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RESEARCH PAPER

Preparation, characterization and control release properties of *Citrus medica L.* essential oil-loaded particles

Mahmoud Hosseinnia [1], Morteza Fathi [1], Mansour Babaei [1]*, Ruhollah Dorostkar [2], Amir Adibzadeh [3]

[1]Health Research Center, Lifestyle institute, Baqiyatallah University of Medical Science, Tehran, Iran
[2]Applied Virology Research Center, Baqiyatallah University of Medical Science, Tehran, Iran
[3]Department of Environment Health, Baqiyatallah University of Medical Science, Tehran, Iran

ABSTRACT

Objective(s): Microencapsulation is the most common technique that has been utilized to increase the stability of bioactive compounds. This study aimed to evaluate the potential of whey protein isolate (WPI) in the microencapsulation of Citrus medica essential oil (CEO) by ultrasonication method.

Materials and Methods: The influences of core-coating ratio (10-100%) and ultrasonication power (50-150W) on the physicochemical properties of microcapsules were evaluated.

Results: Particle diameter of the microparticles increased by increasing the core-coating ratio. PDI value increased and decreased with the increase of core ratio. The highest encapsulation efficiency (EE) (84.8%) belonged to CEO loaded microcapsule with values of US power and core-coating ratio equal 100. Mathematical modeling indicated that the type of release from microcapsule containing CEO in different simulating conditions was fake release and a combination of fake/complex release. SEM results confirmed a spherical shape-like structure. The formation of new interactions between WPI and CEO was confirmed by FT-IR analysis.

Conclusion: The results showed that the encapsulation of *Citrus medica L.* essential oil by biopolymers can be successful.

Keywords: *Citrus medica L., Essential oil, Microencapsulation, Optimization, Release kinetic*

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INTRODUCTION

In recent years, preservatives have been used to extend the shelf life of food products. For this purpose, natural preservatives such as plant extracts and essential oils (EO) are the most in demand in food industry [1]. Herbal extracts and EOs have good antioxidant and antimicrobial activities. Due to their volatile nature and chemical reactivity, herbal extracts and EOs cannot be successfully used in most food systems. Poor miscibility and phase separation are two of the problems resulting from the direct addition of extracts and EOs to the complex foods. Thermal, chemical, and light-induced degradation of bioactive compounds is another problem of these natural food additives [2].

Citrus medica belongs to the family of *Rutaceae*. *Citrus medica* that has two parts: peel and pulp. Essential oil is obtained from the peel of this fruit [3]. The major phenolic compounds of *Citrus medica L.* EO (CEO) are D-limonene, α-pinene, β-myrcene, β-ocimene, carveol, camphene, α-vetivone, β-pinene and 2,4,6-octatriene [4]. The functional properties of CEO including antioxidant and antibacterial activities, have been reported in previous researches [5, 6].

Nowadays, one of the most common techniques utilized for the protection of bioactive compounds against light, moisture, heat, oxygen, etc., is encapsulation. Micro- or nano-encapsulation is a technique that stabilizes bioactive compounds in micro- or nano-particles, aiming to increase their stability against severe conditions [7]. There are various studies on the encapsulation of EOs by different procedures [8]. The formation of stable particles during encapsulation requires the selection of appropriate wall materials [9]. Stabilizing the emulsions and surface activity of proteins, are two important parameters that can

* *Corresponding author: Email: m_babaei5@yahoo.com*
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affect the encapsulation of bioactive compounds. Whey protein isolate (WPI) is a protein that has been used alone or in combination with other biopolymers for the encapsulation of essential oils and extracts [10, 11].

This research aimed to evaluate the capability of WPI as wall material for microencapsulation of *Citrus medica* essential oil using the ultrasonication method. The physical, functional, and structural properties of the developed microcapsules were analyzed.

MATERIALS AND METHODS

Materials

The *C. medica* fruits were harvested at the end of December 2021 from Fars province, Iran. WPI (85%) was purchased from Davisco Foods International (USA). All the reagents were obtained by sigma Co (Germany).

Extraction of essential oil

The *C. medica* peels and water with a ratio of 1 to 5 were placed in a glass Clevenger and heated for 4 hr. The extraction yield of CEO was obtained 2.2%. The extracted CEO was stored in a sterile dark glass at 4 ºC until further experiments.

