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ORIGINAL ARTICLE

Assessment of thermochemical, physicochemical, and biochemical properties of purple cabbage powder converted by different drying systems

Muhammed Taşova[1] · Osman Nuri Öcalan[2] · Samet Kaya Dursun[1] · Onur Saraçoğlu[2]

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Abstract

In this study, effective diffusion values were determined between 3.26–6.07 × 10^{-9} and 1.23–4.02 × 10^{-8} m^2/s. SMER values were calculated between 3–4.1 × 10^{-3} and 9 × 10^{-3}–1.6 × 10^{-2} kg/kWh. SEC values are calculated between 244.99–326.39 and 63.70–111.38 kWh/kg. Evaporating energy values were calculated between 4.83–4.86 and 4.81–4.89 kWh. Carr indexes of the powders were determined between 28.06 and 65.38 and Hausner indexes between 1.77 and 2.90. Minimum color change CD was detected at 70 °C and MTCM at 50 °C drying processes. The total phenolic substance has ranged from 3584.5 to 5774.5 µg GAE g^{-1} dw, total flavonoid substance from 499.3 to 1514.1 mg KE L^{-1} dw, total monomeric anthocyanin from 162.5 to 955.2 µg cy^{-3}-O-glu g^{-1} dw, vitamin C from 500 to 820 mg L^{-1}, and total antioxidant capacity ranged from 21.37 to 33.78 µmol TE g^{-1} dw.

Keywords Drying processes · Phytochemical analysis · Powder properties · Drying kinetics · Energy analyzes

1 Introduction

Purple cabbage (*Brassica oleracea* L.) is one of the most consumed agricultural products in the world, containing high nutritional values such as antioxidants, vitamins, and minerals [28]. Purple cabbage contains vitamins A, B, C, E, B1, and B2 and minerals [17, 18]. Due to the active ingredients it contains, purple cabbage is used in cancer, diabetes, cardiovascular diseases, obesity [5], intestinal diseases [59], edema, burns, and skin lesions [11]. Reported to have a curative effect. Besides the fresh consumption of purple cabbage, it is used as a sauce in yogurts [19], after being dried, in diet dishes, soups [40], and biscuits [26]. Food powder production is constantly developing and increasing. It has been reported that the commercial value of food powder is approximately 14 million dollars, according to 2017 data. It is predicted that this value will be approximately 15 million dollars by 2025. Food powders are used in many areas [20, 50]. Agricultural products are transformed into food powders and given functional properties. However, with the decrease in the weight and volume of agricultural products, profitability increases by decreasing transportation costs and storage costs. Agricultural products are dried before being turned into food powder. The most popular drying methods used in the industry to produce food powder is hot air drying [41]. In the hot air convective drying process used in food powder production, the products can be easily reduced to a safe and storable moisture level [13]. Hot air dryers consume higher amounts of energy than electromagnetic dryers [4]. Another popular method used in powder production is microwave drying. In microwave drying processes, heat is generated inside the product and diffuses from inside to outside. Due to this feature, the heat distribution in microwave dryers is more uniform than in convective dryers. In addition, microwave dryers have lower energy consumption and better quality characteristics than convective dryers [14]. However, the most important disadvantage of microwave drying processes is that the temperature values created by the microwave power (W) in the product are very high. This situation causes color losses, some quality losses, and sometimes burning at sharp points [36]. However, with the

✉ Muhammed Taşova
muhammed.tasova@gop.edu.tr

1 Faculty of Agriculture, Department of Biosystems Engineering, Tokat Gaziosmanpaşa University, 60250 Tokat, Turkey

2 Faculty of Agriculture, Department of Horticulture, Tokat Gaziosmanpaşa University, 60250 Tokat, Turkey

decrease in moisture towards the final stages of drying, low-scoring quality values occur in the product [51]. The quality characteristics of the product can be better preserved by utilizing the energy efficiency and fast drying kinetics of microwave dryers. For this, the temperature value of the heat created by the microwave energy must be controlled. For this purpose, the study focused on the development of a new microwave dryer. By modifying a normal microwave dryer, it is possible to measure the value of the heat generated by the microwave energy in the product in terms of drying temperatures and to control the desired drying temperature.

In this study, purple cabbage powder dried in convective (CD) and modified temperature control microwave (MTCM) dryers at 50, 60, and 70 °C; moisture content, tapped-bulk density, flow properties (Hausner–Carr indexes), color (1); energy consumption, evaporation, efficiency ratio (2); total phenol, flavonoid, anthocyanin, antioxidant activity, and vitamin C (3); moisture rate, drying rate, effective mass diffusion and activation energy (4); and microstructure analyze (5) were investigated.

2 Material and methods

2.1 Purple cabbage and agents

Fresh purple cabbages were harvested from a producer's garden in Tokat, Turkey, in May 2023. Purple cabbage samples were stored at + 4 ± 0.5 °C under refrigerator conditions until the end of the studies. Parmor brand maltodextrin was used to prevent the powder from aggregating. The maltodextrin ($C_{12}H_{22}O_{11}$) agent produced by Parmor Limited Company (Turkey) was used. All chemicals required for phytochemical analyzes were obtained from Merck KGaA (Germany).

2.2 Sample preparation

To prepare the purple cabbage puree, the outer rough leaves of the fresh material were first removed. After the purple cabbage leaves were thoroughly washed with tap water, they were kept in an open environment for a while to dry their rough water. Before being pureed, the samples were chopped long (4–5 cm) with a sharp knife. Shredded cabbage samples Waseem et al. [54] by making minor modifications, it was mixed with distilled water at a ratio of 1:3. The prepared mixture was turned into puree by blanching for 1.5 min with a WARNING brand HGB2WTG4 model, 220–240 V, 50–60 Hz (400 W) glass blender. Ten percent maltodextrin was added to the prepared puree and mixed with a hand blender for 3 min. To transform the dried samples into powder, use a Beko brand 2166 model (700 W) food processor, processed for 1 min.

2.3 Moisture determination of puree

To determine the initial moisture content that oven was set to 70 °C [25] and dried in a drying oven (Şimşek Laborteknik brand-ST-055 model) until the weight change was stabilized. The total moisture content of the samples was determined by Kaveh et al. [25] and calculated according to the method.

