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Structural and interfacial characterization of ciprofloxacin-loaded starch/HPMC sepiolite nanocomposite films

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This study is designed to synthesize drug-loaded polymer nanocomposites based on starch and hydroxypropyl methyl cellulose (HPMC) natural polymers reinforced with sepiolite clay mineral by a polymer solution casting procedure. Sepiolite clay is used to ensure the thermal and mechanical properties of the film. Ciprofloxacin is a second generation, broad-spectrum antibacterial drug. It is commercially available in suspension and tablet forms. Polymer–clay interactions are a very useful approach to change the physiochemical and thermal properties of drug-loaded films, with the major takeaway being that optimized composition and dispersion enhance the performance, providing a foundation for the rational design of novel nanocomposites. Various formulations of these nanocomposite films have been developed with the objectives of being antibacterial, renewable, biodegradable and biocompatible. These nanocomposites have diverse applications in the packaging, medical, food and pharmaceutical industries. Thermogravimetric analysis (TGA) confirmed that the weight residues of drug-loaded nanocomposites have higher thermal stabilities than non-drug-loaded composites. Energy dispersive X-ray analysis (EDX) showed the elemental composition of the mixed components. X-ray diffraction (XRD) confirmed the amorphous and crystalline nature of the starch and HPMC. Fourier transform infrared (FTIR) spectroscopy was used to examine the compatibility of the polymers. Scanning electron microscopy (SEM) showed the better adhesion, distribution and dispersion of the drug and clay particles. This approach not only benefits the scientific community by understanding interactions but also catalyzes further research towards efficient, cost-efficient and multifunctional biomedical material development.

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1. Introduction

Polymer-based drug-loaded films have gained substantial attention in recent years as advanced platforms for localized and controlled drug delivery, mainly in transdermal, topical, wound healing, and biomedical coating applications. The conventional dosing systems, *i.e.*, oral, parenteral and topical, have the limitations of poor targeting, different drug levels, low patient compliance and low bioavailability.[1] Polymeric films offer several unique benefits relative to conventional dosing devices, including increased patient compliance, simplified use, reduced administration frequency, and the ability to deliver drugs to the site of action with minimal systemic drug exposure. The great variety of these systems enables the careful regulation of release kinetics through the reasonable selection of polymer bases and functional additives, thereby maximizing therapeutic efficacy and minimizing negative effects. At the same time, there has been an increasing demand for the development of renewable-resource-based biocompatible materials to deliver drugs due to the pressure of regulatory and environmental regulations. Recent reports have focused on the possibilities of novel biodegradable polymeric films that may be utilized in future pharmaceutical formulations.[2,3] Among these biodegradable polymers, starch is an interesting choice for the preparation of drug-layered films in part because of its availability, renewability, cost and biocompatibility. Starch-based films have a fair film-forming ability and have been explored as a pharmaceutical and biomedical delivery system, both in drug encapsulation and drug-releasing systems. These hydrophilic polymers are preferred because they are biodegradable and biocompatible, show swelling behavior and easily form a gel upon the addition of water. However, despite the above advantages, there are some limitations inherent to the use of

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straight starch in the preparation of drug delivery films. Pure starch films are weak and brittle as regards mechanical stability, highly hydrophilic and sensitive to moisture as regards weight and structure, lack of structural integrity and of poor storage and use. Moreover, the gelation and dissolution of starch under wet conditions are so rapid that bursts of drug delivery are likely to occur, restricting its use as a long-term drug delivery platform. The available literature has repeatedly indicated that the adoption of starch-based films by the pharmaceutical sector cannot be achieved without a proper modification strategy.[4–6] To allay the constraint on the utilization of pure starch, amalgamation with polymers has become a popular and feasible operation to transform the film characteristics without deterioration of the biodegradable character of the matrix polymer. Blending with HPMC, glycerol and reinforcing nanofiller like clays can improve flexibility, reduce hydrophilicity and improve mechanical properties. In this regard, impermeable HPMC has been given significant consideration as an substituent polymer of starch-based systems. HPMC is a semi-synthetic cellulosic derivative with high film forming property, mechanical malleability, chemical stability and swell control. The diffusion constant values for HPMC based systems range from $\sim 10^{-6}$ to 10^{-8} cm^2 s^{-1} depending on polymer grade, water uptake level, and interactions with drugs.[7] HPMC works with starch to promote intermolecular hydrogen-bond-formation networks, which lead to increased tensile strength and tensile resistance to deformation, particularly in humid environments. Furthermore, HPMC plays a part in regulating the diffusion of drugs in the polymer matrix, enabling a greater ability to employ more controlled and predictable drug delivery patterns. According to recent research, starch-HPMC blended systems are structurally stable and highly functional compared to individual polymer films; hence, they are very viable when it comes to pharmaceutical practice. However, other reinforcing components are required to further improve the mechanical and interfacial properties of these blended matrices.[8–10] The incorporation of polymer–clay nanocomposites, where the nanofillers of the clay have synergism with the polymer chains, is one of the strategies to attain further improvements in the nanoscale performance of polymeric drug delivery films. Sepiolite is a naturally found clay mineral and has attracted much attention as a reinforcing agent due to its unusual fibrous structure, high specific surface area and sheer abundance of surface silanol groups. In contrast to the layered type of clays such as montmorillonite, sepiolite delivers a needle form and hence can be highly dispersed in polymer matrices and allows a high degree of interfacial interaction. It has been firmly determined that the insertion of sepiolite significantly increases the bearing capacity against pressure, heat stability, transport resistance, and dimensional stability of biopolymer based composite films. Moreover, sepiolite is highly porous, exhibiting a range of $\sim$0.3–0.6 cm^3 g^{-1}, and has the ability to adsorb drugs and thus facilitate effective drug loading and immobilization, which contributes to the enhancement of drug stability and drug release profile control. As a result, there has been an increase in the focus on the exploitation of sepiolite as a versatile nanofiller to form drug delivery systems when used with biopolymers and, in particular, with hydrophilic polymers.[11–14] Ciprofloxacin is a broad-spectrum fluoroquinolone primarily used in the treatment of bacterial infections, including skin infections, wound infections and implant-associated infections. Ciprofloxacin has several formulation difficulties, despite its clinical significance, so its successful integration with polymeric drug delivery systems is limited. The medication is prone to pH-dependent solubility, photodegradation, and polymorphic conversion, which can adversely impact its stability and pharmacologic efficacy. In the latest studies, it has been argued that the use of polymer–clay nanocomposites can be beneficial to overcoming the above challenges by promoting the interaction of drug matrices to ensure that the drugs can be stabilized and the kinetics of their release can be controlled. Specifically, adsorption of ciprofloxacin on the surfaces of the clay and the closed character of the latter in the polymer networks can decrease burst releases and increase the effectiveness of the long-term curative effect.[15,16] Notwithstanding the growing interest in the use of starch-based films and polymer blending strategies, including the use of nanocomposites reinforced with the help of clay, a critical examination of the available literature proves that there are certain gaps in the existing study. Although multiple studies have been conducted unilaterally regarding the mixture of starches and HPMCs, polymers loaded with sepiolite, and ciprofloxacin-loaded treatments, there are no studies that have acquired data where all 3 substances are combined into a single nanocomposite film.[17–20] The interfacial and structural interactions between starch, HPMC, sepiolite, and particularly ciprofloxacin in the nanoscale are not well understood. A majority of the literature is centered on mechanical performance or drug release behavior, and very few studies associate these properties to the underlying structure and interfaces. Filling this gap is necessary in order to create multifunctional, drug-loaded polymeric films that are more stable and effective (Fig. 1).[14,15]