Preparation of encapsulated CEO powders

Preparation of CEO microcapsules was performed using the ultrasonication method according to our previous research with some modifications [12]. Different amounts of WPI (0.25-2.5 g) were weighted and used for fabrication of microparticles with core-coating ratios of 10-100%. WPI solutions were prepared by mixing WPI with buffer solution (5 mM phosphate buffer, pH 7). The coating solutions were kept in the dark for 24 hr. The constant amount of CEO (0.25 g) was added to the solutions under mechanical agitation for 15 min to form emulsions. Afterward, the microcapsules were sonicated under different ultrasound powers (50-150 W) using an ultrasonic probe (Nextgen Lab500, Sinaptec, France) equipped with titanium sonotrode (14 mm). The sonication time and temperature were at 1 min and 25 °C, respectively. After encapsulation, the samples were freeze-dried and kept in desiccator until further experiments.

Experimental design

The effects of two parameters, including core-coating ratio (CCR) (X_1) and ultrasound power (X2), on different responses of CEO microemulsions including encapsulation efficiency (Y1) and antioxidant activity (Y2), were evaluated using response surface methodology (RSM). The data were analyzed using the software Design Expert version 13 (State-Ease, Minneapolis, MN, USA). The variable factors and the levels of each parameter are given in Table 1.

Table 1. Independent variables and their levels used in RSM

Run	Core-coating ratio (%) (X_1)	US Power (W) (X_2)
1	10	100
2	33	57
3	33	143
4	55	100
5	78	57
6	78	143
7	100	100
8	55	100
9	55	100
10	55	100

Measurement of particle size of the microcapsules

Mean particle size and size distribution of prepared CEO microcapsules were determined by a dynamic light scattering (DLS) (Nanotrac Wave, Microtrac, San Diego, USA). Before the size measurement, dilution of microcapsules with distilled water (1:100) was carried out. All the measurements were performed at 25 °C.

Zeta potential measurement

The purpose of this test was to determine the surface charge of particles. The Nanotrac Wave (Microtrac, San Diego, USA) instrument was used for zeta potential measurement. Firstly, 1 mL of sample was diluted 50 times with deionized water, and then, the samples were poured into the cell and put in the device. The test was carried out at 25 °C.

Encapsulation efficiency of CEO

Measurement of the percentage of total and surface CEO contents within the microcapsules was the purpose of this experiment. Encapsulation efficiency (EE%) was measured according to the method presented in 2021 by Ozdemir et al. with some modifications [13]. Microcapsules were mixed into deionized water (1:20) in a glass beaker. Sonication of the mixture was performed by ultrasonic homogenizer (Nextgen Lab500, Sinaptec, France). Then, 10 mL of hexane was added to the mixture using a heating magnetic stirrer (Ared, Velp Co, Italy) for 20 min, followed by centrifugation (Hettich, Mikro 220R, Germany) at 13000 g for 5 min. The UV/vis spectrophotometer (Lambda 365, Perkin Elmer, USA) was used to read the absorbance of the samples at 245 nm (λ_{max}).

About the surface CEO content, the whatman filter paper was used for the filtration of a mixture of samples and hexane, and the absorbance was read at the same wavelength. The EE% was calculated using the following equation:

$$\text{Encapsulation Efficiency (\%)} = \frac{\text{Total CEO} - \text{Surface CEO}}{\text{Total CEO}} \times 100 \quad (1)$$

Antioxidant activity

The antioxidant activity of microcapsules was determined by the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging potential. The method presented by El-Said et al. in 2014 was used for this experiment [14]. Suspensions of microcapsules (0.1% w/w) were centrifuged according to the above-mentioned method for the disintegration of them. For the pure CEO, the solution of CEO in distilled water was prepared to preserve the CEO concentration in a similar level of microcapsules suspension. Then, 100 µL of supernatant of the centrifuged microcapsules or 100 µL of CEO solution was added to 2.9 mL of 60 µM DPPH solution in methanol. After 30 min of storage in the dark, the absorbance of samples was read at 517 nm. The inhibitory percentage of DPPH free radical was calculated as follows:

$$\text{Radical scavenging activity (\%)} = [(A_c - A_s) / A_c)] \times 100 \quad (2)$$

where Ac is the absorbance of the control sample and As is the absorbance of samples containing microcapsules.

