GIDA
THE JOURNAL OF FOOD
E-ISSN 1309-6273, ISSN 1300-3070

Research / Araştırma
GIDA (2026) 51 (3) 441-457
doi:10.15237/gida.GD25143

THE EFFECTS OF DIFFERENT CARRIER AGENTS AND DRYING METHODS ON SOME PHYSICOCHEMICAL PROPERTIES AND STORAGE STABILITY OF EUROPEAN CRANBERRYBUSH (*Viburnum opulus* L.) POWDER

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Received / Geliş: 26.11.2025; *Accepted* / Kabul: 13.04.2026; *Published online* /Online baskı: 31.05.2026

ABSTRACT

This study evaluated the effects of freeze drying (FD), vacuum drying (VD; 60-80°C), and spray drying (SD), combined with commercial inulin (CI) and maltodextrin (MD), on the physicochemical and functional properties of *Viburnum opulus* L. juice powders. Drying method and carrier composition significantly affected total phenolic content (TPC), total anthocyanin content (TAC), and antioxidant activity ($P<0.05$). TPC of fresh juice (56.12±1.51 mg GAE/g) decreased after drying, with highest retention in FD (up to 52.13±2.01 mg GAE/g) and lowest in SD (27.12±0.55 mg GAE/g). During 60-day storage, TAC losses were limited to 7-8% in FD compared to 25-28% in SD. Storage at 4±1°C reduced phenolic degradation by nearly 50% compared to room temperature. Inulin-based powders showed superior bioactive retention. Overall, VD at 60°C with inulin provided a cost-effective alternative to FD while maintaining high functional quality.

Key words: Storage stability, vacuum drying, carrier agents, bioaccessibility

FARKLI TAŞIYICI AJANLAR VE KURUTMA YÖNTEMLERİNİN GİLABURU (*Viburnum opulus* L.) TOZUNUN BAZI FİZİKOKİMYASAL ÖZELLİKLERİ VE DEPOLAMA STABİLİTESİ ÜZERİNE ETKİLERİ

ÖZ

Bu çalışmada, dondurarak kurutma (FD), vakumlu kurutma (VD; 60-80°C) ve püskürtmeli kurutma (SD) yöntemlerinin, ticari inülin (CI) ve maltodekstrin (MD) ile kullanımının, *Viburnum opulus* L. meyve suyu tozlarının fizikokimyasal ve fonksiyonel özellikleri üzerindeki etkileri değerlendirilmiştir. Kurutma yöntemi ve taşıyıcı kompozisyonunun toplam fenolik madde (TPC), toplam antosiyanin içeriği (TAC) ve antioksidan aktivite üzerinde istatistiksel olarak anlamlı etkileri olduğu belirlenmiştir ($P<0.05$). Taze meyve suyunda 56.12±1.51 mg GAE/g olarak belirlenen TPC değeri kurutma sonrası azalmış; en yüksek korunma FD'de (52.13±2.01 mg GAE/g'a kadar), en düşük değer ise SD'de (27.12±0.55 mg GAE/g) saptanmıştır. 60 günlük depolama süresince TAC kayıpları FD örneklerinde %7-8 ile sınırlı kalırken, SD örneklerinde %25-28 düzeyine ulaşmıştır. 4±1°C'de depolama, oda sıcaklığına kıyasla fenolik bileşiklerin bozunmasını yaklaşık %50 oranında azaltmıştır. İnülin içeren tozların biyoaktif bileşenleri daha iyi koruduğu belirlenmiştir. Sonuç olarak, 60°C'de uygulanan VD yöntemi inülin ile birlikte kullanıldığında, yüksek fonksiyonel kaliteyi koruyarak FD'ye ekonomik açıdan uygulanabilir bir alternatif sunmaktadır.

Anahtar kelimeler: Depolama stabilitesi, vakumla kurutma, taşıyıcı ajanlar, biyoyararlanım

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INTRODUCTION

European Cranberrybush fruits (EC), from plants of the Viburnum genus in the Adoxaceae family, are known as Viburnum opulus L. They are grape-like fruit with a red color and a special astringent taste (Barak et al., 2019). They are native to Europe, northern Africa and central Asia (Ersoy et al., 2017). The dominant organic acid in EC is L-malic acid. It has also been reported in studies that it contains high levels of citric acid (Kajszczak et al., 2020). It also contains polyphenols at the rate of 6.80-8.30 g gallic acid/kg. It has been reported that fruits, of which approximately 9.8% are crude cellulose, contain 6.71% protein. Studies have reported that EC contain vitamin K, viburnin, isovalerianic acid and salic acid, as well as valeric acid, which gives it its unique smell (Velioglu et al., 2006; Ersoy et al., 2017; Barak et al., 2019). It has also been reported that EC is rich in vitamin C and has high antioxidant activity (Kajszczak et al., 2020). EC is used effectively by local people in Turkey against kidney problems such as nephralgia and to pass kidney stones (Altundag and Ozturk, 2011; Ilhan et al., 2014; Barak et al., 2019). There are also studies reporting that EC is used as a hypoglycemic and relieves cough problems (Fujita et al., 1995). Many pharmacological studies such as in vitro studies, in which antibacterial and antioxidant effects of the fruit have been evaluated, have been conducted with EC based on the use of folk medicine (Barak et al., 2019). There have been studies reporting that it has an antiurolithiatic effect, is effective against testicular diseases, and reduces oxidative stress (Zayachkivska et al., 2006; Sarıözkan et al., 2017; Zakłos-Szyda et al., 2019). It has also been reported that EC has positive effects on type II diabetes mellitus and obesity (Zakłos-Szyda, 2020). Recent studies have demonstrated the potential of Viburnum opulus L. as a functional ingredient due to its high phenolic and bioactive compound content (Ozturkoglu-Budak et al., 2025). In addition to all these benefits, EC is difficult to consume directly due to its acidic taste, undesirable aroma and the presence of some unpleasant-smelling components (Kraujalis et al., 2017). Therefore, in recent years, scientists and food industry workers have started to look for different consumption ways of EC (Barak et al., 2019). In the literature, studies on the subject have generally focused on the determination of the physicochemical properties of EC and its benefits on human health (Česonienė et al., 2010; Rop et al., 2010; Kraujalytė, 2013).

For many years, spray drying method (SD) has been used to expand usage area of foods by turning into powder form. As is known, SD is based on the principle of spraying the liquid into a drying chamber in a stream of hot air. However, in addition to the known advantages of SD, it has been reported that it is not an effective method especially in sugar-containing solutions, and it can damage unstable bioactive components due to hot air (Tchabo et al., 2019; Turkiewicz et al., 2020). Freeze drying (FD) has been reported as the best method in the literature for the preservation of unstable components and keeping the color parameters at the best level. The disadvantage of FD has been reported as its high cost and difficulty in industrial use (Michalska et al., 2016; Szychowski et al., 2018). Vacuum drying method (VD), which is an alternative to SD and FD, has been used in the production of fruit powders in recent years. The most important advantage of this method is low energy consumption and maximum protection of the sensory properties of foods (Turkiewicz et al., 2020).

