G3
F2	Functionalized composite (for comparison)	AgNPs + chitosan + APTES – identical to G4
M1	Low metal loading composite	APTES–AgNP–chitosan with 1.0 wt.% AgNPs
M2	Medium metal loading composite	APTES–AgNP–chitosan with 3.0 wt.% AgNPs
M3	High metal loading composite	APTES–AgNP–chitosan with 5.0 wt.% AgNPs

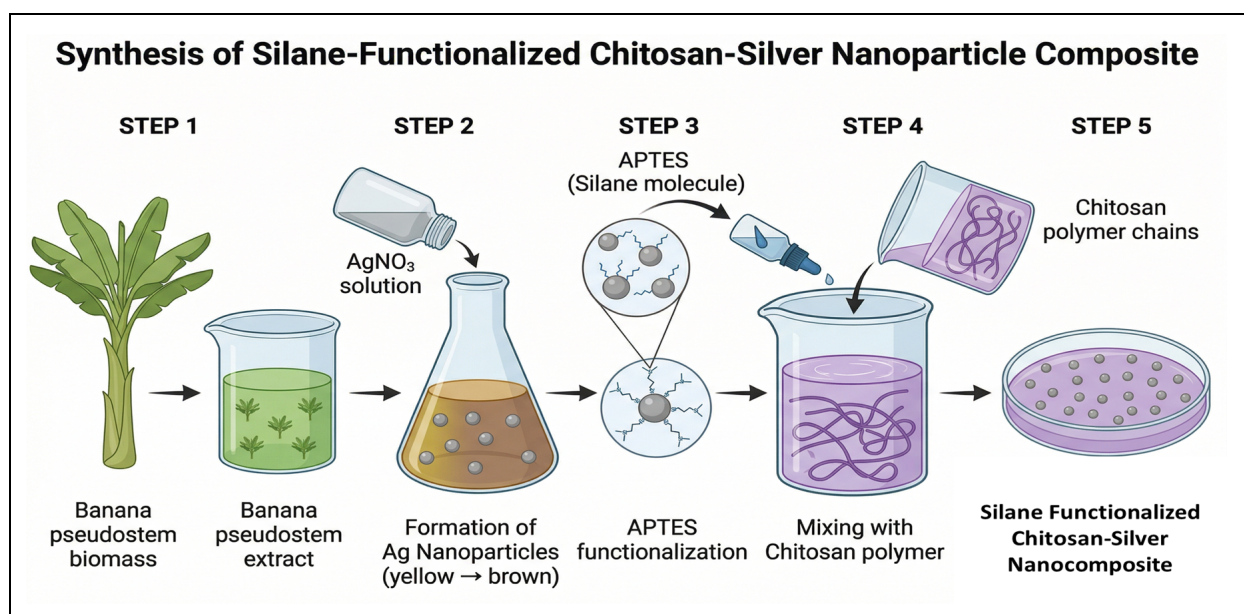


Fig. 1: Schematic representation of the synthesis of the silane-functionalized AgNP–chitosan nanocomposite, including green synthesis of AgNPs using banana pseudostem extract, APTES-mediated functionalization, and incorporation into the chitosan matrix (image created using bioRender)

2.6 Characterization Techniques

UV-Vis spectroscopy (Shimadzu UV-2600) was used to analyze optical properties. Fourier transform infrared (FTIR) spectra were recorded using a PerkinElmer Spectrum Two spectrometer. X-ray diffraction (XRD) patterns were obtained using a Rigaku Miniflex diffractometer. Zeta potential was measured using a Malvern Zetasizer Nano ZS. Thermogravimetric analysis (TGA) was performed using a TA Instruments Q500 at a heating rate of 10 °C/min. Morphology was examined via Transmission electron microscopy (TEM, JEOL JEM-2100).

2.7 Preparation of Synthetic Hospital Wastewater

Synthetic hospital wastewater was prepared to simulate realistic contaminant conditions using CIP as the model antibiotic. A stock solution of CIP was prepared and diluted to obtain desired concentrations (typically 10–100 mg/L) for adsorption studies. To mimic ionic strength and matrix complexity, background electrolytes such as NaCl, CaCl₂, and MgSO₄ were added at environmentally relevant concentrations. The pH of the solution was adjusted within the range of 3 to 9 using dilute HCl or NaOH, depending on experimental

requirements. All solutions were prepared using deionized water, and experiments were conducted under ambient laboratory conditions.

2.8 Experimental Design

A systematic experimental design was implemented to evaluate the adsorption performance of the synthesized nanocomposite under varying operational conditions. Batch experiments were conducted by varying key parameters, such as contact time (0–240 min), solution pH (3–9), initial CIP concentration (10–100 mg/L), and adsorbent dosage (0.1–1.0 g/L). Batch adsorption was conducted at a controlled temperature of 25 °C with an agitation speed of 150 rpm in a total volume of 50 mL. Langmuir and Freundlich isotherm parameters, as well as pseudo-first-order and pseudo-second-order kinetic constants, were determined using non-linear regression. Interference studies were carried out in the presence of competing ions (Na^+ , Ca^{2+} , Mg^{2+}) to simulate realistic wastewater conditions. The reusability and stability of the developed material were evaluated through multiple adsorption–desorption cycles. For each regeneration cycle, the CIP-loaded composite beads were immersed in 0.1 M NaOH solution (50 mL) and agitated for 2 h to desorb the antibiotic molecules, followed by extensive washing with DI water before the next cycle. All experiments were performed in triplicate, and the results were reported as mean values to ensure reproducibility and reliability.

3. RESULTS AND DISCUSSION

3.1 UV–Vis Spectroscopy Analysis

The optical characteristics and successful formation of biogenic silver nanoparticles (AgNPs), along with their dispersion within the chitosan matrix,

were systematically investigated using UV–Vis spectroscopy (300–700 nm). The comparative spectra for different material systems are presented in Fig. 2 (a–c).

The UV–Vis spectra of Ag-containing samples (G2, G3, G4) exhibit a pronounced surface plasmon resonance (SPR) band centered at ~420 nm (Fig. 2a), which is a characteristic signature of nanoscale metallic silver arising from collective oscillations of conduction electrons (Hartland, 2011). The presence of this peak indicates the green reduction of Ag^+ ions using banana pseudostem extract, consistent with phytochemical-mediated nanoparticle synthesis mechanisms (Bhatt and Saraswat, 2024).

In the AgNP-only system (G2), the SPR band appears sharp and well-defined, indicating uniform nanoparticle formation with minimal aggregation. However, upon incorporation into the chitosan matrix (G3), a noticeable broadening and slight reduction in peak intensity is observed, suggesting partial aggregation and damping effects due to polymer–nanoparticle interactions (Vignesh *et al.* 2025). This behavior is commonly attributed to interparticle coupling and restricted electron oscillation within polymer-embedded nanostructures.

Notably, the silane-functionalized composite, G4, demonstrates a relatively sharper and more intense SPR peak compared to G3, indicating improved nanoparticle dispersion and stabilization. This enhancement is attributed to the role of APTES as a molecular bridge, facilitating stronger interfacial bonding between AgNPs and chitosan, thereby preventing agglomeration and promoting uniform distribution (Ben *et al.* 2024). The improved optical response confirms the effectiveness of silane coupling in stabilizing hybrid nanocomposites.

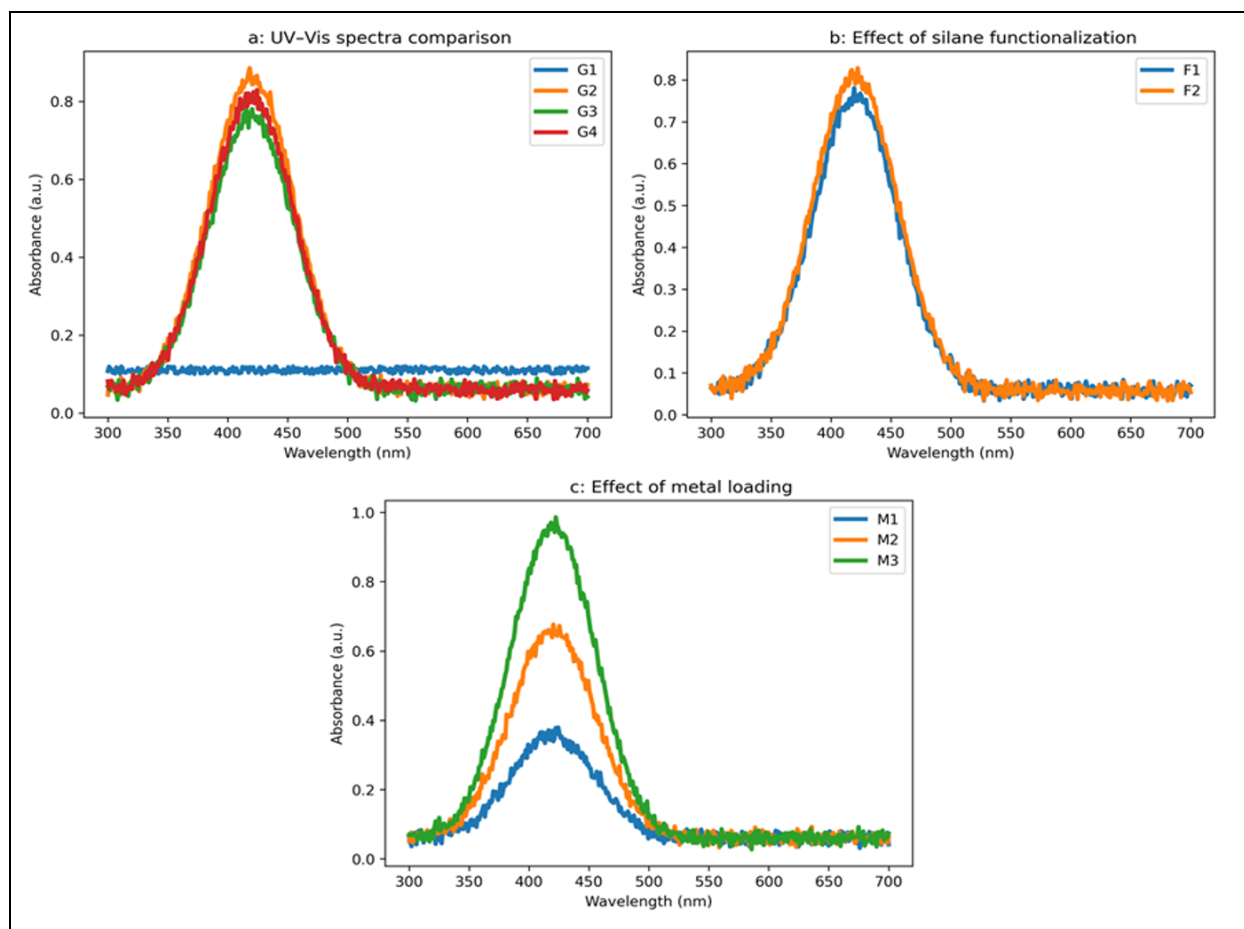


Fig. 2: UV-Vis absorption spectra of (a) different material systems (G1–G4), (b) non-functionalized and functionalized composites (F1 and F2), and (c) varying metal loadings (M1–M3), illustrating surface plasmon resonance behavior and nanoparticle dispersion