Fourier transform infrared (FT-IR) spectroscopy

FTIR analysis was applied to observe the interaction between pure WPI and CEO. The sample preparation was performed by the potassium bromide (KBr) pellet method. After pressing powder, the FT-IR spectrometer (Shimadzu, IR Tracer-100, Japan) was used to record the FT-IR spectra of the samples at a resolution of 4 cm^{-1} and a scanning range from 4000 to 400 cm^{-1}. They were displayed in absorbance mode.

Scanning electron microscopy (SEM)

The surface morphology of microcapsules was investigated by SEM. A thin conductive gold layer was used for this test. Freeze-dried microcapsule was studied under the SEM (EM3200, KYKY, China) at an accelerating voltage of 26 KV. Then the size of microcapsule in the image was determined

The release rate of CEO from microcapsules

Release of *CEO* from WPI microcapsules was performed by two food simulators, including acidic (acetic acid 3% v/v) and fatty (ethanol 85% v/v) food simulators. First, 3 g of WPI microcapsule was mixed with a 100 mL glass vial containing 50 mL of simulators, and then 1 mL of the solution was filtered using a syrup filter. The release rate of CEO was estimated at certain time intervals (30, 60, 90, 120, and 150 h). The absorbance (λ_{max}) was measured at 245 nm using a UV/vis Spectrophotometer (Lambda 365, Perkin Elmer, USA). The calibration curve was constructed by determination of absorptions of different concentrations of essential oil in acetic acid and ethanol.

CEO release kinetics

Different kinetic models were used to determine the type of releasing mechanism of the CEO from the developed encapsulation system. For this purpose, the most common mathematical models, including First-order (3), Korsmeyer-Peppas (4), and Higuchi (5), were used. The adjusted R-squared (R2) and root mean squared error (RMSE) were utilized to determine the best model.

$$M_t = 100\,(1 - \exp(-k_1 . t)) \quad (3)$$

$$M_t = k_{KP} . t^n \quad (4)$$

$$M_t = k_H . t^{0.5} \quad (5)$$

where Mt is EO released in the time of t and k_1, kKP and kH are First-order, Korsmeyer-Peppas and Higuchi constants, respectively.

RESULTS AND DISCUSSION

Particle size and zeta potential

As shown in Fig. 1A, the particle size of the microcapsules was influenced by the core-coating ratio. A direct proportion was observed between the particle size and the core-coating ratio. The particles size of encapsulated compounds has considerable effect on their adsorption and by decreasing the size of particles, the adsorption increases. It has been reported that the particles with submicron size are desirable [15, 16]. Therefore, the formulation with the smallest particles size should select as optimal for encapsulation of bioactive compounds. The effect of ultrasound intensity on the particle size of microcapsules was not significant (P>0.05). All the samples were in micro-scale size range from 148 to 212 nm. The majority of solid tumors has a vascular pore cut-off between 380 and 780 nm, and hence the developed particles are ideal for passive targeting of tumors [17].

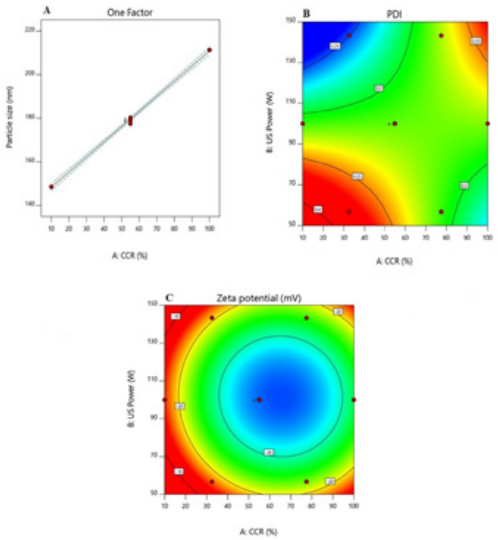

Fig. 1. Particle size (A), PDI (B), and zeta-potential (C) of CEO microcapsules stabilized by different ultrasound powers and core-coating ratios

The PDI values of microcapsules are shown in Fig. 1B. With increase of core-coating ratio up to 55%, D43 microcapsules were decreased, and beyond this point, the particle size of the samples was increased.

The ultrasonic power caused to decrease in the PDI value of microcapsules which is associated with the amphiphilic structure of WPI. WPI has a good emulsifying ability which makes it a carrier with high potential for the producing microcapsules with high level of homogeneous [12]. The same results have been reported by Rashed *et al*. (2019), who used WPI as wall material for the encapsulation of *Lavandula angustifulia* EO [18].

