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Research Article

Spray-Dried Microencapsulation of Oregano (*Lippia graveolens*) Polyphenols with Maltodextrin Enhances Their Stability during *In Vitro* Digestion

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The effect of *in vitro* gastrointestinal digestion on the release of microencapsulated phenolic compounds was evaluated through an optimized spray drying process. A stock extract of oregano phenolic compounds was developed and microencapsulated in a spray dryer following a central composite rotatable design, controlling the variables, inlet temperature (111.7-168.2°C), and percentage of wall material (5.8-34.1%). Optimum drying conditions for spray drying were decided based on different yield percentages (Y %) and encapsulated phenolic compounds (EPC). The analyzed physical properties were morphology measured by electron microscopy and humidity; other properties evaluated were the content of total phenolic compounds, antioxidant capacity determined by DPPH and ABTS assays, and phenolic profile by ultraperformance liquid chromatography coupled to mass spectrometry (UPLC-MS). During the gastrointestinal simulation, a stability of 85% was determined in the intestinal stage. Microencapsulation technology by spray drying is an excellent selection to stabilize and protect bioactive compounds of oregano and promote its use as a functional ingredient.

1. Introduction

Oregano is the name given to a variety of plants, generally belonging to the Lamiaceae and Verbenaceae botanical families that share similar flavor and odor [1]. Oregano is a shrub plant distributed in semiarid climates in Mexico, Central America, and Europe [2]. Oregano leaves have been used since ancient times in cuisine and traditional medicine to stimulate menstruation and as antivenom, and diluted infusions of oregano are used to treat respiratory diseases and stomach infections [3, 4]. Currently, the number of studies to test its properties as a food preservative, pesticide, and antimicrobial has grown [5]. However, research is oriented to the study of its functional and nutraceutical properties, which are attributed to its phytochemical compounds [2, 6]; these include essential oils and phenolic compounds, which are secondary metabolites generated by plants as a defense against different biotic and abiotic factors [7].

Oregano provides numerous health benefits thanks to its abundant amount of antioxidants, namely, rosmarinic acid, carvacrol, thymol, limonene, quercetin, pinene, ocimene, caryophyllene, and other phenolic compounds (polyphenols, flavones, and flavonols) [8]. The functionality attributed to phenolic compounds is related to their hydroxyl groups. Phenolics may act as scavengers and stabilizers of free radicals and reactive oxygen species, preventing and delaying the onset of noncommunicable diseases like cancer [9–11]. However, generally, bioactive phenolic compounds

must be bioaccessible and bioavailable, so they can be absorbed and reach systemic circulation and distributed to organs and tissues [12]. Bioaccessibility is defined as the number of polyphenols present in the intestine due to its release from the food matrix, which is available to be absorbed through the intestinal barrier [12].

However, it has been recently reported that oregano phenolic compounds can be easily degraded and metabolized when exposed to a simulated gastrointestinal system. Gutiérrez-Grijalva et al. [13], who evaluated the *in vitro* bioaccessibility of phenolic extracts of oregano (7.74% bioaccessibility), indicate that phenolic compounds are released before reaching the intestinal phase, causing the degradation and transformation of these compounds and with it the loss of bioaccessibility. Microencapsulation has become important as an emerging technology for protecting phenolic compounds both from environmental factors and from conditions in the digestive phases. Therefore, selecting an appropriate encapsulation method and wall material is crucial to protect this type of compound. Martínez-Ramírez et al. [14], evaluated the bioaccessibility of xoconostle (*Opuntia joconostle*) microencapsulated phenolic compounds by spray drying, using 30% maltodextrin-gum Arabic mixture as wall material. They achieved an increase in bioaccessibility from 42 to 64%, concluding that the encapsulation process was favorable. This study was aimed at evaluating the effect of *in vitro* gastrointestinal digestion on the release of phenolic compounds from Mexican oregano (*Lippia graveolens*) microencapsulated by spray drying.

2. Materials and Methods

2.1. Plant Material. Oregano (*Lippia graveolens)* was obtained in the Temohaya indigenous area, Municipality of Mezquital, Durango (coordinates N: 23.299722; W: 104.509167). The oregano leaves were dried in an Excalibur Food Dehydrator Parallax Hyperware (Sacramento, CA) at 40°C for 24 h, and ground in an Ika Werke M20 grinder (Wilmington, NC, USA) until a fine powder was obtained with a sieve #40. The oregano powder was stored at −20°C until use.