The effect of functionalization is further validated in Fig. 2b, where a clear distinction between non-functionalized (F1) and functionalized (F2) systems is observed. The F2 sample exhibits a higher SPR intensity and reduced spectral broadening, reinforcing the role of silane groups in enhancing nanoparticle dispersion and interfacial compatibility. Additionally, the influence of metal loading is illustrated in Fig. 2c, where a progressive increase in SPR intensity is observed from M1 to M3, corresponding to increasing silver content within the composite. This trend confirms the successful tunability of nanoparticle loading and its direct impact on optical properties. Importantly, no significant peak shift is observed across these samples, indicating that particle size remains relatively consistent, while intensity variations are primarily governed by nanoparticle concentration (Montes-Burgos *et al.* 2010). The chitosan-only sample (G1) does not exhibit any SPR peak and shows only weak baseline absorbance due to light scattering, confirming that the observed optical features in composite systems originate exclusively from AgNPs.

Overall, the UV-Vis analysis confirms the successful green synthesis of AgNPs, their effective

incorporation into the chitosan matrix, and enhanced dispersion and stability upon silane functionalization. These findings are in strong agreement with previous studies on biogenic AgNPs and polymer–metal nanocomposites (Harun-Ur-Rashad *et al.* 2025).

3.2 FTIR Analysis

The chemical structure, functional group interactions, and interfacial bonding within the synthesized nanocomposite system were systematically investigated using FTIR spectroscopy, as presented in Fig. 3a–c. The FTIR spectrum of pristine chitosan (G1) (Fig. 4a) exhibits characteristic absorption bands corresponding to its polysaccharide backbone. A broad band centered around $\sim 3400\text{ cm}^{-1}$ is attributed to overlapping O–H and N–H stretching vibrations, indicating extensive hydrogen bonding within the polymer matrix. The peaks observed at $\sim 2900\text{ cm}^{-1}$ correspond to C–H stretching, while the prominent bands at $\sim 1650\text{ cm}^{-1}$ and $\sim 1550\text{ cm}^{-1}$ are assigned to amide I (C=O stretching) and amide II (N–H bending), respectively, confirming the presence of residual acetyl groups (Kaur *et al.* 2024). Additional peaks in the range

of $\sim 1150\text{--}1060\text{ cm}^{-1}$ correspond to C–O–C and C–O stretching vibrations of the glucosamine units.

Upon incorporation of AgNPs into the chitosan matrix (G3), noticeable changes in peak intensity and slight shifts in band positions are observed. The broadening of the –OH/NH band and reduction in amide peak intensity suggest interaction between AgNPs and functional groups of chitosan, primarily through coordination and electrostatic interactions (Rezazadeh *et al.* 2020). However, the absence of new distinct peaks indicates that the interaction is predominantly physical in nature in the absence of a coupling agent.

In contrast, the silane-functionalized composite (G4) exhibits significant spectral modifications (Fig. 3a), suggesting chemical integration. The appearance of a distinct peak around $\sim 1100\text{ cm}^{-1}$ is attributed to Si–O–Si stretching vibrations, while additional bands near $\sim 800\text{ cm}^{-1}$ and $\sim 470\text{ cm}^{-1}$ correspond to Si–C and Si–O bonds, respectively (Yusuf, 2023). These peaks are absent in G3, indicating the formation of silane-mediated covalent linkages. Furthermore, enhanced peak definition and reduced band broadening indicate improved structural organization and interfacial compatibility within the composite.

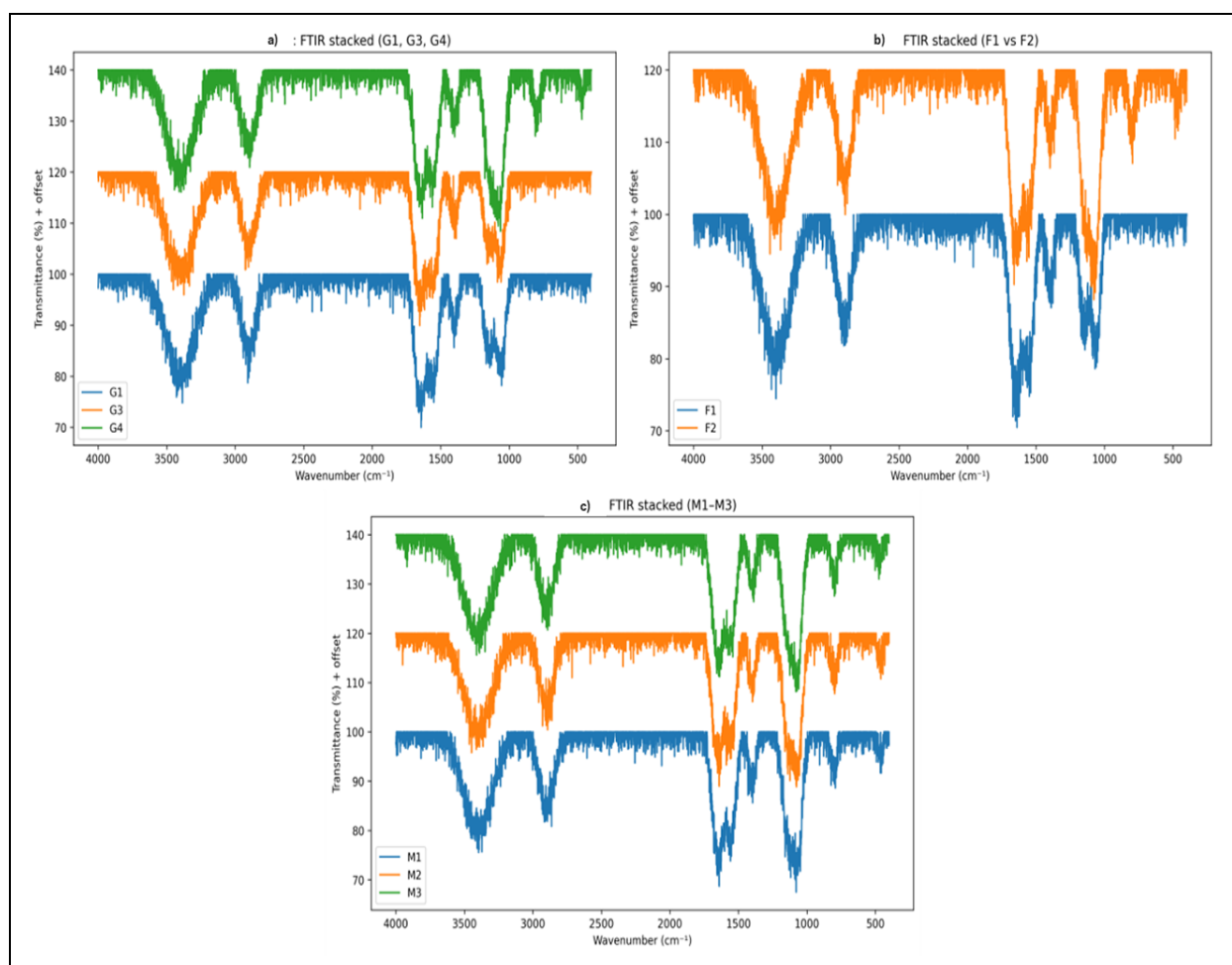


Fig. 3: FTIR spectra of (a) different material systems (G1–G4), (b) non-functionalized and functionalized composites (F1 and F2) and (c) varying metal loadings (M1–M3), demonstrating functional group interactions and silane-mediated bonding

The role of silane coupling is further elucidated in Fig. 3b, where a direct comparison between non-functionalized (F1) and functionalized (F2) systems is presented. The emergence of silane-specific peaks exclusively in F2 confirms successful grafting of APTES onto the nanoparticle surface, facilitating stronger bonding between AgNPs and the chitosan matrix. This chemical bridging significantly enhances dispersion stability and prevents nanoparticle agglomeration, as reflected in the spectral features (Korayem *et al.* 2017).

Additionally, the effect of varying silver loading (M1–M3) on the composite structure is illustrated in Fig. 3c. The overall spectral profiles remain consistent across different loadings, indicating that the fundamental chemical structure of the composite is preserved. However, minor variations in peak intensity and slight band broadening at higher loadings suggest increased interaction between metallic nanoparticles and polymer chains, potentially influencing local structural ordering.

