RESEARCH ARTICLE

Release of curcumin incorporated in albumin loaded silica

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Abstract

In this work, we have prepared a new drug delivery system consisting of silica (SiO_2) as the main carrier, while albumin acted as the co–carrier in order to control the release of drug. The system was prepared by simple wet chemical method. The efficiency of the designed system was tested in the delivery of a hydrophobic drug, curcumin through an *in–vitro* procedure. The results show that the release percentage of curcumin was increased with the presence of the co–carrier. The intermolecular interaction of curcumin with albumin and the competition between them to locate on the surface of silica affect the release system. Besides, the curcumin release amount was corresponded to the composition of the silica carrier in the systems. Consequently, the potential for silica/albumin use as a drug carrier was ascertained.

Keywords: silica, albumin, curcumin, co–carrier, composition, release mechanism, intermolecular interaction

INTRODUCTION

Over the past six decades, drug release has been an important focus in the field of drug delivery. The evolvement in the drug–delivery area led to the exploration of new dosing routes, for instance, transdermal, vaginal, pulmonary and sublingual (Wilson *et al*., 2011). New pharmaceutical compound or 'drug' with increasing complexity and more functions has been progressively formulated and designed by the experts (Barbe *et al*., 2004). The drug, either naturally derived or synthetically produced, are extensively used in controlled drug release in order to optimize bio–efficacy, treatment of particular illness and subsequently improving human life (Fu *et al*., 2010). Each drug has specific demands upon its administration in order to achieve an ideal therapeutic efficiency

Drug release refers to the process of transferring of drug solutes from the primary position in an incorporated matrix to the outer surface, and then to the release medium (Mhlanga *et al*., 2014). The release process can be influenced by number of factors which are the interaction of the drug with the matrix, the properties of the solute and the release environment. In general, two important release mechanisms that associated in drug release are dissolution and diffusion. Dissolution is defined as a process of transferring a drug from its solid phase to the surrounding medium where it is influence by solubility and particle size (Siepmann *et al*., 2012). Diffusion of a substance occurs from regions that have the higher concentration to regions of lower concentration. The movement of the substance is the result of the gradient concentration and also associated with the Brownian motion of the molecules (Siepmann *et al*., 2012).

Silica particle has been used immensely used as drug carrier due to its favorable properties which are hydrophilic, non–toxic, excellent biocompatible and tunable porosity (Gangwar *et al*., 2013 and Barbe *et al*., 2004). Its hydrophilic character due to the presence of hydroxyl groups on its surface avoids its elimination by the reticuloendothelial system, where this would enhance circulation time of drug in blood stream (Horjacada *et al*., 2006). In addition, the use of SiO_2 in cosmetic and foods additives have been approved by US Food and Drug Administration (FDA) as "Generally Recognized As Safe" (Steven *et al*., 2014). Most of the studies on drug delivery use amorphous xerogels (Quintanar–Guerrero *et al*., 2009), fumed silica nanoparticles or mesoporous SiO_2 such as MCM–41 or SBA–15 (Diab *et al*., 2017)

In this work, we want to develop a new SiO_2–based drug delivery system with the incorporation of protein as a co–carrier. It is suggested that the use of co–carrier could controlled the release amount of drug since it can play a role in the intermolecular interaction within the system. Here, egg white protein or ovalbumin is used as the source of albumin. Ovalbumin consists of 385 amino acid residues with a molecular weight of 47 kDa. It has an internal disulfide bond and four free sulphydryl groups (Elzoghby *et al*., 2012). Its tertiary structure was composed of nine α–helices and three β–sheets that folded into a compact globule supported mainly by the hydrogen bonds and disulfide bonds. Besides that, albumin can enhance the solubility of hydrophobic drug where it could bind to the hydrophobic pockets via albumin via hydrophobic or van der Waals interactions (Mohanta *et al*., 2013). The presence of numerous functional groups in protein residues allows the interaction of drug–albumin and albumin–silica. Previously, albumin (human or bovine

serum) has been widely used as a drug carrier in the form of nanoparticles or microparticles (Elzoghby *et al.*, 2012). The preparation techniques of albumin particles include desolvation (coacervation), emulsification and thermal gelation. Nevertheless, there were some issues that arise regarding on the techniques where; desolvation method require the use of crosslinking agent such as glutaraldehyde that could led to toxicity, oil residue and surfactant need to be remove in emulsification method and thermal stabilization method is selectively for heat–tolerate drug.

Here, the incorporation of curcumin to the silica/albumin carrier will be carried out by using simple wet chemical method. The proposed method here promotes feasibility of the preparation step as well as ensuring the integrity of drug is not affected. There will be no employment of chemical modification to the carriers that would probably result in a covalent attachment between the drug and the carrier. This is merely important since the drug need to be certainly detached from the carrier matrix afterward.