The present study focuses on the development of ciprofloxacin-loaded starch/HPMC/sepiolite nanocomposite films. Particular attention is given to their structural and interfacial characteristics. The primary objective is to investigate the effect of HPMC blending and sepiolite reinforcement on the morphology, interfacial interactions, mechanical integrity, and stability of the films. In addition, the loading efficiency and distribution of ciprofloxacin within the nanocomposite matrix are systematically examined. The outcomes of this study are expected to provide valuable insights into polymer–drug–clay interactions and contribute to the rational design of high-quality, freestanding polymeric drug delivery films with potential applications in the pharmaceutical and biomedical fields.

2. Materials and methods

2.1 Experimental reagent

White powder of hydroxypropyl methylcellulose (≥99% purity, density ≈ 1.39 g cm^{-3}, International Laboratory, USA), starch (≥98% purity, density ≈ 1.5 g cm^{-3}, Daejung Kosdaq, Korea), ciprofloxacin hydrochloride (≥98% purity, Global

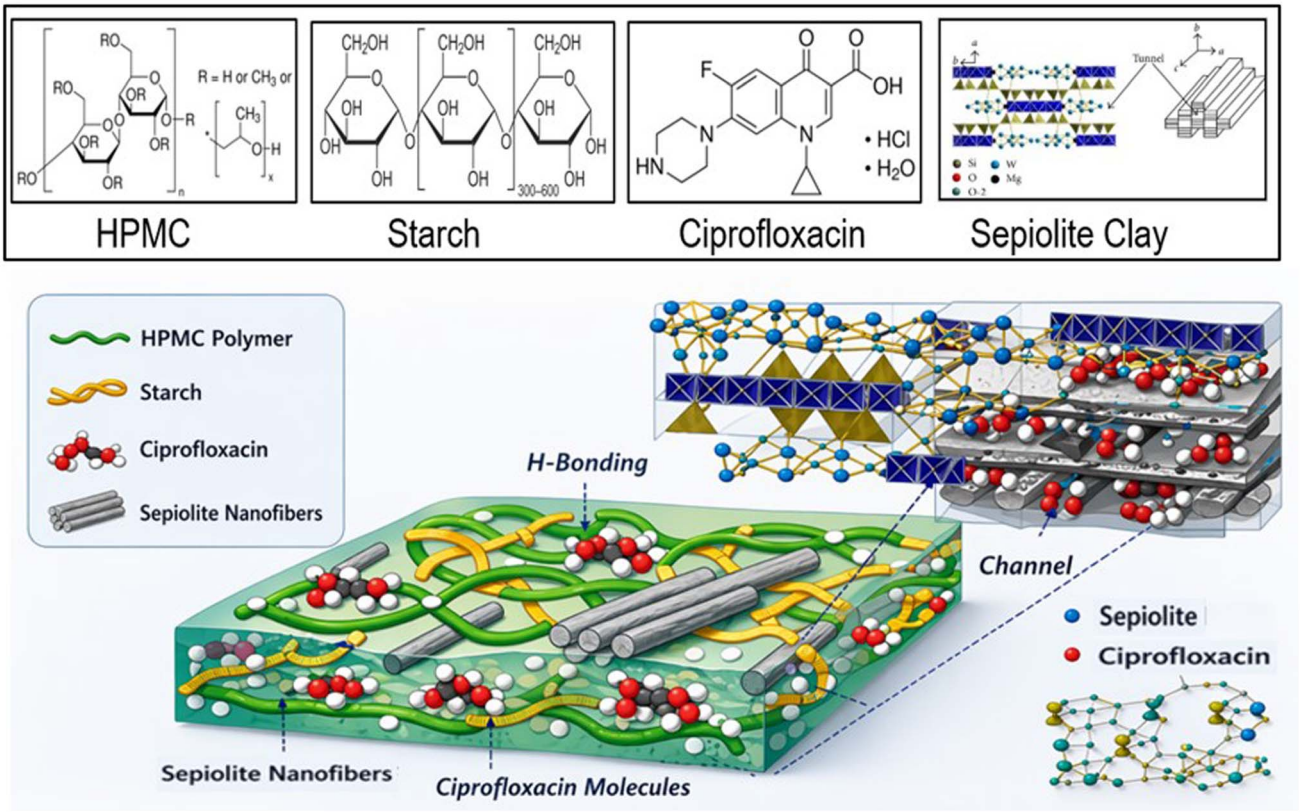


Fig. 1 Structures of HPMC, starch, ciprofloxacin, sepiolite clay and nanocomposite films.[17–20]

Pharmaceuticals, Islamabad), light grey powder sepiolite clay (≥90% purity, International Laboratory, USA), glycerol plasticizer (≥99.5% purity) and distilled water (Sigma-Aldrich) were procured from commercial suppliers and used as received without further purification.

Starch was selected for its hydrophilic and swelling properties, while HPMC has release characteristics and provides gel formation. The clay was used as a reinforcing agent to enhance mechanical strength and minimize burst release. The flexibility was improved by adding glycerol.

2.2 Fabrication of nanocomposite

A polymer solution casting procedure was used to prepare different formulations of starch/HPMC nanocomposites. The HPMC and starch solutions were prepared by dissolving the respective powders separately in 50 mL of distilled water under gentle stirring, followed by mixing with the addition of sepiolite clay. After 15 minutes, the antibiotic ciprofloxacin drug was gradually added to the mixture. Complete dissolution was achieved after the solution was stirred for half an hour at constant temperature (~60 °C); it was then deposited into Petri dishes and placed in a drying oven for 24 hours, resulting in hard, smooth films. The different samples of sans and ciprofloxacin-loaded starch/HPMC nanocomposites films prepared are given in Tables 1 and 2, respectively. A1–A5 are drug-free matrices used to study the intrinsic properties of the polymer blends, such as structural integrity and interactions with each other, while D1–D5 contain a fixed concentration of the drug to assess the influence of optimized polymer blends on the drug.