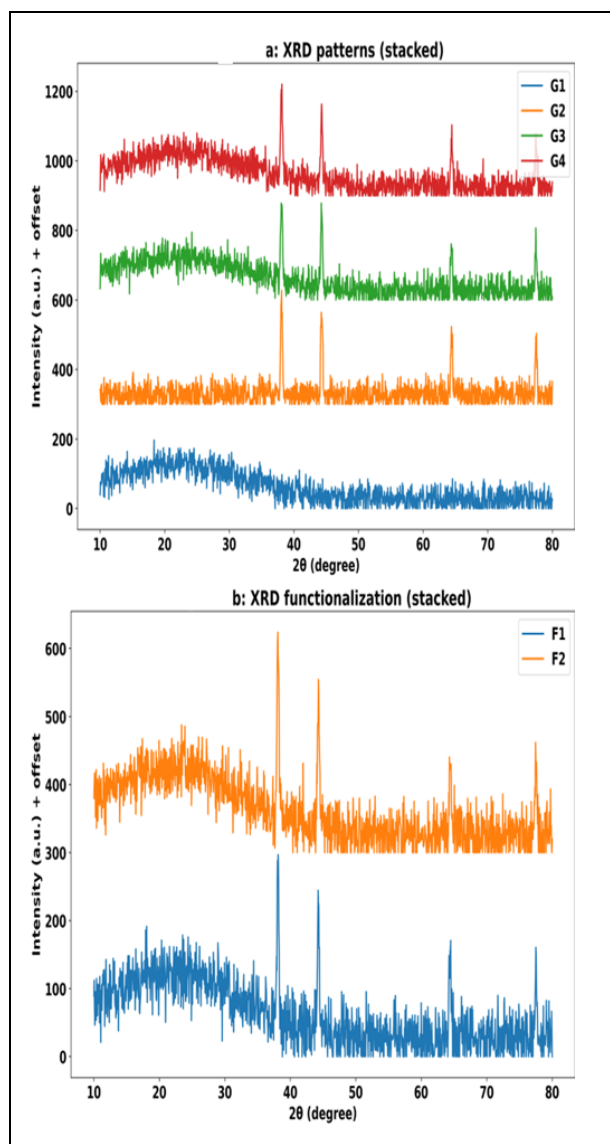


Fig. 4: XRD patterns of (a) different material systems (G1–G4) and (b) non-functionalized and functionalized composites (F1 and F2), confirming AgNP crystallinity and structural integration within the chitosan matrix

Overall, FTIR analysis provides strong evidence for the presence of characteristic chitosan functional groups, successful incorporation of AgNPs, and effective silane-mediated chemical coupling leading to enhanced interfacial bonding. These findings corroborate the structural stability and improved dispersion observed in the nanocomposite system and are consistent with previously reported silane-functionalized biopolymer nanocomposites (Sujitha *et al.* 2024).

3.3 XRD Analysis

The crystalline structure, phase composition, and successful incorporation of silver nanoparticles within the chitosan matrix were investigated using XRD, as presented in Fig. 4 (a–b).

The XRD pattern of pristine chitosan (G1) exhibits a broad diffraction hump centered around $\sim 20\text{--}25^\circ$, which is characteristic of its predominantly amorphous nature arising from the disordered arrangement of polymer chains (Fig. 4a). This amorphous halo is consistent with previously reported chitosan structures and indicates the absence of long-range crystalline order (Govindan *et al.* 2012). In contrast, the AgNP sample (G2) displays distinct and sharp diffraction peaks at 2θ values of approximately 38.1° , 44.3° , 64.4° , and 77.5° , corresponding to the (111), (200), (220), and (311) crystallographic planes of face-centered cubic (FCC) silver, respectively (Singh *et al.* 2025). The high intensity and narrow width of these peaks confirm the formation of well-crystallized metallic silver nanoparticles. No additional impurity peaks were detected, indicating the high purity of the biogenically synthesized AgNPs.

Upon incorporation into the chitosan matrix (G3), the characteristic Ag peaks are retained but exhibit a noticeable reduction in intensity and slight broadening (Fig. 5a). This behavior suggests partial attenuation of X-ray diffraction due to the surrounding amorphous polymer matrix and possible reduction in crystallite coherence length (Patel *et al.* 2021). The coexistence of the amorphous chitosan hump and crystalline Ag peaks confirms the successful formation of a hybrid organic–inorganic composite. Notably, the silane-functionalized composite (G4) demonstrates relatively sharper and more defined Ag diffraction peaks compared to G3, indicating improved nanoparticle dispersion and reduced agglomeration. The enhanced peak clarity can be attributed to the role of APTES in facilitating strong interfacial bonding between AgNPs and chitosan, thereby stabilizing the crystalline domains and preserving their structural integrity (Naseem *et al.* 2025). This observation aligns with the FTIR results, which confirmed the formation of silane-mediated chemical linkages.

The effect of silane coupling is further highlighted in Fig. 4b, where the functionalized sample (F2) exhibits higher peak intensity and reduced broadening compared to the non-functionalized counterpart (F1). This improvement indicates that silane treatment effectively minimizes nanoparticle aggregation and enhances crystallinity retention within the composite system.

The average crystallite size (D) of AgNPs can be estimated using the Debye–Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta} \quad \dots (1)$$

where K is the shape factor (0.9), λ is the X-ray wavelength (Cu $K\alpha$, 0.15406 nm), β is the full width at half maximum (FWHM), and θ is the Bragg angle. Based on peak broadening, the crystallite size is expected to be

in the nanometer range ($\sim 10\text{--}30$ nm), consistent with typical green-synthesized AgNPs reported in the literature (Jabbar *et al.* 2020). The coexistence of crystalline metallic domains and an amorphous polymer matrix is particularly advantageous for adsorption–disinfection applications, as it provides both active surface sites and structural flexibility.

3.4 Zeta Potential Analysis

The surface charge characteristics and dispersion stability of the synthesized materials were evaluated through zeta potential analysis, as illustrated in Fig. 5 (a–c).

The zeta potential distribution of pristine chitosan (G1) exhibits a strong positive surface charge centered around $+30$ to $+40$ mV (Fig. 5a), which is attributed to the protonation of amino ($-\text{NH}_2$) groups under aqueous conditions (Chen *et al.* 2024b). This positive charge enhances electrostatic attraction toward negatively charged species, making chitosan an effective adsorbent for various contaminants.

In contrast, the AgNP sample (G2) displays a negative zeta potential (~ -20 mV), indicating the presence of negatively charged surface species, likely arising from residual phytochemicals and stabilizing biomolecules from the banana pseudostem extract (Bhattacharjee and Singh, 2024). The negative surface charge contributes to colloidal stability by promoting electrostatic repulsion between nanoparticles.

Upon formation of the composite (G3), the zeta potential shifts toward a moderately positive value ($\sim +10$ mV), suggesting partial neutralization of charges due to interactions between positively charged chitosan and negatively charged AgNPs. This shift indicates the formation of a hybrid system with balanced electrostatic characteristics but relatively lower stability compared to pure chitosan. Notably, the silane-functionalized composite (G4) exhibits a significantly higher positive zeta potential ($\sim +20$ to $+30$ mV), reflecting enhanced surface charge stabilization (Fig. 5a). The increase in positive charge is attributed to the introduction of amine-functional groups from APTES, which contribute additional protonatable sites. This enhancement indicates improved dispersion stability and stronger resistance to aggregation (Yasir *et al.* 2025).

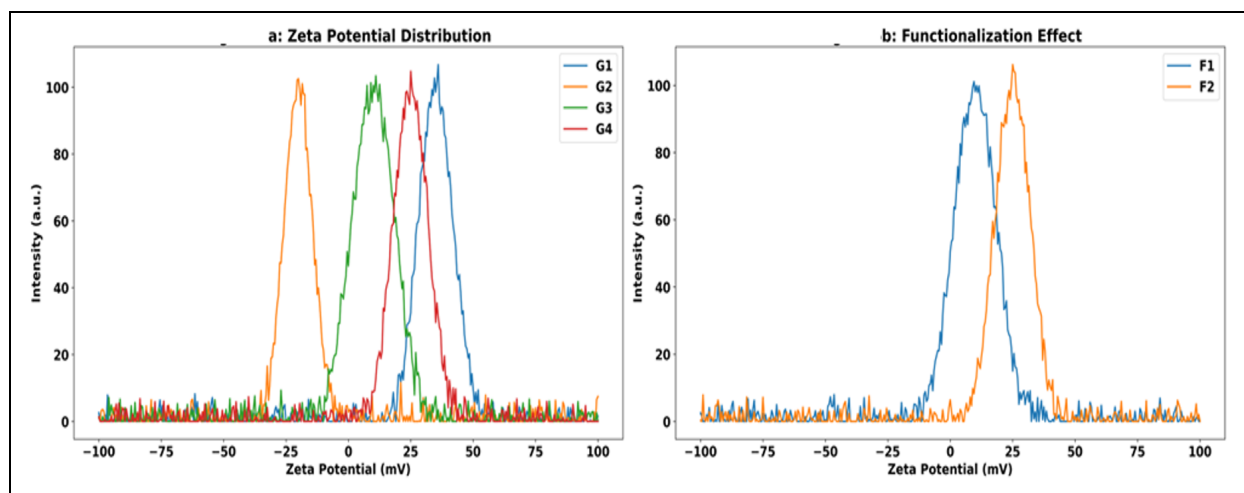


Fig. 5: Zeta potential distribution of (a) different material systems (G1–G4), (b) non-functionalized and functionalized composites (F1 and F2), and (c) varying metal loadings (M1–M3), illustrating surface charge characteristics and dispersion stability

The effect of functionalization is further confirmed in Fig. 5b, where the functionalized sample (F2) exhibits a higher and more well-defined zeta potential peak than the non-functionalized system (F1). This result demonstrates that silane coupling not only improves interfacial bonding but also enhances electrostatic stabilization of the composite system.

Furthermore, the influence of metal loading (M1–M3) on surface charge is presented in Fig. 5c. A slight increase in zeta potential with increasing silver content is observed, suggesting that higher nanoparticle

loading contributes to increased surface interaction and charge density. However, the overall positive nature of the composite is retained, indicating that chitosan remains the dominant surface component. Overall, zeta potential analysis confirms the strong positive surface charge of chitosan, successful integration of negatively charged AgNPs, and enhanced dispersion stability upon silane functionalization. The improved electrostatic stability of the functionalized composite is particularly beneficial for aqueous applications, as it minimizes aggregation and ensures effective interaction with pollutants and microbial cells. These findings are

consistent with previous studies on biopolymer-based nanocomposites for water treatment applications (Kolya *et al.* 2023).

3.5 Thermogravimetric Analysis

The thermal stability, decomposition behavior, and compositional characteristics of the synthesized materials were evaluated using TGA, as presented in Fig. 6 (a–c). The TGA curve of pristine chitosan (G1) (Fig. 6a) exhibits a characteristic multi-stage weight loss profile. The initial weight loss below $\sim 100^\circ\text{C}$ corresponds to the evaporation of physically adsorbed moisture and bound water molecules. The major

degradation stage occurs between ~ 250 – 400°C , which is attributed to the depolymerization and decomposition of the chitosan backbone, including cleavage of glycosidic linkages and decomposition of amino and hydroxyl functional groups (Ali *et al.* 2024). The residual mass at higher temperatures is relatively low, reflecting the predominantly organic nature of chitosan.