The ability of the silica/albumin act as a carrier was used in the in–vitro administration of hydrophobic drug, curcumin. Numerous studies on using curcumin as a therapeutic agent have been carried out due to its anti–oxidant, anti–inflammatory, anti–carcinogenic and anti–bacterial properties (Chereddy *et al.*, 2013, Gangwar *et al.*, 2013, Hatamie *et al.*, 2012, Jithan *et al.*, 2011 and Mathew *et al.*, 2012). The anti–oxidant property of curcumin is contributed to the presence of phenolic –OH and *β*–diketone moiety that have the ability to scavenge the molecular species of active oxygen. However, its hydrophobic nature and poor bioavailability leads to low absorption, high rate of metabolism within the living system and rapid elimination from the body system. Curcumin undergoes rapid degradation in pH 7.4 buffer solution, where it is degraded more than 50% in 30 min release period (Leung *et al.*, 2015). Gangwar *et al.*, (2013) in his study has shown that silica:curcumin conjugates prepared by a modified Stöber method. By using this method, bioavailability character of curcumin was enhanced while its therapeutic activity remains intact. However, in the in–vitro study, 50% of curcumin has been already discovered in the dissolution medium within 7 h of release, where this result is quite discouraging for application that require a slow–release drug. Therefore, there is a need for extensive research on this matter, which do not only enhance the bioavailability of curcumin, but also to keep the multifunctional properties of the conjugated system. Fig. 1 shows the chemical structure of curcumin with the presence of phenolic –OH and *β*–diketone moiety.
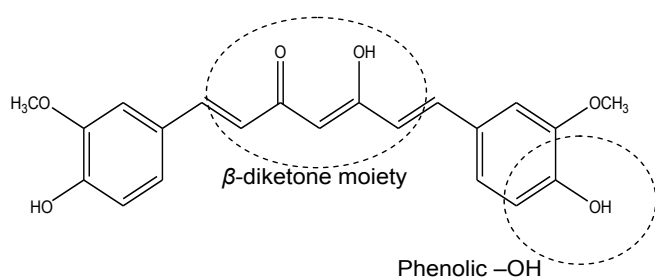

Fig. 1 Chemical structure of curcumin (Leung *et al.*, 2015).

The resulting system was silica/albumin/curcumin (SiO₂/Alb/Cur). The release of curcumin will be conducted through in–vitro procedure and the release medium used was phosphate buffer solution pH 7. The use of albumin as the co–carrier and its effect on release of curcumin from the system will be highlighted. In addition, we attempt to control the release of curcumin by varying the composition of SiO₂ carrier. The rational reason for this attempt is to investigate the relationship of carrier towards the release of curcumin and its particular release mechanism. Consequently, the outcome of the release experiment will give insight of release mechanism of the systems.

EXPERIMENTAL

Materials

Albumin/ovalbumin, from chicken egg white (crystallized and lyophilized, Sigma–Aldrich), tetraethoxysilane (TEOS, Acros), sodium borohydrate (NaBH₄, QRec), curcumin (QRec), ammonia solution (NH₃, 28%, QRec) and ethanol (Merck) were used without further purification. Buffer solution (potassium dihydrogen phosphate, pH 7.00, Merck) and deionized water (DI water) were used in the experiment.

Instrumentations

Synthesized silica–based drug delivery systems were characterized by diffuse reflectance UV–Visible spectroscopy (DR UV–Vis, Perkin Elmer Ultraviolet–visible Spectrometer Lambda 35), Fourier transform infrared–attenuated total reflectance spectroscopy (FTIR–ATR, Thermo Scientific Model Nicolet iS10), thermogravimetric analyzer (TGA, TGA/SDTG 851^e METTLER TOLEDO), and scanning electron microscopy (SEM, JEOL JSM–6390LV). UV–Visible spectrophotometer (Shimadzu 1800) was used to observe the amount of albumin and curcumin in the release medium.

Preparation of SiO₂–based system

Four samples of SiO₂–based drug delivery systems were prepared in this work and are summarized in Table 1. For comparison purpose, albumin/curcumin (Alb/Cur) sample with the weight ratio of 1.0/1.0 (wt/wt) was prepared as a comparison purpose. Studies on the release mechanism of curcumin from the system were investigated by studying the effects of albumin as the co–carrier and the effect of the SiO₂ compositions. Tetraethoxysilane (TEOS) has been used as the precursor for Stöber silica.

Table 1 Experimental detail of SiO₂–based drug delivery systems.

SiO₂–based system	Weight ratio	Abb.
SiO₂/Cur	10.0/1.0	S(10.0)C
SiO₂/Alb/Cur	10.0/1.0/1.0	S(10.0)AC
	8.5/1.0/1.0	S(8.5)AC
	6.0/1.0/1.0	S(6.0)AC

Preparation of Silica/Curcumin (SiO₂/Cur)

SiO₂ particles were prepared by hydrolysis and condensation of TEOS in ethanol, in the presence of ammonia as the catalyst following previous method (Ibrahim *et al.*, 2011). Stöber silica was first prepared by ethanol (0.370 mL, 0.001664 mol), NH₃ (0.042 mL, 0.001664 mol), H₂O (0.150 mL, 0.00832 mol) and the mixture solution was stirred for 5 minutes in a clean, empty glass vial (10.5 mL). Under a gentle stirring condition, a mixture of TEOS (0.370 mL, 0.001664 mol) in ethanol (0.370 mL, 0.001664 mol) was added dropwisely into the vial. Then, the solution containing silica in sol phase was stirred overnight to allow the completion of the hydrolysis process. Next, curcumin (0.01 g) was added directly into the pre–synthesized silica sol under gentle stirring condition. The solution mixture was stirred at room temperature for 24 h. Then, the sample was dried at 40 °C in an oven overnight before being collected and kept in a desiccator.