2.4 Drying processes

The prepared purple cabbage purees were dried with convective (CD) and modified new microwave (MTCM) systems.

2.4.1 Convective drying

A Şimşek Laborteknik brand-ST-055 model convective dryer was used in the hot air drying process. Fresh samples were dried to equilibrium humidity by the convective drying (CD) method at temperatures of 50, 60, and 70 °C and a constant air speed of 2.40 m/s.

2.4.2 Modified temperature controlled microwave

A commercially available Kenwood brand 13J28 model (domestic) microwave oven was used to manufacture the modified microwave dryer. Working principle of modified temperature controlled microwave (MTCM), an Optris brand infrared temperature sensor is mounted on the device to detect the temperature value of the heat created in the product by the microwave oven. Temperature values measured on the product surface are transmitted to a pre-programmed control panel. Drying temperature values determined for drying processes can be adjusted via the control panel. The control panel allows the desired drying temperature value to be entered. The microwave power value on the device is fixed. In all operations, the temperature value created in the product is controlled by working at the maximum output power of 800 W. MTCM automatically stops when the surface temperature of the product reaches the drying temperature pre-entered on the control panel. For purple cabbage puree (15 s), wait for the resting period (dashed) determined in the preliminary trial. After the rest period, when the temperature of the product falls below the determined drying temperature, MTCM automatically starts working again. During this period, if the product temperature does not fall below the drying temperature, MTCM waits for the specified rest period without operating again [36, 48]. Purple cabbage puree was dried in MTCM at temperatures of 50, 60, and 70 °C until equilibrium moisture.

2.5 Drying rate

Equation (1) was used to calculate the drying rate of purees [12].

$$DR = \frac{M_{t-M_{(t+dt)}}}{dt} \tag{1}$$

where *Mt* is the moisture content at time *t* (g moisture/g dry matter), *dt* is the minutes, *DR* is the drying rate (g moisture/g dry matter).

2.6 Moisture rate

Equation (2) was used to determine the rates of moisture removed from the purees [31].

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{2}$$

where *MR* is the moisture rate, *M* is the instant moisture content of the product (g moisture/g dry matter), M_e is the equilibrium moisture content of the product (g moisture/g dry matter), M_o is the initial moisture content of the product (g moisture/g dry matter).

2.7 Effective moisture diffusion value

The effective moisture diffusion value was calculated using equation number 4 [10, 49].

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left[(2n+1)^2\frac{\pi^2}{4}\frac{D_{ff'}}{L^2}\right] \tag{3}$$

$$\text{In } MR = \text{In}\frac{8}{\pi^2} - \frac{\pi^2 D_{eff'}}{4L^2} \tag{4}$$

where D_{eff} is the effective diffusion value (m^2/s), *L* is the half of the slice thickness (m) of the product. *t* indicates the drying time of the product.

2.8 Activation energy value

This function is calculated using equation number 5 [23].

$$D_{eff} = D_0 \exp\left(-\frac{E_A}{RT}\right) \tag{5}$$

where D_0 value is the diffusion coefficient (m^2/s), *R* value is the gas constant (8.3143 kJ/molK), E_a is the activation energy value (kJ/mol), *T* is the drying air temperature (Kelvin).

2.9 Specific moisture absorption rate

Equation (6) was used to calculate the specific moisture absorption rates of drying processes [45].

$$SMER = \frac{\text{Evaporating moisture (kg)}}{\text{Consumption energy (kWh)}} \tag{6}$$

where SMER is the specific moisture extraction rate (kg/kWh).

2.10 Specific energy consumption

Equation (7) was used to calculate the specific energy consumption (kWh) of the drying processes [34].

$$SEC = \frac{E_t}{m_w} \tag{7}$$

where SEC is the specific energy consumption (kWh/kg moisture), E_t is the total consumed energy (kWh), *mw* is the amount of moisture removed (kg).

2.11 Evaporating energy (BE)

Equation (8) was used to calculate the energy value of the evaporated moisture in the drying processes [7, 8].

$$Qw = h_{fg} \times m_w \tag{8}$$

$$hfg = 2.503 \times 10^6 - 2.386 \times 10^3 \times (T_d - 273.16)$$

$$273.16 \le T_d(K) < 338.72$$

$$h_{fg=}\sqrt{(7.33 \times 10^{12} - 1.60 \times 10^7 \times T_d^2)}$$

$$338.72 \le T_d < 533.16$$

where *Qw* is the evaporation energy (kWh), *hfg* is the latent heat of evaporation (kJ/kg), *mw* is the amount of evaporated moisture (kg). *Td* is the drying temperature (K).

2.12 Energy efficiency

Equation (9) was used to calculate the energy efficiency ratios of drying processes [7, 8].

$$\eta = \frac{Q_w}{E_t} \tag{9}$$

where Qw is the evaporation energy (kWh), Et is the total energy consumption (kWh).

2.13 Moisture content of powder

Moisture rates of powder samples produced were determined using equation number 10 [51].

$$Nd.w. = \frac{\text{Initial weight} - \text{last weight}}{\text{last weight}} \times 100 \tag{10}$$

where initial weight is the initial weight of the powder before drying (g), last weight is the weight of the powder after drying (g).

2.14 Tapped-bulk density

Tapped-bulk density values are an important volume weight value for the storage of functional food powders. The tapped and bulk density values of the produced purple cabbage powders were determined by making a minor modification to the method specified in the study of Sejali and Anuar [43]. The tapped density (P_t) value was calculated by filling a 100-ml glass tape measure with purple cabbage powder three times and determining its weight. The bulk density (P_b) value was calculated by placing 10 g of purple cabbage powder on a 100-ml glass tape measure three times and determining the volume value [43].

2.15 Flow properties

Flow property is important in pulverizing, transporting and storing purple cabbage powders. Powder products have two basic flow characteristics. These are the Carr index (CI) and Hausner (HR) index values. The Carr index shows the pourability of the powder. The Hausner index shows the stickiness value of the powder. Equations (11) and (12) were used to calculate the Carr and Hausner indices of the produced powder, respectively [3].

