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Structural Characterisation and Kinetic Evaluation of Quinine Sulphate Release from Polylactic Acid/Chitosan Drug Carrier Systems

HOANG THANH DUC[1,*], NGUYEN THI THU TRANG[2] and NGUYEN ANH TUAN[3]

[1]Department of Chemical and Environmental Technology, HaUI Institute of Technology, Hanoi University of Industry, Hanoi, Vietnam
[2]Nonmetallic Materials Physical Chemistry Laboratory, Institute of Tropical Technology-Vietnam Academy of Science and Technology, Hanoi, Vietnam
[3]Admissions and Communications Center, Viet Tri Industrial University, Phu Tho, Vietnam

*Corresponding author: E-mail: ducht@haui.edu.vn; ducht68@yahoo.com.vn

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This study fabricated polylactic acid/chitosan (PLA/CS) drug delivery materials containing quinine sulphate (QS) to control the release rate of quinine sulphate. FTIR, SEM, and DSC analyses revealed a two-phase heterostructure consisting of a PLA matrix and a dispersed phase composed of micrometre-sized chitosan particles associated with QS. The components in the material are linked together *via* hydrogen bonding interactions between hydroxyl groups. Drug release assays showed that the QS content directly affects the kinetics, with samples containing 10-20% QS exhibiting the highest release rate. Notably, the release rate at pH 7.4 was higher than that at pH 2.0, which is favourable for targeted release in the small intestine. The release behaviour followed the Korsmeyer-Peppas kinetic model and was governed primarily by a Fickian diffusion mechanism. These findings suggest that the PLA/CS/QS material system has considerable potential for dose optimisation and improved therapeutic performance in biomedical applications.

Keywords: Morphology, Composite materials, Polylactic acid, Chitosan, Quinine sulphate.

INTRODUCTION

Polylactic acid (PLA) and chitosan (CS) are the two biopolymers widely used in many different fields [1-3]. In recent years, PLA and CS have affirmed their important application position in the fields of engineering and biomedicine [1-3]. The combination of PLA and CS forms a composite material system with considerable potential as a drug carrier for the treatment of cancer, hypertension and cardiovascular diseases [3-5]. Particularly in nanocomposite form, this material system enables optimisation of drug release kinetics by providing an initial rapid release to achieve therapeutic concentrations, followed by sustained and controlled release over time. This mechanism not only enhances pharmacological efficacy but also helps reduce the dosage and frequency of drug use, thereby limiting drug side effects [6,7].

Quinine sulphate (QS) is an antimalarial drug with a short half-life of approximately 11 h, requiring two to three doses per day [8]. Incorporating quinine sulphate into drug carriers prolongs the drug's concentration duration, reduces the number of daily doses and minimizes side effects [9]. Quinine sulphate has hydroxyl groups that can form hydrogen bonds or electrostatic interactions with the amine (-NH_2) group of chitosan and the carboxyl (-COOH) group of PLA. This allows the drug to be carried on PLA/chitosan materials at high concentrations. Furthermore, quinine sulphate is minimally affected by pH ranges from 2.0 to 7.5 and possesses a characteristic absorption spectrum, easily quantified by spectrophotometry (UV-Vis) or HPLC, making it convenient and accurate for monitoring drug release kinetics using mathematical models such as Korsmeyer-Peppas [10]. Therefore, we chose quinine sulphate to study drug release from PLA/chitosan composite materials to obtain information on structural morphology, the binding between PLA and chitosan and QS, the effect of pH and the kinetics of QS release from PLA/chitosan/quinine sulphate composite materials.

In this study, quinine sulphate (QS)-loaded PLA/CS composite materials were successfully synthesised using the microemulsion method [11,12], with QS content ranging from 10% to 50% by weight. The morphological characteristics and structural bonding of the PCQS materials were analysed using Fourier-transform infrared spectroscopy (FTIR), differential

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scanning calorimetry (DSC) and field-emission scanning electron microscopy (FE-SEM). The effects of QS loading content and environmental pH on the drug release process were investigated over a period of 1 to 3 h at pH 2 and pH 7. The rate of quinine sulphate release was evaluated through the amount of quinine sulphate released from the material over a period of 1 to 30 h. The mechanism and kinetics of quinine sulphate release were determined through the evaluation of the compatibility of kinetic models, including zero-order, first-order, Higuchi (HG), Hixson-Crowell (HCW) and Korsmeyer-Peppas (KMP) models.

EXPERIMENTAL

Chemicals used to prepare the polylactic acid/chitosan (PLA/CS) drug delivery materials containing quinine sulphate (QS) include polylactic acid (viscosity ~2.0 dL/g, Mw ~260,000 g/mol, Mw/Mn ~1.5) in granular form; chitosan (acetylation > 77%, viscosity 1220 cP, Mn = 1.61×10^5 Da); Polyethylene oxide (PEO) (Mw = 100,000, glass transition temperature T_g = -67.0 ºC); quinine sulphate were procured from Sigma-Aldrich, USA.