This study aimed to determine some physicochemical properties and storage stability of EC dried with different drying methods and carrier agents. In addition, the changes in some physicochemical properties of EC powders in an in vitro human digestion simulation were also investigated. Thus, it was aimed to expand the usage area by giving instant feature to EC known for its many benefits on health.

MATERIAL AND METHODS

Material

All chemicals were purchased from Sigma (Taufkirchen, Germany) and Merck (Darmstadt, Germany). EC were procured from a local producer from Kayseri province, Turkey.

Methods

Sample Preparation

EC were washed and pressed by a press machine (Fenglin 40L-SSHP, Laizhou Fenglin, China). The filtrate obtained after pressing was centrifuged at 3000 g for 10 minutes (Allegra X-30, Beckman Coulter, California, USA). Then, commercial inulin (CI) (100%), maltodextrin (MD) (100%) and a mixture of those two (CI and MD were mixed in a ratio of 2:1 and 1:2 (w/w)) were mixed with EC juice at the rate of 15% (w/w) (Turkiewicz et al., 2020). The obtained mixtures were subjected to different drying processes.

Drying Methods

For freeze drying (FD), EC juice was spread on glass trays to a thickness of approximately 0.5 cm and frozen for 1 day at -78°C. Frozen samples were placed in a freeze dryer (LGJ-10, VIKUMER, Shenzhen, China) operating at -84°C and 0.02 mbar absolute pressure. It was dried in 48 hours. The dried samples were ground into fine powder using a grinder. FD sample was used as control sample.

Samples were spray dried (SD) with a laboratory-scale mini spray dryer (OLT-SD8000B, Ollital, Fujian, China). In the double-flow nozzle dryer with an inner diameter of 0.5 mm, the inlet temperature was set to 180°C and the outlet temperature was maintained at 75-80°C. The aspiration rate was adjusted to 70% while the flow speed was set to 450 L/h.

Vacuum drying (VD) was carried out with a vacuum dryer (Isotemp, Model 281A, Fisher Scientific, New Hampshire, USA) at 1 kPa pressure at 60, 70 and 80°C for 72, 48 and 24 h, respectively (Turkiewicz et al., 2020). As a result, the products obtained in the study are listed below.

1. Freeze dried samples (control samples)
2. Spray dried samples
3. Vacuum dried samples at 60°C
4. Vacuum dried samples at 70°C
5. Vacuum dried samples at 80°C

Moisture Content and Water Activity

Moisture contents of the samples were determined by the gravimetric method (Gunel et al., 2018). Water activity values of the samples were calculated by using a water activity equipment (AwTherm, Rotronic, Bassersdorf, Sweden).

Bulk Density, Hygroscopicity, and Solubility

Bulk density and hygroscopicity values of the samples were calculated by using a previous method (Sahin-Nadeem and Ozen, 2014).

1 g of powder sample was added to 100 mL distilled water to determine cold water solubility of microcapsules. The mixture was mixed with a stirrer at 600 rpm for 5 min. Then the mixture was centrifuged at 3000 g for 5 min. 20 mL of supernatant was decanted to pre weighed petri dishes and dried in an oven at 70°C till constant weight was obtained. The percent solubility was calculated by weight difference (Sahin-Nadeem et al., 2011).

Total Phenolic Content (TPC)

TPC of samples was calculated by using Folin-Ciocalteu method (Singleton and Rossi, 1965). 100 µL of diluted sample was mixed with 900 µL of ultra-pure water. Then, 5 mL of 0.2 N Folin-Ciocalteu reagent and 4 mL of Na2CO3 (7.5% in water, w/w) was added to this mixture. The final mixture was mixed and incubated at room temperature for 1 h in the dark. Absorption of sample was measured at 765 nm with Rayleigh Spectrophotometer UV-1800 V/VIS (Beijing, China). TPC was expressed as gallic acid equivalents (GAE) in mg/g dry matter (DM).

Antioxidant Activity (AA)

To determine the free radical-scavenging activity of samples the stable radical 2,2-diphenyl-1-picrylhydrazyl radical (DPPH) was used as reported earlier (Brand-Williams et al., 1995). A series of diluted extracts (5 different concentrations) were prepared with methanol. 6 × 10−5 M DPPH was also prepared in MeOH. Then, 100 µL of the diluted extract and 4 mL of DPPH were put in a test tube. After, the mixture was placed in the dark for 30 minutes. Absorbance at 516 nm was measured using a spectrophotometer (Rayleigh Spectrophotometer, UV-1800 V/VIS, Beijing, China) in reference to the control sample prepared with 80% MeOH instead of diluted extract in DPPH solution. The total AA values of the samples were expressed as percent inhibition of the DPPH radical, calculated by equation (1).

$$I\,(\%)= (A_{C(0)} - A_{S(t)})/\, A_{C(0)}]\ x\ 100 \qquad (1)$$

In the above equation, I, AC and AS are inhibition percentages, and absorbencies of the control and test samples, respectively. IC50 value was determined as the concentration of the sample providing 50% inhibition of the DPPH radical. It was calculated from the plot of concentration versus % percent.

Total Anthocyanin Content (TAC)

The total anthocyanin content was determined by the pH differential method. TAC contents of the samples were expressed as mg cyanidin-3-glucoside (C3G)/100 g dry matter (Giusti and Wrolstad 2001).

In Vitro Human Digestion Simulation

The in vitro human digestion simulation was employed as previously described by Günel et al. (2021). For this purpose, 10 ml of gastric milieu including pepsin enzyme and electrolytes was prepared. First, pH value of the milieu was adjusted to 2. 2.5 ml reconstituted powder sample (1:5 in hot water) was added to the 10 ml of gastric milieu. Then, a shaking water bath adjusted 37°C was used for mixing. After 2 hours, 2 ml of the mixture was set aside as "Gastric Solution" (GS). After adding pancreatin and bile acids to the remaining solution, the pH value of the milieu was adjusted to 6.8 with NaOH (1 M) or HCl (1 M). After the incubation at 37°C for 2 hours, 2 ml of the mixture was set aside as "Bioavailable Solution" (BS). The remaining solution was placed in an ice bath to terminate the enzymatic reaction. Finally, 2 ml of the mixture was set aside as "Colon Solution" (CS). Each sample was stored at -20°C for further analysis. TPC, AA and TAC analyzes were performed on all samples described above.

Reconstituted Product Properties (Sensory Analysis)

EC powders obtained by different drying methods were coded as samples A, B, and C. All powder samples were reconstituted in boiled and cooled water by dissolving 20 g of powder in 100 mL of water. The reconstituted samples were served at 22±2°C. For palate cleansing between samples, panelists were provided with boiled and cooled water stored at 10°C along with plain crackers.

The sensory panel consisted of 15 trained individuals (age range: 25-45 years; gender distribution: 7 females, 8 males) with prior experience in the sensory evaluation of food products. Before evaluation, panelists were trained on the characteristics and sensory expectations of EC beverages. The samples were coded with randomly assigned three-digit numbers and evaluated in sequence, with two-minute breaks for palate cleansing between samples.

Sensory attributes including color, odor, flavor/aroma, bitterness, mouthfeel, and overall taste were assessed using a 9-point hedonic scale (1:very poor, 9:very good). Additionally, purchase tendency was evaluated on a 5-point scale ranging from 1 ("Certainly, I don't buy") to 5 ("Certainly, I buy") (Gunel et al., 2022).