2.15.1 Carr index

$$\text{CI} = \frac{Pt - Pb}{Pt} \times 100 \tag{11}$$

CI index;

(1). $\% \, 0 < \text{CI} \leq \% \, 10$.

The pourability of purple cabbage powder is excellent.

(2). $\% \, 10 < \text{CI} \leq \% \, 15$.

The pourability of purple cabbage powder is good.

(3). $\% \, 15 < \text{CI} \leq \% \, 20$.

The pourability of purple cabbage powder is fair.

(4). $\% \, 20 < \text{CI} \leq \% \, 25$.

The pourability of purple cabbage powder is passable.

(5). $\% \, 25 < \text{CI} \leq \% \, 31$.

The pourability of purple cabbage powder is poor.

(6). $\% \, 31 < \text{CI} \leq \% \, 37$.

The pourability of purple cabbage powder is very poor.

(7). $\% \, 37 < \text{CI}$.

The pourability of purple cabbage powder is very poor.

2.15.2 Hausner index

$$\text{HR} = \frac{Pt}{Pb} \tag{12}$$

HR index;

(1). $1 < \text{HR} \leq 1.11$.

The stickiness of purple cabbage powder is excellent.

(2). $1.11 < \text{HR} \leq 1.18$.

The stickiness of purple cabbage powder is good.

(3). $1.18 < \text{HR} \leq 1.25$.

The stickiness of purple cabbage powder is fair.

(4). $1.25 < \text{HR} \leq 1.34$.

The stickiness of purple cabbage powder is passable.

(5). $1.34 < \text{HR} \leq 1.45$.

The stickiness of purple cabbage powder is poor.

(6). $1.45 < \text{HR} \leq 1.59$.

The stickiness of purple cabbage powder is very poor.

(7). $1.59 < \text{HR}$.

The stickiness of purple cabbage powder is very poor.

where CI is the Carr index (%), HR is the Hausner index, P_t is the tapped density (g/ml), P_b is the bulk density (g/ml).

2.16 Color value

The following equations [2, 38, 46] were used to determine color values [2, 38, 46].

$$\text{Croma C} = \left(a^2 + b^2\right)^{1/2} \quad (13)$$

$$\text{Hue } h^\circ = \tan^{-1}\left(\frac{b}{a}\right) \quad (14)$$

$$\text{Total color difference } \Delta E = \sqrt{(L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2} \quad (15)$$

2.17 Bioactive analyzes

In dried purple cabbage samples, total phenol, flavonoid, anthocyanin, antioxidant activity, and vitamin C contents were measured.

2.17.1 Total phenolic content

Total phenolic content was measured according to the procedure described by Singleton and Rossi [44]. The absorbance values of the extracts were measured at 750 nm in an automated UV–vis spectrophotometer (Model T60U, PG Instruments). Results are expressed as microgram (μg) gallic acid equivalent (GAE) g^{-1} dry weight (dw).

2.17.2 Total flavonoid content

Total flavonoid content was measured according to the procedure described by Zhishen et al. [60]. The absorbances were recorded at wavelengths of 510 nm. Results are expressed as milligram (mg) catechin equivalent (CE) L^{-1} dry weight (dw).

2.17.3 Total anthocyanins

Total anthocyanins were measured according to the procedure described by Tan et al. [47]. The absorbance was recorded at wavelengths of 520 nm and 700 nm for pH 1.0 and pH 4.5 solutions. Results are expressed as microgram (μg) cyanidin-3-O-glucoside g^{-1} dry weight (dw).

2.17.4 Vitamin C

Vitamin C was determined with a digital refractometer (Merck RQflex plus 10) and expressed as mg L^{-1} [1].

2.17.5 Total antioxidant activity

Total antioxidant activity was measured according to the procedure described by Ozgen et al. [35]. The absorbances were recorded at wavelengths of 734 nm. Results are expressed as μmol Trolox equivalent (TE) g^{-1} dry weight (dw).

2.18 Microstructure analysis

Light microscopy (Leica M250c) was used to examine the microstructure of purple cabbage powders produced by MTCM and CD methods. Photographs at a 2-μm scale were obtained by placing purple cabbage powder on the glass slide. Morphological sizes and distributions of the powders were examined in the photographs.

2.19 Statistical analysis

For statistical analysis of color, physico-chemical, and bioactive properties of produced purple cabbage powder, Duncan multiple comparison test ($P < 0.05$) was performed in SPSS 17th program. SigmaPlot 10. The program was used to create the curves of the parameters.

3 Results and discussion

3.1 Drying kinetics

The drying values of purple cabbage powders produced with CD and MTCM drying systems are given in Fig. 1.

In the drying processes, the average moisture values of the samples were dried from 7.43 ± 0.025 to 0.02 ± 0.0015-g moisture/g dry matter. Xu et al. [51] dried the cabbage plant in a hot air dryer and microwave dryers to a final moisture value of < 4% (w.b.). The drying time, humidity and drying rate values of purple cabbage puree were affected by drying methods and temperatures. It was observed that the drying times decreased and the drying rates increased with the increase in drying temperatures. According to Fig. 1, the average drying times of purple cabbage purees dried in the CD method at 50, 60, and 70 °C were determined as 1560, 1440, and 720 min, respectively. For the MTCM method, these values were determined as 382, 362, and 49 min, respectively. The MTCM method reduced the drying time by 81.19% compared to the CD method. Xu et al. [52] determined the average drying times for hot air and