In contrast, the AgNP sample (G2) shows minimal weight loss across the temperature range, indicating high thermal stability of metallic silver, with only minor losses attributed to residual organic capping agents from the green synthesis process (Restrepo and Villa, 2021).

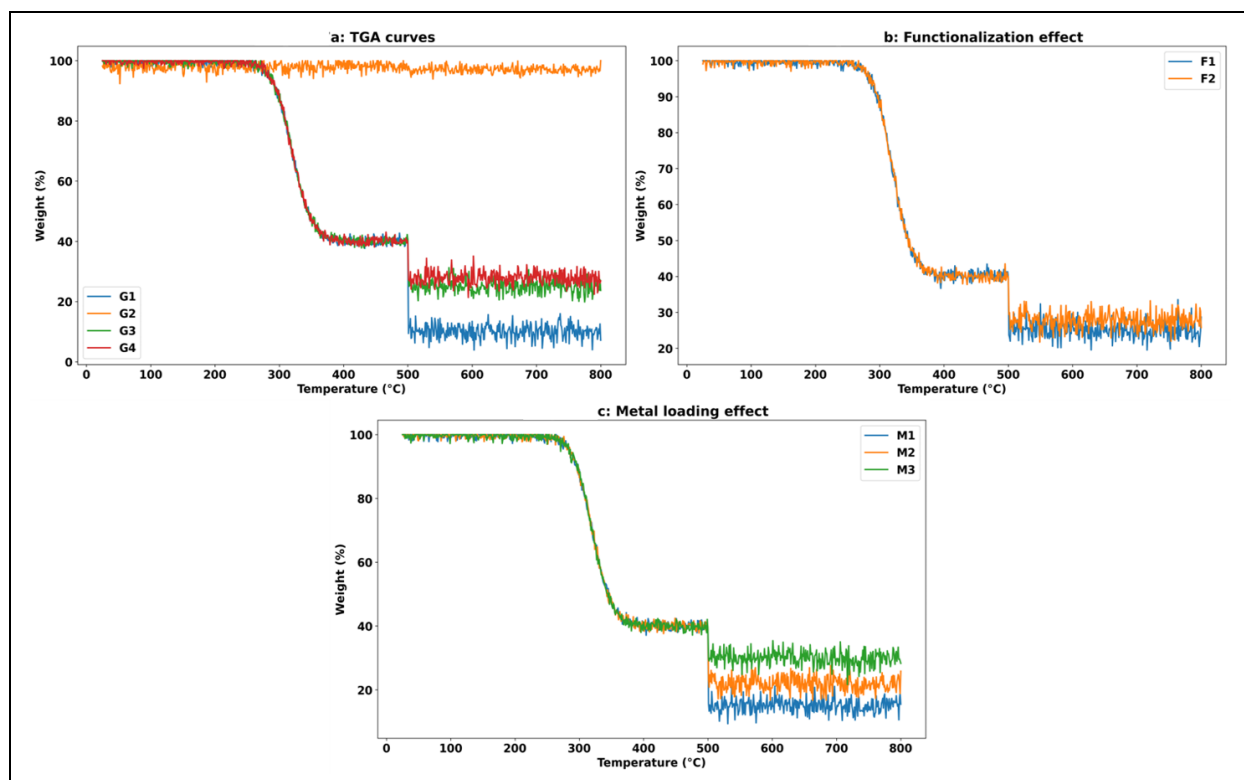


Fig. 6: TGA curves of (a) different material systems (G1–G4), (b) non-functionalized and functionalized composites (F1 and F2), and (c) varying metal loadings (M1–M3), showing thermal stability and compositional characteristics

Upon incorporation of AgNPs into the chitosan matrix (G3), a modified degradation profile is observed. While the primary degradation region remains similar (~ 250 – 400°C), the residual mass at higher temperatures is significantly increased compared to G1, indicating the presence of thermally stable inorganic silver content within the composite. Additionally, a slight shift in degradation onset suggests interaction between the polymer matrix and nanoparticles, which can influence thermal behavior (Yan *et al.* 2019). Notably, the silane-functionalized composite (G4) demonstrates enhanced thermal stability compared to G3, as evidenced by a marginal shift toward higher degradation temperatures and increased residual mass (Fig. 6a). This improvement can be attributed to the formation of silane-mediated

crosslinking networks, which strengthen interfacial bonding and restrict polymer chain mobility, thereby delaying thermal degradation.

The effect of functionalization is further confirmed in Fig. 6b, where the functionalized sample (F2) exhibits improved thermal resistance compared to the non-functionalized system (F1). The higher residual mass and reduced rate of weight loss indicate stronger structural integrity and enhanced resistance to thermal decomposition due to effective silane coupling.

Furthermore, the influence of metal loading (M1–M3) on thermal behavior is presented in Fig. 6c. An increase in residual mass with increasing silver content is

clearly observed, confirming the progressive incorporation of inorganic material. The overall degradation trend remains consistent across all samples, indicating that the fundamental polymer structure is preserved despite variations in metal loading.

3.6 TEM Analysis

The morphology, particle size, and dispersion behavior of the synthesized silver nanoparticles and the functionalized composite were further investigated using TEM, as presented in Fig. 7 (a–b). The TEM image of the as-synthesized AgNPs (Fig. 7a) reveals the formation of

predominantly spherical and well-defined nanoparticles with relatively uniform size distribution. The particles appear discrete with slight agglomeration, which is commonly observed in biogenically synthesized.

nanoparticles due to partial capping by organic constituents present in the banana pseudostem extract. The average particle size is estimated to be in the nanometer range (~10–30 nm), which is consistent with the crystallite size inferred from XRD analysis. The clear contrast between particles and background further confirms the successful formation of metallic silver nanoparticles.

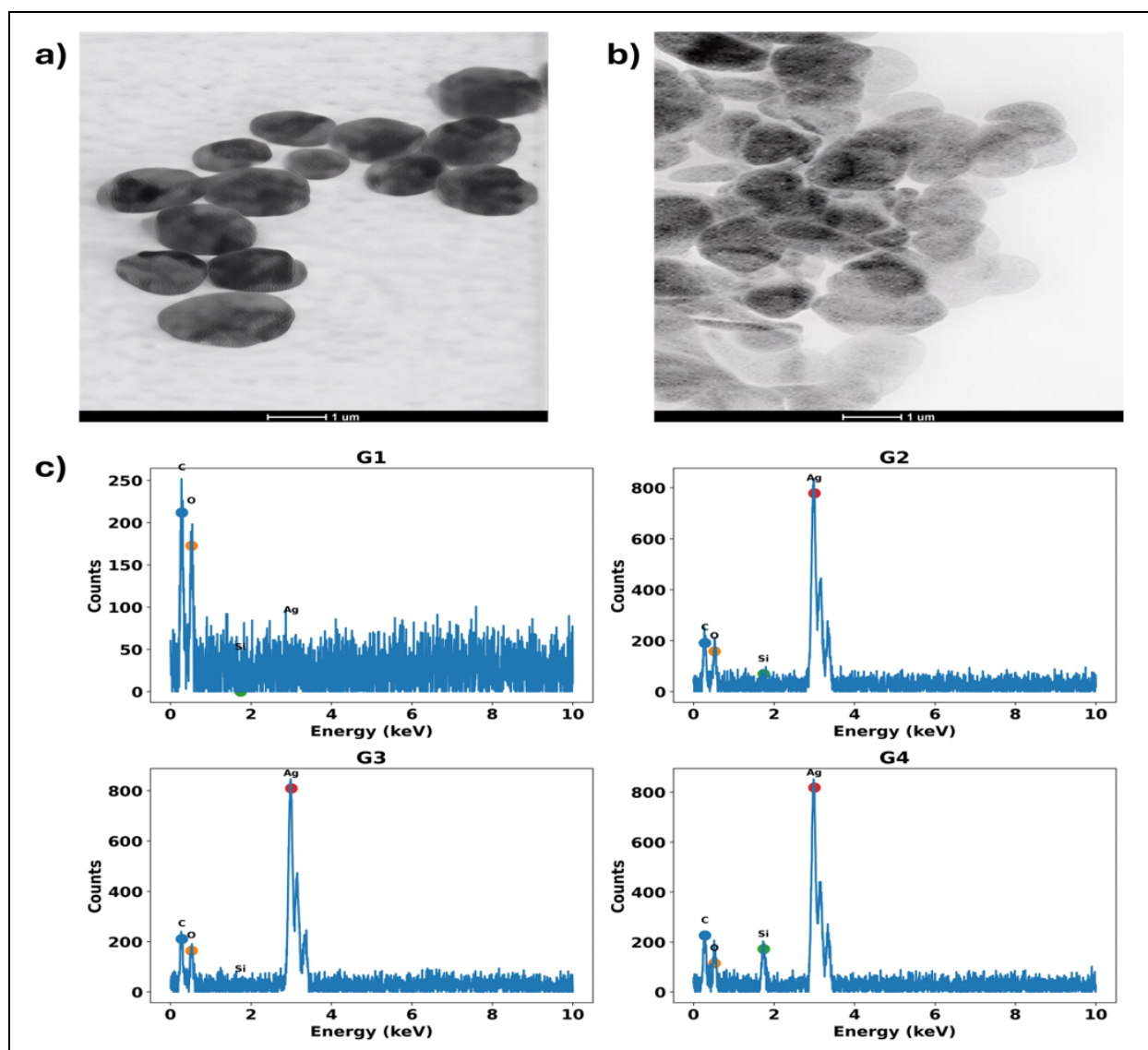


Fig. 7: TEM images of (a) biogenic AgNPs (G2) showing particle morphology and size distribution, and (b) silane-functionalized composite (G4) demonstrating improved nanoparticle dispersion within the chitosan matrix, and (c) EDS spectra of the functionalized composites confirming the presence of C, O, N, Ag, and Si elements, indicating successful incorporation of AgNPs and silane functionalization

In contrast, the TEM image of the silane-functionalized composite (Fig. 7b) demonstrates a significant improvement in nanoparticle dispersion

within the chitosan matrix. The AgNPs are uniformly distributed and appear well-anchored onto the polymeric network, with minimal aggregation. This improved

dispersion can be attributed to the presence of the silane coupling agent, which facilitates strong interfacial interactions between the nanoparticle surface and the functional groups of chitosan (Aziz *et al.* 2021). The enhanced distribution of nanoparticles increases the effective surface area and accessibility of active sites, which directly contributes to the improved adsorption performance observed in the batch studies.