Preparation of Silica/Albumin/Curcumin (SiO₂/Alb/Cur)

SiO₂/Alb/Cur systems (S(10.0)AC, S(8.5)AC and S(6.0)AC) were prepared according to below preparation procedure. For the preparation of S(10.0)AC, Stöber silica was first prepared by ethanol (0.370 mL, 0.001664 mol), NH₃ (0.042 mL, 0.001664 mol), H₂O (0.150 mL, 0.00832 mol) n and the mixture solution was stirred for 5 minutes in a clean, empty glass vial (10.5 mL). Under a gentle stirring condition, a mixture of TEOS (0.370 mL, 0.001664 mol) in ethanol (0.370 mL, 0.001664 mol) was added dropwise into the vial. The solution was stirred overnight to allow the completion of the hydrolysis process. Alb/Cur mixture was prepared with the weight ratio of 1.0/1.0 (wt/wt). For the preparation of Alb/Cur mixture,

albumin (0.01 g) was first weighed in a clean vial and dissolved in distilled water (3 mL). Under stirring condition, curcumin (0.01 g) was added into the solution. After 5 minutes of stirring, acetone (0.2 mL) was added to fully homogenize the solution mixture. The mixture was then left under stirring for 3 h before being added to the pre–synthesized silica in colloidal form. Afterwards, the mixture of Alb/Cur was placed into a clean beaker (25 mL). Under the gentle stirring condition, the pre–synthesized silica sol was added into the solution of Alb/Cur. The mixture was then left under stirring at room temperature for 24 h. Next, the mixture was transferred into a petri dish and covered with perforated aluminium foil. The sample was allowed to dry at room temperature for four days before being collected and kept in a desiccator. The similar steps were repeated for the preparation of S(8.5)AC and S(6.0)AC with the corresponding amount of silica

Preparation of Albumin/Curcumin (Alb/Cur)

Alb/Cur mixture was prepared with the weight ratio of 1.0/1.0 (wt/wt). For the preparation of Alb/Cur mixture, albumin (0.01 g) was first weighed in a clean vial and dissolved in distilled water (3 mL). Under stirring condition, curcumin (0.01 g) was added into the solution. After 5 minutes of stirring, acetone (0.2 mL) was added to fully homogenize the solution mixture. The mixture was then left under stirring for 3 h before transferred into a petri dish and covered with perforated aluminium foil. The sample was allowed to dry at room temperature for four days before being collected and kept in a desiccator.

Release Experiment

An accurately weighed quantity of samples (50 mg) was added to 30 mL of PBS pH 7 and stir gently at 37 °C. At a different time intervals, 3 mL of the buffer solution was removed, and replaced with 3 mL of fresh medium. The sample was sonicated for 5 minutes and then centrifuged for 5 minutes at 4000 rpm to obtain a clear supernatant. The free albumin was detected at 280 nm and curcumin was identified at 427 nm by using a UV–Visible spectrophotometer. Albumin and curcumin content was detected by preparing a standard calibration curve of albumin and curcumin in the phosphate buffer solution prior to analysis.

RESULTS AND DISCUSSION

Fig. 2 shows the infrared spectra for (a) albumin, (b) curcumin, (c) Alb/Cur, (d) Stöber silica (e) S(10.0)C, (f) S(10.0)AC (g) S(8.5)AC and (h) S(6.0)AC. As seen in Fig. 2(a), albumin has a broad vibration peak at around 3293 cm^{-1}. This vibration band was corresponding to the amide A band that consists of N–H stretching (Kong et al., 2007). Albumin also exhibits an intense amide I band at 1649 cm^{-1}, corresponding to C=O stretching, while amide II band at 1541 cm^{-1} corresponded to the out–of phase combination of in–plane C–N stretching and N–H bending of amide groups (Nafisi et al., 2011). The presence of amide I band (1600–1700 cm^{-1}) is related to the protein backbone conformation and it is commonly used to study the conformational change of its secondary structure Significant peak at 1396 cm^{-1} corresponding to the COO– of side chains in albumin can also be clearly seen. Notable peak at 3508 cm^{-1} in Fig. 2(b) of curcumin is due to the presence of free O–H in curcumin. Besides that, there is also a remarkable vibration peak at 1625 cm^{-1} that signifies C=O group, and more intense peak at 1507 cm^{-1} attributed to the C=C vibration band. The presence of aromatic C=C in curcumin were in the range of 1400–1520 cm^{-1}. Vibration bands of the C–O–C group in the range of 1000–1200 cm^{-1} also are observed which were attributed to the symmetric and asymmetric configurations of the C−O−C chains (Hatamie et al., 2012 and Gangwar et al., 2013). The broad feature at around 3420 cm^{-1} on Fig. 2(d) was the characteristic vibration bands of the O–H stretching of surface silanols. The intense band appearing at 1104 cm^{-1} was assigned to –Si–O–Si– asymmetric stretching vibrations. The symmetric stretching vibration of –Si–O–Si– was observed at 797 cm^{-1} and its bending mode appeared at 471 cm^{-1}. The vibrational peak at 952 cm^{-1} was attributable to the Si–O in–plane stretching vibrations of the silanol Si–OH groups. The low

energy band at around 560 cm^{-1} was assigned to the defects in SiO$_2$'s network (Gangwar et al., 2013 and Popat et al., 2012).
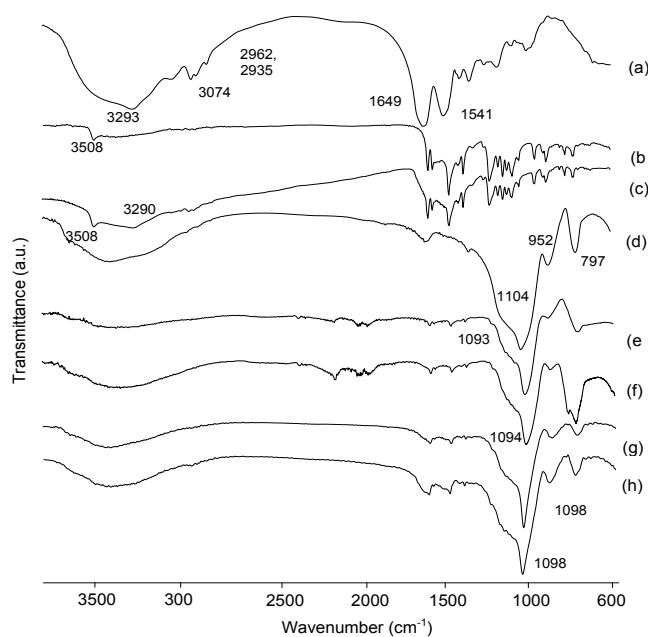