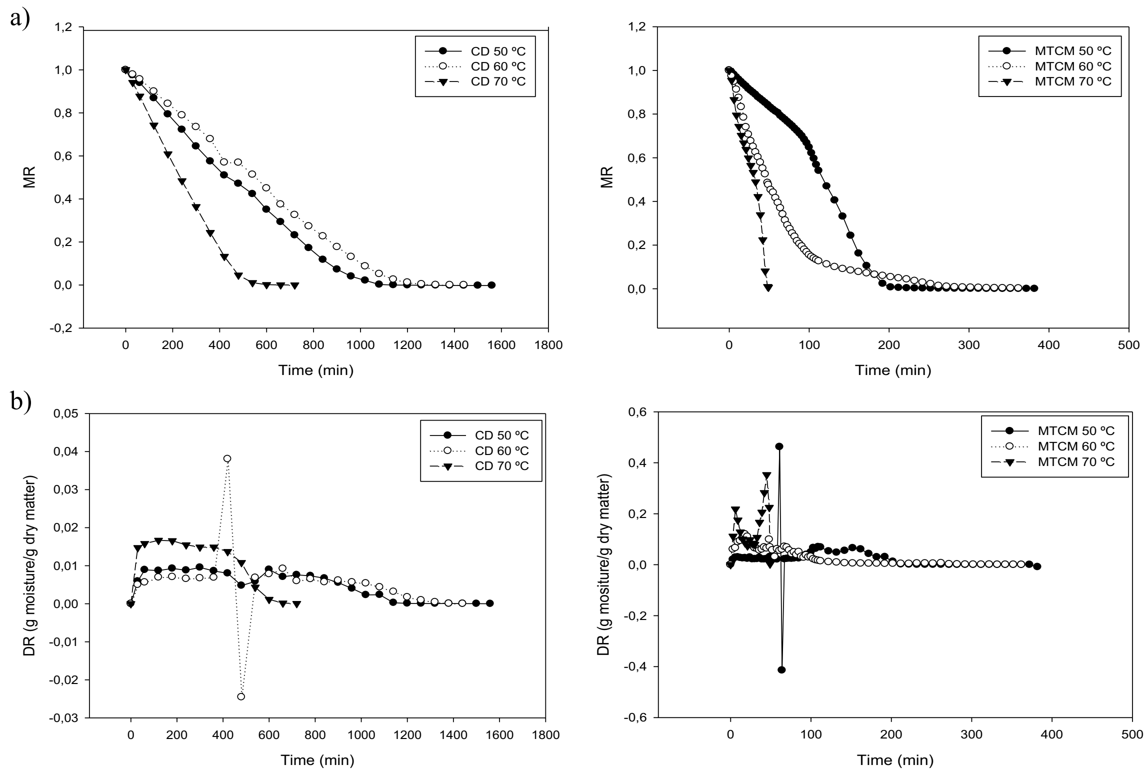


Fig. 1 Drying properties. **a** Moisture rate, **b** drying rate

microwave drying systems as 8.50 and 1.10 h, respectively. The microwave drying system reduced the drying time by 87.06% compared to the hot air drying system. It was observed that the findings obtained in this study, and the findings in the literature were similar in terms of drying time and rates. Yue et al. [59] dried the purple cabbage samples in hot air and microwave dryers to 10% final humidity. The average drying times for the drying processes were determined as 7 and 0.2 h, respectively. It was observed that there were small differences between the drying times obtained in this study and the findings in the literature. The reason for this can be explained by the higher final moisture value of the dried product in the study in the literature. However, the different thermal properties of the drying systems may also have affected the drying times. Average drying rates for CD and MTCM drying methods were determined as 0.0048–0.0103 and 0.1525–0.2050-g moisture/g dry matter min, respectively. The increase in temperature values in the drying systems caused the drying rate of the product to increase. Lekcharoenkul et al. [27] dried the outer (residual) leaves of the cabbage plant at temperatures of 45 and 60 °C in a hot air dryer and reported that the drying rate increased with increasing drying temperature.

Table 1 Effective moisture mass diffusion and activation energy

Drying methods	Temperatures (°C)	Effective diffusion (m^2/s)	R^2	Activation energy (kJ/mol)
	50	2.34×10^{-8}	0.8015	
CD	60	1.22×10^{-7}	0.7924	215.91
	70	3.06×10^{-7}	0.8546	
	50	4.28×10^{-7}	0.7856	
MTCM	60	4.47×10^{-7}	0.9883	13.99
	70	5.27×10^{-7}	0.8200	

3.2 Effective moisture diffusion-activation energy

The effective diffusion and activation energy values of purple cabbage puree are given in Table 1.

According to Table 2, it has been seen that drying methods and temperatures affect the effective diffusion and activation energy values. It was determined that the effective diffusion values increased with the increase in drying temperatures. Since the increase in temperature caused more moisture to be removed from the product per unit of time, the amount of moisture spread increased. Luke et al. [29, 30] dried white cabbage leaves in a hot air dryer at 50, 60, and 70 °C and microwave power values of 240, 400, and 640 W.

Table 2 Physico-chemical values

	CD			MTCM		
Parameters	50 °C	60 °C	70 °C	50 °C	60 °C	70 °C
L	46.75 ± 0.86b	51.63 ± 2.49a	43.38 ± 1.48c	37.45 ± 0.86d	42.64 ± 1.39c	50.97 ± 1.06a
a	17.72 ± 1.97c	13.65 ± 0.53d	12.82 ± 0.92d	23.22 ± 0.74a	20.54 ± 0.77b	17.09 ± 0.33d
b	− 3.53 ± 0.14d	7.08 ± 0.43b	5.01 ± 0.28c	− 6.79 ± 0.38 g	− 4.49 ± 0.48e	15.24 ± 0.58a
C	18.08 ± 1.92c	15.39 ± 0.35d	13.77 ± 0.82e	24.19 ± 0.81a	21.02 ± 0.85b	20.09 ± 0.62b
ΔE	50.15 ± 1.34b	53.88 ± 2.78a	45.52 ± 1.25d	44.59 ± 1.42d	47.54 ± 2.19c	54.79 ± 1.10a
Moisture rate	% 8.46a	% 7.50b	% 5.48d	% 4.98de	% 7.47b	% 6.00c
Tapped density	3.5058a	2.5762ab	3.3428ab	3.1111ab	2.2583b	2.9398ab
Bulk density	1.2089b	1.2178b	1.1600c	1.2222b	1.2756a	1.1333c
Carr index	65.38a	52.24b	64.68a	60.43a	28.06c	60.39a
Hausner index	2.90a	2.11ab	2.89a	2.56ab	1.77b	2.59ab
	L		***a***		***b***	***C***
Fresh	14.72 ± 0.77e		10.29 ± 2.42e		− 5.88 ± 1.22f	11.86 ± 2.69f

The bold numbers in Table 2 indicate the most appropriate values in terms of drying methods

They reported that the effective diffusion values in the hot air drying process varied between 3.26 and 6.07×10^{-9} m^2/s. They found that the effective diffusion values in the microwave drying process varied between 1.23 and 4.02×10^{-8} m^2/s. It has been observed that the data obtained are compatible with the findings in the literature. It is thought that the reason for the small differences detected is due to the difference in the initial and final moisture values of the products. It was found that the effective diffusion values of the drying processes performed in the MTCM system were higher than the CD method, and the activation energy values were lower. Luka et al. [29, 30] and Halil et al. [16] determined in their work. The fact that microwave drying systems create heat directly in the product is thought to be effective in this difference.