Storage Stability

EC powders were stored at room (25±2°C) and refrigerator (4±1°C) temperatures for 60 days. Some physicochemical analyses (moisture content, aw, TPC, AA, TAC) of samples were carried out every 15 days during the storage period. Stored samples were packed with vacuum packaging technique.

Statistical Analysis

Drying processes were performed in two replicates while physicochemical analyses were carried out in duplicate. Results were statistically evaluated by Variance analysis and Duncan's multiple range tests using Statistical Analysis System software (SAS system for Windows V7 prepared by SAS Institute, Cary, NC, ABD).

The experimental design of the study was structured as a comparative factorial design including two main factors: drying method (FD, SD, and VD at three different temperatures: 60°C, 70°C, and 80°C) and carrier agent composition (100% CI, 100% MD, CI:MD 1:2, and CI:MD 2:1). Each drying process was performed in duplicate, and all physicochemical analyses were carried out in duplicate measurements. The experimental conditions were selected based on preliminary trials and literature data (Turkiewicz et al., 2020) to allow systematic comparison of processing parameters and carrier effects.

RESULTS AND DISCUSSION

Moisture Content and Water Activity (aw)

Moisture content values of the EC powder dried with different drying techniques were given in Figure 1. It was determined that different drying methods and carrier agents had a statistically significant ($P<0.05$) effect on the moisture content values of EC powders. While the lowest moisture content among carrier agents was observed in powders containing MD, an increase in moisture value was observed with the addition of CI. In similar studies in which maltodextrin and inulin were used together/comparatively as carrier agents, it was reported that an increase in moisture content occurred with the addition of inulin (de Barros Fernandes et al., 2014; Turkiewicz et al., 2020). As a matter of fact, it has been reported in the literature that different sorption capacities of different carrier agents can cause differences in moisture content (Michalska and Lech, 2018). When the effect of different drying methods on moisture content was examined, it was observed that the samples dried with VD at 60°C had the highest moisture content. It was also determined that the powders with the lowest moisture content were the samples dried at 80°C using the VD drying method. Although VD drying at 80°C and FD drying times were almost the same in all samples, moisture values were found to be higher in FD drying. In addition, the moisture content, which was determined as 91.02% in fresh EC juice, was reduced by approximately 96.45%. The average moisture content value for all samples was calculated as 3.23%. Similar results to those in the present study were also reported for Japanese quince and apple juice powders (Michalska and Lech, 2018; Turkiewicz et al., 2020).

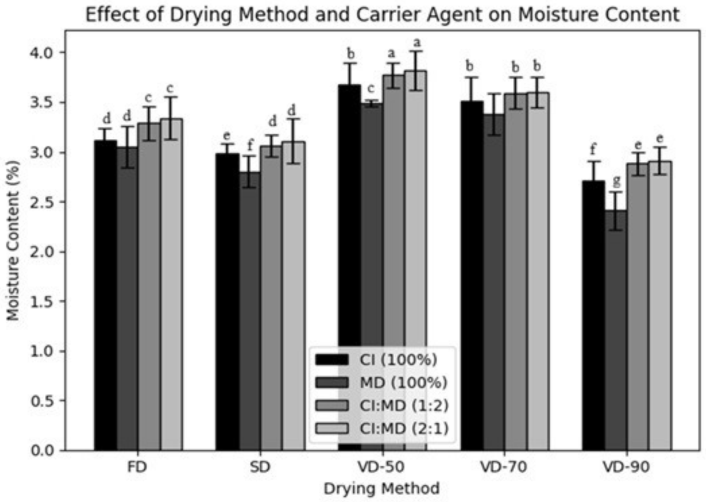

Figure 1. Effect of drying method and carrier agent composition on moisture content (%) of EC powders. Values are expressed as mean±standard deviation (n=2)

Determining the aw value in powder products is very important in terms of both chemical and microbiological stability. It has been reported in studies that microbial growth is minimum, and chemical stability is maximum in foods with low aw value. In literature studies, it has been reported that microbial growth is at the lowest level or even non-existent in aw values below 0.4 and even 0.3 values (Beuchat, 1981; Chotyakul et al., 2012; Michalska and Lech, 2018; Turkiewicz et al., 2020). The aw values of the EC powders obtained in the current study are given in Figure 2. It was determined that the aw values of the samples were below 0.4, and this value decreased even below 0.3 in some samples. The aw values of the samples also showed a similar trend to their moisture content. While different drying methods and carrier agents had a statistically significant ($P<0.05$) effect on the aw values of the samples, the highest and the lowest aw values were determined in samples dried with VD at 50 and 70°C, respectively. Similar to the results in moisture content, the use of inulin as a carrier agent caused an increase in the aw values of the samples. Similar results have been reported in the literature in studies using different carrier agents and drying methods (Araujo-Díaz et al., 2017; Michalska and Lech, 2018; Šturm et al., 2019; Turkiewicz et al., 2020).

The relatively higher aw values observed in samples containing inulin, even under FD and SD conditions, can be attributed to the hygroscopic and amorphous nature of inulin. Inulin is known to possess a high water-binding capacity due to its polysaccharide structure, which facilitates moisture retention within the matrix. However, this interaction does not necessarily result in complete immobilization of water molecules, leading to a relatively higher availability of free water and consequently increased aw values. Moreover, the predominantly amorphous structure formed during drying processes such as freeze drying and spray drying may enhance moisture sorption behavior, further contributing to elevated aw levels. In contrast, carrier agents such as maltodextrin, with lower hygroscopicity and different molecular organization, may promote more effective reduction in water activity. These findings are consistent with previous studies reporting increased moisture retention and aw values in powders containing inulin compared to other carrier agents (Tonon et al., 2008; Saavedra-Leos et al., 2021).

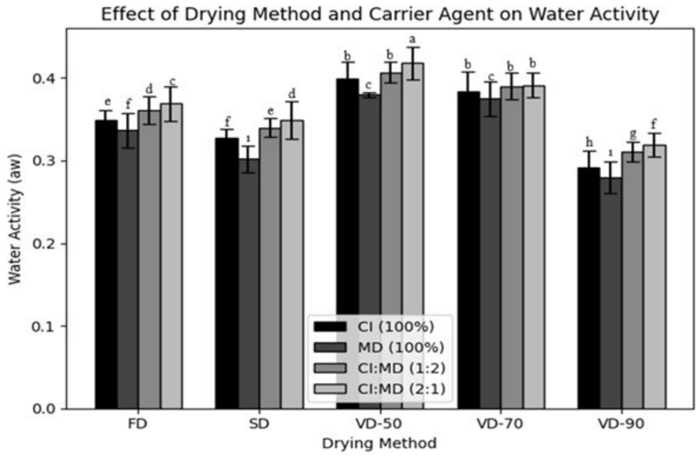

Figure 2. Effect of drying method and carrier agent composition on water activity (aw) of EC powders. Values are expressed as mean±standard deviation (n=2)

