Wiley
Journal of Food Processing and Preservation
Volume 2024, Article ID 7598455, 10 pages
https://doi.org/10.1155/2024/7598455

WILEY

Research Article

Modeling of Release Mechanism of Sage (*Salvia fruticosa* Miller) Phenolics Encapsulated in Alginate Capsule: Physicochemical Properties

Elif Aykın-Dinçer,[1] **Cüneyt Dinçer**,[2,3] **and Osman Kadir Topuz**[4]

[1]*Department of Food Engineering, Akdeniz University, Engineering Faculty, Antalya 07058, Türkiye*
[2]*Food Safety and Agricultural Research Center, Akdeniz University, 07058 Antalya, Türkiye*
[3]*Department of Food Processing, Akdeniz University, Finike Vocational School, 07740 Antalya, Türkiye*
[4]*Department of Seafood Processing Technology, Akdeniz University, Fisheries Faculty, Antalya 07058, Türkiye*

Correspondence should be addressed to Cüneyt Dinçer; cdincer@akdeniz.edu.tr

Received 21 December 2023; Revised 10 June 2024; Accepted 15 June 2024

Academic Editor: Kandi Sridhar

Copyright © 2024 Elif Aykın-Dinçer et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Alginate capsules are promising delivery systems for encapsulation and release of phenolics since they can be fabricated from food-grade biopolymers using mild processes. On the other hand, knowing the release kinetic of the phenolic in the capsules is critical for capsule fabrication and product quality improvement This study is aimed at mathematically modeling the transfer of encapsulated sage (*Salvia fruticosa* Miller) phenolics in alginate particles to water and to determine some physicochemical properties of capsules containing different concentrations of phenolics. The water activity values (aw) of the capsule varied between 0.9976 and 0.9990. Sphericity factors of 1 (37.5 ppm), 2 (75 ppm), 3 (150 ppm), 4 (300 ppm), and control (0 ppm) samples were determined as 0.042, 0.044, 0.043, 0.273, and 0.039, respectively. The yellowness (+b*) value of the samples increased significantly as the added sage extract concentration increased. While the phenolic content of the samples was determined between 0.174 and 1.1831 mg/kg GAE, the antioxidant activity values were determined between 0.9602 and 6.6930. To understand the mechanism of phenolic release from the capsules, six different mathematical models were used (*First Order*, *Higuchi*, *Korsmeyer-Peppas*, *Hixson and Crowell*, *The Peppas-Sahlin*, and *Gompertz*). The highest R^2 (0.9952-0.9979) and the lowest RMSE (1.0171-1.7032) values were calculated in The Peppas-Sahlin among the six models. The Peppas-Sahlin model kinetic parameters indicated the dominance of Fickian diffusion and the minor effect of relaxation process in the mechanism of phenolic release.

1. Introduction

Salvia species are annual or perennial plants that have different characteristics of branches, leaves, and flowers and can grow between 50 and 100 cm [1]. These plant species are predominantly found on sloping lands that are sheltered from the wind, warm, and sunny. These species, which are resistant to winter cold and drought, develop especially well in soils rich in lime content [2]. *Salvia*, a word of Latin origin, means "to heal" or "to cure." Additionally, these plants are widely consumed as herbal tea and flavoring spice [3, 4]. The best-known species of the genus *Salvia*, whose origin and distribution area are the Mediterranean environment, are *Salvia officinalis* and *Salvia fruticosa* [1–3]. However, *S. fruticosa* (synonym *Salvia triloba* L.) can be distinguished from *S. officinalis* due to its trifoliate leaves [4]. It is reported that *S. fruticosa* contains significant amounts of bioactive components such as phenolics and terpenoids, and its antioxidant, antimicrobial, and anti-inflammatory activities [3, 5].

The increasing tendency of conscious consumers towards healthy living increases the usage potential of antioxidant-rich products in the food industry. In this context, it is seen that innovative approaches such as encapsulation have begun to be used for the protection of products rich in phenolic and antioxidants and for their more widespread use in the food industry [6].

Encapsulation can be defined as covering or confining a solid, liquid, or gas phase component or mixture with another substance or system [7]. In encapsulation of the coated substance, active substance, core, inner phase, or filler, the material used in the coating can be expressed as shell, coating material, wall material, encapsulant, membrane, capsule, matrix, external phase, or carrier [8].

There are many techniques for encapsulating of bioactive substance, and the most common techniques are coacervation, gelation, inclusion complex, interfacial polymerization, and emulsion polymerization, and mechanical processes include spray drying, fluidized bed, extrusion, and freeze-drying [6, 7].

The method, also called dripping or ionic gelation, is known as a practical and economical method, it is preferred for small-scale production in laboratory applications, since it is not suitable to produce large quantities of products. However, it is thought that it is possible to commercialize encapsulated food particles by producing large quantities of particles with syringe-extrusion systems developed in recent years [9]. In recent years, this method has also found its place in the production of different products such as caviar, imitation eggs, and capsules in hot and cold drinks in modernist cuisine and has recently gained popularity [10–12].

On the other hand, knowing the release kinetic of the phenolic in the hydrogel capsules is critical for fabrication and product quality [13]. In addition, the kinetics parameters can also be used to estimate the treatment time of capsules in the solution to obtain extract with a specific phenolic content.

There have been more studies using various extracts in hydrogel capsule production recently [10, 14–17]. However, research on understanding and modeling the release of different bioactive compounds in the different target solution in capsule studies is still limited. Therefore, the aim of this study is to mathematically model the transfer of encapsulated sage phenolics in capsules to water and to determine some physicochemical properties of capsules containing different concentrations of phenolics.

2. Materials and Methods

2.1. Preparation of the Sage Phenolic Extracts. Dried sage (*Salvia fruticosa* Miller) was purchased from an herbal market in Antalya, Türkiye. The stems and stalks of the sage samples were cut off, while the leaves were ground by a blender (Beko BKK-2155 Maxi Hand Blender, Turkey) and sieved into 0.5-1 mm particle size by a laboratory test sieve (Retsch, Germany). The phenolic compound extraction was performed in a water bath at 75°C (Heidolph Hei VAP Precision, Germany) for 30 min by shaking sage samples in hot water (ratio: 1/10, w: v) at a speed of 1000 rpm (MTOPS MS3040D Lab. Stirrer, Korea) [18]. The extract solution was filtered with a 106 μm laboratory test sieve (Retsch, Germany). The extract (~3.6°Bx, pH: 5.9, phenolic content: 6.722 mg/kg, antioxidant activity: 39.7615 mg/kg) was kept in the refrigerator (~4°C) until encapsulation.