Characterisation: Fourier transform infrared (FTIR) spectra were recorded on an Impact 410-Nicolet Fourier transform infrared spectro-meter. Optical density was measured on a UV-VIS ultraviolet and visible absorption spectrometer. SEM images of the structural morphology of the PCQS composite material sample were observed using an emission field scanning electron microscope (FESEM S-4800, Hitachi, Japan).

Synthesis: Polylactic acid/chitosan containing quinine sulphate (PCQS) composite material samples ranging from 10% to 50% by weight were synthesised using a modified microemulsion method [11,12]. The morphological and structural characteristics of the PCQS composite material samples were determined through FT-IR, SEM and DSC analysis.

The amount of quinine sulphate released from the composite material was determined by UV-VIS spectroscopy using the formula: % quinine sulphate released = $C_t/C_0 \times 100$, where C_0 and C_t are the carrier drug in the material and the drug released at time t. The quinine sulphate release rate was evaluated through the amount of quinine sulphate released in the test solution over time.

The effect of quinine sulphate content on the release rate of quinine sulphate from PCQS composite material was studied in two different mediums *viz*. pH 2 and pH 7.4.

The kinetics of quinine sulphate release from the composite materials were determined by evaluating the suitability of the following kinetic models: zero-order model (ZO): $W_t = W_o + K_{1.t}$; first-order model (FO): $\log C = \log C_o - K_{2.t}/2.303$; Higuchi model (HG): $W = K_{3.t1/2}$; Hixson-Crowell model (HCW): $W_{o1/3} - W_{t1/3} = K_{4.t}$ and Korsmeyer-Peppas model (KMP): $M_t/M_\infty = K_{5.tn}$.

Preparation of PCQS composites by water/oil/water micro-emulsion method: Initially, 1.2 g of PLA was dissolved in 100 mL dichloromethane to obtain solution n1. Solution n2 was prepared by dissolving 0.6 g chitosan and 20 g PEO in 100 mL of 1% acetic acid. Separately, quinine sulphate (0-50 wt.% with respect to PLA) was dissolved in 15 mL ethanol to form solution d. All solutions were magnetically stirred for 1.5–2 h until complete dissolution.

For emulsion preparation, solution d was added to solution n1, followed by ultrasonication (10 min, 120 Hz) and magnetic stirring (10 min). This sonication and stirring sequence was repeated three times to achieve a homogeneous mixture. Subsequently, solution n2 was introduced gradually and the mixture was further subjected to alternating ultrasonication and stirring cycles (10 min each). After addition of 200 mL distilled water, the dispersion was again treated with alternating sonication and stirring to ensure uniformity. The resulting emulsion was cooled for 2 h and the precipitated composite was collected by centrifugation. The obtained solid was washed twice with distilled water, freeze-dried and ground into powder form. The prepared PCQS composites containing 0, 10, 20, 30, 40 and 50 wt.% QS were labelled as PCQS0, PCQS10, PCQS20, PCQS30, PCQS40, and PCQS50, respectively.

RESULTS AND DISCUSSION

Structural studies of the PCQS composites: The FTIR spectra of the PCQS composite materials exhibit characteristic peaks corresponding to C=N, C-N and C=C stretching vibrations, which are absent in the PLA/CS sample (Fig. 1). Furthermore, significant shifts in the wavenumbers of functional groups were observed. Specifically, the characteristic peaks for C=O and C-O-C groups in PLA/CS, originally at 1770 cm^{-1} and 1081 cm^{-1}, shifted to 1760 cm^{-1} and 1091 cm^{-1} in the PCQS composite, respectively. Furthermore, the C-N stretching vibration peak of quinine sulphate shifted from 1230 cm^{-1} to 1131 cm^{-1} in the PCQS composite. These shifts can be attributed to dipole-dipole interactions between the amine groups in CS or the nitrogen atoms in QS and the carboxyl groups in PLA. Moreover, hydrogen bonding likely occurs between the hydroxyl groups of CS, quinine sulphate and PLA (Table-1).