Bulk Density, Hygroscopicity and Solubility

Bulk density is an important property that closely affects many processes of food powders from transportation to storage. Bulk density of food powders can be affected by many factors such as particle size, particle shape, type of coating material, density of coating material and moisture content of the powder product (Bae and Lee 2008; Goula and Adamopoulos 2012). Low bulk density is not desirable situation as it increases the package volume. In addition, products with low bulk density have a higher risk of oxidation, which reduces the storage stability of the product, as it contains more air between its pores (Barbosa-Cánovas et al., 2005). In the current study, it was observed that different drying methods and different carrier agents also affected the bulk density values of the samples, and the results are given in Table 1. According to the results in Table 1, it was observed that different drying methods and carrier agents had a statistically significant (*P*<0.05) effect on the bulk density of EC powders. Bulk density values of EC powders were determined to vary between 351.56 and 657.46 kg/m3. While the lowest bulk density values were determined in SD and FD dried samples, the highest bulk density values (regardless of carrier agent) were determined in the samples dried at 80°C with VD drying. When the results in terms of carrier agents were examined, it was observed that the lowest bulk density value was determined in powders containing 100% CI, and the highest bulk density value was determined in powders containing CI:MD (2:1) mixture. In similar studies, it was reported that carrier agent combinations provide a higher bulk density value, and this value is directly proportional to the increase in inulin (Tontul and Topuz, 2017; Michalska-Ciechanowska et al., 2020).

Table 1. Bulk density, hygroscopicity and solubility values of the EC powders

Sample	Drying method	Bulk density (kg/m^3)	Hygroscopicity (%)	Solubility (%)
CI (100 %)	FD	351.56l±7.72	19.11^a±0.57	80.13^d±0.97
	SD	389.87^k±5.51	18.40^b±1.11	88.56±1.13
	VD-60	555.78^h±7.12	16.12^g±0.08	65.52^f±0.85
	VD-70	576.85^g±8.25	16.40^f±0.78	63.00^g±1.14
	VD-80	589.81^f±4.52	16.17^g±0.92	60.10^g±1.06
MD (100 %)	FD	498.74^j±8.81	15.16^i±0.77	87.16^{bc}±1.07
	SD	507.56^i±3.87	13.12^j±0.45	94.02^a±1.10
	VD-60	587.63^f±5.12	10.10l±0.06	70.13^e±1.05
	VD-70	598.45^e±5.11	10.08l±0.11	67.52^f±0.88
	VD-80	604.40^{de}±6.58	10.07l±0.00	63.11^g±1.01
CI:MD (1:2)	FD	508.52^i±5.50	17.14^d±1.11	84.16^c±0.56
	SD	490.57^{jk}±8.87	15.12^i±0.88	91.01^{ab}±1.17
	VD-60	612.54^d±9.54	12.13^k±0.58	68.14^{ef}±1.14
	VD-70	622.58^c±4.48	12.22^k±0.98	65.55^f±1.29
	VD-80	638.78^b±4.51	12.11^k±0.56	62.52^g±0.04

Table 1. Continued

CI:MD (2:1)	FD	509.89^{i}±5.57	18.92^{ab}±0.52	82.51^{cd}±2.02
	SD	496.75^{j}±2.22	18.01^{c}±0.21	89.51^{bc}±0.05
	VD-60	628.88^{bc}±6.66	15.91^{gh}±0.07	66.78f±0.88
	VD-70	639.57^{b}±6.45	15.86^{h}±0.04	64.02fg±1.31
	VD-80	657.46^{a}±5.53	15.88^{h}±0.09	61.00g±1.11
Duncan's Multiple Range Test for mean values				
	FD	467.18^{g}±4.41	17.58^{a}±1.84	83.49b±2.95
	SD	471.19^{g}±8.52	16.16^{c}±2.50	90.78a±2.39
	VD-60	596.21^{c}±5.57	13.57^{e}±2.95	67.64e±1.97
	VD-70	609.36^{b}±9.21	13.64^{de}±3.01	65.02e±1.97
	VD-80	622.61^{a}±8.88	13.56^{e}±2.97	61.68f±1.38
	CI (100 %)	493.77^{f}±4.54	16.89^{b}±1.41	74.08d±12.28
	MD (100 %)	559.36^{e}±6.52	11.71^{f}±2.34	76.39c±13.43
	CI:MD (1:2)	574.60^{d}±4.47	13.74^{d}±2.29	74.28d±12.55
	CI:MD (2:1)	586.51^{cd}±5.52	16.92^{b}±1.45	72.76d±12.51

CI: Commercial inulin, MD: Maltodextrin, FD: Freeze drying, SD: Spray drying, VD: Vacuum drying at 60, 70 and 80°C, ±: Standard deviation, Different letters (a-l) in the same column indicate statistically significant (P<0.05) differences between the samples.

Hygroscopicity is a very important property for food powders at many stages, including transportation and storage. The moisture absorption rate and capacity of food powders during processing, transportation and storage depend on the hygroscopicity of that powder. Due to the low glass transition temperature in food powders with high humidity, liquid bridges form between the particles and therefore adhesions occur. As these adhesions continue, critical caking problem arises in food powders. Therefore, the critical hygroscopicity for food powders should be as low as possible (Tontul and Topuz, 2013; Oliveira et al., 2014; Juarez-Enriquez et al., 2017). In the present study, hygroscopicity values of the EC powders dried with different drying techniques and carrier agents are given in Table 1. Both different drying techniques and carrier agents affected significantly (*P*<0.05) to hygroscopic property of the EC powders. According to the results, the highest hygroscopicity value was determined as 19.11±0.57 % in the samples using 100 % CI as carrier agent, while the lowest hygroscopicity value was determined as 10.07±0.00 % in the samples using 100 % MD as carrier agent. It was observed that the hygroscopicity value decreased with the increase of the MD ratio in the carrier agents mixing. In terms of drying methods, the highest hygroscopicity values were determined for the samples dried with FD. While the lowest hygroscopicity values were calculated for the samples dried with VD, it was observed that the change in VD temperatures did not influence the hygroscopicity. It was thought that the difference between the carrier materials was due to the different chemical structures of the carrier materials. Indeed, it was reported in the literature that CI was considered as hygroscopic because it had a branched structure and could absorb ambient moisture faster than MD (Lacerda et al., 2016). It is known that spray-dried samples have lower moisture content and therefore are more inclined to absorb ambient humidity (Du et al., 2014). The results of the current study were found to be compatible with the literature studies in terms of differences between both drying methods and carrier agents (Du et al., 2014; Ma et al., 2014; Teng et al., 2020; Wang et al., 2020).

Solubility is a very important quality parameter for powdered foods, as it affects the functional properties of food powders and defines the behavior of powders in aqueous solutions (Şahin-Nadeem et al., 2013; Michalska et al., 2016). The solubility values of the EC powders obtained in the present study are given in Table 1. It was determined that the solubility values of EC powders varied between 94.02±1.10 % and 61.00±1.11 %. While the highest solubility values were determined in the samples dried with SD, the lowest solubility values were determined in the samples dried with VD. With the increase in temperature in VD drying, a decrease in the solubility values of the samples was also observed. The solubility values of EC powders in which MD was used as a carrier agent were found to be higher than those of EC powders in which CI was used as carrier agent. It has been reported in the literature that lower water solubility is proportional to lower porosity and higher bulk density (Michalska et al., 2016). Indeed, in the present study, it was observed that the bulk densities and solubility value of the EC powders were consistent. It was determined that the water solubility values decreased with the increase in bulk density values. In addition, an increase was observed in the solubility values of the samples containing MD, and it was reported in previous studies that MD had a higher water solubility value than CI (Lacerda et al., 2016).