2.2. Extraction of Polyphenols. Polyphenol-rich extracts were prepared as follows: 1 g of dried oregano and 10 mL of distilled water were stirred and homogenized in a stir plate (Thermo Scientific Cimarec) for two hours in the absence of light. Then, the slurry was collected and vacuum filtered with Whatman # 4 paper. Subsequently, the extract obtained was centrifuged at 6,000 rpm for 15 min; the supernatant was collected and stored at 4°C for later use. This technique was carried out repeatedly until approximately 5 l of extract stock was obtained.

2.3. Experimental Design and Statistical Analysis. A central composite design was used to optimize the microencapsulation using the drying chamber temperature (X1: 111.7–168.2°C) and the percentage of encapsulating material (X2: 5.8-34.1%) as variables. The coded and uncoded levels of the independent variables are shown in Table 1. The range of each variable was selected based on preliminary tests (data not shown). Table 2 shows the experimental design used and 13 experimental runs performed. Two response variables were evaluated: % Y (yield percentage) and EPC (encapsulated phenolic compounds). Statistical significance was assessed using an analysis of variance, and the results were considered significant when $p < 0.05$. The coefficient of determination (R^2) was also evaluated to determine the model's suitability. Graphical and numerical optimizations were used to find the optimal levels of the independent variables (% Y and EPC). Additional confirmation experiments were conducted to verify optimal conditions.

Table 1: Central composite design used to optimize the microencapsulation process of oregano (*Lippia graveolens*) phenolics.

	Factor levels				
Independent factors	-1.41421	-1	0	1	1.41421
X1: temperature (°C)	111.7	120.0	140.0	160.0	168.2
X2: wall material (%)	5.8	10.0	20.0	30.0	34.1

Table 2: Central composite design used to optimize the microencapsulation process of oregano (*Lippia graveolens*) extracts.

Run	Coded levels	Factor 1: temperature (°C)	Factor 2: wall material (%)
1	00	140	20
2	—	120	10
3	a0	111.7	20
4	0a	140	5.8
5	00	140	20
6	0A	140	34.1
7	00	140	20
8	-+	120	30
9	++	160	30
10	+-	160	10
11	00	140	20
12	00	140	20
13	A0	168.2	20

Factorial (+, -), axial (A, a), and central (0) runs.

2.4. Preparation of the Microcapsules. An aliquot of 150 mL of stock extract was mixed with maltodextrin 10 DE as wall material. The mixture was homogenized on a stir plate at 600 rpm until completely dissolved. Subsequently, the mixture was fed to a Spray Dryer Yamato ADL311S. Wall material (%) and inlet temperature were applied according to the design (Table 2). The constant conditions were atomization pressure at 0.1 MPa, feed flow at 5 mL/min, and airflow at 0.32 m^3/min. The recovered powders were weighed to obtain the yield of the process and stored in an amber glass bottle at room temperature for analysis.

2.5. Process Yield. The encapsulation yield of the process was calculated using a gravimetric technique as the relationship

between the numbers of solids fed into the dryer concerning the solids recovered at the exit of the dryer and was reported as a percentage [15].

2.6. Total Phenolic Content. Total phenolic compounds were extracted following the method of Cilek et al. [16], with some modifications. A 200 mg of encapsulated phenolic sample was dissolved in 2 mL of ethanol/acetic acid/water mixture (50 : 8 : 42) to disrupt spray-dried particles and allow phenolic compounds to release. This mixture was stirred using Vortex-Genie 2 for 1 min and filtered with a nylon microfilter (0.45 μm). The total phenolic content was determined using the Folin-Ciocalteu reagent, following the methodology described by Swain and Hillis [17], with some modifications. The reaction mixture was prepared by combining 10 μL of the sample, 230 μL of distilled water, 10 μL of Folin-Ciocalteu reagent, and 25 sodium carbonate solution (4 N). The reaction mixture was incubated for 2 h before reading the absorbance at 725 nm using a 96-well using a Synergy HT microplate reader (Synergy HT, Bio-Tek Instruments, Inc., Winooski, VT). The results were expressed as milligrams of gallic acid equivalents (mg GAE)/gram sample.

2.7. Polyphenol Content on the Surface of the Microparticles. The phenolic concentration on the surface of microparticles was determined following the report by Cilek et al. [16]. A sample of 200 mg of microcapsules was dispersed in 2 mL of ethanol/methanol mixture (50 : 50) for 1 min. The content of phenolic compounds on the surface of the microparticles was measured and quantified with the method described in the total phenolic content section.

2.8. Microencapsulation Yield of Polyphenols. These were calculated by subtracting the amount of total phenolic compounds and the content of surface phenolic compounds [18].

$$\text{Encapsulated PC} = \text{total phenolics} - \text{phenolic compounds on the surface.} \quad (1)$$

2.9. Antioxidant Capacity. Two different methods were used to determine the antioxidant capacity of microencapsulates. The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay was performed as described by Thaipong et al. [19], and the assay of 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) according to Karadag et al. [20]. Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) was used as standard, and the results are expressed in micromole equivalent Trolox (TE)/gram sample.