3.3 Physico-chemical properties

The physico-chemical properties of the purple cabbage powder produced are given in Table 2.

According to Table 2, drying methods and temperature values affected the physico-chemical properties of purple cabbage powder. Drying systems could not preserve the *L*, *a*, *b*, and *C* color values of fresh purple cabbage samples ($P < 0.05$). Wojdylo et al. [56] found a similar situation in the color parameters of strawberries dried in vacuum and microwave ovens. It was determined that the brightness values of the powder samples were higher than the fresh ones ($p < 0.05$). The reason for this is that the whiteness index increases as the moisture moves away from the products and/or the carrier agent ($14.72 < L$) is used. It was found that the values of purple cabbage powders were lower than the fresh ones. The removal of moisture by thermal processes caused an increase in the density of red color pigment in the product. Chen et al. [9] reported that the color pigment intensified with the decrease of moisture content in the black mulberry fruit dried by microwave and convective methods. CD and MTCM systems of purple cabbage samples affected *L* and *a* value ($P < 0.05$). Yue et al. [59], when they compared the dried samples with the fresh ones, stated that the *L* and *a* values increased in the hot air drying method and the *L* and *a* values decreased in the microwave drying method. It was seen that the relationship between the study in the literature and the findings obtained within the scope of this study was compatible with the samples dried with hot air. The difference between the samples dried by the microwave method was that the carrier agent was not used and the amount of thermally decomposed pigment was higher than the increase in density. The lowest total color change among purple cabbage powders was determined in powder samples produced at CD 70 °C and MTCM 50 °C temperatures. Since the drying time of the product is reduced at high temperatures in the CD method, the color change is better preserved than at low temperatures. Hu et al. [21] stated that at low temperatures, the color change is higher as the product is exposed to heat for a longer time. In the MTCM method, on the other hand, a color change is better preserved, since the amount of energy on the inner surface of the product at low temperatures remains at a lower level than at high temperatures. There was no significant difference ($P < 0.05$) between the temperatures of CD 60 °C and MTCM 60 °C, and between CD 70 °C and MTCM 50 °C in terms of moisture content of the produced purple cabbage powders. The lowest moisture content was determined ($P < 0.05$) in the samples dried at CD 70 °C (5.48%) and MTCM 50 °C (4.98%). Kathiman et al. [24], determined the moisture content of the dust they produced as the lowest 4.84% and the highest 8.29%. This may be because the moisture content of the product is lowered more easily at high temperatures for the CD method, and because high temperatures cause caramelization in the MTCM method, it may have made it difficult to remove moisture. Bazaria and Kumar [6] found that the moisture content of the dust they produced at high temperatures was lower than those produced at low temperatures. The Carr indexes (pourability) of the powders produced at 60 °C temperatures in CD and MTCM drying systems were found to be significantly different from the others ($P < 0.05$). Among the powders, it was found that only those produced at MTCM 60 °C had a "weak" Carr index, while the others were at a "very very weak" level ($P < 0.05$). Santos et al. [42] reported that the Carr index of the fruit powder they produced varied between 15.95 and 25.90%. The reason why the data in the literature is lower than the data in this study may be due to the lower moisture content of the powder (3.65–6.15%). It was observed that the Hausner indexes (adhesiveness) of all the powders produced were at the "very very weak" level ($P < 0.05$). This may indicate that there is no stickiness or that it occurs at a very low level. Watharkar et al. [55] reported that drying temperatures (50, 60, and 70 °C) affect the Hausner rates in the banana powder production process. They found that Hausner ratios varied between 1.11 and 1.23. The findings in the literature were found to be lower than the data in this study (1.77–2.90). Fruits with high sugar content are expected to have a lower Hausner ratio and a higher stickiness level. The sugar content of the banana fruit within the scope of the study was reported to be 20.84%.

3.4 SMER and SEC values

The distribution of time-dependent SMER and SEC energy consumption values during the drying processes is given in Fig. 2.

According to Fig. 2, it is seen that drying systems and temperatures are effective in energy analysis. Average SMER values were found between $3–4.1 \times 10^{-3}$ for CD and $9 \times 10^{-3}–1.6 \times 10^{-2}$ kg/kWh for MTCM. It was found that the SMER values determined in the CD method were lower than the MTCM method. Average SEC values ranged from 244.99 to 326.39 for CD and 63.70–111.38 kWh/kg for MTCM. It was determined that the SEC values determined in the CD method were higher than the MTCM method. The reason for the high SMER and SEC values in the CD method may be due to the higher amount of energy consumed. Rojas et al. [39] found that SEC energy consumption values varied between 82.50 and 150.90 kWh/kg in their study with a hot air drying system. The findings in the literature were found to be consistent with those in this study. The SEC energy consumption values generally increased in the final stages of the drying process. This is because the amount of moisture removed from the product towards the end of drying decreased, thus increasing SEC (kWh/kg) values. Wang