Fig. 1C shows the zeta potential values of CEO microcapsules. The effect of ultrasound power and CCR on the net surface charge of samples is similar to that observed for PDI. The net charge of WPI stabilized microcapsules was negative because the isoelectric point of WPI shows acidic pH (pH 4-5).

Encapsulation efficiency of CEO

EE is an important factor for distinguishing the performance of the encapsulation process. The high value of EE shows the high bioaccessibility of bioactive compounds. The effects of US power and core-coating ratio on EE% of CEO loaded microcapsules are shown in Fig. 2A. The highest EE% was achieved when the core-coating ratio and ultrasound power were 100% and 100 W, respectively. High EE of CEO loaded microcapsules could be attributed to the antisolvent precipitation of whey protein to enclose polyphenols. In 2020, Tavares

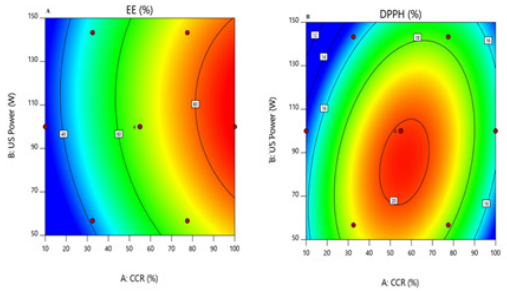

Fig. 2. Encapsulation efficiency (A), antioxidant activity (B) of CEO-loaded microcapsules

et al. observed the highest EE for encapsulation of ginger essential oil when WPI was used in wall material combination [19]. In conclusion, the high value of EE observed in this work demonstrated that the developed encapsulation system could be introduced as a viable system for retention of CEO.

Antioxidant activity

Fig. 2B shows the effect of US power and core-coating ratio on the DPPH free radical scavenging activity of microcapsules. The results showed that the DPPH scavenging activity of microcapsules was increased and decreased by increasing the core-coating ratio at proportions lower and higher than 55%, respectively. Degradation of a part of phenolic compounds after drying and during storage caused to decrease in the antioxidant potential of microcapsules. The unencapsulated phenolic compounds that are attached to the surface of microcapsules are susceptible to vaporization and physicochemical degradation, undergo facile disintegration, and leads to a decrease in the antioxidant activity of microcapsules. Other researchers had a similar opinion about the antioxidant activity of microencapsulated plant extracts and its correlation with EE [20, 21].

Optimization and desirability

The optimized values for independent variables of this research, such as CCR and US power, were estimated by the desirability function approach. The calculated values and responses, including polydispersity index and antioxidant activity at optimal conditions, are shown in Table 2. The particle size of the sample was 180.12 nm where the optimal values of CCR and ultrasonication power were 54.7%, and 107.6 W, respectively. The value of overall desirability for the predicted zone was equal to 0.65. Then, optimal microcapsule was prepared according to the defined objectives, and their structural properties were studied.

Table 2. WPI-stabilized microcapsules containing CEO characterize

Factor name	Goal	Optimized value	Desirability (%)
		Microcapsule	Microcapsule
A: core/coating ratio (%)	In range	55	100
B: US Power (W)	In range	108	100
Particle size (nm)	Minimize	180.11	49.65
PDI	Minimize	0.31	44.48
Zeta potential (mV)	Minimize	-34.86	88.87
EE (%)	Maximize	67.08	65.32
DPPH (%)	Maximize	19.87	90.95

Controlled release rate of CEO

Fig. 3 (A and B) shows the controlled release properties of CEO from WPI stabilized microcapsule in food-simulating media (acidic and fatty). It can be observed that the release data could be fitted effectively by the First-order model and the Korsmeyer-Peppas models in fatty and acidic media, respectively. According to Fig. 3, in the first 15 hr, about 25.5% and 29% *CEO* were released in acidic and fatty media, respectively. The release of EO from the microcapsule surface is the reason for the initial high release rate. A dual effect of WPI in changing the release rate of EO has also been reported in a recent study [22].

Kinetic modeling of CEO

The experimental results showed a non-linear trend in the controlled release of CEO from micro coating, and therefore, the mathematical models used for kinetic modeling are: First-order model, Korsmeyer-Peppas, and Higuchi model. The variables of the tested models and evaluation criteria are shown in Table 3.