Total Phenolic Content

In this study, the total phenolic content (TPC) of powders obtained from EC juice showed significant ($P<0.05$) variations depending on the drying method and the type of carrier agent used. The TPC value of fresh EC juice was determined as 56.12±1.51 mg GAE/g dry matter, and a decrease in this value was observed after drying (Table 2). However, the extent of this reduction varied according to the type of carrier and the drying technique applied.

Table 2. Total phenolic content, antioxidant activity and total anthocyanin content of the EC powders

Sample	Drying method	TPC (mg GAE/g)	AA (µL/mg DPPH)	TAC (mg C3G/100 g)
Fresh EC juice	-	56.12 ± 1.51	23.55 ± 1.13	26.58 ± 1.17
CI (100 %)	FD	$52.13^{a}\pm2.01$	$24.16^{e}\pm0.16$	$24.16^{a}\pm0.56$
	SD	$30.10^{f}\pm0.56$	$28.58^{b}\pm1.11$	$19.51^{d}\pm0.77$
	VD-60	$48.16^{b}\pm0.09$	$25.50^{d}\pm0.56$	$22.50^{b}\pm0.70$
	VD-70	$46.11^{c}\pm0.19$	$25.76^{d}\pm1.10$	$22.10^{b}\pm0.54$
	VD-80	$43.13^{e}\pm1.21$	$26.00^{c}\pm0.98$	$21.57^{c}\pm0.56$
MD (100 %)	FD	$49.10^{b}\pm1.11$	$24.66^{e}\pm0.14$	$24.02^{a}\pm0.44$
	SD	$27.12^{g}\pm0.55$	$29.06^{a}\pm1.05$	$18.54^{e}\pm1.14$
	VD-60	$46.02^{c}\pm0.89$	$25.75^{d}\pm0.78$	$22.02^{b}\pm0.05$
	VD-70	$43.92^{de}\pm1.14$	$26.02^{c}\pm0.78$	$21.85^{c}\pm0.59$
	VD-80	$40.58^{e}\pm0.45$	$26.74^{c}\pm1.13$	$21.0^{0c}\pm0.54$
CI:MD (1:2)	FD	$51.56^{a}\pm0.13$	$24.50^{e}\pm0.88$	$24.08^{a}\pm0.45$
	SD	$29.54^{f}\pm1.58$	$28.88^{ab}\pm1.10$	$19.00^{d}\pm0.41$
	VD-60	$47.58^{c}\pm2.02$	$25.65^{d}\pm0.55$	$22.35^{b}\pm1.10$
	VD-70	$44.58^{d}\pm1.10$	$25.89^{d}\pm0.41$	$22.01^{b}\pm0.85$
	VD-80	$41.76^{e}\pm1.13$	$26.40^{c}\pm1.12$	$21.14^{c}\pm0.25$
CI:MD (2:1)	FD	$51.96^{a}\pm0.15$	$24.40^{e}\pm0.58$	$24.10^{a}\pm0.00$
	SD	$29.99^{f}\pm1.14$	$28.65^{b}\pm0.22$	$19.24^{d}\pm0.14$
	VD-60	$48.00^{b}\pm1.05$	$25.55^{d}\pm0.88$	$22.41^{b}\pm0.12$
	VD-70	$45.10^{cd}\pm0.89$	$25.80^{d}\pm0.11$	$22.06^{b}\pm0.14$
	VD-80	$42.02^{e}\pm1.01$	$26.20^{c}\pm0.87$	$21.34^{c}\pm0.06$

Table 2. Continued

Duncan's Multiple Range Test for mean values			
FD	$51.19^{a}\pm1.02$	$24.43^{d}\pm0.56$	$24.09^{a}\pm1.10$
SD	$29.28^{g}\pm1.11$	$28.79^{a}\pm0.88$	$19.07^{d}\pm0.02$
VD-60	$47.44^{b}\pm0.98$	$25.61^{c}\pm0.74$	$22.32^{b}\pm0.56$
VD-70	$44.92^{c}\pm0.08$	$25.87^{bc}\pm0.62$	$22.01^{b}\pm0.87$
VD-80	$41.87^{e}\pm1.00$	$26.34^{b}\pm0.63$	$21.26^{c}\pm0.85$
CI (100 %)	$43.93^{d}\pm1.03$	$26.00^{b}\pm0.74$	$21.97^{bc}\pm0.74$
MD (100 %)	$41.34^{e}\pm1.02$	$26.45^{b}\pm0.51$	$21.48^{c}\pm0.14$
CI:MD (1:2)	$43.00^{de}\pm1.13$	$26.26^{b}\pm0.40$	$21.71^{c}\pm0.56$
CI:MD (2:1)	$43.41^{d}\pm1.10$	$26.12^{b}\pm0.44$	$21.83^{bc}\pm0.13$

CI: Commercial inulin, MD: Maltodextrin, FD: Freeze drying, SD: Spray drying, VD: Vacuum drying at 60, 70 and 80°C, ±: Standard deviation, Different letters (a-l) in the same column indicate statistically significant ($P<0.05$) differences between the samples.

Among all carrier groups, FD yielded the highest TPC values. Specifically, the sample containing 100% CI as a carrier exhibited a TPC value of 52.13 ± 2.01 mg GAE/g, which was quite close to the fresh juice. Similarly, the CI:MD carrier mixtures (in ratios of 1:2 and 2:1) dried by FD also retained high TPC values, 51.56 ± 0.13 and 51.96 ± 0.15 mg GAE/g respectively. These results indicate that FD, which operates at low temperature and oxygen-limited conditions, effectively minimizes thermal degradation and oxidative losses of phenolic compounds (Li et al., 2020; Babaei Rad et al., 2025). In contrast, SD resulted in the lowest TPC values across all carrier combinations. For instance, the sample containing 100% MD as carrier showed a TPC value of 27.12 ± 0.55 mg GAE/g. The high temperature and rapid water evaporation inherent in the SD process likely caused degradation of heat-sensitive phenolic compounds, contributing to this decrease (Tonon et al., 2008; Zhang et al., 2023). Similarly, recent optimization studies on European cranberrybush juice powders have emphasized that drying temperature and air flow conditions significantly influence phenolic retention and powder quality (Ozcelik, 2024). Additionally, the increased surface area and air exposure during atomization may enhance oxidative losses (Ji et al., 2012).

The TPC values obtained via VD decreased gradually with increasing temperature. For example, samples with CI carrier showed TPC values of 48.16 ± 0.09 mg GAE/g at 60°C, 46.11 ± 0.19 mg GAE/g at 70°C, and 43.13 ± 1.21 mg GAE/g at 80°C. This trend indicates thermal degradation of phenolic compounds and a potential reduction in antioxidant activity at higher temperatures (Li et al., 2020). Therefore, lower temperatures are recommended in VD to preserve phenolic compounds. Regarding the effect of the carrier type, samples containing CI generally exhibited higher TPC values, while MD samples showed lower values. This difference can be attributed to inulin's oligosaccharide structure, which better encapsulates and stabilizes phenolic compounds against oxidation (Babaei Rad et al., 2025). Moreover, powders obtained from CI:MD mixtures exhibited higher TPC compared to pure MD samples. Especially, the CI:MD (2:1) mixture demonstrated synergistic effects that enhanced phenolic compound preservation (Zhang et al., 2023).