2.2. Preparation of Alginate Capsules Containing Sage Phenolic Extracts. The methods described by Topuz et al. [12] and Nguyen et al. [11] were slightly modified and used in the encapsulation of sage extract. Accordingly, 2% (w/v) sodium alginate solution was prepared at 60°C using a mechanical stirrer (MTOPS MS3040D Lab. Stirrer Korea). Seven capsule solutions (600, 450, 300, 150, 75, 37.5, and 0 ppm) were prepared using sage extract (~3.6°Bx) and sodium alginate solution (Figure 1) and cooled to room temperature. Alginate capsule solution without sage extract was named as the control sample (0 ppm). Sage extract-alginate solutions were dripped into the 2% $CaCl_2$ gelling solution from 3 cm using a syringe (1 mm needle hole diameter) to form sage-encapsulated capsules. The calcium chloride solution containing capsules was gently stirred with a magnetic stirrer (MR Hei-Tec, Heidolph Co., Schwabach, Germany) for 5 min to prevent sticking of sage capsules. Then, sage capsules were washed with distilled water to remove any excess Ca^{2+} from their surface. The sage capsules (Figure 2) were kept at 4°C for a maximum of 2 days until the analysis was performed.

Phenolic content, antioxidant activity analyses, and kinetic experiments were carried out with samples at four different concentrations (37.5, 75, 150, and 300 ppm), since capsule formation could not be formed with solutions containing 450 and 600 ppm of sage extract.

2.3. Dry Matter Content and Water Activity (aw) Measurement. Dry matter analysis of the samples was carried out by drying them in an oven at 105°C until constant weight. The dry matter content of the samples was given as % after weighing before and after drying [19]. The water activity (aw) value of the samples was determined using a water activity device (AquaLab 4TE, Decagon Devices, Washington, USA) [5].

2.4. Capsule Size and Shape Measurements. The mean diameters (D) and sphericity factors (SF) of the capsules were measured using a digital caliper and the equations (Equations (1) and (2)) below [20].

$$D = \frac{d_{\max} + d_{\min}}{2}, \tag{1}$$

$$\mathrm{SF} = \frac{d_{\max} - d_{\min}}{d_{\max} + d_{\min}}, \tag{2}$$

where $d_{\max}$ is the maximum diameter of a capsule and $d_{\min}$ is the minimum diameter. Eight capsules were used for each measurement.

2.5. Bulk Density Measurement. The bulk density of the samples was determined according to the method described by Aykın-Dinçer et al. [19]. Accordingly, 5 g of sample was weighed into a 25 mL graduated cylinder and the volume

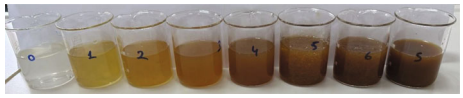


Figure 1: Appearance of alginate solutions mixed with different proportions of sage extracts.

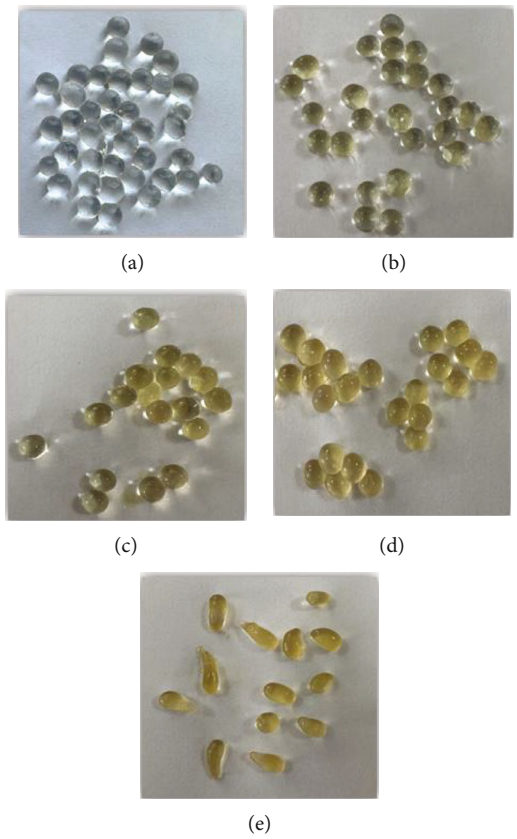


Figure 2: Appearance of alginate capsules ((a) control sample (0), (b) sample 1, (c) sample 2, (d) sample 3, and (e) sample 4).

(mL) used to determine bulk density was measured. Bulk density was calculated by dividing the mass of the samples by the volume of the cylinder occupied by the samples.

2.6. Color Measurement. Color measurement of the capsule samples was performed using a colorimeter (Chroma Meter CR-400, Konica Minolta, Osaka, Japan) (8 mm light hole; 2° observer). The light source of the device is a pulsed xenon lamp, and a D65 illuminator was used for the measurements. Samples were placed in the measuring holder of the color device to cover the bottom of the holder, and color measurement was performed from 8 different points, and average $L*$, $a*$, and $b*$ values were recorded [12].

2.7. Determination of Total Phenolic Content and Antioxidant Activity. Extraction of the phenolic compounds from the capsule samples was performed according to the method of Dinçer et al. [21] with some modifications. One gram of the sample was weighed into a 50 mL tube, and after the capsules were crushed with a glass rod in the tubes, 50 mL of 80% methyl alcohol was added. The tubes were placed in an ultrasonic bath (Bandelin Sonorex Digiplus, 160/640 W, 35 kHz, Germany), and phenolic compounds were extracted at 40°C for 30 min. Then, the sage extracts were filtered through coarse filter paper and kept at 4°C until the analyses.

Total phenolic content was determined with the Folin-Ciocalteu Assay [21]. 2.5 mL of 0.2 N Folin-Ciocalteu reagent was added to 0.5 mL of extract, and then, 2 mL Na_2CO_3 (75 g/L) was added, and the mixture was incubated at 50°C for 5 minutes. The absorbance of the cooled solution was recorded using a spectrophotometer (Thermo Scientific Evolution 160 UV-Vis, USA) at 760 nm. Results are given in mg gallic acid equivalents (GAE)/kg.