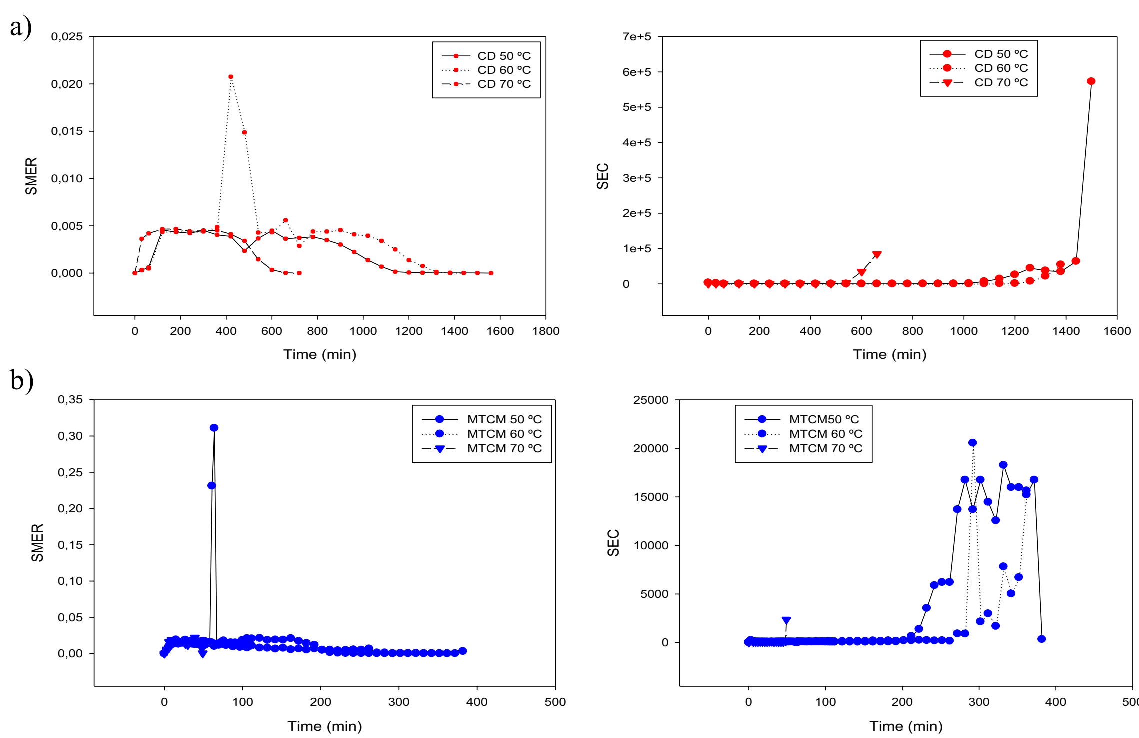


Fig. 2 Energy consumption values (**a**) CD, **b** MTCM

et al. [53] dried onions into powder using hot air, freeze-drying and microwave-assisted freeze-drying methods. The average SEC energy consumption values of the drying processes were determined as 7–9 × 10^5 kJ/kg (195–250 kWh/kg). The reason why the SEC values in the literature are higher than the findings obtained in this study is that they carried out the drying processes at a temperatures of 45 °C. At low drying temperature, the product reaches the desired moisture level in a longer time. This event increased the amount of energy consumed by the device.

3.5 Evaporating energy values

The steam energy and energy efficiency ratios of the drying processes are given in Fig. 3.

According to Fig. 3, drying temperatures and methods affected the steam energy values and energy efficiency rates. Steam energy values for CD and MTCM methods were determined between 4.83–4.86 and 4.81–4.89 kWh, respectively. It was observed that the steam energy values were close to each other in the drying processes. This situation was affected by the fact that the total amount of moisture removed in both methods was close to each other. Rabha et al. [37] reported that they calculated the evaporation energy value as 0.6636 kWh (2.37 MJ/kg) in the pepper drying study carried out at 50 °C in a convective dryer. The reason why the steam energy value stated in the literature is slightly lower than the scope of the study may be due to the low drying temperatures and the different physical properties of the pepper (moisture, micro-structure, physico-chemical, etc.). The energy efficiency ratios determined for the CD and MTCM methods varied between 1.60–2.15 and 5.77–9.13, respectively. Motevali et al. [32] determined that the energy efficiency rate of the daisy drying process in the hot air vacuum type drying system varies between 1.42 and 6.53%. It has been found that the energy efficiency determined for the MTCM drying system is higher than the CD method. The reason for this is that the amount of energy consumed in microwave drying systems is lower than in hot air dryers. Motevali et al. [33] determined the energy efficiency rate of the chamomile drying process in the microwave drying system between 8.25 and 13.07%. Vishwanathan et al. [57] suggested that hot air dryers should be converted into hybrid drying systems by integrating them with microwave dryers because their energy efficiency is lower than microwave dryers.

3.6 Bioactive properties

3.6.1 Total phenolic content

The total phenol content of purple cabbage powders was significantly affected by drying methods and degrees of temperature (Fig. 4). In the CD method, temperatures above 50 °C preserved better the total phenol content. In the MTCM method, however, low temperature (50 °C) was more effective. The increase in temperature in MTCM caused decreases in total phenol content. As a result, temperatures

Fig. 3 Evaporating energy and energy efficiency values

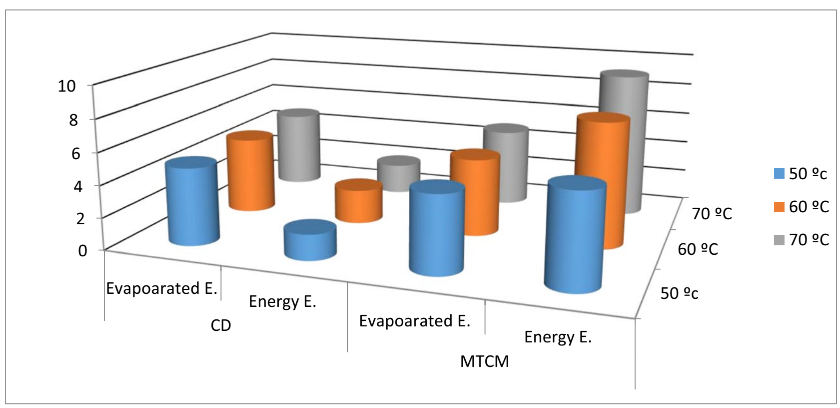
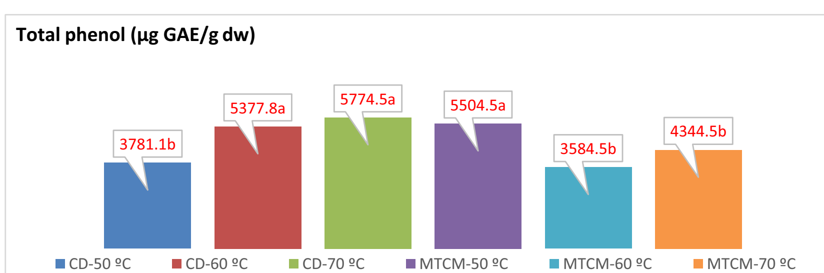


Fig. 4 Total phenolic content values



of 60–70 °C in CD and 50 °C in MTCM were more suitable for total phenol.