Table 1 A series of films made without drug nanocomposites

S. No.	Starch (g)	HPMC (g)	Clay (mg)	Drug (mg)	Glycerol (L)
A1	100.0	0.00	150	0	0.0025
A2	0.0	100.0	150	0	0.0025
A3	70.0	30.0	150	0	0.0025
A4	50.0	50.0	150	0	0.0025
A5	30.0	70.0	150	0	0.0025

Table 2 D series of films made with drug-loaded nanocomposites

S. No.	Starch (g)	HPMC (g)	Clay (mg)	Drug (mg)	Glycerol (L)
D1	100.0	0.0	150	750	0.0025
D2	0.00	100.0	150	750	0.0025
D3	70.0	30.0	150	750	0.0025
D4	50.0	50.0	150	750	0.0025
D5	30.0	70.0	150	750	0.0025

3. Characterization techniques

The following characterization methods were employed to ascertain the chemical and physical characteristics of the ciprofloxacin-loaded nanocomposite films, as shown in Fig. 2. The annealing temperature and thermal stability of the thin films were studied by thermogravimetric analysis (DTG-60 Instrument, Shimadzu). FTIR spectroscopy (Thermo Scientific Nicolet 6700 spectrophotometer) was utilized for structure analysis. X-ray diffraction studies were performed (Xpert-Pro

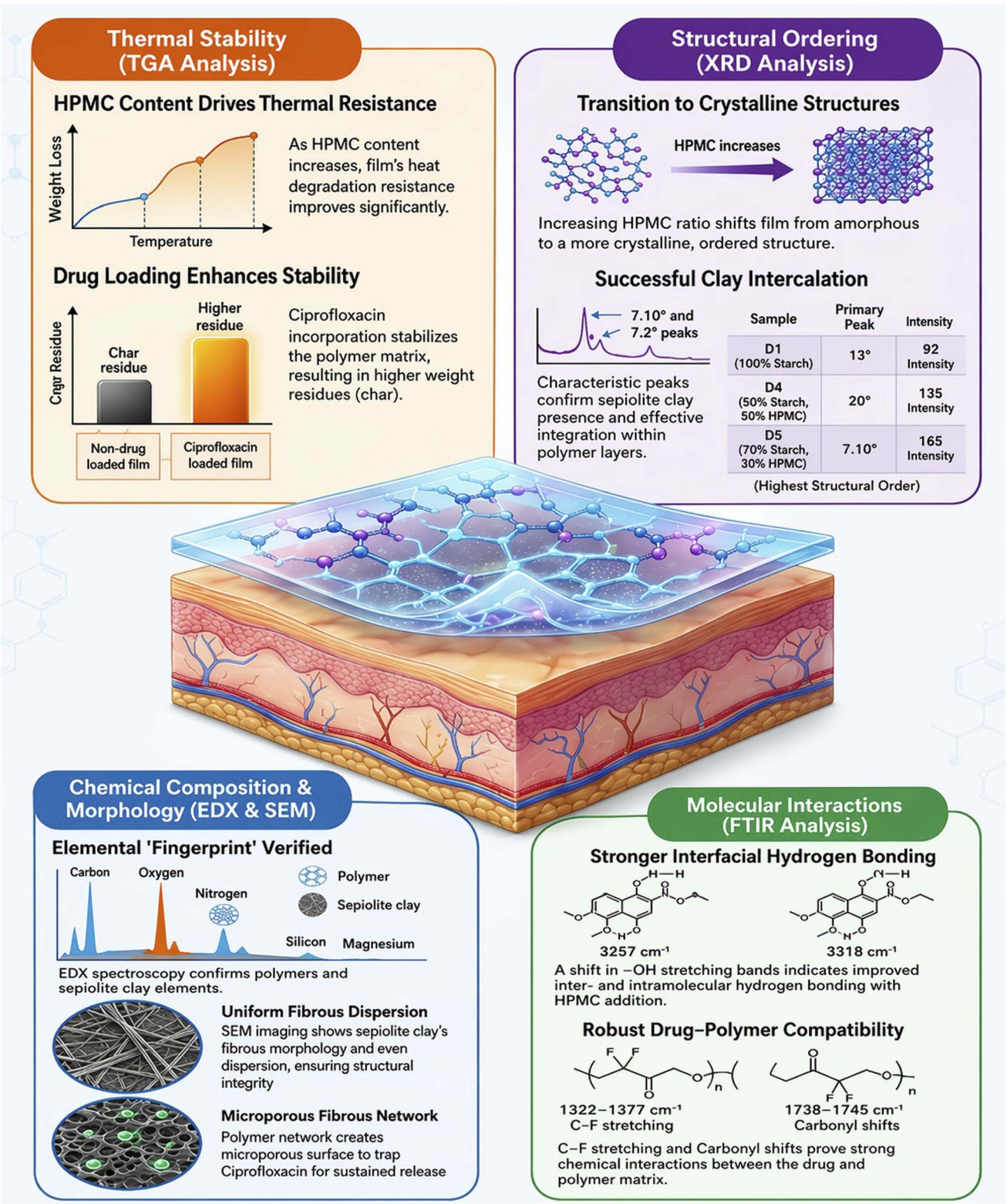


Fig. 2 TGA, EDX, SEM, XRD and FTIR spectroscopic studies of the nanocomposite films.

Table 3 Weight losses of A1–A5 at 100 °C, 200 °C, and 300 °C

S. No.	% wt loss at 100 °C	% wt loss at 200 °C	% wt loss at 300 °C
A1	~4–5%	~28–30%	~60–65%
A2	~3–4%	~30–32%	~50–55%
A4	~4–5%	~27–29%	~55–60%
A5	~3–4%	~25–28%	~45–50%

Analytical) and the morphology was analysed by scanning electron microscopy (Joel, JED, 2300). For the elemental composition, the films were covered with a layer of gold after being laid on an aluminium pan using carbon tape and then examined *via* energy dispersive X-ray spectroscopy (EDX) using the same SEM instrument (JSM 6400F SEM, JEOL, Tokyo, Japan) kept at 20.194 kV (Table 3).