In conclusion, TPC values were significantly influenced by both the drying method and the type of carrier used. For optimal preservation of functional compounds, the use of protective carriers such as inulin combined with gentle drying techniques like VD is recommended. Additionally, VD can be considered a cost-effective alternative to FD, offering higher retention of phenolic compounds compared to SD.

Antioxidant Activity

In this study, the antioxidant activity of EC powders was expressed as the sample concentration required to inhibit 50% of the DPPH radical (IC50). It is important to note that an increase in IC50 value indicates a decrease in antioxidant activity, meaning that a lower IC50 corresponds to a higher antioxidant capacity (Brand-Williams et al., 1995).

Fresh EC juice exhibited the lowest IC50 value of 23.55±1.13 μL/mg DPPH, indicating the highest antioxidant activity (Table 2). Among drying methods, FD preserved IC50 values closest to the fresh sample, demonstrating the best retention of antioxidant activity. For instance, the FD sample containing 100% CI carrier showed an IC50 value of 24.16±0.16 μL/mg. Conversely, spray drying SD resulted in the highest IC50 values, indicating a significant reduction in antioxidant activity. For example, the SD sample with 100% CI carrier exhibited an IC50 of 28.58±1.11 μL/mg, reflecting the lowest antioxidant capacity. This decline may be attributed to the high temperature and rapid water evaporation during spray drying, which can degrade heat-sensitive antioxidant compounds (Tonon et al., 2008; Zhang et al., 2023).

In samples dried by VD, IC50 values increased with rising temperature, corresponding to a decrease in antioxidant activity. For example, the CI carrier samples showed IC50 values of 25.50±0.56 μL/mg at 60°C, 25.76±1.10 μL/mg at 70°C, and 26.00±0.98 μL/mg at 80°C. This trend indicates enhanced thermal degradation of antioxidant compounds with increasing temperature (Li et al., 2020).

Regarding carrier material effects, samples containing CI generally exhibited lower IC50 values compared to those with maltodextrin MD, suggesting that inulin is more effective in preserving antioxidant compounds (Babaei Rad et al., 2025).

In conclusion, FD combined with inulin as a carrier at low temperatures is the most suitable method for preserving the antioxidant activity of EC powders. Conversely, SD should be applied cautiously due to its negative impact on antioxidant activity.

Total Anthocyanin Content

The drying method and carrier type had a significant ($P<0.05$) effect on the total anthocyanin content (TAC) of EC juice. The TAC value of fresh EC juice was determined as 26.58±1.17 mg C3G/100 g, and a decrease was observed after all drying processes (Table 2). This reduction is expected due to the high sensitivity of anthocyanins to heat, oxygen, and light, which can accelerate their degradation during drying processes (Patras et al., 2010).

According to the obtained data, freeze drying (FD) best preserved the TAC content. Particularly, the sample dried by FD using inulin as a carrier exhibited a TAC value of 24.16±0.56 mg, which was significantly higher than that of the spray-dried (SD) sample with the same carrier (19.51±0.77 mg). Similar trends were observed for other carrier types, supporting the conclusion that FD is more effective in preserving heat-sensitive compounds such as anthocyanins. This finding aligns with previous studies reporting that freeze drying minimizes losses of bioactive compounds by providing low temperature and oxygen-free conditions (Ratti, 2001; Harnkarnsujarit and Charoenrein, 2011).

Spray drying resulted in the lowest TAC values across all carrier types. This can be attributed to the high temperatures applied during the short drying time, which cause thermal degradation of anthocyanins. Similar observations have been reported in the literature, where spray drying leads to significant losses in anthocyanins and other antioxidants due to exposure to elevated temperatures (Quek et al., 2007; Tonon et al., 2008). For example, the SD sample containing only maltodextrin had a TAC value of 18.54±1.14 mg, approximately 23% lower than the corresponding FD sample.

Vacuum drying (VD) yielded temperature-dependent results. Drying at 60°C preserved TAC relatively well; however, a notable decline was observed as the temperature increased. For instance, the TAC values of inulin-containing VD samples were 22.50±0.70 mg at 60°C and decreased to 21.57±0.56 mg at 80°C. These findings indicate that the degradation rate of anthocyanins increases with temperature, consistent with previous studies (Saavedra-Leos et al., 2021; Omolola et al., 2017).

When examining the effect of carrier type on TAC content, samples with pure inulin generally exhibited higher TAC values compared to those with pure maltodextrin. This may be related to the higher glass transition temperature of inulin and its ability to offer better protection against oxidative degradation (Fang and Bhandari, 2010). Carrier mixtures (CI:MD at ratios of 1:2

and 2:1) resulted in TAC values lower than pure inulin but higher than pure maltodextrin, suggesting that carrier combinations can have a balancing effect in preserving functional compounds. For example, the FD sample with CI:MD at a 2:1 ratio had a TAC value of 24.10±0.00 mg, whereas the corresponding SD sample was measured at 19.24±0.14 mg.

Overall, both drying method and carrier composition play crucial roles in the retention of anthocyanins. Vacuum drying, especially due to its controllable temperature conditions, stands out as an advantageous method for preserving anthocyanins. When applied within optimal temperature ranges, vacuum drying not only minimizes the loss of bioactive compounds but also offers a more economical alternative to freeze drying in terms of processing time and energy consumption. Conversely, spray drying involving high temperatures is disadvantageous for the preservation of thermolabile compounds such as anthocyanins. Carrier selection is also an important factor that supports the stability of functional components during these processes.

In Vitro Human Digestion Simulation

Products produced with 100% inulin were selected for the in vitro human digestion simulation analysis due to their superior antioxidant activity, total phenolic content, and total anthocyanin levels compared to other formulations. The in vitro digestion simulation results (Table 3) clearly demonstrated the release behavior of powders obtained from Gilaburu fruit using different drying methods across gastrointestinal phases. No significant phenolic release was observed in the gastric phase (pH 2) for all samples, whereas the majority of the release occurred in the intestinal phase (pH 6.8, in the presence of bile and pancreatin). This phenomenon can be attributed to the acid-stable nature of inulin, used as the carrier material, which protects phenolic compounds and facilitates controlled release (Akram et al., 2019). Although the amount of phenolics reaching the colonic phase was limited, potential prebiotic effects and microbial fermentation may occur in this phase (Rodríguez-Daza et al., 2021). When comparing drying methods, freeze drying yielded the most successful results in terms of phenolic compound preservation and bioaccessibility (Tan et al., 2020). Vacuum drying showed lower phenolic stability and release profiles compared to freeze drying but was significantly superior to spray drying. In this context, considering both production costs and functionality, vacuum drying emerges as a preferable method for functional food production.