Diphenylpicrylhydrazyl (DPPH) assay was based on the method described by Fernández-León et al. [22]. Briefly, 950 μL of 6×10^{-5} M 2,2-diphenyl-1-picrylhydrazyl (DPPH) solution was added to 50 μL of the working samples. After that, the mixtures were shaken and incubated in the dark at room temperature for 30 min. Absorbances of the samples were measured at 515 nm using a spectrophotometer (Thermo Scientific Evolution 160 UV-Vis, USA). Results are given in mg Trolox/kg.

2.8. Release Kinetic of Phenolics in Water. Kinetic experiments were carried out with samples at four different concentrations (37.5 (1), 75 (2), 150 (3), and 300 (4) ppm). (Since the capsule could not be formed with solutions containing 45 (5) and 600 ppm (6) sage, the sample without sage (0 ppm) was not used in the kinetics study because it was a control sample). Equally weighed capsules of each concentration were added to a fixed volume of release media separately. The ratio of the capsules to water was 1 : 20 (g/mL). The suspension was stirred at 250 rpm on a magnetic stirrer at 25°C. At each sampling time (1, 3, 5, 7, 10, 15, 20, 30, 40, 60, and 90 min), 2 mL aliquots was withdrawn from the mixture followed by returning the same volume of fresh water.

To understand the mechanism of phenolic release from the capsules, six different mathematical models were used (*First Order*, *Higuchi, Korsmeyer-Peppas*, *Hixson and Crowell*, *The Peppas-Sahlin*, *Gompertz*). Kinetic parameters of phenolic release were calculated by plotting and fitting the mean release data vs. time for model equations (Eqs. (3)–(8)), expressed as follows [11, 23, 24]:

$$\text{First order model}: \frac{M_t}{M_{\text{eq}}} = 100[1 - \exp(-kt)], \quad (3)$$

$$\text{Higuchi model}: \frac{M_t}{M_{\text{eq}}} = kt^{(1/2)}, \quad (4)$$

$$\text{Korsmeyer} - \text{Peppas}: \frac{M_t}{M_{\text{eq}}} = kt^n, \quad (5)$$

$$\text{Hixson and Crowell}: \frac{M_t}{M_{\text{eq}}} = 100 \times \left[1 - (1 - kt)^3\right], \quad (6)$$

$$\text{The Peppas} - \text{Sahlin} : \frac{M_t}{M_{\text{eq}}} = k_1 t^m + k_2 t^{2m}, \quad (7)$$

$$\text{Gompertz} : \frac{M_t}{M_{\text{eq}}} = \exp\left(\alpha \exp\left(\beta \log t\right)\right), \quad (8)$$

where M_t and M_{eq} are the cumulative amount of phenolic released at time t (M_t) and at equilibrium time (M_{eq}) versus time to the equation of the corresponding mathematical models. k, k_1, k_2, m, n, α, and β are model constants.

Two criteria were used to evaluate the models: the coefficient of determination (R^2) and root-mean-square error (RMSE) (Eqs. (9) and (10)). Lower RMSE and higher R^2 values indicate that the data fit the models better. SigmaPlot 14.0 program (Systat Software Inc., USA) was used to calculate the data.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(\text{MR}_{\text{pre},i} - \text{MR}_{\text{exp},i}\right)^2}{\sum_{i=1}^{N}\left(\overline{\text{MR}_{\text{pre}}} - \text{MR}_{\text{EXP},i}\right)^2}, \quad (9)$$

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(\text{MR}_{\text{pre},i} - \text{MR}_{\text{exp},i}\right)^2\right]^{1/2}. \quad (10)$$

2.9. Statistical Analysis. Experiments were performed in duplicate. Statistical analysis was performed using the SAS version 7 (SAS Institute Inc., Cary, NC, USA). ANOVA was conducted, and Duncan's multiple range tests were used to compare the significant means.

3. Results and Discussion

3.1. Dry Matter Content and Water Activity (aw) of Sage Capsules. The dry matter content and water activity (aw) values of the sage capsules are given in Figure 3(a). It was determined that the dry matter content of the samples varied between 1.99% and 2.18%, and the sage extract ratio used in the production of the capsules did not have a statistically significant effect on the dry matter amount. The aw values of the samples varied between 0.9976 and 0.9990 (Figure 3(a)). It was observed that the aw values of the samples were not statistically significantly affected by the ratio of sage extract used in the production of the capsules.

da Silva Carvalho et al. [25] produced spheres by ionic gelation method by coating the anthocyanin extract of jussara (juçara) fruit (*Euterpe edulis* Martius) with alginate, alginate + chitosan, alginate + chitosan, alginate + whey concentrate, and alginate + gelatin. Researchers reported the dry matter content of the samples as between 6.7% and 7.7%. Additionally, the dry matter content of alginate capsules without added anthocyanin extract was determined as 5.6%. In another study in which chokeberry phenolics were encapsulated by spray drying, cocrystallization, and ionic gelation, the moisture content of the capsules produced by the ionic gelation method using 2% sodium alginate, 2.5% $CaCl_2$, and 20% w/w (17°Bx) was reported as 96.52% (dry matter content 3.48%) [26].

Cutrim et al. [27] reported the moisture content values of the samples as 1.63% and 79.17%, and the aw values as 0.5498 and 0.9928, respectively, in their study in which they encapsulated green tea polyphenols with spray chilling and ionic gelation methods. In addition to the concentration and amount of extract used in the production of alginate capsules, the ratio of other substances used in production and the production method can also affect the dry matter content and aw value.

