International Communications in Heat and Mass Transfer 169 (2025) 109664

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Effects of kiwi powder produced by hybrid microwave drying method on drying kinetics, energy parameter, thermal, physicochemical and bioactive properties

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ARTICLE INFO

Keywords:
Kiwi powder
Hybrid drying
Carrier agents
Energy analysis
Quality

ABSTRACT

In this study, drying process was carried out at different temperatures as 50, 60 and 70 °C by using hybrid dryer (convective + microwave) at 350 W output power for kiwi powder production. Hybrid dryers provide superior product quality and bioactive compound preservation, along with higher drying and energy efficiency compared to conventional systems. Before the drying process, two different carrier agents as maltodextrin and lactose were used for kiwi puree at a fixed rate of 2.5 %. Carrier agents such as maltodextrin and lactose help preserve and improve some physical and chemical properties of the final products obtained in powder production. Drying rate, moisture content, effective moisture diffusion, specific moisture absorption rate, energy consumption (SMER and SEC), evaporation energy, energy efficiency, exergy analysis, thermal properties, grinding process efficiency, Tapped, bulk density, Carr, Hausner indexes, color, total phenolic, flavonoid, and antioxidant capacity properties of the produced powders were investigated. As a result of the study, the drying rates of the drying processes were determined in the range of 0.0840–0.0948 g moisture/ g dry matter.min. Effective moisture diffusion values were determined as 3.06–3.71 $\times 10^{-7}$ m^2/s. Steam energy, energy efficiency, SMER and SEC values were calculated in the ranges of 3.62–3.95 kWh, 4.2–5.2 %, 0.00190–0.00131 kg/kWh and 763.5–897.13 kWh/kg, respectively. Ex_{in}, Ex_{out} and Ex_{evap} values were determined in the ranges of 1.45–3.85 J/s, 0.13–0.59 J/s and 0.054–0.095 kJ/kg, respectively. Thermal conductivity, specific heat, thermal diffusivity and density values were found to vary in the ranges of 0.20–0.22 W/mK, 844.84–846.10 J/kgK, 2.95 $\times 10^{-7}$-3.25 $\times 10^{-7}$ m^2/s and 756.55–764.69 kg/m^3, respectively. Grinding process efficiency, tapped and bulk density, Carr and Hausner indices were determined in the ranges of %92.54–97.95, 1.79–2.52 g/ml, 1.38–1.72 g/ml, 27.32–42.15 % and 1.07–1.27, respectively. The produced kiwi powders could not preserve the brightness and red/green color values of fresh kiwi puree statistically ($p < 0.05$). The yellow/blue and chroma values of the samples dried by adding lactose at 350 W + 70 °C preserved the color value of fresh kiwi puree. The lowest total color change value was also determined in this method. The highest total phenolic and flavonoid content was determined in the samples dried by adding lactose at 350 W + 70 °C, while the total antioxidant capacity value was determined in this method.

1. Introduction

Kiwi fruit (*Actinidia*) is a subtropical fruit of Asian origin that is consumed widely around the world and grown in certain regions of the world, including Turkey it should be noted. [1,2]. As of 2023, approximately 4.5 million tons of kiwi will be produced worldwide, and the top 10 countries, including China and Türkiye, have produced a large portion of the global kiwi production [3]. Kiwi fruit is rich in folic acid, ascorbic acid and antioxidant compounds. In addition, it is rich in vitamin C, fiber, potassium, vitamins A and E [4]. It has become popular worldwide thanks to its rich bioactive properties [5]. Some scientific reports indicate that fruits with high bioactive compound content can play a role in the prevention and supportive treatment of various diseases, and fruit and vegetable consumption is considered one of the basic elements of balanced and healthy nutrition models [6]. This fruit, which has a high nutritional content and is important for human health, should be preserved in order to be accessible in all seasons of the year.