Korsmeyer-Peppas model was chosen as the most suitable model in the acidic food simulator (R2 = 0.993). The n value in this model show the release mechanism of the active substance from microcapsule. *n* values in acidic medium was found to be 0.587 (0.45<n<0.89). Therefore, the type of controlled release in these simulators is fake release [23]. For the fatty food medium, first-order model (R2 = 0.989) showed better result. The Higuchi is one of the most well-known mathematical models to describe the release properties of the systems with diffusion mechanisms [24].

Morphology observation by SEM

The SEM image of the CEO microencapsulated by WPI particles is shown in Fig. 4. There are no fractures in the micrographs that indicated an efficient microencapsulation process. WPI stabilized microcapsule had a spherical shape-like. The mean diameter of the WPI microcapsule calculated from the SEM images was about 250 nm, which is similar to the result obtained by DLS analysis. Similarly, several studies have been

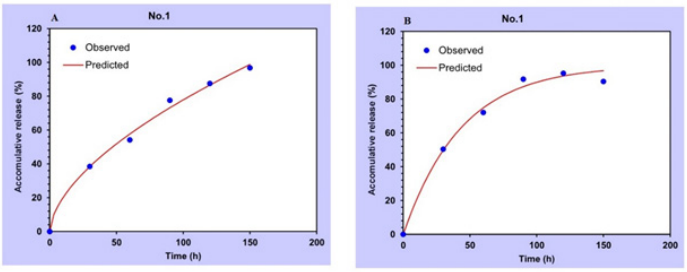

Fig. 3. Release profile of CEO from microcapsule incubated in acidic food-simulating (A), and fatty food-simulating (B)

Table 3. Kinetic parameters of fitted mathematical models

Parameters		
	Acidic	Fatty
	First-order model	
K_1	0.016	0.023
R^2	0.985	0.989
RMSE	4.42	3.77
	Korsmeyer-Peppas model	
K_{KP}	5.22	6.82
n	0.587	0.354
R^2	0.993	0.962
RMSE	3.02	7.14
	Higuchi model	
K_H	7.805	8.57
R^2	0.988	0.945
RMSE	3.89	8.58

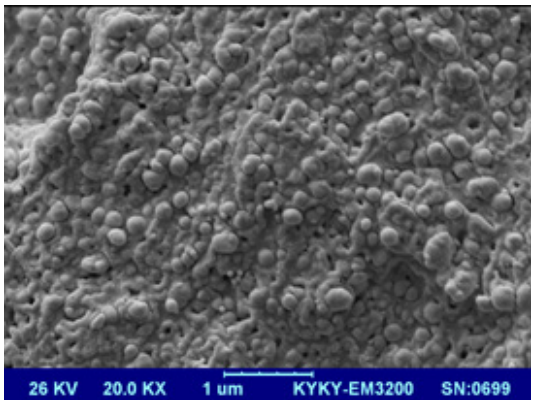

Fig. 4. SEM image of CEO microcapsule stabilized by WPI

reported that the particle size of nanostructured encapsulation systems observed by SEM is correlated with those obtained by DLS analysis [25, 26]. In 2016, Yang *et al*. prepared cinnamon essential oil nanocapsules with chitosan and WPI as coating materials. They were observed to form particles with sizes of 100-200 nm [27].

FT-IR spectroscopy

Fig. 5 (A, B, and C) show FT-IR spectra of pure WPI, CEO, and freeze-dried microcapsules, respectively. The band at 3400 cm^{-1} for CEO is related to the hydroxyl group of the acidic carboxyl group (COOH) on the benzene ring of phenolic acids. Vibrations of C-C stretching of aromatic rings observed at 1650 cm^{-1}. Peak observed at 1110 cm^{-1} is attributed to the asymmetrical C=O vibration [28]. The pure WPI powder showed several specific absorption peaks. The peaks appeared at 667 and 1075–1458 cm^{-1} are related to C-N groups and (N-H, C-N) bonds. The peaks detected at 1652 and 1703 cm^{-1} are related to C=O groups [29].