3.2. Capsule Size, Shape, and Bulk Density Measurements. The size and shape of capsules are important parameters to consider in the formulation of pharmaceutical and food products, as spherical capsules with uniform size distribution are desired for the active functional ingredient to be effective at the targeted level [28]. The results of the diameter and sphericity factor of the produced sage capsules are presented in Figure 3(b). It was determined that the diameter of the capsule samples varied between 2.134 mm and 2.566 mm, and an increase was observed with the increase in sage concentration, but this was statistically insignificant. Sphericity factor (SF) values of 1, 2, 3, 4, and control samples were determined as 0.042, 0.044, 0.043, 0.273, and 0.039, respectively. Chan et al. [20] stated that the shape of alginate capsules can be classified in 4 different types: spherical-shaped, tear-shaped, pear-shaped, and egg-shaped. They also reported in their study that capsules can be expressed as spherical if the sphericity factor value is less than 0.05. According to this evaluation, the samples in this study except sample number 4 can be classified as spherical. This may be related to the phenolic extract/alginate concentration. As a matter of fact, capsule formation was not observed in other samples where the extract concentration increased. Similar results have been reported in study where phenolic compounds were encapsulated by different methods. Çam et al. [29] reported that the microcapsules obtained in the spray dryer with samples with lower phenolic substance content were more stable. On the other hand, Toprakçı et al. [30] reported the average SF value of the samples as 0.047 in their study in which they encapsulated the active substance consisting of sour cherry biowaste. The results of the bulk density of the capsules are presented in Figure 3(c). It was determined that the bulk density of the samples varied between 0.784 g/mL and 0.917 g/mL, and an increase was observed with the increase in sage concentration, but this was statistically insignificant. Toprakçı et al. [30] reported in their study that the bulk density value of alginate microcapsules of sour cherry biowaste was 0.54 g/mL.

3.3. Color Values, Phenolic Content, and Antioxidant Activity of the Samples. Figure 3(d) shows the $L*$, $a*$, and $b*$ color values of the sage capsule samples. As the concentration of sage extract added to the samples increased, the $L*$ value decreased, but this change was not observed at a statistically significant level. In addition, the highest $L*$

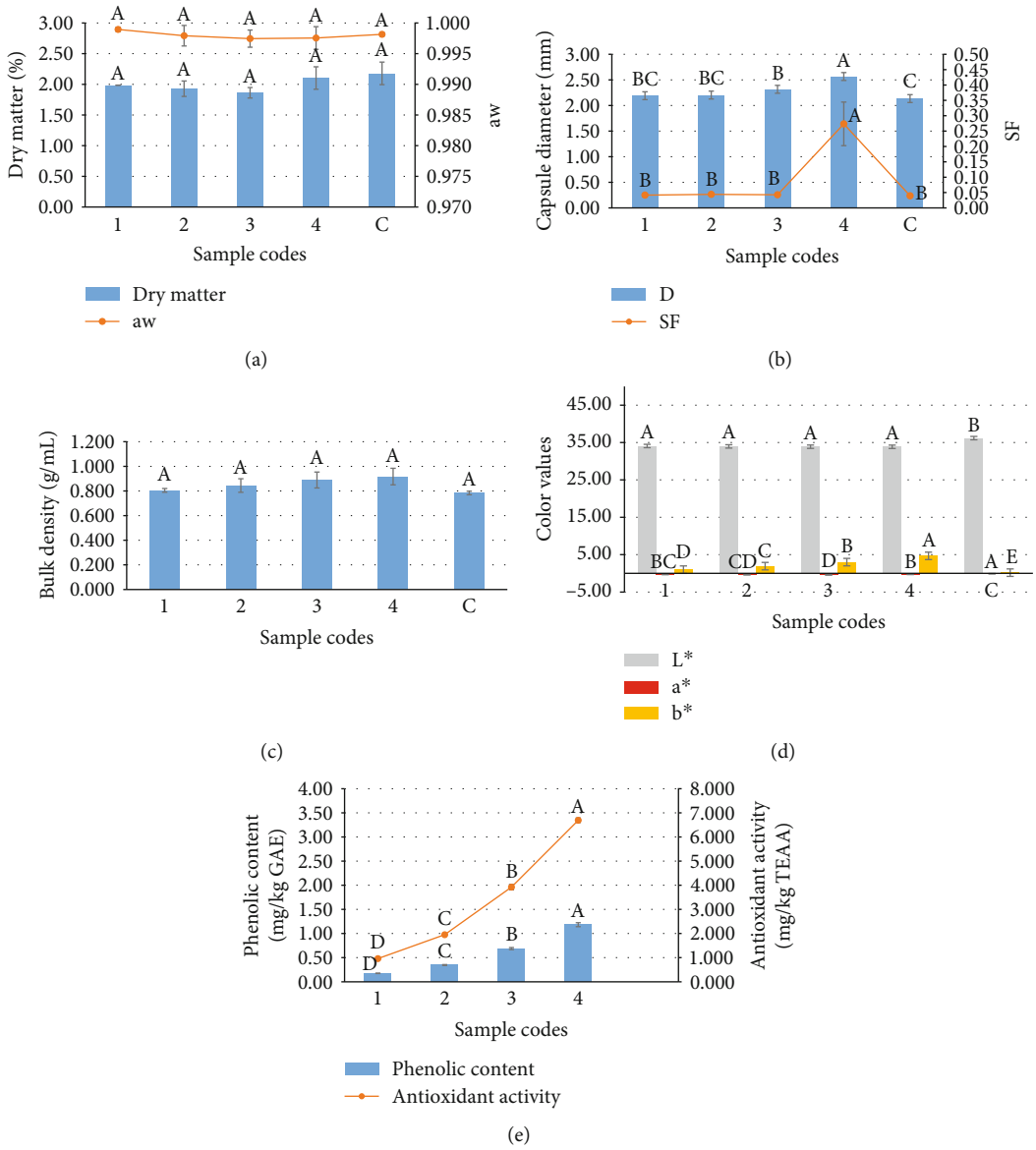


Figure 3: Some physicochemical properties of the capsules ((a) dry matter and aw values of the samples; (b) capsule diameter (D) and SF values of the samples; (c) bulk density values of the samples; (d) $L*$, $a*$, and $b*$ color values of the samples; (e) phenolic content and antioxidant activity of the samples.

value was determined in the control sample, and it was determined that the $L*$ value of this sample was statistically higher than the other samples. The highest $a*$ value was determined in the control sample with -0.11, while the lowest $a*$ value was determined in sample number 3 with -0.42. The $+b*$ value of the samples described as yellowness value was determined between 0.18 (control sample) and 4.67 (sample number 4). Additionally, as can be seen from Figure 2, the yellowness value of the samples increased significantly as the added sage concentration increased. In a study where green tea phenolics were encapsulated, $L*$, $a*$, and $b*$ values were reported as 84.69, 1.12, and 9.87, respectively [27].