4. Results and discussion

4.1 Thermogravimetric analysis (TGA)

TGA was performed to examine the thermal stability of unloaded starch and HPMC nanocomposites (A1–A5) and those with drug formulations (D1–D5) in nitrogen atmosphere. All samples exhibit a three-stage decomposition pattern with weight losses around 100 °C, 200 °C, and 300 °C due to moisture removal, gradual breakdown of the polymer matrix and bulk decomposition of the polymer matrix, respectively, as shown in Fig. 3 and 4.

Fig. 3 shows that the initial decrease in weight at 100 °C is attributed to the removal of adsorbed water and, among the samples, A5 showed the highest thermal stability. The next decomposition at 200 °C is due to the decomposition of the polysaccharide rings along with dehydration; in this case, the A5 sample again showed superior resistance against weight loss. At the last stage of decomposition, the A1 formulation was found to have high char residue and A5 had the lowest.[21–24] These analyses show that enhancing the content of HPMC polymer can improve the thermal stability of the system, as further summarized in Table 4.

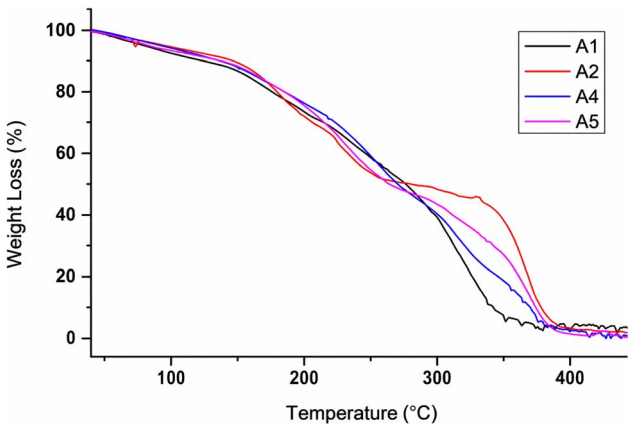


Fig. 3 TGA curves of the A1, A2, A4, and A5 samples.

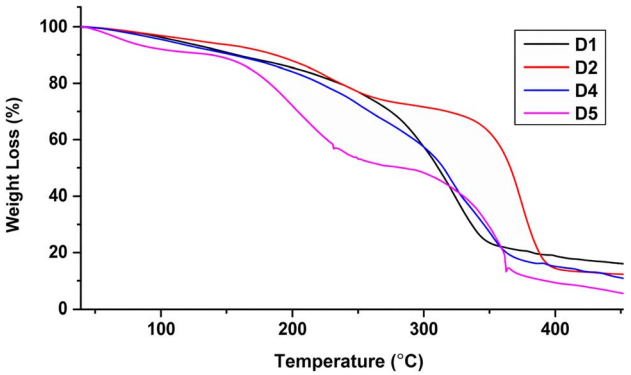


Fig. 4 TGA curves of the D1, D2, D4, and D5 samples.

Table 4 Thermal analyses of D1–D5 at 100 °C, 200 °C, and 300 °C

S. No.	% wt loss at 100 °C	% wt loss at 200 °C	% wt loss at 300 °C
D1	~3–4%	~20–22%	~55–60%
D2	~2–3%	~18–20%	~30–35%
D4	~3–4%	~22–25%	~50–55%
D5	~4–5%	~40–45%	~45–50%

As seen in Fig. 4, the D1 to D5 formulations demonstrate an initial degradation of approximately 2–5% at 100 °C due to moisture evaporation, and moderate loss is observed at 200 °C, with D5 exhibiting higher weight loss. At 300 °C, significant degradation occurs, where D2 shows comparatively higher thermal resistance.[25,26] These analyses show that enhancing the content of HPMC polymer can improve the thermal stability of the drug-loaded system, as further summarized in Table 4.

4.2 Energy dispersive X-ray spectroscopy (EDX) analysis

EDX analysis was performed to study the chemical constituents of the nanocomposite samples and to verify the successful addition of the constituent materials. The spectra of A4 and D4 showed low-intensity peaks of Si, Cl, Ca, Mg, and Cu related to the presence of the sepiolite nanoclay in a relatively small quantity within the blend. The dominant high-intensity peaks of C, O, and N are ascribed to the polymeric matrix, confirming the carbon- and oxygen-rich composition of the starch/HPMC polymers. These results confirm the successful formation of the polymer–clay nanocomposite system, as shown in Fig. 5a and b.[27–30]

4.3 X-ray diffraction spectroscopy (XRD) analysis

XRD characterizations were performed to determine the crystalline and amorphous characteristics of the nanocomposites and the influence of variations in polymer, drug, and clay contents. The XRD examination demonstrated the intercalation and exfoliation processes, as well as the short-range order of the molecular components, in the polymer nanocomposites. The

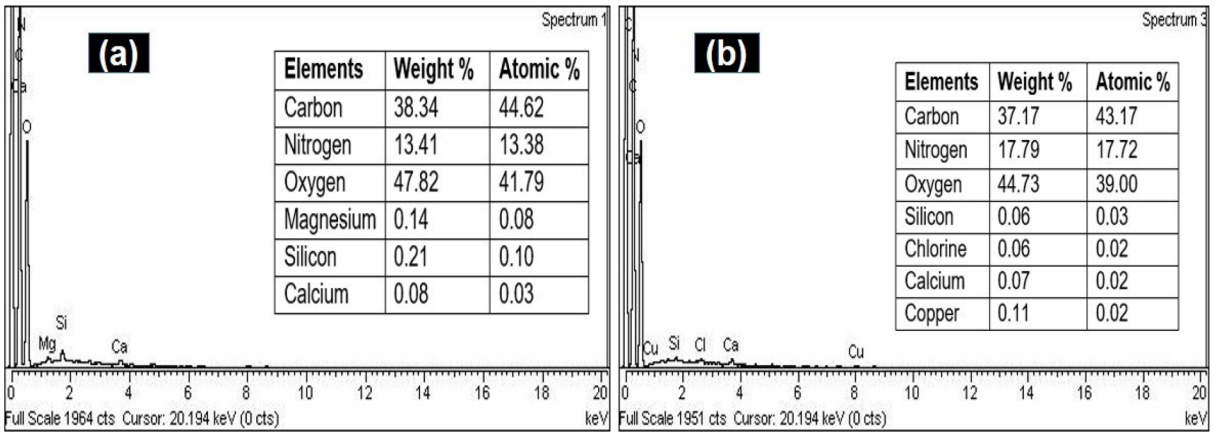


Fig. 5 EDX analyses of (a) A4 sample and (b) D4 sample.