Fig. 2 FTIR spectra of samples (a) albumin, (b) curcumin, (c) Alb/Cur, (d) Stöber silica, (e) S(10.0)C, (f) S(10.0)AC, (g) S(8.5)AC and (h) S(6.0)AC.

Referring to Fig. 2(c) of Alb/Cur, a minimal shift of amide A band of albumin (3293 to 3290 cm^{-1}) can be observed. Then, there is no shifting shown by the vibration band of –OH group of curcumin at 3508 cm^{-1}. These results suggested that in the Alb/Cur system, albumin might not interact intermolecularly through the hydrogen bond between the N–H group of amide A of albumin (3293 cm^{-1}) with the hydroxyl –OH of curcumin (3506 cm^{-1}). However, we cannot further clarify that curcumin can be physically bonded through the enolic –OH group at 3375 cm^{-1} into the electronegative oxygen in the carbonyl backbone of albumin that stabilized protein secondary structure. This is due to the overlapping vibration peaks in the range of 1500–1700 cm^{-1}. As shown in Fig. 2(e–h), the asymmetric stretching of –Si–O–Si– band in S(10.0)C, S(10.0)AC, S(8.5)AC and S(6.0)AC systems are shifted to the higher energy region. This reveals that albumin and curcumin might attach to the silanol surface of silica carrier. The vibration bands corresponded to the free –OH of curcumin was not present in all of the SiO$_2$/Alb/Cur samples as being overlapped by the O–H stretching band of silanols of SiO$_2$. Apart from that, there was overlapping of general vibration bands for albumin and curcumin in the range of 1640–1500 cm^{-1}. These vibration bands include the stretching of C=O, N–H bend, and CN stretching of albumin, C=C, C=O and aromatic C=C of curcumin.

Through FTIR spectra, it is impossible to identify the specific interaction of albumin (co–carrier) with curcumin, albumin with SiO$_2$, and SiO$_2$ with curcumin. However, it can be stipulated that albumin and curcumin were interacted with the SiO$_2$ carrier through the silanol group of SiO$_2$, as proved by the shifting of –Si–O–Si– asymmetric stretching band in Fig. 2(e–h).

Fig. 3 shows DRUV spectra of samples (a) curcumin (b) Alb/Cur (c) S(10.0)C, (d) S(10.0)AC, (e) S(8.5)AC and (f) S(6.0)AC. Curcumin exhibits an absorbance peak at ~474 nm due to the π–π* transition of the conjugated diaryl heptanoid chromophore groups (Gangwar et al., 2013 and Hatamie et al., 2012). Fig. 3(b–f) shows that this characteristic peak is seen to be intact in Alb/Cur and SiO$_2$/Alb/Cur systems. Broadening of signature absorbance peak with a bathochromic shift in Alb/Cur system might indicates the interaction of curcumin towards albumin. Then, the signature peak exhibited a hypsochromic shift as curcumin interacted with SiO$_2$ carrier in the S(10.0)C, S(10.0)AC, S(8.5)AC and S(6.0)AC systems. Referring to

the Fig. 3(c–d), the signature peak was shifted to a different direction in S(10.0)C and S(10.0)AC systems. The possible explanation that could justify this occurrence is due to the nature of interaction of curcumin with the albumin, and curcumin with the SiO₂/albumin carrier in the S(10.0)C and S(10.0)AC systems, respectively. Up to this stage, the effect of albumin as the co–carrier remain unclear (from the spectroscopic studies) as there is no difference shown by DRUV spectra of S(10.0)C and S(10.0)AC systems. This matter will be discussed further in TGA analysis.
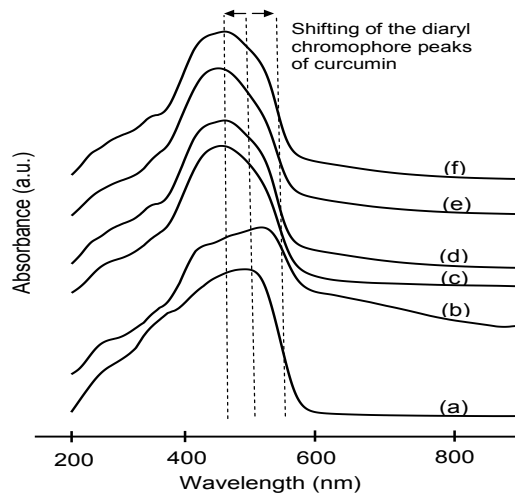

Fig. 3 DRUV spectra of samples (a) curcumin, (b) Alb/Cur, (c) S(10.0)C, (d) S(10.0)AC, (e) S(8.5)AC and (f) S(6.0)AC.