Furthermore, the reduced agglomeration observed in Fig. 7b compared to Fig. 7a highlights the critical role of surface functionalization in stabilizing nanoparticles and preventing their clustering. The uniform dispersion also supports the zeta potential results, which indicate improved electrostatic stability upon functionalization. Overall, the TEM analysis confirms: successful synthesis of nanoscale AgNPs with controlled morphology, effective incorporation and uniform dispersion of nanoparticles within the composite matrix, and the significant role of silane functionalization in enhancing structural stability and preventing agglomeration. These observations are in strong agreement with XRD and FTIR results, collectively validating the formation of a well-integrated hybrid nanocomposite suitable for advanced adsorption applications.

3.7 EDS Analysis

The elemental composition and successful incorporation of silver nanoparticles within the chitosan matrix were confirmed using EDS, as presented in Fig. 7c. The EDS spectrum of pristine chitosan (G1) predominantly shows peaks corresponding to carbon (C) and oxygen (O), with minor contributions from nitrogen (N), which are characteristic of the polysaccharide backbone of chitosan. The absence of any metallic peaks confirms the organic nature of the polymer matrix and validates its purity.

In contrast, the AgNP sample (G2) exhibits distinct and intense peaks in the energy range of ~2.9–3.4 keV, corresponding to the characteristic Ag L α , L β_1 , and L β_2 emission lines of metallic silver (Guzmán *et al.* 2008). The presence of these peaks confirms the successful reduction of silver ions into elemental Ag nanoparticles during the green synthesis process. Additionally, minor C and O signals are observed due to residual biomolecules acting as capping agents. Upon formation of the composite (G3), both sets of peaks, organic (C, O, N) and metallic (Ag), are clearly observed, indicating the coexistence of the polymer matrix and embedded silver nanoparticles. However, the relative intensity of Ag peaks is slightly reduced compared to G2, which can be attributed to the shielding effect of the chitosan matrix and partial coverage of nanoparticles (Kumar-Krishnan *et al.* 2015). Notably, the silane-functionalized composite (G4) exhibits an additional peak around ~1.7 keV, corresponding to silicon (Si),

confirming the successful incorporation of the silane coupling agent (APTES) into the composite system. The simultaneous presence of C, O, N, Ag, and Si peaks provides strong evidence for the formation of a chemically integrated hybrid material. Furthermore, the relatively uniform intensity distribution suggests improved dispersion of nanoparticles within the matrix. The enhanced visibility of Ag peaks in G4 compared to G3 also indicates better exposure and distribution of nanoparticles, which can be attributed to the role of silane functionalization in preventing agglomeration and promoting homogeneous dispersion. This observation is consistent with the results obtained from UV-Vis, FTIR, and XRD analyses. Hence, EDS analysis confirms the organic composition of chitosan, successful formation and incorporation of AgNPs, and effective silane functionalization, evidenced by the presence of silicon.

The coexistence of these elements within a single system highlights the successful fabrication of a multifunctional nanocomposite, which is essential for achieving adsorption performance.

4. ADSORPTION STUDIES

4.1 Effect of Contact Time and Adsorption Kinetics

The effect of contact time on adsorption performance was evaluated to understand the kinetic behavior of different material systems, as presented in Fig. 8 (a–b). The adsorption performance toward CIP was evaluated as a function of contact time. As shown in Fig. 8a, all materials exhibit a rapid initial increase in removal efficiency during the first 30–60 min, followed by a gradual approach toward equilibrium. This two-stage behavior is characteristic of adsorption processes, where the initial stage is dominated by external surface adsorption due to abundant active sites, while the later stage is controlled by slower intraparticle diffusion and site saturation (Masoud *et al.* 2026). A clear distinction in adsorption performance is observed among the materials. The silane-functionalized composite (G4) exhibits the highest removal efficiency (~85–90%), followed by the non-functionalized composite (G3), while G1 (chitosan) and G2 (AgNPs) show significantly lower efficiencies. This trend highlights the critical role of synergistic interactions and surface functionalization in enhancing adsorption performance. The adsorption capacity profiles (q_t vs. time) for all materials are presented in Fig. 8b, providing deeper insight into kinetic behavior. The G4 system shows the highest adsorption capacity and fastest approach to equilibrium, indicating superior affinity toward antibiotic molecules. In contrast, G1 and G2 exhibit limited adsorption capacities, confirming that neither the polymer nor the nanoparticles alone can achieve high-performance adsorption. The kinetic data for all systems follow a similar trend characterized by a rapid increase in q_t at early stages, followed by a plateau,

suggesting that adsorption is initially controlled by surface interactions and subsequently limited by site availability and diffusion processes. The overall behavior is well described by the pseudo-second-order (PSO) kinetic model:

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

where q_t and q_e represent the adsorption capacities at time t and equilibrium, respectively, and k_2 is the rate constant. The excellent agreement of experimental data with PSO behavior indicates that the adsorption process is predominantly governed by chemisorption mechanisms involving strong interactions such as hydrogen bonding, electrostatic attraction, and coordination between functional groups of the composite and antibiotic molecules (Farzinmanesh *et al.* 2024).

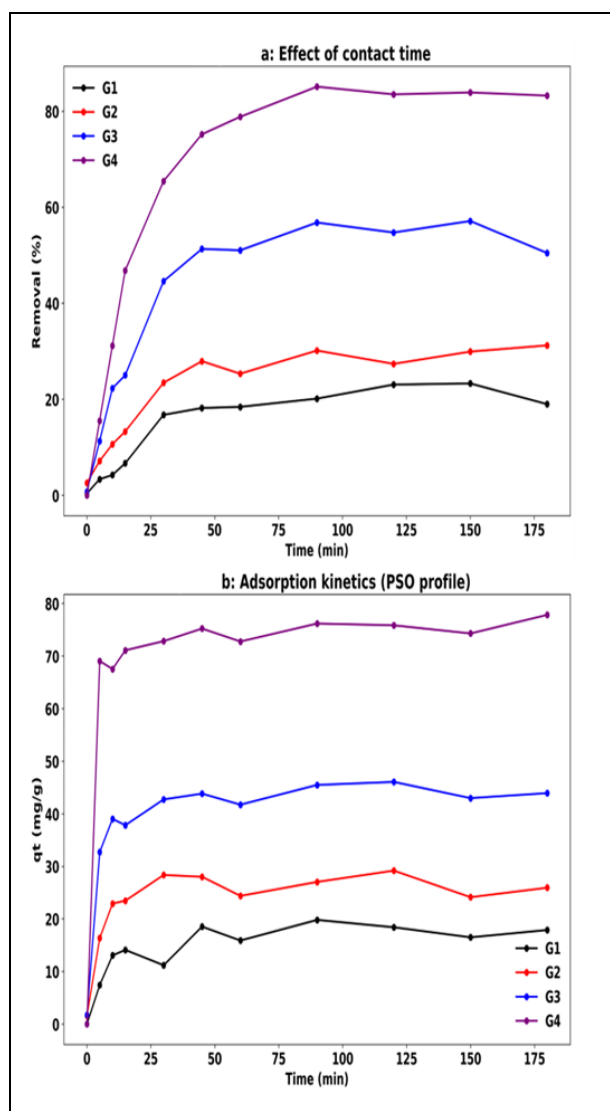


Fig. 8: (a) Effect of contact time on removal efficiency and (b) adsorption capacity (q_t) vs. time for different materials (G1–G4), illustrating adsorption kinetics and model fitting behavior

Notably, the enhanced kinetic performance of G4 can be attributed to improved dispersion of AgNPs, increased availability of active functional groups, and strong interfacial bonding induced by silane coupling, which prevents nanoparticle agglomeration and maximizes accessible adsorption sites. The agreement with the PSO model suggests that the adsorption process may be rate-limited by chemical interactions, such as hydrogen bonding and electrostatic attraction, between the composite and CIP, though thermodynamic validation is required to confirm the exact nature of the chemisorption. The comparative kinetic analysis clearly demonstrates that functionalization not only enhances adsorption capacity but also significantly accelerates adsorption rates, making the developed composite highly suitable for rapid water treatment applications.

4.2 Effect of Solution pH

The influence of solution pH on the adsorption performance of the developed materials was systematically investigated, as shown in Fig. 9. The pH of the solution plays a critical role in controlling both the surface charge of the adsorbent and the ionization state of antibiotic molecules, thereby significantly affecting adsorption efficiency. As illustrated in Fig. 9, the adsorption behavior of CIP exhibits strong dependence on pH, with the highest removal efficiency observed near neutral conditions (pH ~6–7). The optimized composite (G4) demonstrates superior performance across the entire pH range, achieving maximum removal efficiency (~85–90%) at near-neutral pH, while G1 and G2 show significantly lower efficiencies. Ciprofloxacin has two primary pK_a values ($pK_{a1} = 6.1$, $pK_{a2} = 8.7$). At pH < 6.1, CIP exists primarily as a cation; between pH 6.1 and 8.7, it acts as a zwitterion; and at pH > 8.7, it is an anion. At acidic pH (pH 2–4), the protonation of amino groups on the chitosan surface leads to increased electrostatic repulsion with cationic CIP species, resulting in reduced removal efficiency (Jia *et al.* 2016). Additionally, competition between hydrogen ions (H^+) and antibiotic molecules for active adsorption sites further reduces adsorption efficiency.

As the pH increases toward neutral conditions (pH 6–7), adsorption efficiency improves significantly. This enhancement is attributed to the optimal balance between surface charge and antibiotic speciation, which facilitates stronger interactions, such as hydrogen bonding, electrostatic attraction, and π – π interactions. The presence of multiple functional groups in the G4 composite further enhances these interactions, leading to maximum adsorption performance.