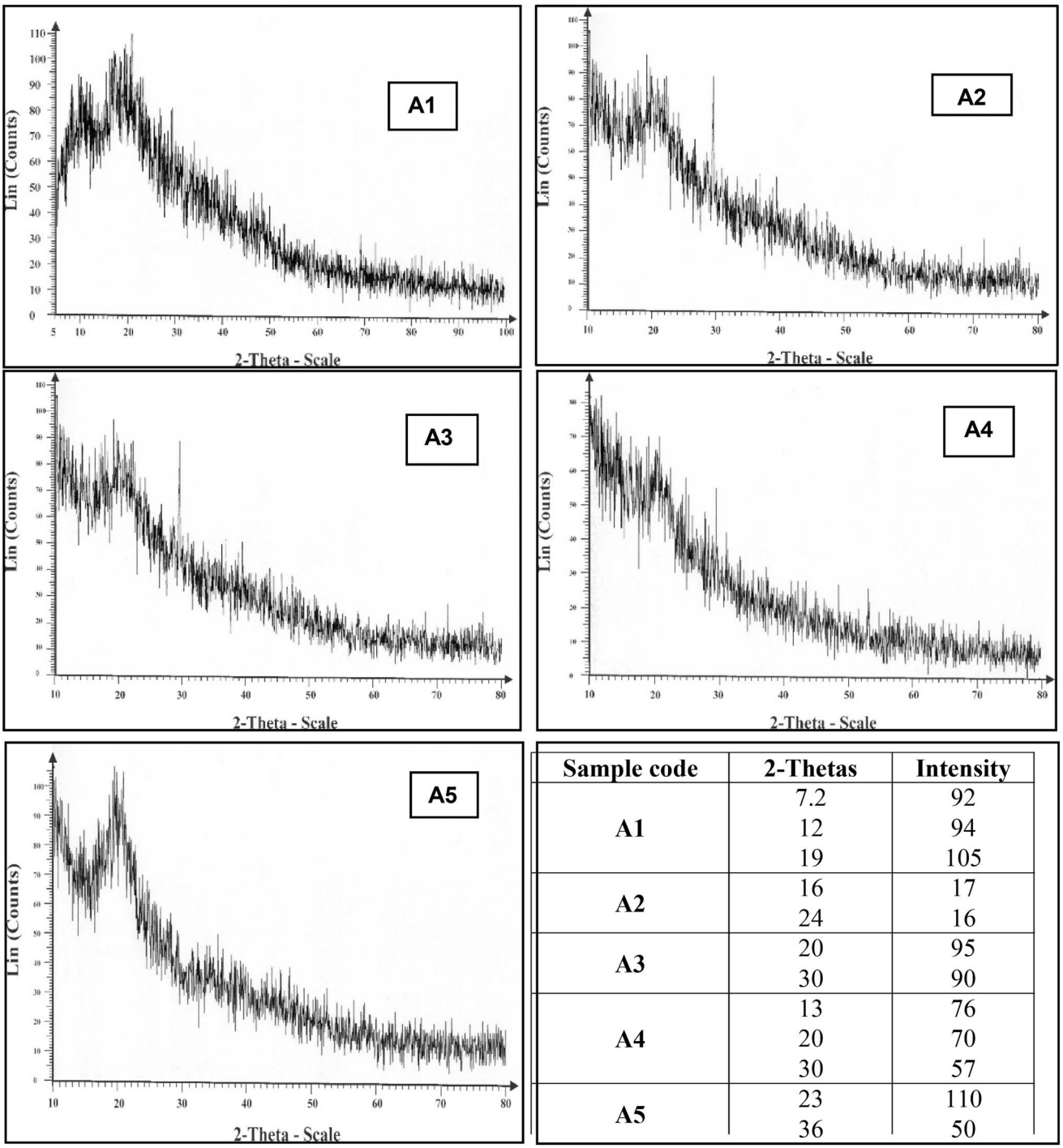
relatively low signal-to-noise ratio is due to the minute amorphous polymer matrix; low drug loading shows weak peaks and good dispersion. The characteristic peaks of the A1 sample at 12° and 19° confirm the crystalline nature, and the peak at 7.2° is due to sepiolite clay, which confirms the nanocomposite formation. Broad reflection peaks at 16° and 24° show the semi crystalline nature of HPMC in the A2 sample. The additional structural arrangement appearing at 20° and 30° of the A3 sample is attributed to polymer clay interactions in A3. New peaks of low intensity at 13°, 20°, and 30° are related to the intercalations of the nanocomposite. The structural modification within the polymer matrix observed in the A5 formulation is confirmed by reflections at $2\theta = 23°$ and 36°. The XRD analysis confirmed that the polymers mixed with clay significantly improved the crystalline structure, while starch performed a crucial role in the intermolecular interaction and formation of the nanocomposite, as shown in Fig. 6. The structural changes in the ciprofloxacin-loaded formulations were confirmed by the XRD analysis. Characteristic peaks in the D1 formulation at 13° and 19° confirm the formation of the composite, and the reflection at 7.10° shows the existence of clay. Ciprofloxacin has diffraction peaks around 19° and 22°, exhibiting its crystalline nature.[31–33] The D2 formulation composed of 100% HPMC showed a peak at 7.10° (intensity ≈ 132) due to crystalline sepiolite, indicating effective polymer–clay interlayer incorporation. In D3, with 70% starch and 30% HPMC, multiple low-intensity reflections at 16°, 25°, 47°, 58°, and 73° suggest a primarily amorphous polymer–drug composite. In contrast, D4 with equal amounts of starch and HPMC contains strong peaks at 10° and 20° with high intensities (≈125 and 135), indicating improved structural ordering. The D5 formulation with 30% starch and 70% HPMC reveals intense reflections at 7.10° and 20° (≈165 and 155), indicating significantly increased crystallinity due to the higher HPMC content. These studies show that HPMC increases improved the arrangement and crystallinity in the ciprofloxacin loaded nanocomposite systems, as shown in Fig. 7.