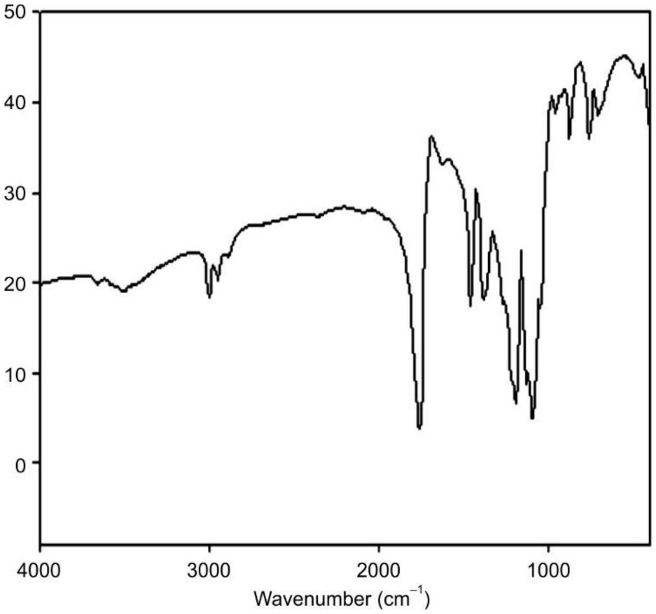

Fig. 1. FTIR spectrum of PCQS30 composite material

TABLE-1
CHARACTERISTIC VIBRATION PEAK POSITIONS OF FUNCTIONAL GROUPS IN QUININE SULPHATE, PLA/CS (PC) COMPOSITE AND PLA/CS/QUININE SULPHATE (PCQS) MATERIALS

Samples	ν(C=O) (cm^{-1})	ν(C-O-C) (cm^{-1})	ν(C-N) (cm^{-1})
QS	–	1089	1197
PC	1758	1081	–
PCQS10	1759	1088	1103
PCQS20	1751	1090	1107
PCQS30	1756	1091	1122
PCQS40	1759	1090	1126
PCQS50	1758	1092	1130

Thermal studies: The differential scanning calorimetry (DSC) analysis (Fig. 2) of PLA, CS and the PLA/CS composite revealed that the glass transition temperature Tg and melting temperature (T_m) of PLA were 54.7 ºC and 150.5 ºC, respectively, while the T_g of CS was 90.5 ºC. Upon incorporating CS into the PLA matrix, the T_g of the resulting composite shifted toward higher values compared to that of neat PLA, indicating a degree of miscibility between the two components. This shift in the T_g can be attributed to dipole-dipole interactions and hydrogen bonding between the amine and hydroxyl groups of CS and the carboxyl groups of PLA, as well as the structural reorganisation of the PLA crystalline phase.

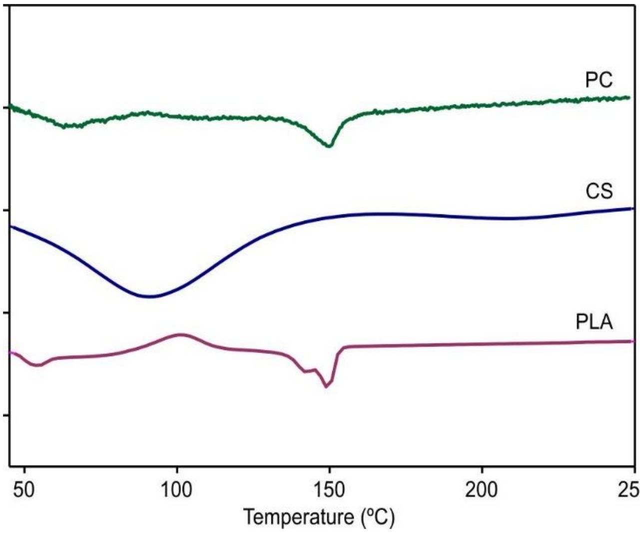

Fig. 2. DSC plots of PLA, CS and PLA/CS composite materials

The DSC plots of quinine sulphate and PCQS composite materials with different QS contents (Fig. 3) show that quinine sulphate has a T_m at 238.5 ºC. The T_m values of the PCQS composite materials all shift towards being larger than the T_m of PLA and smaller than the T_m of quinine sulphate. This demonstrates that quinine sulphate is compatible with CS and PLA. The shift in T_m of PCQS is due to the dipole-dipole interactions and hydrogen bonding between the >C=N- and hydroxyl groups in quinine sulphate with the carboxyl groups in PLA, as well as a rearrangement of the PLA structure. The characteristic DSC values of PLA, CS and PCQS composite materials with different QS contents are listed in Table-2.

TABLE-2
DSC CHARACTERISTICS OF PLA, CS AND PCQS COMPOSITE MATERIALS WITH DIFFERENT QS CONTENT

Samples	T_g (ºC)	T_m (ºC)	ΔH_m (J/g)	χ_c^* (%)
PLA	54.7	150.5	8.50	9.1
CS	90.6	205.3	18.5	–
QS	–	238.5	57.8	–
PC	64.8	151.1	16.0	17.2
PCQS10	73.8	162.3	34.8	37.4
PCQS20	72.6	163.2	27.1	29.1
PCQS30	69.3	162.3	30.5	32.7
PCQS40	70.9	162.6	32.9	35.3
PCQS50	73.2	163.9	33.7	36.2

where: Degree of crystallinity cc (%) = $\Delta H_m \times 100/\Delta H_m^*$, with ΔH_m^* = 93.1 J/g (PLA); T_g: glass transition temperature; T_m: melting temperature; ΔH_m: melting enthalpy.