Phenolic content and antioxidant activity values of the samples are presented in Figure 3(e). While the phenolic content of the samples was determined between 0.174 and 1.1831 mg/kg GAE, the antioxidant activity values were determined between 0.9602 and 6.6930. As the concentration of sage extract added to the alginate solution increased, both phenolic content and antioxidant activity values increased significantly. Benković et al. [14] reported the phenolic content in alginate capsules prepared by adsorption on lavender, peppermint, thyme, sage, and lemon balm extracts for 16 hours as 0.19 to 0.59 mg GAE/g capsules. On the other hand, Cutrim et al. [27] reported the phenolic content of the samples as 27.44 and 2.38 mg/g, respectively, in their study in which they encapsulated green tea polyphenols with spray chilling and ionic gelation methods.

The relationship between the increase in concentration of sage extracts in solution and the increase in $b*$ color

Table 1: Pearson's correlation matrix of sage extract concentration, color values, phenolic content, and antioxidant activity.

	Pearson's correlation coefficients (r)					
	Concentration	$L*$	$a*$	$b*$	Phenolic content	Antioxidant activity
Concentration	1					
$L*$	-0.848525984	1				
$a*$	0.403990741	0.13316	1			
$b*$	0.988988849	-0.91687	0.270588	1		
Phenolic content	0.996336564	-0.88693	0.326271	0.996251	1	
Antioxidant activity	0.995584964	-0.89017	0.318702	0.996507	0.999965	1

value, phenolic, and antioxidant activity is also revealed by the Pearson correlation matrix in Table 1. There appears to be a high correlation between these values. It can also be seen from Table 1 that there is a negative correlation (~ -0.85) between the increase in concentration and $L*$ values. It is seen that the correlation between $b*$ value and phenolic, $b*$ value and antioxidant activity, and phenolic and antioxidant activity is quite high.

3.4. Release of the Sage Phenolic and Its Kinetic. The release profile results of sage phenolic capsules in water are presented in Figure 4. Phenolic release rates were faster at the beginning of the treatment and then slowed over time, as shown in Figure 4. The reason is the difference in phenolic concentration between solution and capsules that decreases over time [31]. Similar trends were reported by Benković et al. [14] for sage, thyme, peppermint, lavender, and lemon balm capsule phenolic release. While the cumulative release in sample 1 was only 35.32% in the first 30 minutes, this value was determined as 53.95% in sample 4. Phenolic release of sample 1 at the end of the 90 min of process was determined as 64.67% while those of samples 2, 3, and 4 were determined as 70.73, 72.53, and 73.96, respectively. The highest phenolic release occurred in sample 4, which contained the highest concentration of sage extract.

First Order, Higuchi, Ritger-Peppas, Hixson and Crowell, The Peppas-Sahlin, and Gompertz models were used to understand the mechanism of phenolic release from the capsules. The coefficient of determination (R^2) and the coefficient of determination root-mean-square error (RMSE) values were calculated for each model as they provide the suitability of the model for the given experimental data set. Lower RMSE and higher R^2 values represent the suitability of the data to the models. In addition, the estimated k, k_1, k_2, n, m, α, and β kinetic parameters of the models are given in Table 2. R^2 values of the chosen models were calculated between 0.6712 and 0.9979 while RMSE values of the models were varied between 1.0032 and 12.8066. The lowest RMSE and the highest R^2 values were calculated in The Peppas-Sahlin and Korsmeyer-Peppas models, respectively. In addition, Figures 5(a), 5(b), 5(c), 5(d), 5(e),and 5(f), present a comparison of experimental and predicted data for the phenolic release in relation to models. The model with the closest observed and predicted values (Figure 5(e)) was observed

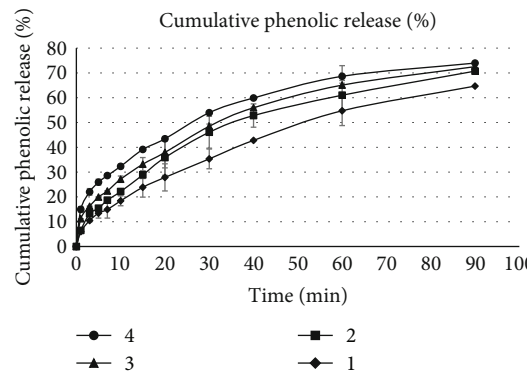


Figure 4: Effect of different initial phenolic concentration on cumulative release of the sage phenolic encapsulated in alginate capsules.

as The Peppas-Sahlin. On the other hand, the model with the lowest suitability with the experimental data was determined as Hixson and Crowell.

Benković et al. [14] analyzed the adsorption and release processes of Lamiaceae plant extracts (peppermint, lavender, sage, lemon balm, and thyme) on alginate microparticles. Among the 4 models used in the study (Zero Order, First Order, Korsmeyer-Peppas, and Higuchi), the most appropriate model was reported to be Korsmeyer-Peppas ($R^2 \geq 0.8194$). On the other hand, in studies in which curcumin [32] and *Mentha spicata* essential oil [33] were microencapsulated, it was reported that The Peppas-Sahlin was the most successful model in explaining the release mechanism.

The k value (Table 2) of the models is defined as the release rate constant. The increase in the concentration of sage extract loaded into the samples increased the k value, that is, the phenolic release rate from the capsules, in the First Order, Higuchi, Ritger-Peppas, and Hixson and Crowell models.

In the Gompertz model, α determines the undissolved fraction at time $t = 1$ and is defined as the position or scale parameter; β = dissolution rate per unit time is defined as the shape parameter. This model initially has a steep rise and gradually converges to the asymptotic maximum dissolution [34]. In this study, it is seen that as the concentration

Table 2: Identified parameters obtained by the model equations to the experimental phenolic release data for capsules.