3.6.2 Total flavonoid content

Total flavonoid values were significantly affected by CD and MTCM methods. In the CD method, the decrease in temperature negatively affected the flavonoid content. In the MTCM method, on the contrary, the increase in temperature caused a decrease (Fig. 5). The highest flavonoid value was obtained in MTCM at 50 °C. Ultimately, the optimum temperatures for total flavonoids were determined as 70 °C for CD and 50 °C for MTCM.

3.6.3 Total monomeric anthocyanin content

The anthocyanin content of purple cabbage powders was affected by drying methods and degrees of temperature. In the CD method, compared to 50 °C, the anthocyanin content was better preserved at 60 and 70 °C. When MTCM is examined, on the contrary, it is seen that anthocyanin values decrease as the temperature increases (Fig. 6). Low temperature (50 °C) was more effective in the MTCM method. In light of the findings, the optimum drying temperature for anthocyanin was determined as 60–70 °C for CD and 50 °C for MTCM.

3.6.4 Vitamin C content

Significant differences occurred between vitamin C values in drying methods with the effect of temperatures (Fig. 7). The highest vitamin C was detected in the CD method at 70 °C. In the CD method, vitamin °C values decreased with the decrease in temperature. When looking at MTCM, the highest vitamin C was observed at 50 °C, while the lowest vitamin C was determined at 60 °C. According to the data, in terms of vitamin C, the more suitable method was the application of 70 °C temperature in the CD method.

3.6.5 Total antioxidant activity

Antioxidant activities were significantly affected by drying methods and temperatures (Fig. 8). Antioxidant activity

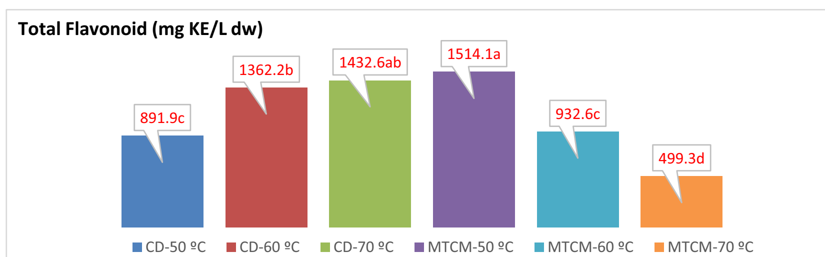


Fig. 5 Total flavonoid content values

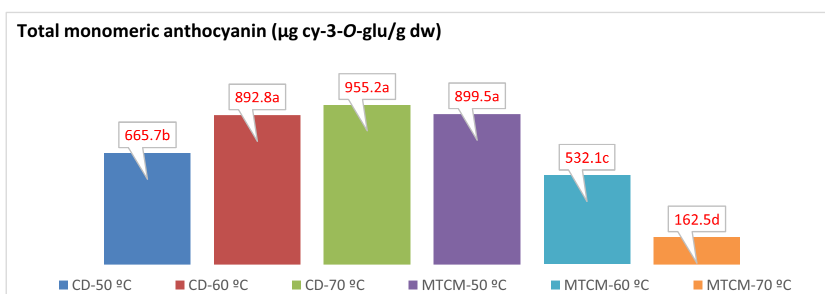


Fig. 6 Total monomeric anthocyanin content values

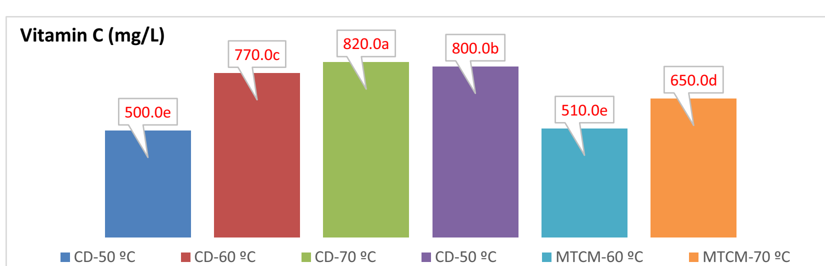


Fig. 7 Vitamin content values

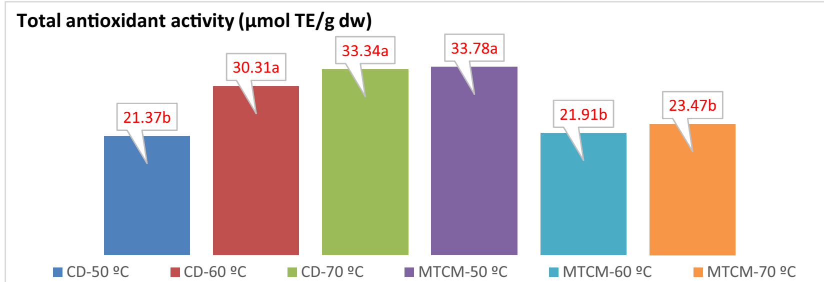


Fig. 8 Total antioxidant activity values

was higher in the CD method at temperatures above 50 °C. In the MTCM method, the highest antioxidant activity was detected at 50 °C. Antioxidant activity decreased at temperatures above 50 °C. As a result, temperatures of 60–70 °C in CD and 50 °C in MTCM were more suitable for antioxidant activity.