Table 3. In vitro human digestion simulation results of the EC powders

Sample	Digestion Phase	AA (µL/mg DPPH)	TPC (mg GAE/g)	TAC (mg C3G/100 g)
Before Simulation		24.44±2.22	51.88±2.17	25.06±1.54
FD	GS	9.52b±1.10	4.56b±0.88	2.52b±0.00
FD	BS	2.24c±0.12	42.00a±2.13	18.52a±1.14
FD	CS	10.56a±1.11	3.89b±1.12	2.70b±0.13
Before Simulation		29.06±1.98	30.85±2.03	20.00±1.88
SD	GS	10.28a±0.14	3.45b±0.00	1.85b±0.00
SD	BS	6.54b±0.06	23.01a±1.15	14.54a±0.74
SD	CS	11.54a±0.08	2.65b±0.08	2.02b±0.07
Before Simulation		25.70±2.12	49.56±2.54	23.02±1.98
VD-60	GS	10.00a±0.00	4.21a±0.22	1.82b±0.04
VD-60	BS	3.80b±0.16	40.00a±1.78	17.44a±0.08
VD-60	CS	11.03a±0.13	4.00a±0.00	2.06b±0.09

FD: Freeze drying, SD: Spray drying, VD-60: Vacuum drying at 60°C, AA: Antioxidant activity, TPC: Total phenolic content, TAC: Total anthocyanin content, GS: Gastric solution, BS: Bioavailable solution, CS: Colon solution ±: Standard deviation, Different letters in the same column indicate statistically significant (*P*<0.05) differences between the samples.

Reconstituted Product Properties (Sensory Analysis)

In the sensory evaluation study, powder samples that exhibited statistically the highest values in total antioxidant activity, total anthocyanin content, and total phenolic content were selected. These samples were produced using 100% CI as the carrier agent. While the FD and SD samples were directly included in the evaluation, the VD sample obtained at 60°C-shown to have the highest bioactive compound content-was selected for analysis. Fresh EC juice was used as the control sample.

The sensory evaluation results (Figure 3) showed that fresh EC juice received the highest scores in terms of color, aroma, and taste. Among the dried powder samples, the FD sample demonstrated a strong performance in color, taste, and mouthfeel. The vacuum-dried sample at 60°C (VD-60) scored higher in odor and mouthfeel compared to the other dried samples and showed flavor and aroma results close to those of the FD sample. SD samples received lower scores across all sensory attributes, indicating a disadvantage in terms of product quality. Considering that higher bitterness scores represent lower bitterness perception, fresh juice exhibited the highest bitterness, followed by FD and VD-60 samples, while SD samples showed a more pronounced bitterness. These differences in bitterness may be attributed to the concentration of compounds or chemical reactions occurring during drying. In terms of mouthfeel, fresh juice and FD samples offered a softer and more pleasant texture, while VD-60 also provided an acceptable performance. Overall, the results indicate that VD is a promising alternative to FD, both in preserving sensory quality and from an economic standpoint. Therefore, VD emerges as a cost-effective and quality-preserving method for the production of EC powders.

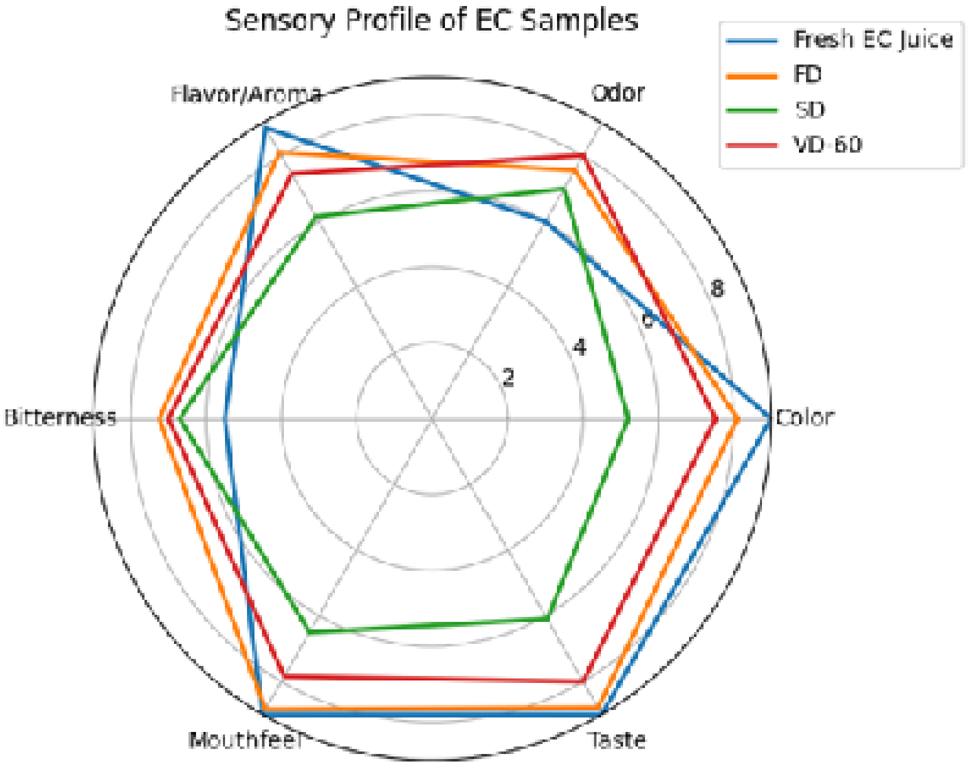

Figure 3. Sensory profile of fresh EC juice and dried EC powder samples evaluated using a 9-point hedonic scale. Values represent mean scores (n=15)

Storage Stability

The storage stability of EC powders was systematically investigated under different drying techniques (FD, VD, and SD) and two storage temperatures (25±2°C and 4±1°C). Physicochemical parameters including TPC, AA, and TAC were monitored every 15 days over a 60-day storage period. The results indicated that phenolic compounds decreased by approximately 11-12% in FD, 20-25% in VD, and 30-35% in SD samples (Table 4). A similar trend was observed for TAC and antioxidant activity, confirming that drying method significantly affects the long-term preservation of bioactive compounds.