Samples	Parameters	First Order	Higuchi	Korsmeyer-Peppas	Hixson and Crowell	The Peppas-Sahlin	Gompertz
	R^2	0.9414	0.991	0.9977	0.9083	0.9979	0.9925
	RMSE	4.8158	1.8903	1.0032	6.0256	1.0171	1.802
	k	0.8479	51.5587	52.6391	0.2454		
	n			0.5606			
1	k_1					58.0331	
	k_2					-5.1792	
	m					0.6007	
	α						3.9498
	β						0.3661
	R^2	0.9285	0.9905	0.9906	0.8776	0.9974	0.9793
	RMSE	6.0125	2.1906	2.2882	7.8648	1.2557	3.3945
	k	1.1235	60.2443	60.3735	0.3161		
	n			0.5059			
2	k_1					87.5645	
	k_2					-25.7097	
	m					0.6752	
	α						4.0889
	β						0.3146
	R^2	0.9150	0.9897	0.9915	0.8615	0.9959	0.987
	RMSE	7.8402	2.6340	1.9191	9.7957	1.5814	2.6775
	k	1.3538	66.5828	65.9209	0.3778		
	n			0.4731			
3	k_1					84.4969	
	k_2					-20.6183	
	m					0.5604	
	α						4.1391
	β						0.2747
	R^2	0.7741	0.9383	0.9934	0.6712	0.9952	0.9889
	RMSE	10.6143	5.5453	1.8996	12.8066	1.7032	2.4723
	k	1.5717	70.0718	66.5155	0.4318		
	n			0.3719			
4	k_1					87.2649	
	k_2					-20.4419	
	m					0.4608	
	α						4.1944
	β						0.2238

of sage extract added to the samples increases, the α value increases from 3.9498 to 4.1944, and the β value decreases from 0.3661 to 0.2238.

The n value in the Korsmeyer-Peppas model is known as the release exponent that defines the release mechanism, and it is stated that the mechanical limits of n depend on the geometry of the material on which the active components are loaded [35]. For cylindrical systems, the release mechanism is expressed by the Fickian diffusion mechanism when $n \leq 0.45$, by non-Fickian transport when $0.45 < n < 0.89$, by state II (relaxation) transport when $n = 0.89$, and by super state II transport mechanisms when $n > 0.89$. Anomalous diffusion or non-Fickian diffusion refers to the combination of both diffusion and erosion-controlled rate release. In this

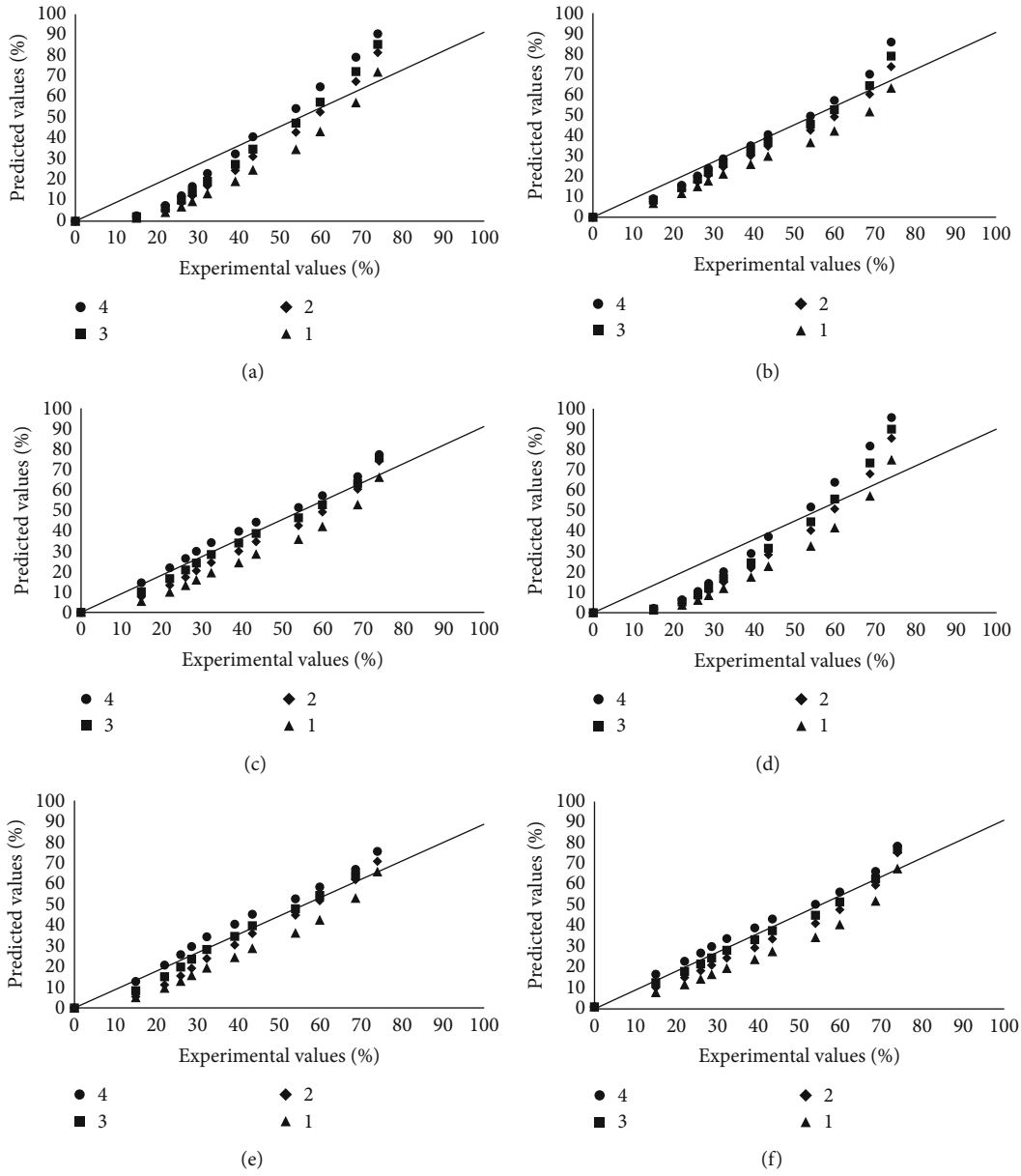


Figure 5: Residuals between experimental and predicted data for the phenolic release in relation to models ((a) First Order, (b) Higuchi, (c) Korsmeyer-Peppas, (d) Hixson and Crowell, (e) the Peppas-Sahlin, and (f) Gompertz).

study, it was determined that the n value of the samples changed between 0.37 and 0.56 depending on the added sage concentration. According to the Korsmeyer-Peppas model, it is concluded that both diffusion and erosion-controlled release mechanisms occur for samples 1 and 2, while the Fickian diffusion mechanism occurs for samples 3 and 4.