4.4 Scanning electron microscopy (SEM) analysis

SEM analysis was performed to study the surface morphologies of nanocomposite A4, composed of equal contents of starch and HPMC without drug loading, and the drug-loaded nanocomposite D4 at low and high magnifications, as shown Fig. 8. The findings demonstrated that sepiolite clay has a characteristic fibrous morphology and significantly affects the surface of the polymer matrix.[34] The A4 sample exhibits a relatively uniform surface lacking discernible cracks between the fillers of the two polymers, indicating strong phase compatibility. However, localized gaps observed in certain areas are due to the preparation method, suggesting minute interfacial disorders. On the other hand, the drug-loaded D4 sample shows a more homogeneous morphology with uniform dispersion of sepiolite clay within the polymer matrix. SEM analysis confirmed that drug loading promotes improved structural uniformity and filler distribution within the nanocomposite system. The minor surface roughness and porous structures in the SEM images suggest that the polymer network assists ciprofloxacin entrapment, which contributes to the sustained release behavior.[35,36]

4.5 Fourier transform-infrared spectroscopy (FTIR) analysis

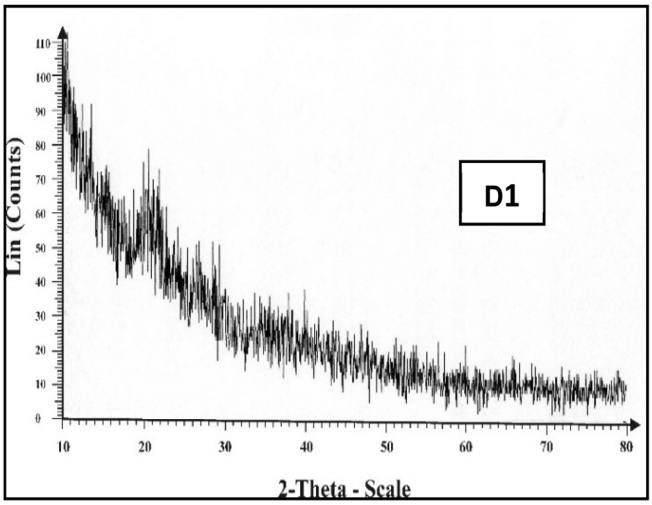
FTIR was performed to check the bonding among the constituents of starch and HMPC. Fig. 9 and 10 show the spectra of formulations A1–A5 and D1–D5, and the typical absorption peaks of the major functional groups are given in Tables 5 and 6. The FTIR spectra show an –OH stretching band in the range of 3277.5–3414 cm^{-1}, indicating hydrogen-bonding within the starch/HPMC nanocomposites. The A1 formulation made from pure starch shows the –OH stretching at 3277.5 cm^{-1}, while the A2 of pure HPMC has the band at 3386 cm^{-1}, reflecting the stronger hydroxyl bonding with HPMC. In the blended samples, the –OH stretching peaks for A4 and A5 appear at 3291 cm^{-1} and 3414 cm^{-1}, respectively, demonstrating a gradual shift toward higher wavenumbers with increasing HPMC quantity. This shift shows improved inter- and intra-molecular hydrogen bonding within the polymer matrix. The slight shift and

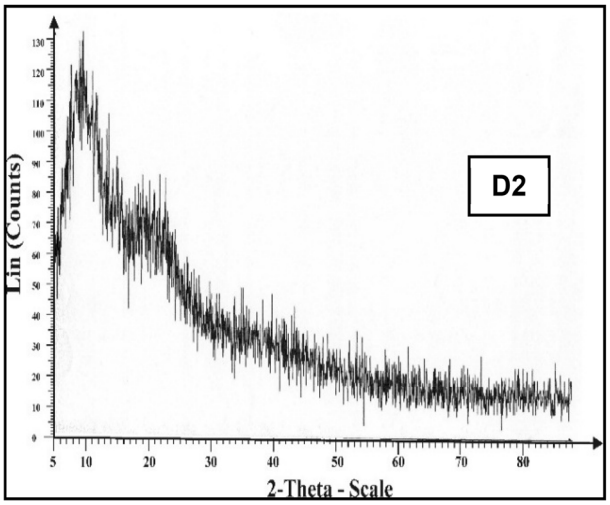


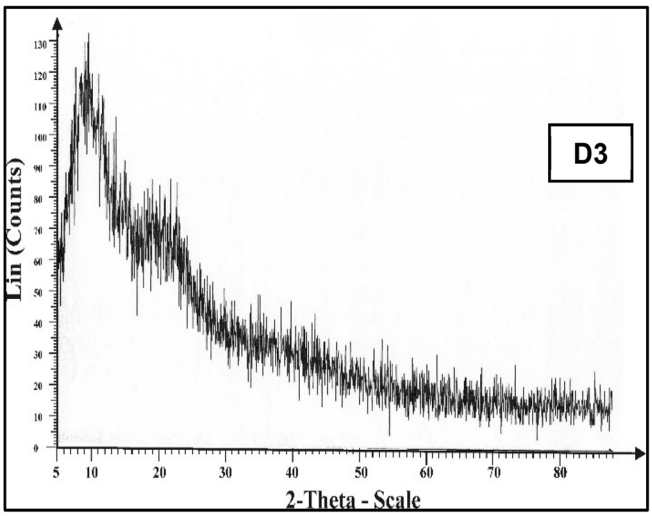
Sample code	2-Thetas	Intensity
A1	7.2	92
	12	94
	19	105
A2	16	17
	24	16
A3	20	95
	30	90
A4	13	76
	20	70
	30	57
A5	23	110
	36	50

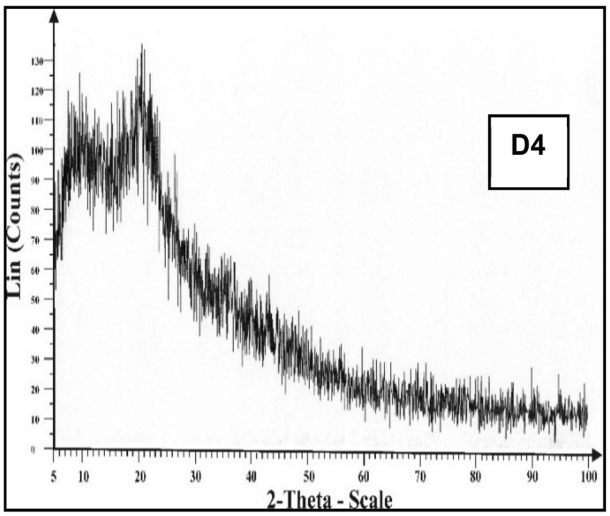
Fig. 6 Impact of polymer quantity on the intensity *versus* 2θ of the A1 to A5 samples.