For WPI stabilized microcapsule, the intensity of absorption bands at 1652 and 1703 cm^{-1} related to C=O groups of amide type I was increased

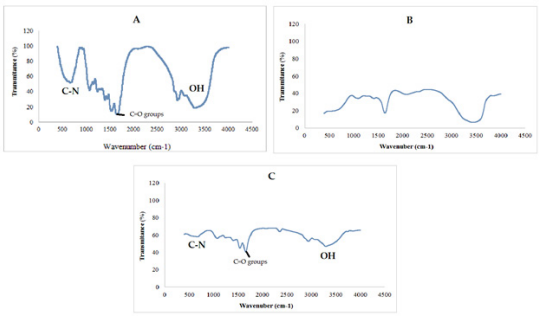

Fig. 5. FT-IR spectra of pure WPI (A), CEO (B) and WPI microcapsule powder (C)

drastically. Another change in the WPI spectrum after the incorporation of CEO was decreasing the intensity of C-N groups absorption at 667 cm^{-1}. These observations reflect that CEO ingredients interacted with protein chains via amid bonds or hydrogen bonding. In 2013, Bagheri *et al*. reported non-covalent interactions for WPI-date palm bit extract microcapsules [28].

CONCLUSION

The performance of WPI in microencapsulation of *C. medica* essential oil was studied. Comparing the effect of variable factors on the particle size characteristics of WPI microcapsules demonstrated that the effect of core ratios is increasable. The equal amount of WPI/CEO showed better performance in protecting the CEO phenolic compounds. The optimum values of ultrasound power and CCR of CEO-loaded microcapsules were determined by RSM. The First-order model and Korsmeyer-Peppas models had better performance among other fitted models in fatty and acidic food media, respectively. WPI microcapsules showed spherical shapes. New interactions between WPI and CEO ingredients are confirmed by FT-IR analysis. The performance and application of these microcapsules can be investigated in food formulation.

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CONFLICTS OF INTEREST

We declare that there is no conflict of interest.

REFERENCES

1. Olatunde OO, Benjakul S. Natural preservatives for extending the shelf-life of seafood: A revisit. Compr. Rev. Food Sci. Food Saf. 2018; 17.6:1595-1612.
2. Almasi H, Zandi M, Beigzadeh S, Haghju S, Mehrnow N. Chitosan films incorporated with nettle (*Urtica Dioica L.*) extract-loaded nanoliposomes: II. Antioxidant activity and release properties. J Microencapsul. 2016; *33*.5:449-459.
3. Okhli S, Mirzaei H, Hosseini SE. Antioxidant activity of citron peel (Citrus medica L.) essential oil and extract on stabilization of sunflower oil. OCL. 2020; 27:32.
4. Gao Z, Zhong W, Chen K, Tang P, Guo J. Chemical composition and anti-biofilm activity of essential oil from Citrus medica L. var. sarcodactylis Swingle against Listeria monocytogenes. Ind Crops Prod. 2020; 144:112036.
5. Li ZH, Cai M, Liu YS, Sun PL, Luo SL. Antibacterial activity and mechanisms of essential oil from Citrus medica L. var. sarcodactylis. Molecules. 2019; 24.8:1577.
6. Lou Z, Chen J, Yu F, Wang H, Kou X, Ma C, Zhu S. The