In The Peppas-Sahlin model, m is the diffusional exponent, and k_1 and k_2 are diffusion and erosion constants, respectively. The lower and negative k_2 values (relaxation kinetic constant) in The Peppas-Sahlin equation compared to k_1 value (diffusion rate constant) indicate the dominance of Fickian diffusion and the minor effect of relaxation process in the mechanism of phenolic release (Table 2). In addition, the ratio (R) of relaxational over Fickian (F) contribution can be calculated by [32]

$$\frac{R}{F} = \frac{k_2}{k_1}.t^m. \tag{11}$$

The R/F ratio vs. time graph is shown in Figure 6. The R/F factor was calculated to be negative (Figure 6), indicating that the phenolic release is predominantly controlled by diffusion phenomenon. Similar results regarding k_1, k_2, and R/F values in The Peppas-Sahlin model were reported by Kour et al. [32] for the release of encapsulated curcumin.

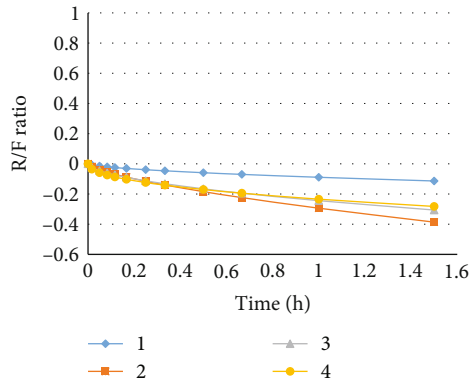


Figure 6: Relaxation (R) contribution/Fickian (F) contribution ratio with respect to time.

4. Conclusion

Capsules are promising delivery systems for encapsulation and release of phenolics since they can be fabricated from food-grade biopolymers using mild processes. In this study, sage phenolics at different concentrations were successfully encapsulated with sodium alginate. The yellowness ($+b^*$) value of the samples increased significantly as the added sage extract concentration increased. In addition, as the concentration of sage extract added to the alginate solution increased, both phenolic content and antioxidant activity values increased significantly. However, when the sage extract concentration increased to 300 ppm and above, the spherical shape of the capsules was distorted and even the capsule could not be formed. On the other hand, among the 6 models tested, The Peppas-Sahlin model, with the highest R^2 and lowest RMSE values, was suggested as the most successful model in describing the release mechanism of sage phenolics. Peppas-Sahlin model kinetic parameters indicating the phenolic release are predominantly controlled by diffusion phenomenon. In addition, studying the release mechanism of phenolics from capsules in different food simulants as well as water may contribute to the more common use of capsules in the food industry.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Elif Aykın-Dinçer conducted the conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing, reviewing, and editing. Cüneyt Dinçer conducted the conceptualization, data curation, formal analysis, investigation, methodology, resources, software, visualization, writing, reviewing, and editing. Osman Kadir Topuz conducted the conceptualization, data curation, investigation, resources, software, visualization, writing, reviewing, and editing.

References

[1] P. H. Davis, *Flora of Turkey and the East Aegean Islands, Vol. 3*, Edinburg University Press, Edinburg, 1982.

[2] H. Baydar, "Tıbbi, Aromatik ve Keyf Bitkileri Bilimi ve Teknolojisi," *Süleyman Demirel Üniversitesi*, vol. 51, p. 216, 2005.

[3] C. Dincer, A. Topuz, H. Sahin-Nadeem et al., "A comparative study on phenolic composition, antioxidant activity and essential oil content of wild and cultivated sage (Salvia fruticosa Miller) as influenced by storage," *Industrial Crops and Products*, vol. 39, pp. 170–176, 2012.

[4] H. Gali-Muhtasib, "Anticancer and medicinal properties of essential oil and extracts of East Mediterranean sage (Salvia triloba)," *Advances in Phytomedicine*, vol. 2, pp. 169–180, 2006.

[5] H. Şahin-Nadeem, C. Dinçer, M. Torun, A. Topuz, and F. Özdemir, "Influence of inlet air temperature and carrier material on the production of instant soluble sage (Salvia fruticosa Miller) by spray drying," *LWT - Food Science and Technology*, vol. 52, no. 1, pp. 31–38, 2013.

[6] A. G. Tarone, C. B. B. Cazarin, and M. R. M. Junior, "Anthocyanins: new techniques and challenges in microencapsulation," *Food Research International*, vol. 133, article 109092, 2020.

[7] M. Koç, M. Sakin, and F. Kaymak-Ertekin, "Mikroenkapsülasyon ve Gıda Teknolojisinde Kullanımı," *Pamukkale University Journal of Engineering Sciences*, vol. 16, no. 1, 2010.

[8] S. Ray, U. Raychaudhuri, and R. Chakraborty, "An overview of encapsulation of active compounds used in food products by drying technology," *Food Bioscience*, vol. 13, pp. 76–83, 2016.

[9] T. Çoruhli, *Encapsulation of black mulberry anthocyanins by ionic gelation method and optimization of encapsulation parameters by response surface method*, Istanbul Technical University, Institute of Science and Technology, Department of Food Engineering, Master's Thesis, 2013.

[10] D. Díaz-Bandera, A. Villanueva-Carvajal, O. Dublán-García, B. Quintero-Salazar, and A. Dominguez-Lopez, "Release kinetics of antioxidant compounds from Hibiscus sabdariffa L. encapsulated in gelatin beads and coated with sodium alginate," *International Journal of Food Science & Technology*, vol. 48, no. 10, pp. 2150–2158, 2013.

[11] Q. D. Nguyen, T. V. L. Nguyen, T. T. D. Nguyen, and N. N. Nguyen, "Encapsulation of roselle anthocyanins in blank alginate beads by adsorption and control of anthocyanin release in beverage by coatings with different molecular weight chitosan," *Journal of Food Processing and Preservation*, vol. 46, no. 4, Article ID e16438, 2022.