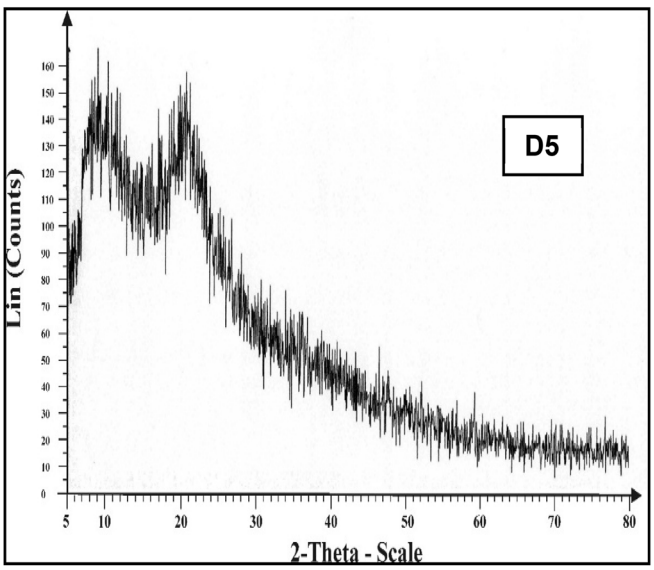
variation in band intensity suggests the formation of hydrogen bonding between the polymers within the nanocomposite.[37] The addition of sepiolite clay is confirmed by the Si–O–Si stretching bands observed at 1002.93, 1016.00, 1050.33, and 1056.87 cm^{-1} for A1 to A5, respectively, shown in Table 5. The stepwise shift of this band toward higher frequencies with increasing HPMC quantity reveals stronger polymer–clay interactions. Collectively, the FTIR outcomes demonstrate that higher HPMC amounts promote stronger hydrogen bonding and increase the interfacial interaction with sepiolite, contributing to the improved structural integration of the reinforced nanocomposite, as shown in Fig. 9.[38–41]











Sample code	2-Thetas	Intensity
D1	13	92
	19	80
D2	7.10	132
	19	85
D3	16	19
	25	16
	47	13
	58	13
	73	11
D4	10	125
	20	135
D5	7.10	165
	20	155

Fig. 7 Impact of ciprofloxacin concentration on the intensity *versus* 2θ of the D1 to D5 samples.

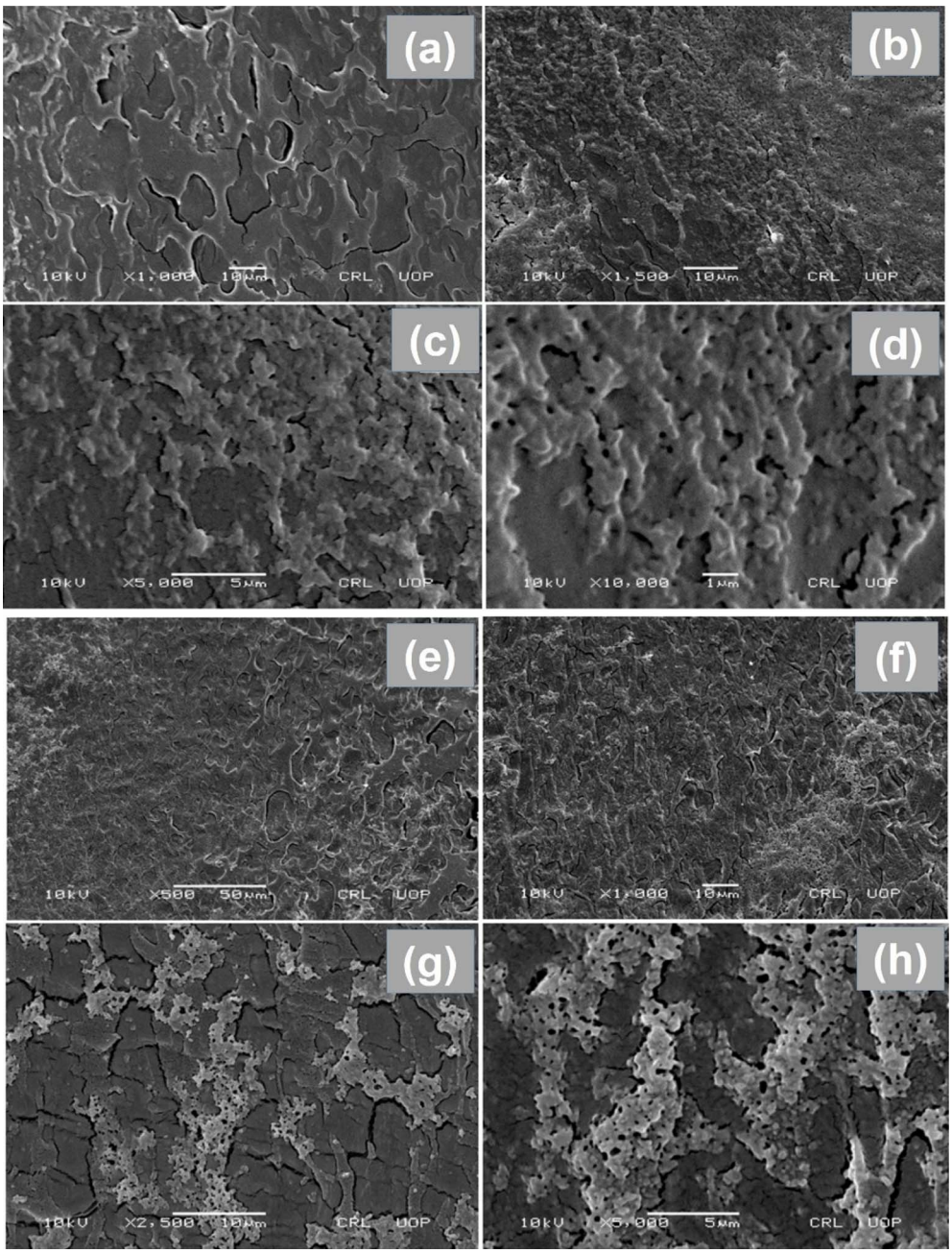


Fig. 8 SEM images for the A4 sample (a–d) and D4 sample (e–h) under different resolutions.

The FTIR study of the drug-loaded starch and HPMC nanocomposite formulations shows important –OH stretching bands in the range of 3257–3298 cm^{-1}, indicating hydrogen-bonding within the polymer matrix. The D1 sample of 100% starch has the –OH band at 3257.06 cm^{-1}, whereas, in sample D2 of 100% HPMC, it was observed at 3318.36 cm^{-1}, aligned with stronger hydroxyl interactions in HPMC. In the blended samples, the –OH stretching shifts to 3250.52, 3386.20, and 3297.93 cm^{-1} for D3, D4, and D5, respectively, as shown in Table 6, indicating integrative polymer interactions and improved compatibility, with the increasing HPMC amount further reinforcing hydrogen bonding.