The morphology of Stöber SiO₂ particles, SiO₂/Alb/Cur systems and Alb/Cur are displayed in Fig. 4. As shown in Fig. 4(a), SiO₂ particles that were prepared following the Stöber method exhibits particle size of 100–300 nm. The sample of S(10.0)C in Fig. 4(b) revealed that the system has an irregular and heterogenous surface morphology. The surface shows random aggregates of SiO₂ particles and an elongated–bar–like structures that can be attributed to the curcumin, similar to the morphology of untreated curcumin reported by Yadav *et al.*, (2014). Incorporation of albumin as the co–carrier does bring forth change to the surface morphology of the synthesized SiO₂–based system. It can be observed that S(10.0)AC, S(8.5)AC and S(6.0)AC systems in the Fig. 4(c–e) exhibited a homogenous surface morphology. The bar–like structure which was expected to be curcumin, was incorporated within the SiO₂ particles together with the co–carrier. As shown in the Fig. 4(f), Alb/Cur sample demonstrate a heterogenous surface morphology where irregular block–like shape appeared.

Thermal analysis of the SiO₂–based drug delivery systems was investigated using TG as shown in Fig. 5. Fig. 5(a) illustrated that Alb/Cur exhibits three stages of weight loss, where 3% of moisture was removed initially. The second stage of weight loss of the sample from 160–470 °C (45%) can be attributed to the collective degradation of albumin and curcumin that were loosely attached to one another or near to the sample surface. The degradation of curcumin has been reported to be in the range of 200–400 °C (Mathew *et al.*, 2012). The weight loss of protein around 300 °C was caused by the breakdown of the amino acid residues, as well as the cleavage of the peptide bonds in the albumin (Aswathy *et al.*, 2012). Albumin and curcumin that curcumin that interact strongly between them or located in the sample core was suggested to be degraded starting at 470–900 °C (46%).
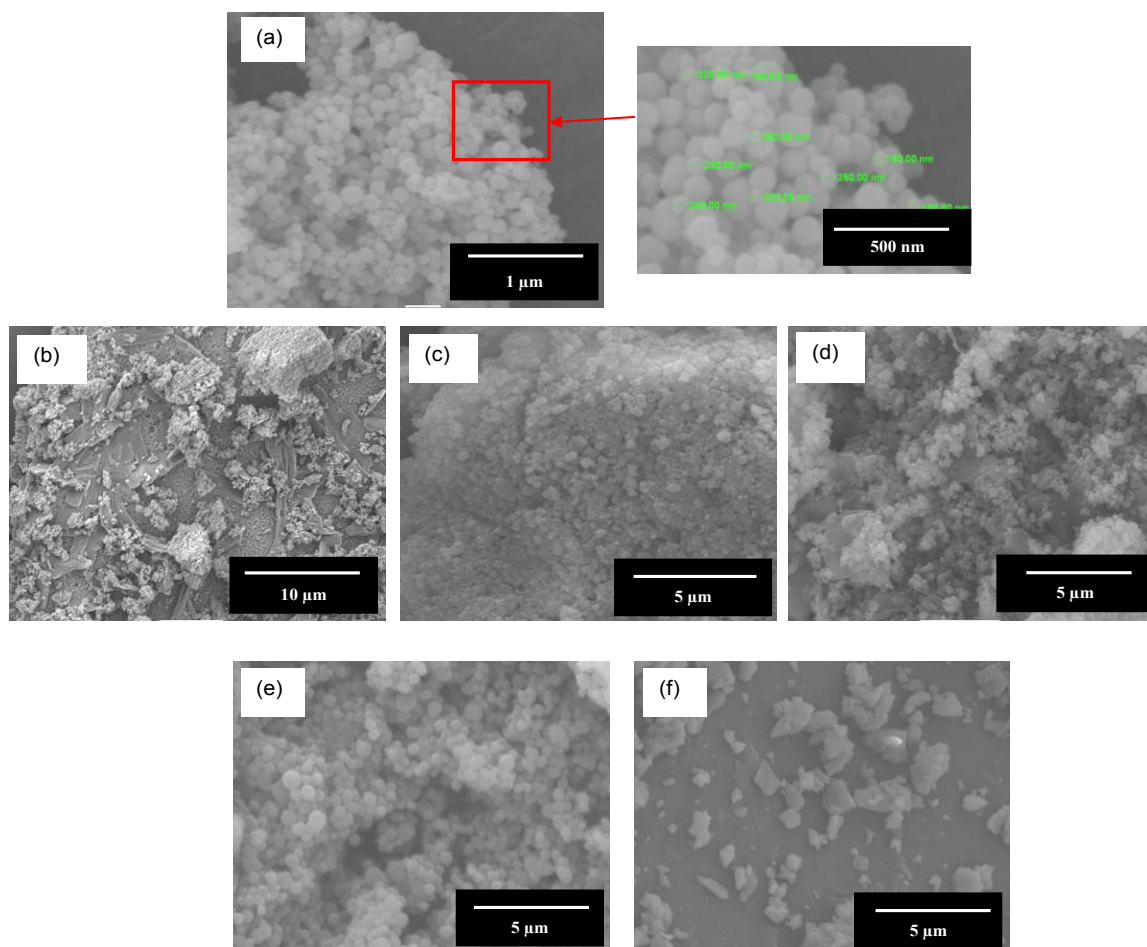

Fig. 4 SEM images of samples (a) Stober SiO₂, (b) S(10.0)C, (c) S(10.0)AC, (d) S(8.5)AC and (e) S(6.0)AC and (f) Alb/Cur.

Referring to Fig. 5(b), it can be observed that S(10.0)C exhibits three stages of weight loss. It is shown that 5% of water was removed initially. Then, the sample was further degraded from 200 °C to 500 °C, with a mid–point at 300 °C. This 7% of weight loss can be attributed to the curcumin that was loosely incorporated between the SiO_2 particles or curcumin that near to the surface of sample. The third weight loss of 6% in the range of 500 °C to 700 °C is might corresponded to degradation of curcumin that adsorbed strongly to the silanol's surface of SiO_2.