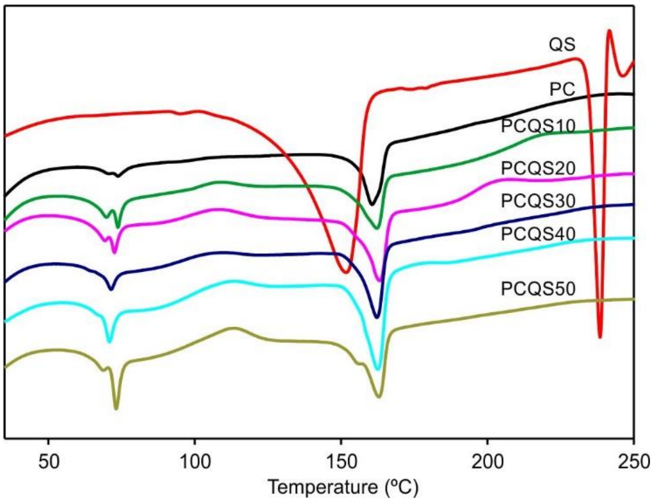

Fig. 3. DSC plots of quinine sulphate and PCQS composite materials with different QS content

Based on the differential thermal analysis and FTIR results, the interfacial interactions in the PCQS composites are attributed primarily to the hydrogen bonding among the hydroxyl groups of PLA, chitosan and QS. In addition, the intermolecular dipole–dipole interactions are likely formed between the >C=N functional groups of quinine sulphate, the amino ($-NH_2$) groups of chitosan and the carboxyl groups of PLA, contributing to improved phase compatibility within the composite system (Fig. 4a-b).

Morphological studies: SEM micrographs of the PCQS10 composite (Fig. 5) show a heterogeneous two-phase morphology consisting of a continuous PLA matrix and a dispersed CS/QS phase. The CS and QS components are uniformly distributed within the PLA matrix, while QS aggregates with chitosan to form spherical particles that are firmly embedded in the PLA substrate. The dispersed particles observed in the PCQS10 sample range from approximately 50 to 200 μm in size and are evenly distributed over the PLA surface. Similar surface morphologies were also observed for the PCQS20, PCQS30, PCQS40 and PCQS50 composites.

Compared with the binary PLA/CS blend, the PCQS composites exhibited an increase in dispersed phase size, which can be attributed to the aggregation of quinine sulphate with chitosan and PLA through intermolecular hydrogen bonding