The emergent peaks at 1322–1377 cm^{-1} are due to the C–F stretching of ciprofloxacin, which is enhanced due to strong polymer–drug compatibility. The carbonyl stretching of ciprofloxacin occurs at 1738.5–1745.0 cm^{-1}, reflecting robust interactions between the drug carbonyl groups and polymer hydroxyls. These studies confirm that the blended polymer matrix supports strong drug–polymer interactions, improving the structural integration and stability of the nanocomposite, as shown in Fig. 10.[42–44]

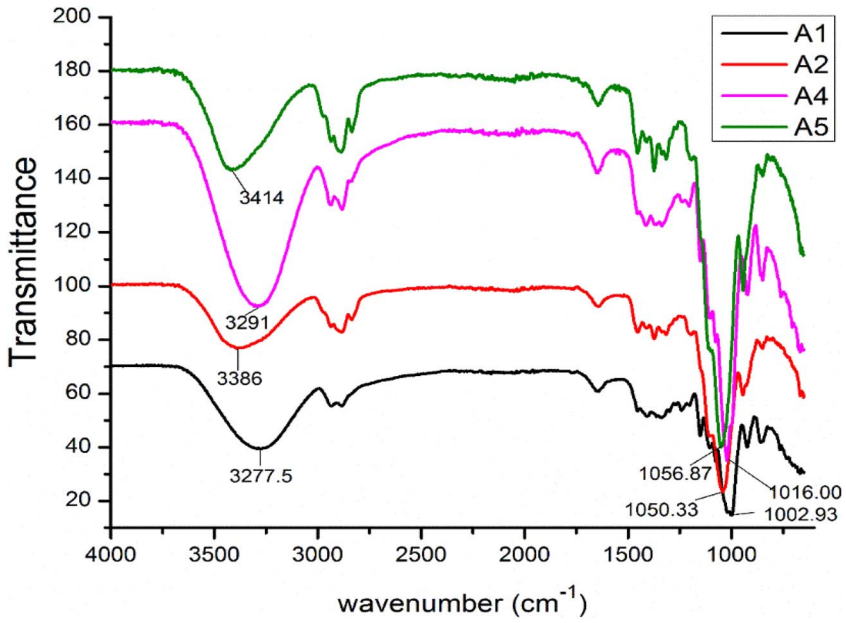


Fig. 9 FTIR spectra of the A1, A2, A4 and A5 samples.

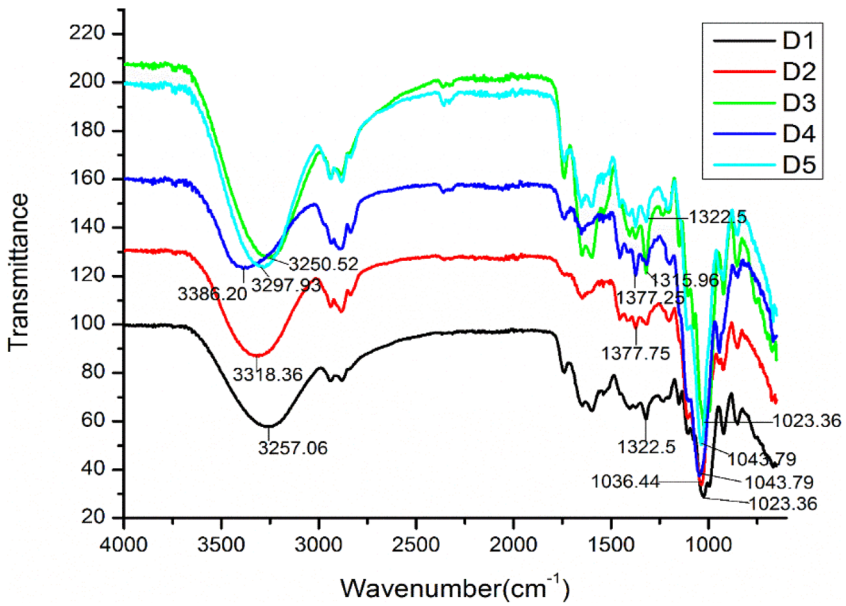


Fig. 10 FTIR spectra of the D1, D2, D3, D4, and D5 samples.

Table 5 FTIR spectroscopic studies of the A1, A2, A4, and A5 formulations

Functional group (stretching in cm^{-1})			Observed values (cm^{-1})			
Starch polymer	HMPC polymer	Sepiolite clay	Sample A1	Sample A2	SampleA4	SampleA5
C–O–H 3200–3400	C–O–H 3400–3500	—	3277.5	3386	3291	3414
—	—	Si–O–Si 980–1070	1002.9	1016.0	1050.3	1056.8

Table 6 FTIR spectroscopic studies of the D1, D2, D3, D4, and D5 samples

Functional group (stretching in cm^{-1})				Observed values (cm^{-1})				
Starch	HMPC	Sepiolite	Ciprofloxacin	D1	D2	D3	D4	D5
C–O–H 3200–3400	C–O–H 3400–3500	—	—	3257.01	3318.360	3250.50	3386.20	3297.90
—	—	Si–O–Si 980–1070	—	1023.30	1036.440	1023.30	1043.790	1043.70
—	—	—	–C=O 1705–1725	1738.50	1656.770	1751.50	1738.50	1745.00
—	—	—	–C–F 1100–1250	1322.50	1377.70	1315.90	1377.20	1322.50

5. Conclusion

The present study successfully demonstrates the development of starch and hydroxypropyl methylcellulose (HPMC)-based nanocomposite films loaded with ciprofloxacin for potential transdermal drug delivery applications. Energy dispersive X-ray (EDX) analysis confirmed the elemental composition and purity of the films, while scanning electron microscopy (SEM) revealed a smooth, crack-free morphology and uniform dispersion of the sepiolite clay within the polymer matrix, indicating strong interfacial compatibility. Fourier transform infrared (FTIR) spectroscopy verified the presence of significant intermolecular interactions among the starch, HPMC, sepiolite, and ciprofloxacin, as evidenced by characteristic peak shifts and functional group identification. X-ray diffraction (XRD) analysis further indicated the crystalline nature of the composites, with increased crystallinity observed at higher HPMC concentrations, which may influence mechanical strength and drug release behavior. Overall, the developed drug loaded polymer clay-based films with enhanced structure and thermal properties exhibit promising structural, morphological, and physicochemical properties, making them suitable candidates for controlled transdermal drug delivery systems; this is particularly relevant for resource limited settings and can guide researchers in optimizing the polymer blends and nanofiller. This approach not only benefits the broader community by uncovering interactions but also spurs research towards efficient, cost-friendly and multifunctional biomedical material development. However, further *in vitro* and *in vivo* investigations are necessary to evaluate the drug release kinetics, long-term stability, and therapeutic efficacy.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data were analyzed and used in this study are available upon a reasonable request from the corresponding author. All relevant experimental data, including characterization results (SEM, FTIR, XRD, and TGA) and raw measurements, are maintained in the institutional repository and can be shared in accordance with the journal's policies.

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