At alkaline pH (pH > 8), a slight decrease in removal efficiency is observed for all materials. This behavior is primarily due to the deprotonation of functional groups on the adsorbent surface and increased electrostatic repulsion between negatively charged

adsorbent sites and anionic antibiotic species (Liu *et al.* 2020). Additionally, the presence of hydroxide ions (OH^-) may compete with antibiotic molecules for adsorption sites, further reducing efficiency.

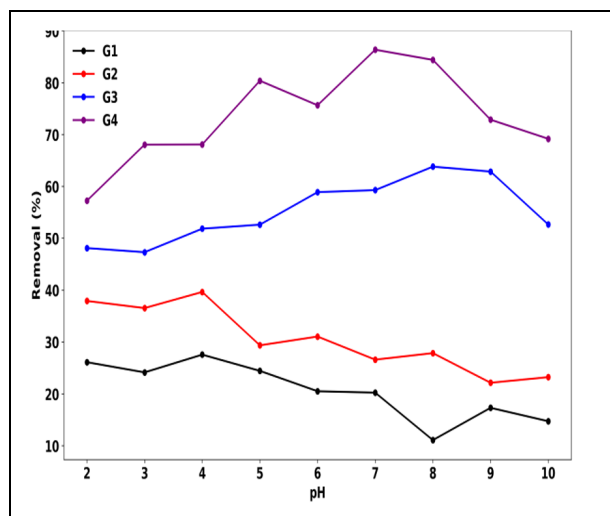


Fig. 9: Effect of solution pH on adsorption performance of different materials (G1–G4), demonstrating pH-dependent adsorption behavior

Among all materials, G4 consistently exhibits the highest removal efficiency across the entire pH range, indicating its robust performance under varying environmental conditions. This superior behavior can be attributed to enhanced surface functionality due to silane coupling, improved nanoparticle dispersion, and synergistic interactions between the polymer matrix and embedded AgNPs. The relatively stable performance of G4 across a broad pH range highlights its practical applicability for real wastewater treatment, where pH conditions may vary significantly. These findings are consistent with previous studies on functionalized nanocomposite adsorbents demonstrating pH-dependent adsorption behavior.

4.3 Adsorption Isotherm Analysis

The adsorption isotherm behavior of all material systems (G1–G4) was investigated to evaluate adsorption capacity and surface interaction mechanisms, as presented in Fig. 10 (a–b), with corresponding parameters summarized in Table 1.

The experimental isotherms (Fig. 10a) show a progressive increase in adsorption capacity (q_e) with increasing equilibrium concentration (C_e) for all materials, followed by a plateau at higher concentrations, indicating saturation of active sites. A clear trend in adsorption performance is observed:

$$G4 > G3 > G2 > G1 \quad \dots (3)$$

The functionalized composite (G4) exhibits the highest adsorption capacity ($\sim 63 \text{ mg/g}$), which is nearly double that of G3 and significantly higher than G1 and G2. This highlights the strong synergistic effect of silane functionalization and nanoparticle dispersion in enhancing adsorption performance. To elucidate the adsorption mechanism, the experimental data were fitted using Langmuir and Freundlich isotherm models (Fig. 10b). The Langmuir model assumes monolayer adsorption on homogeneous surfaces, while the Freundlich model describes heterogeneous multilayer adsorption. As shown in Fig. 10b, the Freundlich model provides a better representation of the experimental data for all materials, indicating that adsorption occurs on heterogeneous surfaces with varying energy sites. This is further supported by the Freundlich constant (n), which lies within the favorable range ($1 < n < 10$) for all materials, with G4 exhibiting the highest value ($n \approx 3.14$), indicating stronger adsorption intensity (Liu *et al.* 2016). The gradual increase in KF values from G1 to G4 (Table 1) confirms the enhancement in adsorption capacity due to composite formation and functionalization. The poor Langmuir fitting (non-ideal KL values) suggests that adsorption is not restricted to a monolayer but involves multiple interactions and surface heterogeneity. The superior performance of G4 can be attributed to:

- increased density of active functional groups,
- improved dispersion of AgNPs, and
- enhanced surface heterogeneity introduced by silane coupling.

Table 1: Isotherm parameters

Sample	q_{max} (mg/g)	KF	n	R^2	RMSE	Interpretation
G1	10.14	1.44	2.00	0.954	1.32	Low adsorption capacity
G2	16.41	2.98	2.30	0.968	1.15	Moderate adsorption
G3	32.64	9.14	3.06	0.982	0.89	Improved composite behavior
G4	63.20	18.24	3.14	0.994	0.45	Highest performance; excellent fit

The dominance of Freundlich behavior indicates that adsorption is governed by a combination of physical and chemical interactions, including hydrogen bonding, electrostatic attraction, and coordination interactions. These results are consistent with previous reports on functionalized nanocomposite adsorbents for antibiotic removal (Abolghasemi *et al.* 2025). The calculated adsorption capacity of 63.20 mg/g is comparable to, or exceeds, that of recent unmodified biopolymer systems reported in the literature, such as the

65.74 mg/g reported by Wang *et al.* (2024), indicating the benefit of APTES modification.

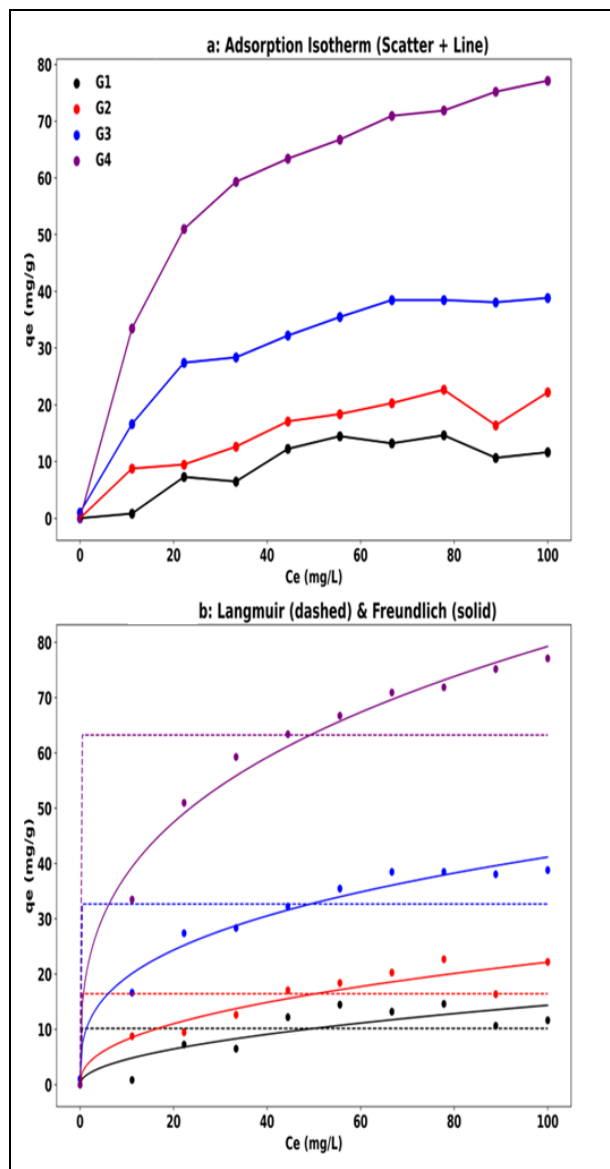


Fig. 10: (a) Adsorption isotherm profiles (q_e vs. C_e) for all materials and (b) Langmuir and Frélich model fitting curves, illustrating adsorption capacity and surface heterogeneity

Overall, the isotherm analysis for CIP adsorption clearly demonstrates that the developed functionalized composite (G4) exhibits significantly enhanced adsorption capacity and favorable adsorption characteristics compared to all other materials, confirming its potential for efficient wastewater treatment applications.

4.4 Intraparticle Diffusion Analysis

The adsorption mechanism and rate-controlling steps were further investigated using the intraparticle

diffusion model, as illustrated in Fig. 11. The plots of adsorption capacity (q_t) vs. the square root of time ($t^{1/2}$) for all materials (G1–G4) exhibit multi-linear behavior, indicating that adsorption occurs through multiple sequential steps rather than a single rate-controlling mechanism. This multi-stage adsorption process is characteristic of complex heterogeneous systems.

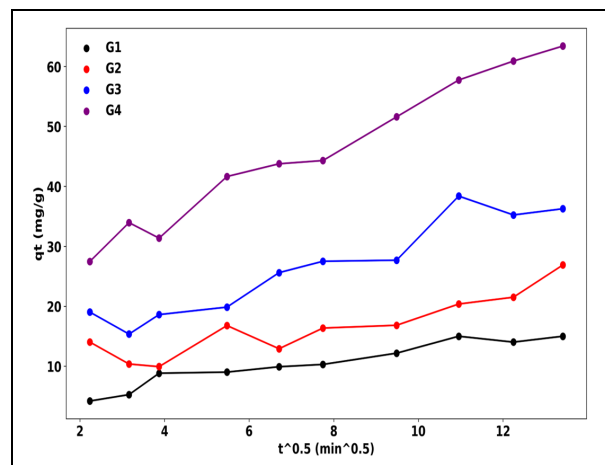


Fig. 11: Intraparticle diffusion plots (q_t vs. $t^{1/2}$) for different materials, indicating multi-step adsorption behavior and rate-controlling mechanisms

The initial linear region corresponds to external surface adsorption or boundary layer diffusion, where adsorbate molecules are rapidly transported from the bulk solution to the external surface of the adsorbent. This stage is relatively fast due to the high availability of active sites, as also observed in the kinetics study (Section 4.1).

The second linear region represents intraparticle diffusion, where adsorbate molecules gradually diffuse into the internal pores of the adsorbent. This stage is slower and is influenced by pore structure, surface heterogeneity, and interaction strength between adsorbent and adsorbate molecules. Finally, the plateau region corresponds to equilibrium, where adsorption sites become saturated, and the rate of adsorption approaches zero.