TGA curve of S(10.0)AC, S(8.5)AC and S(6.0)AC in Fig. 5(c–e) demonstrates two weight losses. The moisture content of the S(10.0)AC, S(8.5)AC and S(6.0)AC system was 6%, 3% and 4%,
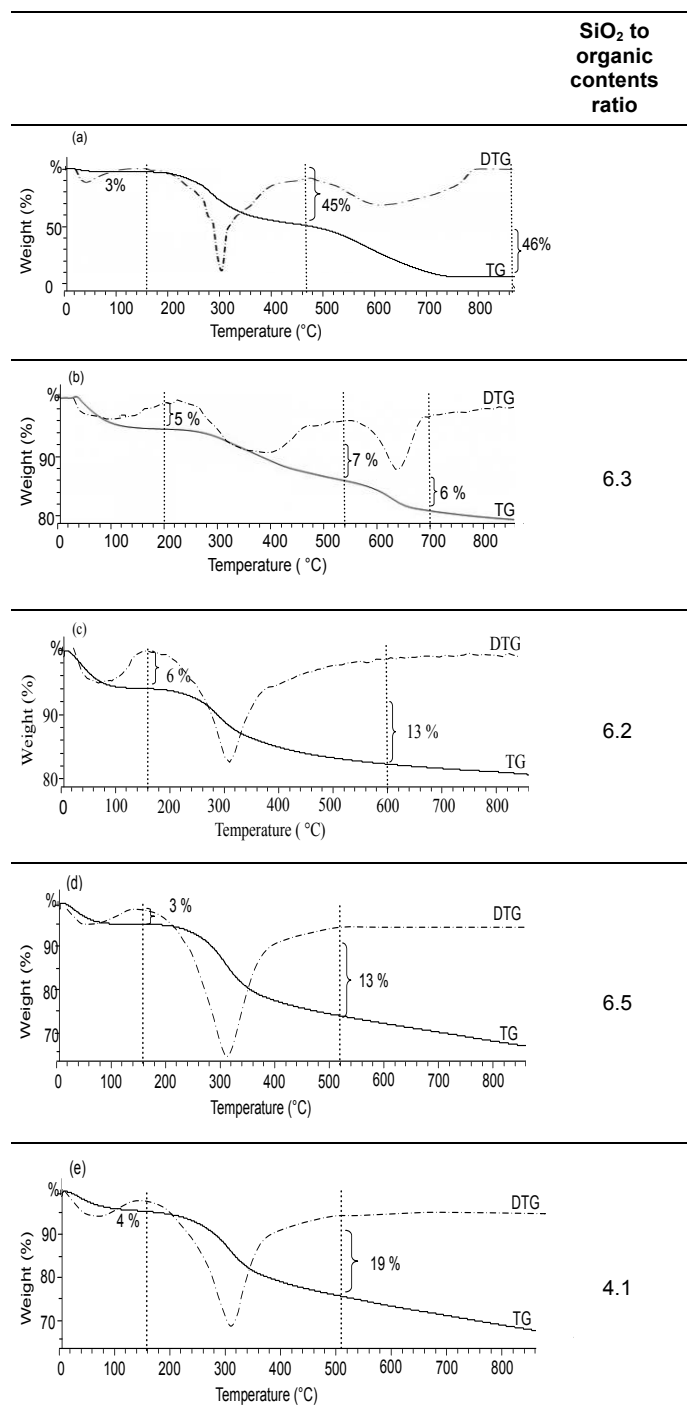
respectively. The second weight loss of S(10.0)AC started at 150 °C, reaching mid–point at 310 °C and ended at 600 °C. The S(8.5)AC system then exhibited the second weight loss from 160 °C to 520 °C with a mid–point of 320 °C. As for the S(6.0)AC system, the second weight loss occurred in the range of 160 °C to 510 °C, reaching mid–point of 320 °C. The second weight loss can be attributed to the gradual degradation of albumin and curcumin that was attached to the external surfaces of SiO_2. Based on the results here, it can be seen that the degradation range of second weight loss of SiO_2/Alb/Cur system was slightly delayed as the system has a higher composition of SiO_2. It is suggested that a more stable system was attained when the amount of carrier was increased since higher –OH groups of SiO_2 were available for the attachment with albumin and curcumin. The difference of weight loss stage between S(10.0)C and S(10.0)AC proved that there was an effect of the co–carrier in the intermolecular interaction between curcumin and SiO_2 carrier.

The cumulative release percentage of the S(10.0)C, S(10.0)AC, S(8.5)AC and S(6.0)AC systems and its total release percentage are shown in Fig. 6 and 7. Referring to Fig. 6, it can be exclaimed that curcumin exhibit three stages of release. In the first stage of release, curcumin exhibited a quick or 'burst' release within 10 h release period. Curcumin that was located at or near to the surface of sample was released immediately into the buffer solution during the initial stage. Up to 20 h, a slow released of curcumin can be seen afterwards. In this stage, it is hypothesized that the concentration of curcumin between the system and the release medium has come near to the equilibrium state. Therefore, this resulting in a low release of curcumin in all of the systems. In the last stage, the release of curcumin was continued as a combined result of the disintegration of the silica carrier and the diffusion of curcumin along the diffusional medium. On the other hand, the highest release percentage of curcumin within 28 h was exhibited by the S(8.5)AC system (55%) as can be seen in Fig. 7. As for the S(6.0)AC, S(10.0)AC and S(10.0)C systems, the release percentage of curcumin founded was 44%, 39% and 31%, respectively.
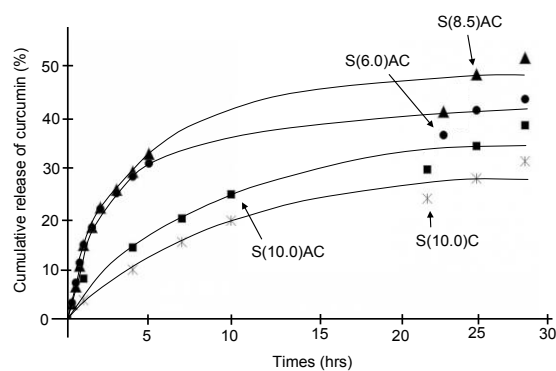
SiO₂ to organic contents ratio