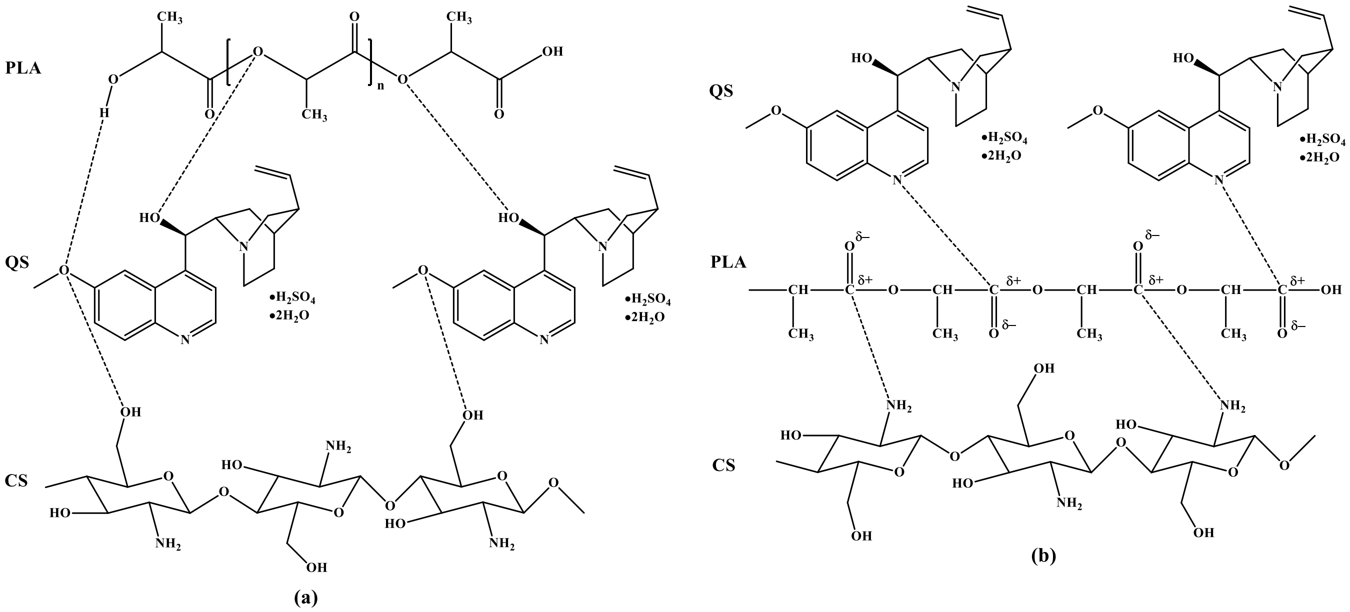

Fig. 4. Hypothesis regarding (a) hydrogen bonding and (b) dipole interaction between functional groups of PLA, CS and quinine sulphate in PCQS composite material

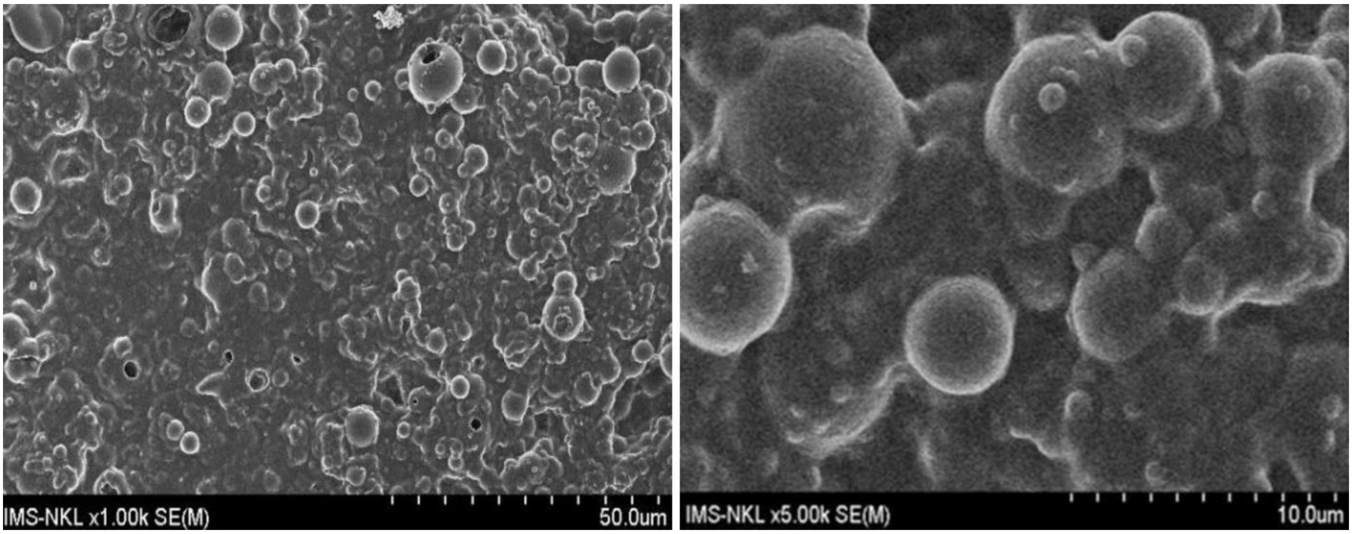

Fig. 5. SEM micrographs of the PCQS10 composite at 1000x and 5000x magnifications

among hydroxyl groups. In addition, the incorporation of PEO during synthesis improved the compatibility and interfacial adhesion among PLA, CS and QS phases. These observations confirm the presence of hydrogen bonding and dipole–dipole interactions between the functional groups of PLA, CS and QS, contributing to enhanced phase adhesion and interfacial interactions within the PCQS composites.

Effect of QS content on quinine sulphate release from PCQS composites: The effect of QS content in PCQS composites on the QS release rate was investigated in two media: an acidic environment (pH = 2) and a weakly alkaline environment (pH = 7.4). The amount of QS released from PCQS samples over a period of 1-30 h in solutions of pH 2 and pH 7.4 is presented in Table-3.

In an acidic medium (pH 2), the cumulative release of quinine sulphate (QS) from the PCQS composites remained below 50% after 30 h of immersion. An increase in QS loading above 20 wt.% resulted in a reduction in the release rate. Among the samples, PCQS20 exhibited the highest QS release (44.23%) after 30 h, followed by PCQS10 (41.68%). In contrast, PCQS30 and PCQS40 showed comparatively lower release, while PCQS50 exhibited the slowest release, reaching only 33.41% after 30 h (Table-3).