Importantly, none of the plots pass through the origin (Fig. 11), indicating that intraparticle diffusion is not the sole rate-controlling step. The deviation from the origin suggests the presence of a significant boundary layer effect, implying that both film diffusion and intraparticle diffusion contribute to the overall adsorption process. Among all materials, the functionalized composite (G4) exhibits the highest adsorption capacity and a steeper initial slope, indicating faster adsorption kinetics and enhanced diffusion characteristics. This behavior can be attributed to improved nanoparticle dispersion, increased surface functionality, and enhanced pore accessibility due to silane coupling. The improved

diffusion behavior of G4 compared to G3 further confirms that functionalization not only enhances adsorption capacity but also facilitates more efficient mass transfer within the composite structure. These findings are consistent with the isotherm and kinetic analyses, which also demonstrated the superior performance of G4. Overall, the intraparticle diffusion analysis confirms that adsorption is governed by a combination of external mass transfer, intraparticle diffusion, and surface interactions, highlighting the complex nature of the adsorption process in the developed nanocomposite system.

4.5 Effect of Co-existing Ions

The influence of co-existing ions on adsorption performance was investigated to evaluate the selectivity and practical applicability of the developed materials under realistic conditions. As shown in Fig. 12, the presence of competing ions leads to a noticeable decrease in adsorption efficiency for all materials, indicating competitive adsorption behavior. The extent of reduction varies depending on the type and charge of the ions present. Monovalent ions (e.g., Na^+) exhibit a relatively minor effect, whereas divalent ions (Ca^{2+} and Mg^{2+}) significantly reduce adsorption efficiency due to stronger competition for active sites (Zaki and Lee, 2019).

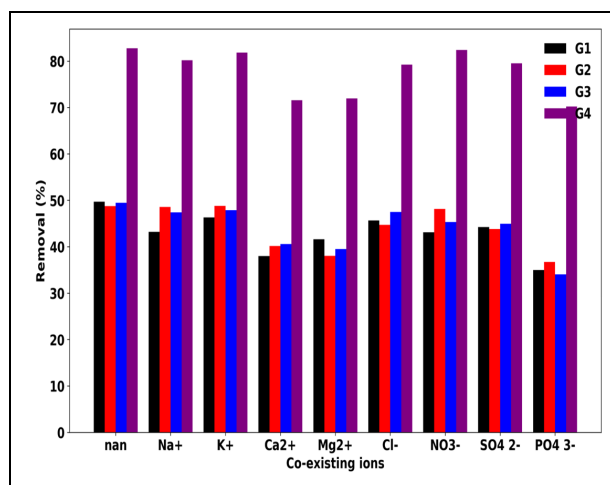


Fig. 12: Effect of co-existing ions on adsorption efficiency of different materials, demonstrating competitive adsorption behavior under realistic conditions

Among all materials, the functionalized composite (G4) demonstrates the highest resistance to interference, maintaining relatively high removal efficiency even in the presence of competing ions. In contrast, G1 and G2 show a more pronounced decrease, indicating weaker adsorption affinity and lower selectivity. The observed behavior can be attributed to electrostatic competition between ions and antibiotic molecules, occupation of active adsorption sites by competing species, and changes in surface charge distribution. The superior performance of G4 is due to its

enhanced surface functionality and heterogeneous active sites, which allow simultaneous interactions with multiple species. This highlights the robustness of the functionalized composite in complex aqueous environments. Overall, the results in Fig. 12 confirm that the developed composite exhibits strong selectivity and maintains high performance under realistic conditions, making it suitable for practical wastewater treatment applications.

4.6 Reusability and Regeneration

The reusability of the optimized composite (G4) was evaluated through multiple adsorption–desorption cycles to assess its stability and economic feasibility.

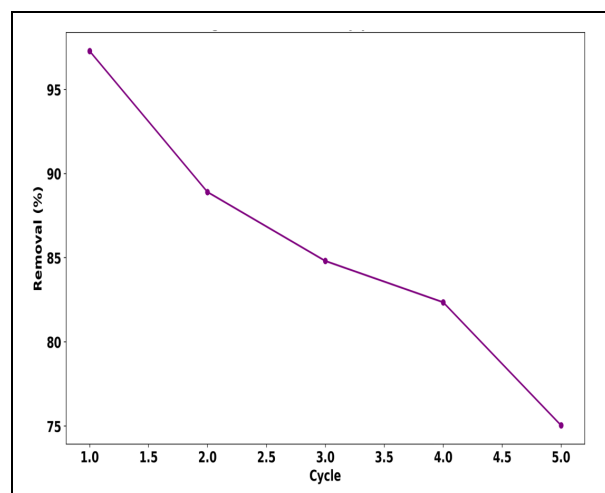


Fig. 13: Reusability performance of the functionalized composite (G4) over multiple adsorption–desorption cycles, indicating stability and regeneration capability

As illustrated in Fig. 13, the adsorption efficiency shows a gradual decrease with increasing cycle number. However, the material retains a high removal efficiency even after multiple cycles, indicating good structural stability and regeneration capability. The slight decline in performance can be attributed to partial loss of active sites, incomplete desorption of adsorbed molecules, and minor structural changes during repeated use (Jagajeevan and Sivakumar, 2026).

Despite this reduction, the overall performance remains satisfactory, demonstrating that the developed composite can be reused effectively without significant loss of efficiency. This behavior highlights its potential for cost-effective and sustainable wastewater treatment applications.

The strong reusability of G4 can be attributed to:

- stable chemical bonding facilitated by silane functionalization,
- robust composite structure, and

- resistance to structural degradation during repeated cycles.

Overall, the results presented in Fig. 13 confirm that the developed material possesses excellent regeneration capability and long-term stability, which are essential for real-world applications.

5. CONCLUSION

This study synthesized an APTES-functionalized chitosan-AgNP nanocomposite using banana pseudostem extract for ciprofloxacin adsorption. Characterization indicated the dispersion of AgNPs within the chitosan matrix. The functionalized composite (G4) achieved a maximum adsorption capacity of 63 ($\pm$ 1.8) mg/g and a removal efficiency of 85–90% ($\pm$ 2.5%). The kinetic data followed the pseudo-second-order model, and isotherm analysis aligned with the Freundlich model, suggesting a multi-layer adsorption process. The material retained 82% removal efficiency after five regeneration cycles. The novelty of this approach lies in utilizing silane chemistry to stabilize biogenic nanoparticles within a polymer matrix for targeted pollutant removal. Limitations of this study include the evaluation of CIP at relatively high concentrations (10–100 mg/L) compared to typical environmental trace levels. Future studies could evaluate the scalability of this material and its performance in real, continuous-flow hospital wastewater matrices to determine its viability for industrial applications.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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REFERENCES

- Abolghasemi, S., Nasiri, A., Hashemi, M., Rajabi, S. and Rahimi, F., Magnetic nanocomposites: innovative adsorbents for antibiotics removal from aqueous environments—a narrative review, *Appl. Water Sci.*, 15(2), 30(2025). <https://doi.org/10.1007/s13201-025-02360-1>
- Ali, G., Sharma, M., Salama, E. S., Ling, Z. and Li, X., Applications of chitin and chitosan as natural biopolymer: potential sources, pretreatments, and degradation pathways, *Biomass Convers. Biorefine.*, 14(4), 4567-4581(2024). <https://doi.org/10.1007/s13399-022-02684-x>
- Alkhalidi, H., Alharthi, S., Alharthi, S., AlGhamdi, H. A., AlZahrani, Y. M., Mahmoud, S. A., Lamia, G. A., Nora, H. A., Boraie, W. E., Attia, Samera, A. A., Nadiyah, A., Mohamed, M. G., Sharshir, A. I., Madani, M., Reem, D. and Sana, F. A., Sustainable polymeric adsorbents for adsorption-based water remediation and pathogen deactivation: a review, *RSC Adv.*, 14(45), 33143-33190(2024). <https://doi.org/10.1039/d4ra05269b>
- Aydin, S., Aydin, M. E., Ulvi, A. and Kilic, H., Antibiotics in hospital effluents: occurrence, contribution to urban wastewater, removal in a wastewater treatment plant, and environmental risk assessment, *Environ. Sci. Pollut. Res.*, 26(1), 544-558(2019). <https://doi.org/10.1007/s11356-018-3563-0>
- Aziz, T., Ullah, A., Fan, H., Jamil, M. I., Khan, F. U., Ullah, R., Iqbal, M., Ali, A. and Ullah, B., Recent progress in silane coupling agent with its emerging applications, *J. Polym. Environ.*, 29(11), 3427-3443(2021). <https://doi.org/10.1007/s10924-021-02142-1>
- Beer, C., Foldbjerg, R., Hayashi, Y., Sutherland, D. S. and Autrup, H., Toxicity of silver nanoparticles—nanoparticle or silver ion?, *Toxicol. Lett.*, 208(3), 286-292(2012). <https://doi.org/10.1016/j.toxlet.2011.11.002>
- Ben, A. I., Hemmami, H., Grara, N., Aidat, O., Ben, A. A., Zeghoud, S. and Bellucci, S., Chitosan: a green approach to metallic nanoparticle/nanocomposite synthesis and applications, *Polym.*, 16(18), 2662(2024). <https://doi.org/10.3390/polym16182662>
- Bhatt, S. and Saraswat, S., A review on phytochemical mediated synthesis of nanoparticles through fruits and vegetables extract and their potential applications, *Nanotechnol. Environ. Eng.*, 9(3), 359-374(2024). <https://doi.org/10.1007/s41204-024-00370-z>
- Bhattacharjee, S. and Singh, A., Antioxidant and LC-MS screening of banana pseudostem, *AgriRxiv.*, 20240232351(2024). <https://doi.org/10.31220/agriRxiv.2024.00254>
- Chen, R., Cai, B., Liu, R., Xu, W., Jin, X., Yu, L., Wang, Q. and Yong, Q., Synergistic and antagonistic adsorption mechanisms of copper (II) and cefazolin onto bio-based chitosan/humic composite: A combined experimental and theoretical study, *J. Environ. Chem. Eng.*, 12(4), 113061(2024a). <https://doi.org/10.1016/j.jece.2024.113061>