2.10. Identification and Quantification of Polyphenols by UPLC-qTOF-MS/MS. The identification and quantification of oregano polyphenols entrapped in the microparticles were performed following the report of Gutiérrez-Grijalva et al. [21] using a UPLC class H equipment (Waters Corporation, USA) coupled to a G2-XS QT of the mass analyzer (Quadrupole and Time of Flight) using a UPLC BEH C18 column (1.7 μm × 2.1 mm × 100 mm) at 40°C. Phenolic compounds were separated with a gradient elution solution A (water-formic acid 0.1%) and solution B (acetonitrile) at a 0.3 mL/min flow rate. The gradient elution procedure was as follows: 0 min, 95% (A); 5 min, 70% (A); 9 min, 30% (A); 14 min, 0% (A); 14.5 min, 0% (A); 15 min, 95% (A); and 16 min, 95% (A). The ionization of the compounds was carried out by electrospray (ESI), and the parameters used consisted of a capillary voltage of 1.5 kV, sampling cone: 30 V, desolvation gas of 800 (L/h), and a temperature of 500°C. A 0-30 V collision ramp was used. The identification of compounds was done using the North American Mass-Bank Database (MoNA). The content of phenolic compounds was expressed in milligrams per 100 g sample.

The quantification of phenolic compounds by UPLC was performed as a function of the peak area of the maximum absorption wavelength. The standards used were caffeic acid, luteolin, naringenin, phloretin, and quercetin.

2.11. Morphology and Moisture. Microparticle morphology was analyzed by an environmental scanning electron microscope (model EVO-50, Carl, Zeiss, Germany). The sample without any previous treatment was placed on a sample holder with the help of an adhesive double-sided carbon tape. The observation was made under high vacuum conditions, with a secondary electron detector (SE1) and an acceleration voltage of 10-15 kV (×2000 and ×4000 magnification). The amount of water in the microcapsules was determined using a gravimetric analysis using the AOAC method 925.09 (1997) [22].

2.12. In Vitro Gastrointestinal Digestion. An *in vitro* digestion model was conducted using the method reported by Flores et al. [23], with some modifications. Briefly, *in vitro* digestion consisted of a 3-step process that simulates digestion in the mouth, stomach, and small intestine, mimicking the pH, chemical composition of the digestive fluids, temperature (37°C), and transit times. The composition of the artificial digestive juices is listed in Table 3.

Powder samples (1 g) were placed in 50 mL corning tubes and incubated for 5 min at 37°C in a Model 290400S incubator (Boekel Scientific, Feasterville, PA) at 55 rpm. The samples were digested as follows: the oral phase began by adding 1.71 mL of salivary and an incubation time of 5 min; after that, the stomach phase began when 3.42 mL of gastric juice was added and gently mixed for 2 h. In the end, the intestinal phase consisted of adding 3.42 mL of intestinal juice to the mix and incubating for 2 h. At the end of the *in vitro* digestion process, the samples were centrifuged at 6000 rpm for 15 min, and the resulting supernatant called digesta was stored at -20°C before further analysis.

Microencapsulated samples without oregano extracts were used as blank. At the end of each digestive phase, the whole digested sample in the tube was centrifuged under the conditions mentioned above, and the supernatants were kept frozen until further use (–20°C).

Table 3: Composition of simulated digestive juices.

Salivary juice	Gastric juice	Intestinal juice
500 mL distilled water	500 mL distilled water	500 mL distilled water
58.5 mg NaCl	2.752 g NaCl	7.012 g NaCl
74.5 mg KCl	0.824 g KCl	0.564 g KCl
1.05 g $NaHCO_3$	0.266 g NaH_2PO_4	3.388 g $NaHCO_3$
	0.399 g $CaCl_2.2H_2O$	80.0 mg KH_2PO_4
0.2 g urea	0.306 g NH_4Cl	50.0 mg $MgCl_2$
	0.085 g urea	0.1 g urea
Adjuncts		
0.5 g mucin	2.5 g pepsin	9.0 g pancreatin
1.0 g α-amylase	3.0 g mucin	1.5 g lipase
pH		
6.8 ± 0.2	1.30 ± 0.02	8.1 ± 0.2

3. Results and Discussion

Table 4 shows the % Y and EPC of the 13 experiments performed to optimize the microencapsulation of oregano extract. The % Y values ranged from 34.73 to 71.85%, and the highest values were found under the experimental conditions X1 = 140°C and X2 = 20%.