[12] O. K. Topuz, T. Aygün, and G. N. Ural, "Caviar-like hydrogel beads containing different concentrations of NaCl and melanin-free squid ink," *Food Bioscience*, vol. 36, p. 100652, 2020.

[13] S. K. Giri and S. Prasad, "Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms," *Journal of Food Engineering*, vol. 78, no. 2, pp. 512–521, 2007.

[14] M. Benković, I. Sarić, A. Jurinjak Tušek, T. Jurina, J. Gajdoš Kljusurić, and D. Valinger, "Analysis of the adsorption and release processes of bioactives from Lamiaceae plant extracts

on alginate microbeads," *Food and Bioprocess Technology*, vol. 14, no. 7, pp. 1216–1230, 2021.

[15] V. Đorđević, B. Balanč, A. Belščak-Cvitanović et al., "Trends in encapsulation technologies for delivery of food bioactive compounds," *Food Engineering Reviews*, vol. 7, no. 4, pp. 452–490, 2015.

[16] P. C. L. Hui, W. Y. Wang, C. W. Kan et al., "Microencapsulation of traditional Chinese herbs—PentaHerbs extracts and potential application in healthcare textiles," *Colloids and Surfaces B: Biointerfaces*, vol. 111, pp. 156–161, 2013.

[17] A. C. Tomé and F. A. da Silva, "Alginate based encapsulation as a tool for the protection of bioactive compounds from aromatic herbs," *Food Hydrocolloids for Health*, vol. 2, article 100051, 2022.

[18] E. Aykın-Dinçer and C. Dinçer, "Modeling of sage (Salvia fruticosa Miller) phenolics diffusion in meat cubes during ultrasound assisted vacuum impregnation," *Food Bioscience*, vol. 53, p. 102755, 2023.

[19] E. Aykın-Dinçer, M. Özdemir, and A. Topuz, "Quality characteristics of bone broth powder obtained through Refractance Window™ drying," *LWT*, vol. 147, p. 111526, 2021.

[20] E. S. Chan, B. B. Lee, P. Ravindra, and D. Poncelet, "Prediction models for shape and size of ca-alginate macrobeads produced through extrusion–dripping method," *Journal of Colloid and Interface Science*, vol. 338, no. 1, pp. 63–72, 2009.

[21] C. Dinçer, I. Tontul, I. B. Çam et al., "Phenolic composition and antioxidant activity of Salvia tomentosa Miller: effects of cultivation, harvesting year, and storage," *Turkish Journal of Agriculture and Forestry*, vol. 37, no. 5, pp. 561–567, 2013.

[22] M. F. Fernández-León, A. M. Fernández-León, M. Lozano et al., "Retention of quality and functional values of broccoli 'Parthenon' stored in modified atmosphere packaging," *Food Control*, vol. 31, no. 2, pp. 302–313, 2013.

[23] T. Lu and T. L. Ten Hagen, "A novel kinetic model to describe the ultra-fast triggered release of thermosensitive liposomal drug delivery systems," *Journal of Controlled Release*, vol. 324, pp. 669–678, 2020.

[24] N. A. Peppas and J. J. Sahlin, "A simple equation for the description of solute release. III. Coupling of diffusion and relaxation," *International Journal of Pharmaceutics*, vol. 57, no. 2, pp. 169–172, 1989.

[25] A. G. da Silva Carvalho, M. T. da Costa Machado, H. D. D. F. Q. Barros, C. B. B. Cazarin, M. R. M. Junior, and M. D. Hubinger, "Anthocyanins from jussara (*Euterpe edulis* Martius) extract carried by calcium alginate beads pre-prepared using ionic gelation," *Powder Technology*, vol. 345, pp. 283–291, 2019.

[26] P. Tzatsi and A. M. Goula, "Encapsulation of extract from unused chokeberries by spray drying, co-crystallization, and ionic gelation," *Waste and Biomass Valorization*, vol. 12, no. 8, pp. 4567–4585, 2021.

[27] C. S. Cutrim, I. D. Alvim, and M. A. S. Cortez, "Microencapsulation of green tea polyphenols by ionic gelation and spray chilling methods," *Journal of Food Science and Technology*, vol. 56, no. 8, pp. 3561–3570, 2019.

[28] N. D. Arriola, P. I. Chater, M. Wilcox et al., "Encapsulation of Stevia rebaudiana Bertoni aqueous crude extracts by ionic gelation–effects of alginate blends and gelling solutions on the polyphenolic profile," *Food Chemistry*, vol. 275, pp. 123–134, 2019.

[29] M. Çam, N. C. İçyer, and F. Erdoğan, "Pomegranate peel phenolics: microencapsulation, storage stability and potential ingredient for functional food development," *LWT-Food Science and Technology*, vol. 55, no. 1, pp. 117–123, 2014.

[30] İ. Toprakçı, M. Torun, and S. Şahin, "Development of an encapsulation method for trapping the active materials from sour cherry biowaste in alginate microcapsules," *Food*, vol. 12, no. 1, p. 130, 2023.

[31] F. Hamedi, M. Mohebbi, F. Shahidi, and E. Azarpazhooh, "Ultrasound-assisted osmotic treatment of model food impregnated with pomegranate peel phenolic compounds: mass transfer, texture, and phenolic evaluations," *Food and Bioprocess Technology*, vol. 11, no. 5, pp. 1061–1074, 2018.

[32] P. Kour, S. Afzal, A. Gani et al., "Effect of nanoemulsion-loaded hybrid biopolymeric hydrogel beads on the release kinetics, antioxidant potential and antibacterial activity of encapsulated curcumin," *Food Chemistry*, vol. 376, article 131925, 2022.

[33] M. Mehran, S. Masoum, and M. Memarzadeh, "Microencapsulation of Mentha spicata essential oil by spray drying: optimization, characterization, release kinetics of essential oil from microcapsules in food models," *Industrial Crops and Products*, vol. 154, article 112694, 2020.

[34] P. Costa and J. M. S. Lobo, "Modeling and comparison of dissolution profiles," *European Journal of Pharmaceutical Sciences*, vol. 13, no. 2, pp. 123–133, 2001.

[35] S. N. Raza and N. A. Khan, "Role of mathematical modelling in controlled release drug delivery," *International Journal of Medical Research and Pharmaceutical Sciences*, vol. 4, no. 5, pp. 84–95, 2017.