Table 4. Storage stability of the EC powders

Days	Samples	25±2°C			4±1°C		
		TPC (mg GAE/g)	**AA (µL/mg DPPH)**	**TAC (mg C3G/100 g)**	**TPC (mg GAE/g)**	**AA (µL/mg DPPH)**	**TAC (mg C3G/100 g)**
0. Day	FD	50.56^{a}±1.12	24.10^{c}±0.56	25.03^{a}±0.44	50.44^{a}±2.23	24.02^{c}±0.59	25.01^{a}±0.03
	SD	31.01^{b}±1.11	30.04^{a}±1.11	20.06^{c}±0.88	30.91^{b}±1.98	30.58^{a}±0.22	20.10^{a}±0.17
	VD-60	50.03^{a}±2.08	27.52^{b}±1.01	23.11^{b}±1.01	50.01^{a}±1.99	27.03^{b}±1.02	22.95^{b}±1.88
15. Day	FD	48.51^{a}±0.56	24.88^{c}±1.36	24.25^{a}±0.25	49.80^{a}±2.09	24.49^{c}±1.04	24.74^{a}±1.12
	SD	28.30^{b}±1.14	32.62^{a}±0.58	18.27^{c}±0.00	29.40^{b}±2.04	31.35^{a}±0.09	19.20^{c}±0.85
	VD-60	46.92^{a}±2.22	28.87^{b}±0.87	21.68^{b}±0.78	48.75^{a}±1.19	28.04^{b}±0.98	22.38^{b}±1.14
30. Day	FD	47.40^{a}±2.15	25.40^{c}±1.17	23.40^{a}±0.17	49.00^{a}±1.45	24.90^{c}±1.11	24.00^{a}±0.92
	SD	25.50^{b}±1.17	35.51^{a}±1.23	16.54^{c}±0.79	28.00^{b}±0.03	32.48^{a}±1.06	18.20^{c}±0.96
	VD-60	44.02$^{a\pm}$2.85	30.50^{b}±2.01	20.40^{b}±0.96	47.00^{a}±0.58	29.14^{b}±1.07	21.68^{b}±1.16
45. Day	FD	45.10^{a}±2.24	26.45^{c}±2.00	22.88^{a}±1.17	47.96^{a}±1.16	25.40^{c}±0.00	23.84^{a}±0.87
	SD	23.30^{b}±1.18	38.74^{a}±2.13	15.10^{c}±1.15	27.02^{b}±1.63	34.09^{a}±1.89	17.30^{c}±2.10
	VD-60	41.25^{a}±2.00	32.71^{b}±1.89	19.11^{b}±0.78	45.70^{a}±1.27	30.07^{b}±0.08	21.12^{b}±2.03
60. Day	FD	43.45^{a}±2.00	27.18^{c}±1.78	22.00^{a}±2.01	47.01^{a}±2.08	25.64^{c}±1.05	23.08^{a}±0.08
	SD	21.10^{b}±0.88	41.80^{a}±1.01	13.70^{c}±1.19	25.90^{b}±1.69	35.40^{a}±0.09	16.50^{c}±0.52
	VD-60	39.20^{a}±0.98	34.55^{b}±2.07	17.91^{b}±0.07	45.00^{a}±2.06	31.02^{b}±1.12	20.30^{b}±1.11

FD: Freeze drying, SD: Spray drying, VD-60: Vacuum drying at 60°C, AA: Antioxidant activity, TPC: Total phenolic content, TAC: Total anthocyanin content, ±: Standard deviation, Different letters in the same column indicate statistically significant ($P<0.05$) differences between the samples.

The superior stability observed in FD samples can be attributed to the low-temperature and oxygen-limited conditions of the process, which minimize structural disruption and oxidative reactions. Previous studies have similarly reported that freeze-dried fruit powders retain higher phenolic and anthocyanin levels during storage compared to thermally processed powders (Michalska and Lech, 2018; Tan et al., 2020). The highly porous structure formed during freeze drying may also reduce internal thermal stress and slow oxidative degradation mechanisms (Ratti, 2001).

Among the vacuum drying conditions, 60°C was selected as the representative condition for detailed evaluation, as higher temperatures (70 and 80°C) resulted in increased degradation of bioactive compounds. Therefore, VD-60 was considered the optimal condition in terms of balancing product quality and processing efficiency. Vacuum drying demonstrated intermediate stability. The reduced oxygen environment during VD limits oxidative reactions, which are known to accelerate phenolic degradation during storage (Omolola et al., 2017). However, increasing the drying temperature resulted in greater losses, indicating temperature-dependent degradation kinetics. Similar patterns have been reported in fruit and vegetable powders subjected to vacuum or convective drying, where elevated temperatures enhance degradation rates of thermolabile compounds such as anthocyanins and vitamin C (Saavedra-Leos et al., 2021).

Spray-dried samples exhibited the highest decline in TPC, TAC, and antioxidant activity. This may be associated with exposure to elevated inlet temperatures and rapid moisture removal during atomization, which can promote structural collapse and increase susceptibility to oxidation (Quek et al., 2007; Tonon et al., 2008). Furthermore, thermal stress during spray drying may initiate partial degradation of phenolic compounds, making them more vulnerable to subsequent storage-induced oxidation. The use of inulin as a carrier agent contributed positively to storage stability. Inulin has been reported to form a protective matrix around encapsulated compounds, reducing oxygen permeability and moisture-induced degradation (Lacerda et al., 2016; Šturm et al., 2019). Its relatively high glass transition temperature may also contribute to improved structural stability during storage, thereby enhancing retention of phenolic compounds.

Storage temperature was another critical factor influencing stability. Samples stored at 4±1°C exhibited significantly lower degradation rates compared to those stored at room temperature. Reduced storage temperature slows oxidation reactions, enzymatic activity, and non-enzymatic browning processes, resulting in improved retention of phenolics and anthocyanins (Lee and Kader, 2000; Michalska and Lech, 2018). These findings emphasize the importance of appropriate storage conditions in maintaining the functional quality of fruit-derived powders.

Overall, although freeze drying ensured maximum preservation of bioactive compounds, vacuum drying at moderate temperature (60°C) provided a balanced approach between biochemical stability and economic feasibility. These findings highlight the importance of optimizing both drying parameters and storage conditions to ensure functional quality and industrial applicability of EC powders.

CONCLUSION

This study comprehensively evaluated the effects of different drying techniques (freeze drying, vacuum drying, and spray drying) and carrier agents (inulin and maltodextrin) on the physicochemical, functional, and sensory properties of European Cranberrybush (EC) powders. Among the drying methods, freeze drying preserved the highest levels of bioactive compounds, including total phenolic content, antioxidant activity, and anthocyanins. However, vacuum drying, especially at 60°C, demonstrated a promising balance between bioactive compound retention and processing efficiency, offering a cost-effective alternative to freeze drying.

Inulin proved to be a more effective carrier agent than maltodextrin in protecting phenolic compounds and maintaining antioxidant properties during both drying and storage. Moreover, in vitro digestion simulations confirmed that inulin contributes to the controlled release and bioaccessibility of phenolic compounds, particularly in the intestinal phase.

Sensory evaluations revealed that although fresh juice had the highest acceptability, powders obtained via vacuum and freeze drying maintained satisfactory sensory characteristics, while spray-dried powders showed significant quality losses. During storage, low temperatures (4±1°C) significantly enhanced the stability of bioactive compounds in all powder types.

Overall, this study highlights vacuum drying combined with inulin as an efficient and economically viable method for producing functional EC powders with high stability, favorable sensory attributes, and potential health benefits. These findings provide a solid foundation for the industrial application of EC in the development of functional food products.

DECLARATION OF COMPETING INTEREST

The author declare no conflict of interest.

AUTHOR CONTRIBUTION

Zehra GÜNEL; prepared samples, analyses, reporting, and writing.

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Cite this article as:
Günel Z. (2026) The effects of different carrier agents and drying methods on some physicochemical properties and storage stability of European Cranberrybush (Viburnum opulus L.) powder. GIDA (2026) 51 (3) 441-457 doi: 10.15237/gida.GD25143

Nasıl Atıf Yapılır?:
Günel Z. (2026) Farklı taşıyıcı ajanlar ve kurutma yöntemlerinin Gilaburu (*Viburnum opulus* L.) tozunun bazı fizikokimyasal özellikleri ve depolama stabilitesi üzerine etkileri GIDA (2026) 51 (3) 441-457 doi: 10.15237/gida.GD25143