6.3

6.2

6.5

4.1

Fig. 5 TG and DTG curves of samples (a) Alb/Cur, (b) S(10.0)C, (c) S(10.0)AC, (d) S(8.5)AC and (e) S(6.0)AC.

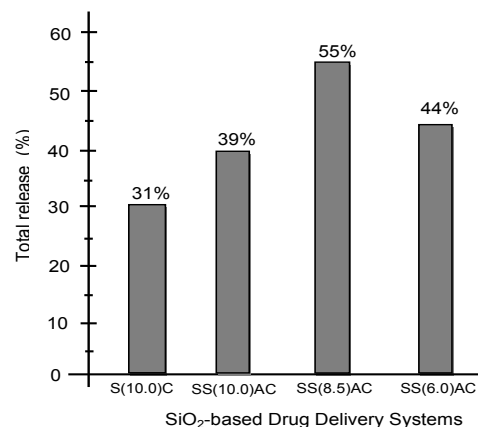**Fig. 6** Cumulative release of curcumin from SiO_2–based systems.

Fig. 7 Total cumulative release of curcumin in 28 h.

Based on the observed experimental results, it can be justified that the use of albumin as the co–carrier and the composition variation of SiO₂ in the system are interrelated to the cumulative release data of the systems. Firstly, it can be seen here that the use of albumin as the co–carrier here caused an increase of cumulative release percentage of curcumin. Referring to the Fig. 7, total release of curcumin from the S(10.0)C system is 31%. The presence of albumin as the co–carrier in the SiO₂–based system caused an increase of curcumin amount up to 39% (S(10.0)AC). The higher percentage of curcumin release of S(10.0)AC in contrast to the S(10.0)C system can be attributed to the intermolecular interaction of curcumin with the albumin network. In our case, albumin might undergo conformational change or structural rearrangement since protein is susceptible to the surrounding environment. During the preparation step, acetone has been used to increase the solubility of curcumin in water. The presence of electronegative oxygen atom in acetone can interrupted the intra–molecular hydrogen bonds that stabilized the protein tertiary structure. As a result, the non–polar amino acid side chains that were located initially within the hydrophobic core are more flexible and hence available for interaction with curcumin. The interaction of albumin with curcumin also can increase the solubility of curcumin in the aqueous medium (Mohanta *et al*., 2013 and Thomas *et al*., 2014). The overall phenomenon discussed above explained the effect of albumin as the co–carrier that associated to the increase of cumulative release percentage of curcumin from S(10.0)AC as compared to the S(10.0)C system. Other factor that can contribute to the higher amount of curcumin release was albumin competed with curcumin in order to be adsorbed on the SiO₂ surface. This indirectly decreases the availability of –OH group of SiO₂ to be interacted with curcumin. The difference of the weight loss stages between the S(10.0)C and S(10.0)AC systems in the TG studies verify the effects of albumin as the co–carrier in the SiO₂–based systems. Schematic representation of the possible intermolecular interaction in the S(10.0)C and S(10.0)AC systems is given in Fig. 8. The figure demonstrated that curcumin interacted intermolecularly with albumin through hydrophobic interaction (aromatic side of curcumin with the aromatic and aliphatic side chains in albumin), and hydrogen bond (–OH enolic of curcumin with the C=O of albumin).

Secondly, it can be pointed out that there is an effect of the composition of the SiO₂ carrier towards the cumulative release percentage of curcumin. As can be seen in Fig. 6, release profile of the S(8.5)AC and S(6.0)AC systems show a different release pattern as compared to the S(10.0)AC systems. A higher burst release of curcumin up to 10 h was shown by S(8.5)AC (~40%) and S(6.0)AC systems (~35%) comparable to the S(10.0)AC systems (25%). Then, all of the systems continued to exhibit a slower release of curcumin from 10 h to 28 h. Referring to Fig. 7, the total cumulative release percentage of curcumin of the S(10.0)AC, S(8.5)AC and S(6.0)AC systems shown a different amount which was expected due to the SiO₂ carrier composition.