In a weakly alkaline medium (pH 7.4), QS release occurred more rapidly than at pH 2. More than 50% of the incorporated QS was released within 12 h for all samples. PCQS20 again demonstrated the highest release efficiency, reaching 62.98% after 12 h. However, composites containing higher QS concentrations showed slower release behaviour. PCQS50 displayed the lowest release rate, with 50.54% release after 12 h and 54.72% after 30 h (Table-3). These results indicate that the QS content strongly influences the release behaviour of the PCQS composites under both acidic and weakly alkaline conditions. Increasing the QS loading beyond 20 wt.% reduced

TABLE-3
CUMULATIVE QS RELEASE FROM PCQS COMPOSITE MATERIALS IN A pH = 2 AND 7.4 SOLUTION

Time (h)	Amount of QS released (%)									
	PCQS10		PCQS20		PCQS30		PCQS40		PCQS50	
	pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4
1	22.34	32.54	24.46	34.76	21.97	29.98	22.65	26.78	19.97	29.09
2	24.76	35.78	25.78	37.89	24.12	33.56	23.98	28.98	20.34	30.96
3	26.83	36.52	28.43	42.56	25.16	35.62	26.76	34.78	22.89	33.56
4	29.89	39.12	29.78	44.21	26.98	38.78	27.75	36.79	23.68	36.78
5	31.12	40.89	30.69	45.95	27.56	39.78	28.76	42.67	24.82	38.45
6	32.95	43.89	32.14	50.95	29.62	45.68	29.98	43.63	25.67	40.09
7	33.56	47.04	34.54	54.49	30.12	49.67	31.89	44.58	26.71	44.68
8	35.21	52.48	36.13	57.78	32.56	52.43	32.09	48.94	28.42	48.08
12	38.96	61.96	37.89	62.89	36.25	55.68	33.73	53.21	30.05	50.54
16	39.34	65.34	40.34	63.76	36.57	57.21	34.78	54.89	31.34	53.67
20	40.45	67.98	42.14	64.54	37.29	58.97	36.07	55.05	32.92	54.07
24	41.75	69.78	43.58	65.21	37.49	58.68	36.71	56.21	33.15	53.89
26	42.09	70.72	44.01	65.56	38.67	59.02	36.92	56.11	33.32	55.04
28	42.12	70.98	44.54	65.21	38.34	58.97	37.02	56.78	33.45	54.89
30	41.68	70.03	44.23	65.78	38.98	58.79	37.01	55.98	33.41	54.72

the release rate, whereas the PCQS20 sample exhibited the most efficient QS release profile.

Effect of medium pH on the release of QS from PCQS composites: The PCQS20 composite, which exhibited the highest QS release rate, was selected to investigate the effect of solution pH on QS release behaviour. Two media, pH = 2 and pH = 7.4, were chosen to simulate the acidic gastric environment and the slightly alkaline intestinal environment of the human body, respectively. Evaluating the influence of pH on QS release is important for determining whether the drug carrier promotes greater drug release in the stomach or in the small intestine, thereby improving drug efficacy while minimizing degradation and gastric irritation.

Table-4 demonstrate that the pH of the medium significantly affects QS release from the PCQS20 composite. After 30 h, the cumulative QS release reached only 41% at pH = 2, whereas approximately 70% release was achieved at pH = 7.4. These findings indicate that the QS release rate in a weakly alkaline medium is considerably higher than that in an acidic medium, which is favourable for enhanced drug absorption in the small intestine.

TABLE-4
AMOUNT OF QS RELEASED FROM PCQS20 MATERIAL IN pH = 2 AND pH = 7.4 SOLUTIONS

Time (h)	% QS, pH = 2.0	% QS, pH = 7.4
1	24.46	34.76
2	25.78	37.89
3	28.43	42.56
4	29.78	44.21
5	30.69	45.95
6	32.14	50.95
7	34.54	54.49
8	36.13	57.78
12	37.89	62.89
16	40.34	63.76
20	42.14	64.54
24	43.58	65.21
26	44.01	65.56
28	44.54	65.21
30	44.23	65.78

A rapid release of QS was observed during the initial 12 h, followed by a slower and more stable release phase. The results suggest that the QS release behaviour can be effectively controlled by incorporating PEO as a compatibilizer and by adjusting the drug loading during fabrication of the PCQS composites. This observation is consistent with the findings reported by Prabaharan *et al.* [5] for PLA/CS-based lamivudine drug delivery systems.

Release kinetics of QS from PCQS composites: The kinetics of QS release from PCQS materials in pH = 2 and 7.4 solutions over 1-30 h were studied by analyzing and evaluating QS release processes using kinetic models: zero-order, first-order, Higuchi, Hixson-Crowell and Korsmeyer-Peppas.

The cumulative release of QS from the PCQS composites in solutions of pH = 2 and pH = 7.4 over 1-30 h was analysed using different kinetic models. Regression analysis and kinetic equations were generated using MS Excel in order to determine the release mechanism of QS from the composite carrier system.