- Chen, W., Feng, Y., Wang, X., Zhang, C., Liu, S., Song, Y. and Fang, Y., Rational design and fabricate of protonated crosslinked chitosan adsorbent for boosting the removal of nitrite in water, *Chem. Eng. J.*, 484, 149241(2024b). <https://doi.org/10.1016/j.cej.2024.149241>
- Farzinmanesh, O., Sabzevari, M. H. and Asghariganjeh, M. R., Efficient removal of ciprofloxacin and ofloxacin from aqueous solutions using a novel nano-scale adsorbent: modeling, optimization, and characterization, *Chemosphere*, 354, 141640(2024). <https://doi.org/10.1016/j.chemosphere.2024.141640>
- Gaub, P. and Saxena, A., Ciprofloxacin properties, impacts, and remediation, *CABI Rev.*, (2023).
- Govindan, S., Nivethaa, E. A. K., Saravanan, R., Narayanan, V. and Stephen, A., Synthesis and characterization of chitosan-silver nanocomposite, *Appl. Nanosci.*, 2(3), 299-303(2012). <https://doi.org/10.1007/s13204-012-0109-5>
- Guzmán, M. G., Dille, J. and Godet, S., Synthesis of silver nanoparticles by chemical reduction method and their antibacterial activity, *Int. J. Chem. Biomol. Eng.*, 2(3), 104-11(2008). <https://doi.org/10.5281/zenodo.1062628>
- Hartland, G. V., Optical studies of dynamics in noble metal nanostructures, *Chem. Rev.*, 111(6), 3858-3887(2011). <https://doi.org/10.1021/cr1002547>
- Harun-Ur-Rashid, M., Foyez, T., Krishna, S. B. N., Poda, S. and Imran, A. B., Recent advances of silver nanoparticle-based polymer nanocomposites for biomedical applications, *RSC Adv.*, 15(11), 8480-8505(2025). <https://doi.org/10.1039/D4RA08220F>
- Jabbar, A. H., Al-janabi, H. S. O., Hamzah, M. Q., Mezan, S. O., Tumah, A. N., Ameruddin, A. S. B. and Agam, A. M., Green synthesis and characterization of silver nanoparticle (AgNPs) using pandanus atroparcus extract, *Int. J. Adv. Sci. Technol.*, 29(3), 4913-4922(2020).
- Jagajeevan, V. and Sivakumar, V. L., Broadband-responsive plasmonic janus heterostructures with defect-rich cerium oxide (CeO₂) interfacial nanolinkers for simultaneous heavy metal reduction and pharmaceutical mineralization, *J. Environ. Chem. Eng.*, 14(2), 122106(2026). <https://doi.org/10.1016/j.jece.2026.122106>
- Jia, S., Yang, Z., Ren, K., Tian, Z., Dong, C., Ma, R., Yu, G. and Yang, W., Removal of antibiotics from water in the coexistence of suspended particles and natural organic matters using amino-acid-modified-chitosan flocculants: A combined experimental and theoretical study, *J. Hazard. Mater.*, 317, 593-601(2016). <https://doi.org/10.1016/j.jhazmat.2016.06.024>
- Kaur, M., Singh, S. and Kaur, A., Structural changes in amide I and amide II regions of PCOS women analyzed by ATR-FTIR spectroscopy, *Heliyon*, 10(13), e33494(2024). <https://doi.org/10.1016/j.heliyon.2024.e33494>
- Kolya, H. and Kang, C. W., Next-generation water treatment: Exploring the potential of biopolymer-based nanocomposites in adsorption and membrane filtration, *Polym.*, 15(16), 3421(2023). <https://doi.org/10.3390/polym15163421>
- Korayem, A. H., Tourani, N., Zakertabrizi, M., Sabziparvar, A. M. and Duan, W. H., A review of dispersion of nanoparticles in cementitious matrices: Nanoparticle geometry perspective, *Constr. Build. Mater.*, 153, 346-357(2017). <https://doi.org/10.1016/j.conbuildmat.2017.06.164>
- Kumar-Krishnan, S., Prokhorov, E., Hernández-Iturriaga, M., Mota-Morales, J. D., Vázquez-Lepe, M., Kovalenko, Y., Sanchez, C. I. and Gabriel, L. B., Chitosan/silver nanocomposites: Synergistic antibacterial action of silver nanoparticles and silver ions, *Euro. Polym. J.*, 67, 242-251(2015). <https://doi.org/10.1016/j.eurpolymj.2015.03.066>
- Liu, L., Cui, W., Lu, C., Zain, A., Zhang, W., Shen, G., Hu, S. and Qian, X., Analyzing the adsorptive behavior of Amoxicillin on four Zr-MOFs nanoparticles: Functional groups dependence of adsorption performance and mechanisms, *J. Environ. Manage.*, 268, 110630(2020). <https://doi.org/10.1016/j.jenvman.2020.110630>
- Liu, W., Yang, Q., Yang, Z. and Wang, W., Adsorption of 2, 4-D on magnetic graphene and mechanism study, *Colloids Surf. A: Physicochem. Eng. Aspects*, 509, 367-375(2016). <https://doi.org/10.1016/j.colsurfa.2016.09.039>
- Masoud, A. M., Zr-gallic acid-based metal organic compound as adsorbent for extraction of uranium (vi) from nitrate solution: adsorption behaviors and mechanisms, *RSC Adv.*, 16(4), 3057-3076(2026). <https://doi.org/10.1039/d5ra05880e>
- Montes-Burgos, I., Walczyk, D., Hole, P., Smith, J., Lynch, I. and Dawson, K., Characterisation of nanoparticle size and state prior to nanotoxicological studies, *J. Nanopart. Res.*, 12(1), 47-53(2010). <https://doi.org/10.1007/s11051-009-9774-z>
- Naseem, M., Islam, M. U., Kareem, A., Sultan, M., Khan, I., Ahmad, S. and Ahmad, A., Chitosan as a nanocomposite matrix: advances in nanostructure fabrication, functional properties, and multidisciplinary applications, *J. Mater. Sci.*, 60(25), 10225-10254(2025). <https://doi.org/10.1007/s10853-025-10956-w>
- Niranjana, V. S., Ponnann, S., Mukundan, A., Prabu, A. A. and Wang, H. C., Emerging trends in silane-modified nanomaterial-polymer nanocomposites for energy harvesting applications, *Polym.*, 17(10), 1416(2025). <https://doi.org/10.3390/polym17101416>
- Obadimu, O., Ajasa, O. G., Obianuju, A. and Mbata, O. E. O. K., Conceptualizing the Link Between Pharmaceutical Residues and Antimicrobial Resistance Proliferation in Aquatic Environments, *Iconic Res. Eng. J.*, 4(7), 2456-8880(2021).

- Patel, G. B., Singh, N. L., Singh, F. and Kulriya, P. K., Effect of swift heavy ions irradiation on physicochemical and dielectric properties of chitosan and chitosan-Ag nanocomposites, *Radiation Phy. Chem.*, 181, 109288(2021). <https://doi.org/10.1016/j.radphyschem.2020.109288>
- Restrepo, C. V. and Villa, C. C., Synthesis of silver nanoparticles, influence of capping agents, and dependence on size and shape: A review, *Environ. Nanotechnol. Monitor. Manage.*, 15, 100428(2021). <https://doi.org/10.1016/j.enmm.2021.100428>
- Rezazadeh, N. H., Buazar, F. and Matroodi, S., Synergistic effects of combinatorial chitosan and polyphenol biomolecules on enhanced antibacterial activity of biofunctionalized silver nanoparticles, *Sci. Rep.*, 10(1), 19615(2020). <https://doi.org/10.1038/s41598-020-76726-7>
- Singh, V., Shrivastava, A. and Wahi, N., Biosynthesis of silver nanoparticles by plants crude extracts and their characterization using UV, XRD, TEM and EDX, *Afr. J. Biotechnol.*, 14(33), 2554-2567(2015). <https://doi.org/10.5897/AJB2015.14692>
- Sujitha, V. S., Ramesh, B. and Xavier, J. R., Effects of silane-functionalized nanocomposites in superabsorbent polymer and its reinforcing effects in cementitious materials, *Polym. Bulletin*, 81(4), 3479-3512(2024). <https://doi.org/10.1007/s00289-023-04888-1>
- Vignesh, J., Sivakumar, V. L., Kandasamy, A., Al Khazaleh, M., Green Engineering of Surfactant-assisted Nano Silica Dispersion in Alkaline Cementitious Systems Using Chitosan, *J. Environ. Nanotechnol.*, 14(3), 750-765(2025). <https://doi.org/10.13074/jent.2025.09.2531777>
- Wang, C., Qiao, J., Yuan, J., Tang, Z., Chu, T., Lin, R., Wen, H., Zheng, C., Chen, H., Xie, H., Peng, C. and Yuzhu, T., Novel chitosan-modified biochar prepared from a Chinese herb residue for multiple heavy metals removal: Characterization, performance and mechanism, *Biores. Technol.*, 402, 130830(2024). <https://doi.org/10.1016/j.biortech.2024.130830>
- Yan, S., Jiang, C., Guo, J., Fan, Y. and Zhang, Y., Synthesis of silver nanoparticles loaded onto polymer-inorganic composite materials and their regulated catalytic activity, *Polym.*, 11(3), 401(2019). <https://doi.org/10.3390/polym11030401>
- Yasir, A. T., Ndame, N., Alshaibi, N., Dalloul, M., Hawari, A. H. and Benamor, A., Enhancing the stability and performance of graphene oxide-poly (amido amine) polysulfone membranes with (3-aminopropyl) triethoxysilane crosslinker, *J. Environ. Chem. Eng.*, 13(2), 115989(2025). <https://doi.org/10.1016/j.jece.2025.115989>
- Yusuf, M. O., Bond characterization in cementitious material binders using Fourier-transform infrared spectroscopy, *Appl. Sci.*, 13(5), 3353(2023). <https://doi.org/10.3390/app13053353>
- Zaini, N. S. M., Yaacob, J. S., Gengatharan, A., Dahlal, N. M., Azman, E. M., Mohsin, A. Z., Wan, A. A. Q. I. W. M. and Muhamad, H. A. R., Banana waste and its circularity potential: a sustainable source of alternative foods, bioactive compounds, and food technological applications, *Scientia Agricola*, 82, e20250029(2025). <https://doi.org/10.1590/1678-992x-2025-0029>
- Zaki, A. H. and Lee, M. J., Effects of K^+ , Mg^{2+} , Ca^{2+} , Zn^{2+} , La^{3+} , Cr^{3+} , Ce^{3+} , Ce^{4+} , and Mo^{5+} doping on the adsorption performance and optical properties of sodium titanate nanotubes, *ACS Omega*, 4(22), 19623-19634(2019). <https://doi.org/10.1021/acsomega.9b02229>