During the drying and powdering of fruits and vegetables, the time of the heating process is significant in terms of preserving some nutrients. In particular, the structure of phenolic compounds (flavonoids, anthocyanins, etc.) and vitamins (vitamin C, etc.), which have antioxidant properties, deteriorates in direct proportion with the time they are exposed to high temperatures. Tan et al. [47] reported that significant phytochemical losses occurred in red cabbages dried in an oven with compressed air circulation at 60 °C for 10 h. As a result of our study, with the increase in temperature in the convective dryer (CD), since the time the product is exposed to heat decreases (7 h), the bioactive substances have undergone less degradation. In the MTCM method, however, the bioactive substances deteriorated more with the increase in temperature. The reason for the underlying contradiction here lies in the working principle of the microwave oven. The electromagnetic waves produced in the microwave oven directly interact with the water molecules in the food and transfer their energy to the food. Since microwaves do not interact with air molecules as in the CD method, they do not heat the entire cooking area, and they penetrate all layers of the food simultaneously, owing to their long wavelengths [15]. The heating process takes place very quickly with the effect of microwave power (W), but the temperature sensors inside the oven detect it late. As a result, the temperature of 70 °C in the CD method and 50 °C in the MTCM method was more effective in keeping to bioactive substances. However, Izli et al. [22] reported that in the production of pumpkin powder, 200 W-80 °C temperature application in the MTCM method preserved the total phenolic substance and antioxidant activity content better than 60 and 70 °C. Here, there may be two main reasons for the discrepancy: first, different products in the trial may react differently; second, it may be due to the use of microwave power at low levels in the study in the literature. The higher the microwave power, the over-effective the temperature. Both microwave power and temperature to be high accelerate the degradation of bioactive ingredients. Yuan et al. [58] reported that the best method to retain nutrients for cooking broccoli has steam cooking compared to a microwave oven (1000 W). In another drying study with cabbage (*Brassica oleracea* L. *var capitata* L.), Luka et al. [61] observed that total flavonoid and phenolic contents decreased but antioxidant capacity increased when the drying temperature was increased from 50 to 60 °C and 70 °C in a hot air oven. These findings in the literature are in agreement with our findings in terms of antioxidants, but not in terms of total phenol and flavonoids. This discrepancy may be due to the different plant material and drying equipment used. In the same study, Luka et al. [61] reported that if the microwave drying power levels were increased from 195 to 307 W and 521 W, the flavonoid content decreased but the phenolic matter and antioxidant capacity increased. In our study, keeping the temperature constant at 50 °C in modified temperature controlled microwave (MTCM) operating at maximum 800 W output power preserved the bioactive substances better. Increasing the temperature to 60 °C and 70 °C in terms of MTCM negatively affected these substances.

3.7 Microscopic properties

The photographs obtained for the morphological particle size analysis of the produced purple cabbage powders are given in Fig. 9.

According to Fig. 9, in the morphological images (2 µm) obtained for the CD method, it was observed that the monoization and microization increased with the increase in drying temperature. This situation may have been caused by the easier removal of moisture with the increase in temperature. The monotonization of the powders produced by the MTCM method was weaker than the CD method. It has been determined that with the increase of the temperature in the drying processes between the MTCM drying system, texelization, and microization are better at temperatures other than 70 °C. However, the

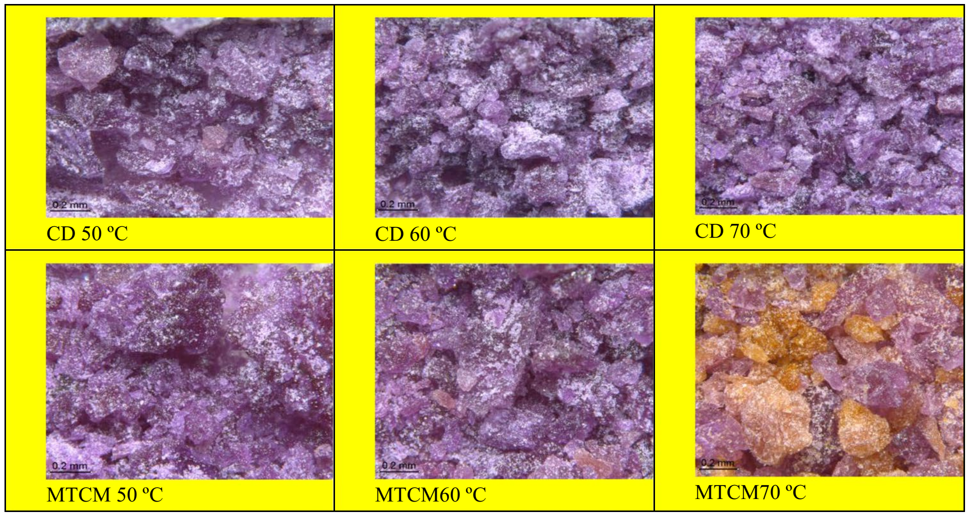


Fig. 9 Microscopic properties

internal thermal energy of the product was higher at 70 °C in the MTCM drying system caused the sugars to caramelize. It is thought that this event causes more aggregation by preventing the separation of dust particles and causes significant changes in the color values of the powders.

4 Conclusion

It has been observed that drying systems and temperatures are effective on the physical, physico-chemical, and energy analyzes of purple cabbage powders produced by drying. It was observed that the drying rate, humidity rate, and effective moisture diffusion values of the MTCM method were higher than the CD method. It has been found that the MTCM drying system is more advantageous than the CD drying system in terms of SMER, SEC steam energy, and energy efficiency values. It was observed that drying processes were effective on the color values of the powder. It was found that CD 70 °C drying process was better in terms of chroma, and CD 70 °C and MTCM 50 °C drying processes were better in terms of total color change ($P < 0.05$). It was determined that drying processes affected the physical and flow properties of purple cabbage powder. In terms of Carr index values, the powders produced were found to be at "weak" and "very very weak" levels. In terms of Hausner index values, it was determined that the powders produced were at "very very weak" levels. Drying processes affected the morphological properties of the powders at the microscopic scale. For the CD method, it was observed that the powder size decreased and became monotonous at high drying temperatures, while in the MTCM method, sugars were exposed (color change) and aggregated (aggregated) at high temperatures. In the CD method, decreasing temperatures negatively affected the bioactive substances. In the MTCM method, however, increasing temperatures negatively affected these substances. It has been determined that the optimum temperature for keeping bioactive substances is 70 °C in the CD method and 50 °C in the MTCM method.

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Author contribution Muhammed Taşova: planning, data processing, article writing. Osman Nuri Öcalan: laboratory work, data processing, article writing. Samet Kaya Dursun: laboratory work, data processing. Onur Saraçoğlu: planning, editing.

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Data availability All the data used in the manuscript are available in the tables and figures.

Declarations

Ethical approval This study has been prepared in accordance with ethical standards.

Competing interests The author declare no competing interests.

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