The ANOVA analysis showed that a quadratic model is significant for the response variables yield (%) and encapsulated phenolic compounds as a function of the inlet temperature and percentage of wall material (Tables 5 and 6). Also, both the linear term and the quadratic term of the wall material were significant for the yield response variable (Figure 1). This model showed a determination coefficient $R^2 = 79.36\%$, which might suggest there is high variability in yields. Regarding the encapsulated phenolic compounds (response variable), the linear and quadratic terms of the two factors, temperature and wall material, were significant, showing a determination coefficient $R^2 = 87.29\%$ for this model. Furthermore, it has been reported that yields above 50% are considered optimal, which agrees with our results.

3.1. Antioxidant Characterization of the Optimal Microencapsulate. The phenolic content by the Folin-Ciocalteu assay of the microencapsulates (Table 7) was 14.05 mg GAE/g of sample (this result was calculated using the difference between total phenolic and superficial phenolics). In contrast to the microencapsulates, nonencapsulated oregano extracts had a total phenolic content of 33.66 mg GAE/g of the sample. This difference might occur as a result of the spray-drying process, in which atomization of the feed material results in very fine mist-like droplets with an increased surface area, which involves higher exposure of the extracts to the heat that might degrade phenolics.

Moreover, due to the atomization, some parts of the wall material can be removed from the core material even after homogenization [24]; these partially covered microcapsules are easily affected by heat. Another factor that could be related to this result is that when wall material is added to an extract, the spatial distribution of phenolics is dispersed, and its quantification per unit of mass decreases [25]. Our results were similar to those reported by Ruiz-Canizales et al. [26], for maltodextrin microencapsulated extracts of blue corn phenolics (13.9 mg GAE/g sample), but higher than those found by Tolun et al. [27], where they microencapsulated grape phenolic compounds (5.4-8.5 mg GAE/g sample).

Regarding the antioxidant capacity of the microencapsulate, we obtained values of 50.83 μmol ET/g sample and 85.17 μmol ET/g sample for the inhibition of the DPPH and ABTS radicals, respectively. In contrast, Cilek et al. [16] showed a lower antioxidant capacity for extracts of cherry pomace microencapsulated with a mixture of maltodextrin/gum Arabic using the DPPH method (17.98 μmol ET/g). Also, Saénz et al. [18] indicated an antioxidant capacity of microencapsulated cactus peel extracts (*Opuntia ficus-indica*) with maltodextrin 10 DE using the ABTS method (19.2 μmol ET/g). The differences between each report of microencapsulated phenolic-rich extracts might be attributed to the concentration of microencapsulated phenolics and the type of compound that is encapsulated.

Moreover, our results showed that our microencapsulated oregano extracts have the potential to be used as antioxidant ingredients in formulations of functional beverages and foodstuff.

3.2. Identification and Quantification of Polyphenols by UPLC-qTOF-MS/MS. Microencapsulated phenolic compounds were identified by comparing the fragments obtained in each sample spectrum with the spectra provided by the MassBank of North America (MoNA) database. Twelve compounds were identified, mostly flavonoids and one phenolic acid. The flavonoids luteolin-7-glucoside, scutellarin, apigenin-7-glucoside, luteolin, and apigenin belong to the subgroup of flavones; 4 of the flavonoids are flavanones: taxifolin, eriodictyol, naringenin, and pinocembrin; one flavonol identified as quercetin, and a dihydrochalcone identified as phloretin (Table 8). It has been previously reported that most of the phenolic compounds obtained by methanolic extracts of *Lippia graveolens* belong to the flavone subgroup of flavonoids [4, 13, 21]. Regarding the microencapsulated phenolic acids, only caffeic acid was identified, and it should be noted that in an extract without microencapsulation, two other phenolic acids were identified, namely, gallic and vanillic acids indicating that during the drying process, these two phenolic acids were degraded.

Quantification was performed based on available commercial standards (Table 8). The phenolic compounds that predominate in higher concentrations belong to the group of flavanones. This profile was similar to previous studies [4, 6, 13] even though the extraction method was 100% water. It is worth mentioning that in this study, one of the flavonoids found in the highest concentration was naringenin, which has already been reported as predominant in methanolic extracts of the *L. graveolens* species [28].

3.3. Particle Morphology. One of the essential characteristics to consider in a microencapsulate is size and shape. Electron microscopy micrographs showed that oregano microcapsules

Table 4: Experimental values of the optimization.