Based on these result, it can be realized that the release of curcumin are affected by the composition of SiO₂ carrier. Curcumin was released in 'burst' from the S(8.5)AC and S(6.0)AC compared to the S(10.0)AC systems during the first stage. Due to the lower composition of the SiO₂ carrier, the system provides lower capacity of primary interaction by the silanol groups. It was suggested that there are two affinity of interaction provided by SiO₂ particle. The higher affinity of interaction between albumin and curcumin with SiO₂ particle was suggested to be developed through the silanol surface. Besides albumin and curcumin interacted to the surface of SiO₂, they can also bind loosely in the secondary pore of SiO₂. As the system have less amount of SiO₂ carrier, more curcumin was attached loosely in between the SiO₂ particles resulting in a quick release after the immersion of sample.
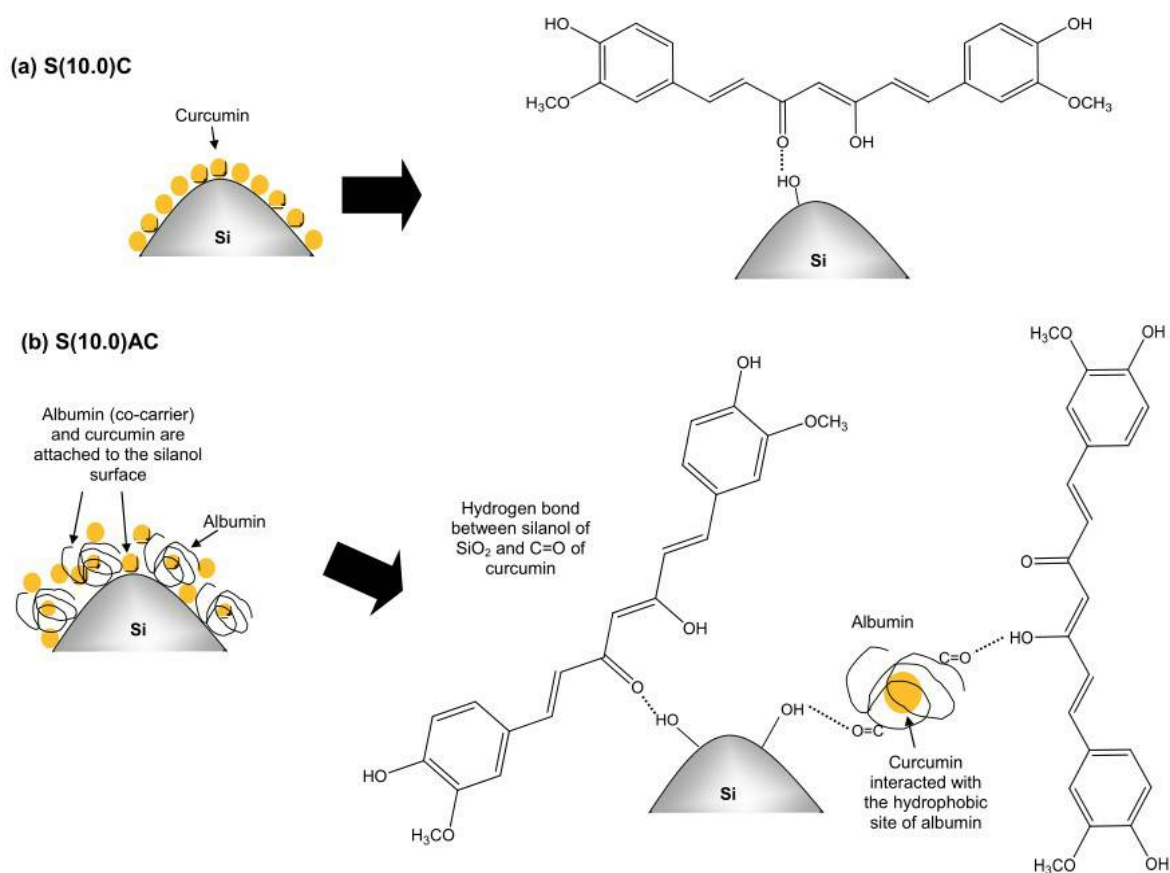

Fig. 8 Possible intermolecular interactions of SiO₂, albumin and curcumin

In the case of the S(10.0)AC systems, less curcumin was founded in the buffer solution after 28 h release period (39%). Since the system have a higher amount of SiO_2 carrier, more number of silanol groups were present for the attachment of curcumin. Besides that, the higher amount of silica carrier can decelerate the diffusion progress of curcumin during the release process. Therefore, this factor explained the lower release amount of curcumin from S(10.0)AC in contrast to the S(8.5)AC and S(6.0)AC systems. S(10.0)AC systems is also a more stable system as proven by the delay of the degradation range of the second weight loss in TGA result.

Thirdly, it can be highlighted here that the total release percentage of curcumin from S(6.0)AC shows a decreasing trend as compared to the S(8.5)AC system (see Fig. 7). It is suggested that in this ratio, a good intermolecular interaction between albumin and curcumin has been formed, where this could decelerated the diffusion rate of curcumin in the diffusional medium. In other words, due to the decrease of SiO_2 amount, higher number of interaction between albumin and curcumin were formed where this could led to the decreasing amount of curcumin. This deduction is in agreement to the TGA studies, where higher amount of organic content was degraded in the second weight loss stage of S(6.0)AC system. This result also might support the role of albumin as the co–carrier in the SiO_2–based system.

CONCLUSION

In conclusion, we have successfully prepared new SiO_2–based drug delivery system and studied the drug release mechanisms. The drug release mechanism is generally occurred through the disintegration of the carrier and the diffusion of the drug. The results show that the release of curcumin from the SiO_2–based system can be controlled by the addition of albumin as the co–carrier and the composition of SiO_2 carrier. The presence of albumin as the co–carrier caused an increase of curcumin release due to the intermolecular interaction of albumin with the curcumin, and albumin competed with curcumin in order to be adsorbed on the silanol surfaces. The total release of curcumin from the SiO_2/Alb/Cur systems and its release mechanism was strongly depended on the composition of silica carrier. The different strategies and intermolecular interactions described in this work may be useful in designing a sustainable and controlled drug release system, that can meet the medical demands of pharmaceutical applications.

ACKNOWLEDGEMENT

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