The graphs, kinetic equations and regression coefficients for QS release from the PCQS20 sample in a pH = 2 medium are presented in Fig. 6. Among the evaluated models, the Korsmeyer-Peppas model exhibited the highest correlation coefficient ($R^2 = 0.9845$) indicating the best fit for the experimental data. The release behaviour followed the exponential equation: $M_t/M_\infty = kt_n$, where M_t/M_∞ represents the fractional drug release at time t, K is the kinetic constant related to the drug-polymer system and n is the diffusion exponent associated with the release mechanism.

For the PCQS20 sample, the diffusion exponent was n = 0.193, which is lower than 0.43, indicating that the QS release follows Fickian diffusion according to the Korsmeyer-Peppas model (Table-5). This suggests that QS diffusion occurs along the concentration gradient, from regions of higher concentration to lower concentration. Similar results were obtained for PCQS10, PCQS30, PCQS40 and PCQS50 in the pH = 2 and 7.4.

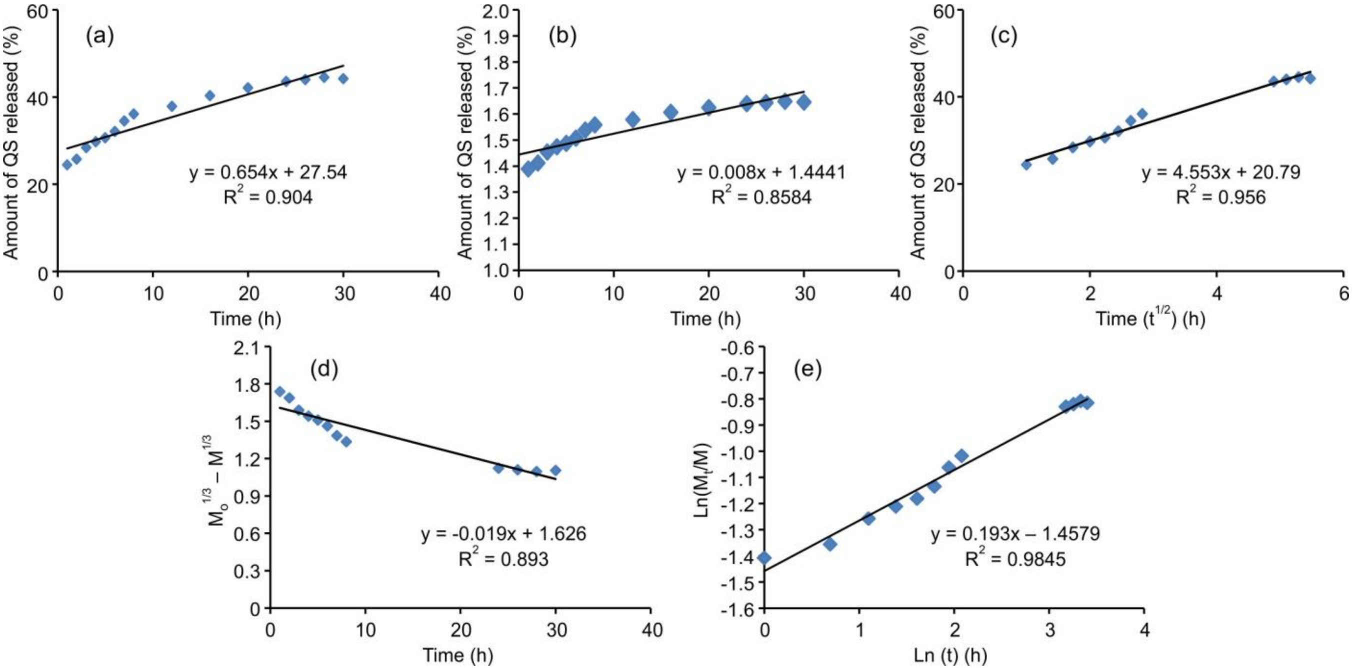

Fig. 6. Kinetic models reflecting the dependence of amount of QS released from PCQS20 material on time in a pH = 2 solution: (a) zero-order kinetic equation, (b) first-order kinetic equation, (c) Higuchi model kinetic equation, (d) Hixson-Crowell model kinetic equation and (e) Korsmeyer-Peppas model kinetic equation

TABLE-5
DIFFUSION CONSTANTS ACCORDING TO KORSMEYER-PEPPAS MODEL AND DIFFUSION MECHANISMS

Diffusion constant (K)	Diffusion mechanism
≤ 0.43	Fick diffusion
0.45 < K < 0.89	Non-fick diffusion
K ≥ 0.89	Non-fick kinetics, first-order, zero-order kinetics

Table-6 shows that all PCQS composites exhibited the highest R^2 values with the Korsmeyer-Peppas model in both acidic and weakly alkaline media, confirming that this model best describes the QS release behaviour. The diffusion exponent values for PCQS10 were 0.192 (pH = 2) and 0.026 (pH = 7.4); for PCQS30, 0.177 and 0.018; for PCQS40, 0.152 and 0.019; and for PCQS50, 0.169 and 0.019, respectively. Since all n values are below 0.43, the release mechanism can be classified as Fickian diffusion.