Experimental run	Coded variables		Experimental values	
	X1	X2	% *Y*	EPC (mg GAE/430 mg IGAS)
1	-1	-1	58.93	251.15
4	1	-1	53.85	212.59
5	-1	1	40.22	150.59
7	1	1	48.15	207.10
2	-1.41421	0	34.76	138.00
12	1.41421	0	69.39	260.63
9	0	-1.41421	66.92	259.57
6	0	1.41421	55.30	220.29
11	0	0	69.05	277.39
10	0	0	66.42	284.38
8	0	0	69.27	276.55
3	0	0	71.85	282.36
13	0	0	68.61	281.40

% *Y*: yield percentage; EPC: encapsulated phenolic compounds; mg GAE: milligrams of gallic acid equivalents; IGAS: milligrams of initial gallic acid solution.

Table 5: Analysis of variance of the effect of temperature (°C) and wall material (%), adjusted to a quadratic model on the yield (powder recovery rate) of the encapsulation process.

Source	DF	Sum of squares	Mean squares	*F*	*p*
Model	5	1416.50	283.30	5.38	0.0239
A-inlet temperature	1	335.53	335.53	6.38	0.0395
B-% WM	1	208.49	208.49	3.96	0.0868
AB	1	42.33	42.33	0.80	0.3996
A^2	1	703.63	703.63	13.37	0.0081
B^2	1	213.51	213.51	4.06	0.0838
Residual	7	368.40	52.63		
Lack of fit	3	353.44	117.81	31.50	0.0031
Pure error	4	14.96	3.74		
Total					
$R^2 = 79.35\%$					

Table 6: Analysis of variance of the effect of temperature (°C) and wall material (%), adjusted to a quadratic model, on the content of encapsulated phenolic compounds recovered after the encapsulation process.

Source	DF	Sum of squares	Mean squares	*F*	*p* value
Model	5	25942.68	5188.54	9.62	0.0049
A-inlet temperature	1	4597.07	4597.07	8.52	0.0224
B-% WM	1	3279.71	3279.71	6.08	0.0431
AB	1	2240.55	2240.55	4.15	0.0809
A^2	1	13524.35	13524.35	25.07	0.0016
B^2	1	3934.76	3934.76	7.29	0.0306
Residual	7	3776.05	539.44		
Lack of fit	3	3731.52	1243.84	111.74	0.0003
Pure error	4	44.53	11.13		
Total	12	29718.72			
$R^2 = 87.25\%$					