antioxidant, antibacterial, antibiofilm activity of essential oil from Citrus medica L. var. sarcodactylis and its nanoemulsion. LWT. 2017; 80:371-377.
7. Ghorbanzade T, Jafari SM, Akhavan S, Hadavi R. Nano-encapsulation of fish oil in nano-liposomes and its application in fortification of yogurt. Food Chem. 2017; 216:146-152.
8. Nedovic V, Kalusevic A, Manojlovic V, Levic S, Bugarski B. An overview of encapsulation technologies for food applications. Procedia Food Sci. 2011; 1:1806-1815.
9. Raeisi S, Ojagh SM, Quek SY, Pourashouri P, Salaün F. Nano-encapsulation of fish oil and garlic essential oil by a novel composition of wall material: Persian gum-chitosan. LWT. 2019; 116:108494.
10. Alehosseini A, Sarabi-Jamab M, Ghorani B, Kadkhodaee R. Electro-encapsulation of Lactobacillus casei in high-resistant capsules of whey protein containing transglutaminase enzyme. LWT. 2019; 102:150-158.
11. Mahdi AA, Al-Maqtari QA, Mohammed JK, Al-Ansi W, Aqeel SM, Cui H, Lin L. Nanoencapsulation of Mandarin essential oil: Fabrication, characterization, and storage stability. Foods. 2021; 11.1:54.
12. Hosseinnia M, Khaledabad MA, Almasi H. Optimization of Ziziphora clinopodiodes essential oil microencapsulation by whey protein isolate and pectin: A comparative study. Int. j. Biol. Macromol. 2017; 101:958-966.
13. Ozdemir N, Bayrak A, Tat T, Altay F, Kiralan M, Kurt A. Microencapsulation of basil essential oil: utilization of gum arabic/whey protein isolate/maltodextrin combinations for encapsulation efficiency and in vitro release. J. Food Meas. Charact. 2021; 15:1865-1876.
14. El-Said MM, Haggag HF, El-Din HMF, Gad AS, Farahat AM. Antioxidant activities and physical properties of stirred yoghurt fortified with pomegranate peel extracts. Ann. Agric. Sci. 2014; 59.2:207-212.
15. Tiwari, R., & Takhistov, P. Nanotechnology-enabled delivery systems for food functionalization and fortification. Nanotechnology research methods for foods and bioproducts. 2012; 55-101.
16. Fathi M, Emam-Djomeh Z, Aliabbasi N. Developing two new types of nanostructured vehicles to improve biological activity and functionality of curcumin. Food Biosci. 2021; *44*:101386.
17. Zahr AS, Davis CA, Pishko MV. Macrophage uptake of core–shell nanoparticles surface modified with poly (ethylene glycol). Langmuir. 2006; 22(19);8178-8185.
18. Rashed MM, Zhang C, Ghaleb AD, Li J, Nagi A, Majeed H, Tong Q. Techno-functional properties and sustainable application of nanoparticles-based Lavandula angustifolia essential oil fabricated using unsaturated lipid-carrier and biodegradable wall material. Ind Crops Prod. 2019; 136:66-76.
19. Tavares L, Noreña CPZ. Encapsulation of ginger essential oil using complex coacervation method: Coacervate formation, rheological property, and physicochemical characterization. Food Bioproc Tech. 2020; 13.8:1405-1420.
20. Tan SP, Kha TC, Parks S, Stathopoulos C, Roach PD. Optimising the encapsulation of an aqueous bitter melon extract by spray-drying. Foods. 2015; 4.3:400-419.
21. Kuck LS, Noreña CPZ. Microencapsulation of grape (Vitis labrusca var. Bordo) skin phenolic extract using gum Arabic, polydextrose, and partially hydrolyzed guar gum as encapsulating agents. Food Chem. 2016; 194:569-576.
22. Volić M, Pajić-Lijaković I, Djordjević V, Knežević-Jugović Z, Pećinar I, Stevanović-Dajić Z, Bugarski B. Alginate/soy protein system for essential oil encapsulation with intestinal delivery. Carbohydr. Polym. 2018; 200:15-24.
23. Arora G, Malik K, Singh I. Formulation and evaluation of mucoadhesive matrix tablets of taro gum: Optimization using response surface methodology. Polim Med. 2011; 41.2:23-34.
24. Gouda R, Baishya H, Qing Z. Application of mathematical models in drug release kinetics of carbidopa and levodopa ER tablets. J. Dev. Drugs. 2017; 6.02:1-8.
25. Al-Kinani MA, Haider AJ, Al-Musawi S. Design, construction and characterization of intelligence polymer coated core–shell nanocarrier for curcumin drug encapsulation and delivery in lung cancer therapy purposes. J Inorg Organomet Polym Mater. 2021; 31(1):70-79.
26. Rezaei A, Kamali B, Kamali AR. Correlation between morphological, structural and electrical properties of graphite and exfoliated graphene nanostructures. Measurement. 2020; 150:107087.
27. Yang K, Liu A, Hu A, Li J, Zen Z, Liu Y, Li C. Preparation and characterization of cinnamon essential oil nanocapsules and comparison of volatile components and antibacterial ability of cinnamon essential oil before and after encapsulation. Food Control. 2021; 123:107783.
28. Bagheri L, Madadlou A, Yarmand M, Mousavi ME. Nanoencapsulation of date palm pit extract in whey protein particles generated via desolvation method. Food Res. Int. 2013; 51.2:866-871.
29. Ramos ÓL, Reinas I, Silva SI, Fernandes JC, Cerqueira MA, Pereira RN, Malcata FX. Effect of whey protein purity and glycerol content upon physical properties of edible films manufactured therefrom. Food hydrocoll. 2013; 30.1:110-122.