The comparatively low regression coefficients obtained for the zero-order and first-order models indicate that these models are less suitable for describing QS release from the PCQS composites. This behaviour may be attributed to the biphasic release profile, consisting of an initial rapid release during the first 12 h followed by a slower and more controlled release stage. These results confirm that QS release from the PCQS composites follows the Korsmeyer-Peppas kinetic model and proceeds predominantly through Fickian diffusion.

Based on the interfacial interactions, the morphological characteristics and release kinetics, the PLA/chitosan-based carrier system demonstrates effective drug encapsulation and controlled release capability. Compared with conventional drug carriers such as liposomes and inorganic nanoparticles (*e.g.*

TABLE-6
KINETIC PARAMETERS DATA OF QS RELEASE FROM PCQS COMPOSITE MATERIALS IN pHs = 2 AND 7.4 SOLUTIONS

Model		PCQS10		PCQS20		PCQS30		PCQS40		PCQS50	
		pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4	pH = 2	pH = 7.4
ZO	R^2	0.821	0.898	–	0.771	0.849	0.760	0.833	0.755	0.867	0.799
	K	0.592	1.371	–	0.953	0.532	0.903	0.433	0.883	0.445	0.832
FO	R^2	0.821	0.859	–	0.724	0.865	0.712	0.848	0.687	0.899	0.753
	K	0.592	0.011	–	0.007	0.007	0.008	0.421	0.008	0.430	0.008
HG	R^2	0.932	0.909	–	0.880	0.970	0.867	0.934	0.871	0.964	0.895
	K	5.065	8.723	–	7.020	3.694	6.658	3.061	6.542	3.083	6.077
HCW	R^2	0.858	0.934	–	0.790	0.881	0.768	0.815	0.747	0.871	0.813
	K	0.578	0.031	–	0.021	-0.017	0.022	-0.014	0.022	-0.015	0.021
KMP	R^2	0.982	0.919	–	0.924	0.986	0.948	0.979	0.918	0.979	0.947
	K	0.193	0.026	–	0.018	0.177	0.018	0.152	0.019	0.169	0.019

ZO: zero-order model, FO: first-order model, HG: Higuchi, HCW: Hixson-Crowell model, KMP: Korsmeyer-Peppas model.

TABLE-7
COMPARISON OF SOME CHARACTERISTICS OF PLA/CHITOSAN DRUG CARRIER MATERIAL WITH OTHER DRUG CARRIER MATERIALS

Characteristic	PLA/chitosan	Liposomes (lipid system) [13]	Inorganic carrier (nano silver, silica) [14]
Sustainability	Very high: PLA creates a strong mechanical framework, providing better protection for the medication	Low: Easily destroyed by enzymes or changes in temperature/pH	Very high: Stable crystal structure
Drug release control	Dual: Initially fast-releasing chitosan, followed by extended-release PLA	Difficult to control: Rapid drug release often occurs when the lipid membrane ruptures	Slow release: Usually occurs through structural voids
Biocompatibility	Good: Both break down into non-toxic substances	Good: Because it has a similar structure to a cell membrane	Moderate: May cause accumulation of heavy metals and long-term toxicity

silver or silica nanoparticles), PLA/chitosan composites offer several advantages, including improved biocompatibility, controlled release behaviour, and enhanced drug protection (Table-7). These findings suggest that the PLA/chitosan system is a promising platform not only for quinine sulphate delivery but also for the controlled delivery of other therapeutic agents, including antihypertensive drugs, cardiovascular drugs, antibiotics and vaccines.

Conclusion

The release behaviour of quinine sulphate (QS) from the polylactic acid/chitosan/quinine sulphate (PCQS) composites is significantly influenced by the drug loading content. An increase in QS loading leads to a decrease in the release rate, while the highest release efficiency was observed for composites containing 10-20 wt.% QS. The QS release process from the PCQS composites is best described by the Korsmeyer-Peppas kinetic model, indicating that drug diffusion into the release medium follows Fickian diffusion behaviour. The release rate of QS in acidic media is lower than that observed in weakly alkaline media (pH = 7.4). In the weakly alkaline environment, the release process occurs in two stages: an initial rapid release within the first 12 h, followed by a slower and more controlled release phase. These findings demonstrate that the PCQS based composite system is capable of providing sustained and stable drug release in the small intestine, while reducing drug degradation in the stomach and improving drug absorption efficiency.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language. The authors reviewed and edited the content and take full responsibility for the published work.

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