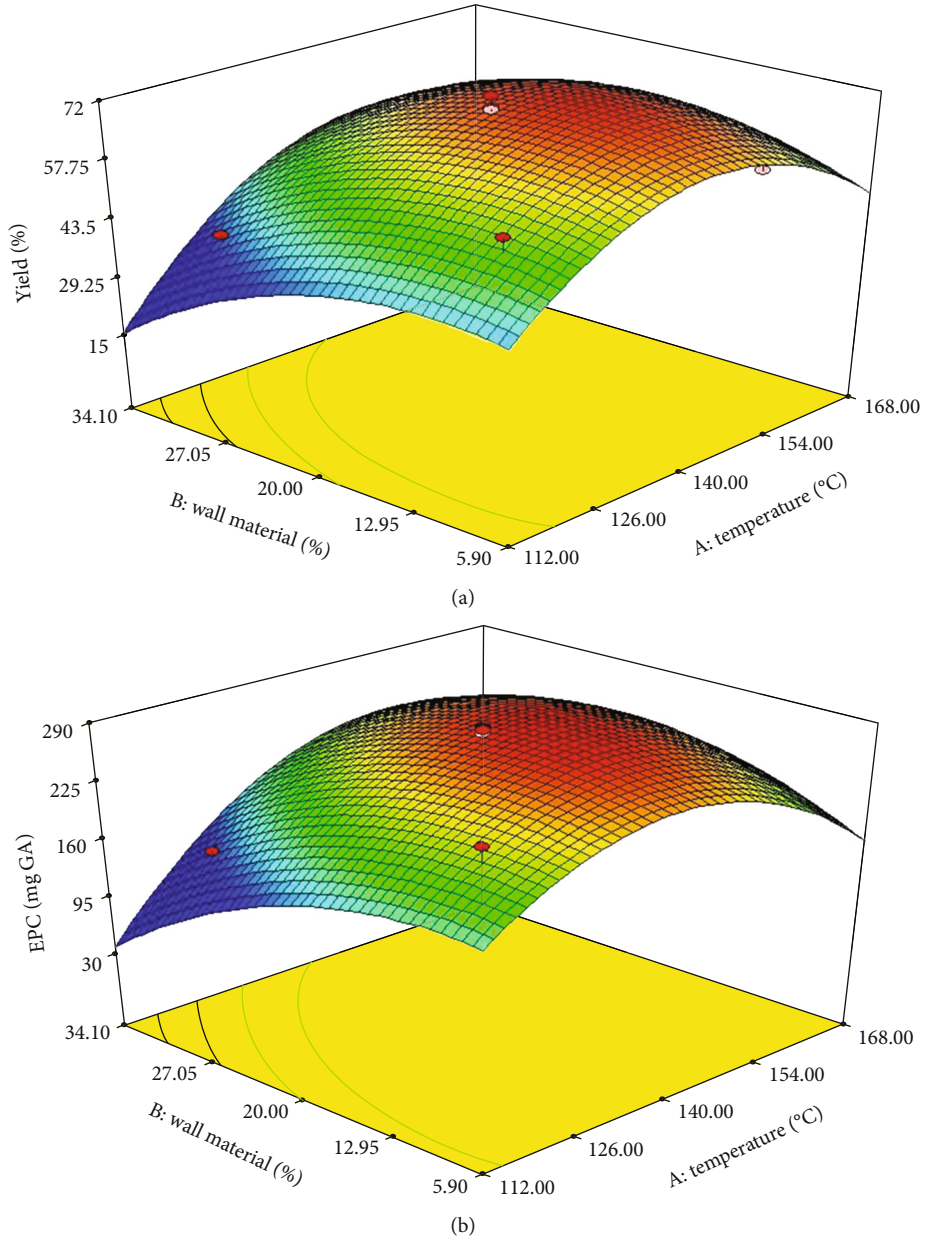

Figure 1: Response surface for (a) yield (%) and (b) encapsulated phenolic compound in microencapsulated oregano (*Lippia graveolens*) extracts.

Table 7: Content of encapsulated phenolic compounds and antioxidant capacity of microencapsulated oregano (*Lippia graveolens*) extracts.

Sample	TPC (mg GAE/g sample)	SPC (mg GAE/g sample)	EPC (mg GAE/g sample)	AC by DPPH (μmol TE/g sample)	AC by ABTS (μmol TE/g sample)
Optimized microcapsules	14.45 ± 0.34	0.40 ± 0.02	14.05 ± 0.31	50.83 ± 0.25	85.17 ± 2.07

TPC: total phenolic compounds; SPC: surface phenolic compounds; EPC: encapsulated phenolic compounds; AC: antioxidant capacity. Data shown as means ± standard deviation of three replicates ($n = 3$).

have a particle size between 2 and 12 μm and a spherical shape with depressions (Figure 2). The spherical form of the atomized powders is based on the principle of generation of droplets by spraying and conversion of these droplets into particles by evaporation of the solvent [29]. A similar study by Rezende et al. [30], show that most samples presented spherical conformation, without agglomeration, irregular shapes, and few fissures. However, some showed a smooth surface characteristic of microparticles produced by a spray-drying process. They mention that roughness in the microparticles is usually attributed to particle shrinkage due to the drastic loss of moisture followed by cooling [30].

Table 8: Identification and quantification of phenolic compounds in microencapsulated powder of oregano (*Lippia graveolens*) extracts.

TR (min)	MS^2	$[M-H]^-$	MS^2 (m/z)	Identification	Compound type	Quantification
4.15	180.04	179.03	134.03, 135.04, 179.03	Caffeic acid	Phenolic acid	147.55 ± 6.92^a
5.41	448.10	447.09	284.03, 285.03, 447.09	Luteolin-7-glucoside	Flavone	130.11 ± 14.40^e
5.49	462.08	461.07	164.98, 285.04, 461.07	Scutellarin	Flavone	3.51 ± 0.15^e
5.65	304.05	303.05	125.02, 285.03, 303.04	Taxifolin	Flavanone	249.06 ± 31.01^e
6.08	432.10	431.09	268.03, 269.04, 431.09	Apigenin-7-glucoside	Flavone	20.09 ± 2.09^e
7.30	288.06	287.05	135.04, 151.00, 287.05	Eriodictyol	Flavanone	112.44 ± 9.54^e
7.36	286.04	285.03	133.02, 151.00, 285.03	Luteolin	Flavone	96.93 ± 4.61^b
7.38	302.04	301.03	151.00, 178.99, 301.03	Quercetin	Flavonol	18.87 ± 1.99^c
7.95	270.05	269.04	117.03, 151.00, 269.04	Apigenin	Flavone	28.75 ± 2.51^e
7.97	272.06	271.06	119.04, 151.00, 271.06	Naringenin	Flavanone	204.65 ± 17.39^e
8.01	274.08	273.07	123.04, 167.03, 273.07	Phloretin	Dihydrochalcone	21.35 ± 1.43^d
9.45	256.07	255.06	151.00, 213.05, 255.06	Pinocembrin	Flavanone	28.20 ± 1.70^e

[a]μg caffeic acid/g microencapsulated, [b]μg luteolin /g microencapsulated, [c]μg quercetin /g microencapsulated, [d]:μg floretin /g microencapsulated, [e]μg quercetin equivalent/g microencapsulated. Results are shown as mean ± standard deviation of three replicates ($n = 3$).

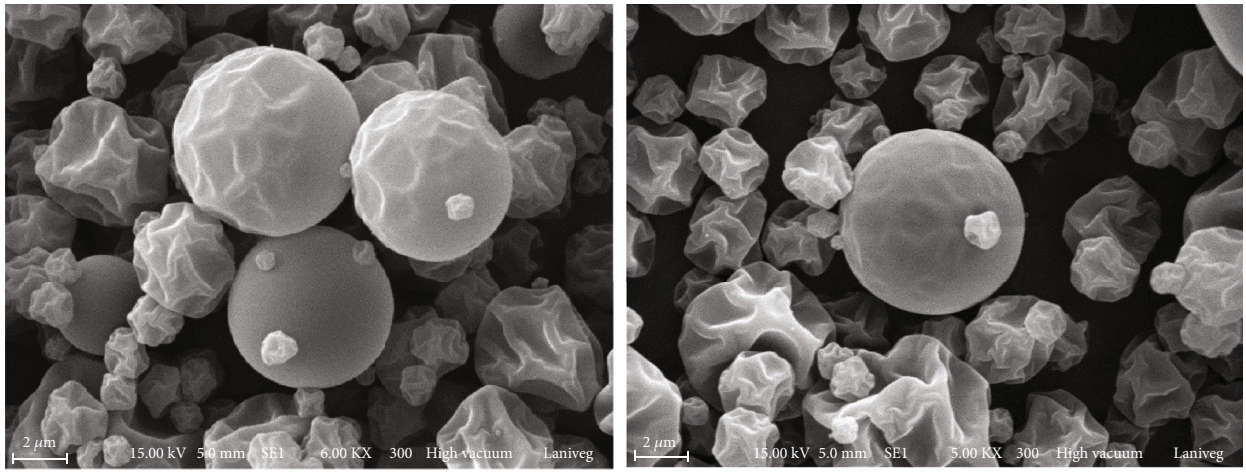

Figure 2: Micrographs of the microparticle structure of phenolic compounds of oregano (L*ippia graveolens*) produced with maltodextrin 10 DE as wall material, using spray drying.

Regarding particle size, González et al. [31] found a unimodal particle size distribution in OLE-SA microparticles, with sizes ranging from 0.25 μm to 20 μm. Regarding this, minimal variability in size is desirable not to affect the sensory properties of the final product where it is applied. Furthermore, the pressure of the atomization air and the hydrolysis degree of maltodextrin may also influence the microcapsules characteristics. In this sense, it has been reported that higher dextrose equivalents in maltodextrin might yield a smoother surface in the microcapsules. In this study, we used low hydrolysis degree maltodextrin for its characteristics, such as longer shelf life and high glass transition temperature [32]. Furthermore, Ruiz-Canizales et al. [26], obtained maltodextrin-coated microparticles from blue corn phenolics with a spherical particle size of 1 to 10 μm, with marked depressions. Also, Çam et al. [33] analyzed the structure of microencapsulates of maltodextrin and gum Arabic for phenolics from pomegranate peel, reporting an average particle size of 10 μm and spherical shape. The particles obtained showed low moisture (3.55%) and higher yield (77.42%), while low humidity prevents phenolic compound oxidation, and yields of >50% are considered optimal for microencapsulation with maltodextrin [25, 34].

3.4. Stability of Oregano Microencapsulates. To evaluate the release of the microencapsulated oregano phenolic compounds during gastrointestinal digestion, we evaluated the total phenolic content at the end of each digestive phase. The results (Figure 3) showed a release of phenolics in the salivary stage of 83.34%. In comparison, in the gastric phase, there was an increase presenting 91.38%, and finally, in the intestinal stage, there was a slight decrease, finding a release of 85.05%. There were no significant differences between the three phases among the release of encapsulated phenolic compounds and the control. This may indicate that there was no significant degradation of phenolic compounds,

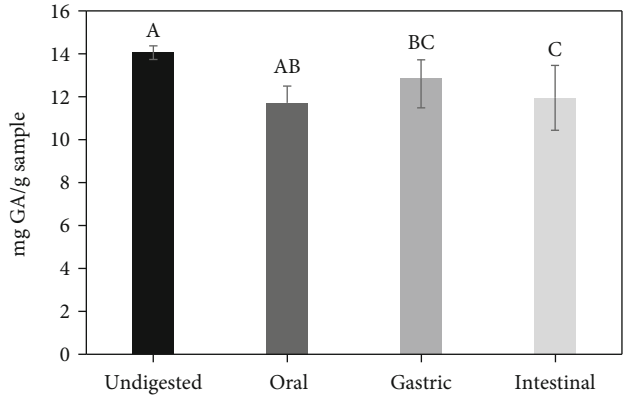

Figure 3: Total phenolic content of microencapsulated extracts during the in vitro digestion process.

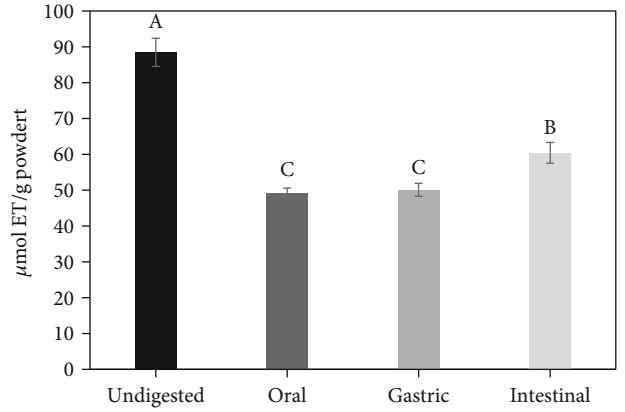

Figure 4: Antioxidant capacity of microencapsulated extracts during the in vitro digestion process.

and then, it could be assumed that the use of the microencapsulation process was an effective protector. In a previous study Gutiérrez-Grijalva et al. [13], the bioaccessibility of phenolics in nonencapsulated oregano extract was evaluated, finding a bioaccessibility in the intestinal stage of 7.46%. The authors mentioned that pH changes during *in vitro* digestion are among the main factors affecting the stability of phenolic compounds, causing their degradation or metabolism [35, 36].

Similar results were obtained by Ruiz-Canizales et al. [26], who evaluated the release of microencapsulated blue corn phenolics with maltodextrin 30 DE and showed a release of phenolics from the matrix of 98% and 88% during the gastric and intestinal phases, respectively. The authors stated that acid solubilization and hydrolysis of the polymer matrix (maltodextrin) could occur in gastric conditions. In intestinal conditions, enzymatic hydrolysis can occur, as well as interferences can happen in the Folin-Ciocalteu test due to the presence of reducing sugars. One of them is glucose, a powerful reducing sugar that composes maltodextrin molecules. Additionally, the study by Ruiz-Canizales et al. [26] obtained a percentage of antioxidant capacity in the intestinal stage of 60% compared to their control, similar to what we found in our study (Figure 4). The antioxidant capacity results of our microencapsulated extracts were found at 88.46, 49.34, 50.08, and 60.43 μmol ET/g powder for the undigested, oral, gastric, and intestinal phases, respectively.

Martínez Cifuentes [37] submitted to an *in vitro* digestion process free and microencapsulated extracts of taxo (*Passiflora mollisima*), blackberry (*Rubus glaucus* Benth), and mortiño (*Vaccinium floribundum* Kunth). Microencapsulation was performed using maltodextrin and maltodextrin-gum Arabic. The author found that the phenolic content of free lyophilized extracts decreased 30, 57, and 50% during the gastric phase for taxo, blackberry, and mortiño, respectively. Furthermore, microencapsulated extracts of these fruits showed a bioaccessibility from 72 to 83%, suggesting that microencapsulation protected phenolics from degradation and metabolism due to pH changes, as previously mentioned. It was also shown that microencapsulated protected phenolics even at the end of the intestinal phase, where an increase in antioxidant capacity was observed in taxo and blackberry of 133% and 166%, respectively. This was similar to the study by Ydjedd et al. [38], who evaluated the effect of gastrointestinal digestion *in vitro* on encapsulated and nonencapsulated phenolic compounds of ripe carob pulp, showing an antioxidant capacity of the encapsulates up to 10 times greater in the intestinal phase compared to the nonencapsulated ones.

This might be attributed to the fact that the antioxidant capacity depends on the type and concentration of phenolic compounds present in the microencapsulated extracts since there are a variety of chemical structures that, by interacting with the wall material, may or may not withstand the gastric conditions.

4. Conclusion

We found that the optimal conditions to microencapsulate oregano phenolics by spray drying are an inlet temperature of 145°C and a percentage of wall material of 16%. Moreover, the aim of this work was to optimize the microencapsulation conditions of oregano phenolics with low DE maltodextrin, to enhance the bioaccessibility of oregano phenolics. This was achieved as we reported that the stability was around 85%, which suggests that maltodextrin microencapsulation is a suitable and optimal alternative for protecting these phytochemicals. However, further studies should be performed for this technology to be used in the development of functional foods or dietary supplements.

Data Availability

All data are included within the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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