Kiwifruit, even if stored under cold chain conditions, has a limited

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https://doi.org/10.1016/j.icheatmasstransfer.2025.109664

shelf life due to tissue softening and loss of nutrients, especially vitamin C [7]. Kiwifruit, which is a delicate fruit, can be converted into secondary products (fruit powder, etc.) by removing moisture (drying) in order to expand its usage areas, extend its shelf life and increase its added value. In this context, obtaining products in powder form from kiwifruit both increases its commercial value and provides advantages in transportation and storage processes by reducing the volume and weight of the product. In addition, products in powder form can be processed more easily and can be used more effectively in food formulations thanks to its concentrated taste and aroma profile [8]. It is reported that the obtained fruit powders are widely used as functional ingredients in many food products such as baby food, baby biscuits, bakery products and various snack foods [9,10]. Drying is a preservation method that aims to prevent spoilage due to microbial growth and enzymatic reactions by removing water content from fresh products. In this process, it is aimed to preserve the original aroma, taste and color properties of the product as much as possible [11]. The oldest known drying method is to dry the products in natural conditions under the sun or shade by laying them in open areas. Although this method is advantageous in terms of being low-cost and environmentally friendly, it has various disadvantages such as limited applicability throughout the year, the need for a large drying area, the risk of not reaching the targeted final moisture level and sensitivity to environmental factors such as dust, rain, wind, insects and birds [12–14]. Conventional artificial drying, which is one of the widely preferred methods in the drying industry, has disadvantages such as high initial investment cost and energy consumption, but the convective drying technique provides more homogeneous heat distribution on the product compared to natural drying, shortens the drying time and allows higher quality end products to be obtained [15–17]. The microwave drying method, which has attracted increasing attention in recent years, unlike conventional hot air drying, allows moisture to diffuse from the inside to the outside by directly penetrating the interior of the product and providing internal heat production. This mechanism contributes to a significant shortening of the drying time and increased energy efficiency [18]. In recent years, the hybrid (microwave + convective) drying method, which is created by combining microwave and convective dryers, has been increasingly preferred. Hybrid drying systems can provide increased drying performance, optimized energy use, improved moisture transfer kinetics, superior product quality, and higher effectiveness in preserving nutrients and bioactive compounds compared to traditional drying methods [19]. However, the energy consumption of these drying processes is generally high, and it is estimated that 10–25 % of the total energy consumption worldwide is used only by the drying industry and related processes [20]. In this context, in order to reduce fruit powder production costs and ensure sustainability, it is critical to develop innovative techniques to minimize energy consumption in drying processes and to preserve bioactive components. Carrier agents provide advantages such as preventing agglomeration, increasing powder fluidity, preserving active components (stability), and preventing undesirable taste and odor in the final product. Maltodextrin is a starch-based carrier agent, while lactose is a protein-based carrier agent. They are widely used for microencapsulation due to their ease of access and low cost [21]. There are some studies in the literature on the conversion of kiwi fruit into powder. Dirim et al. [22] investigated the physical and chemical properties of kiwi, quince and squash powders produced by vacuum-assisted freeze-drying technique. For this reason, they added maltodextrin to fruit purees by 10 % of their weight. As a result of the study, they determined that the highest vitamin C and bulk density were found in kiwi powders, while stickiness and fluidity properties were at a moderate level. Çalışkan et al. [23] examined the properties of kiwi powders they produced by freezing in their study. They added different rates (0 % and 10 %) of maltodextrin to kiwi purees. As a result of the study, they reported that the addition of maltodextrin affected the effective diffusion values, while it was determined that it reduced corrosiveness, increased volume and compressed densities, wettability, solubility and glass transition temperature. Bogusz et al. [24] investigated the microstructural changes of kiwi puree using the foam drying + freeze drying method and its effect on the physical properties of the powders. As a result of the study, they determined that there were changes in dry matter, water activity, structure and hygroscopic properties.

Literature reviews indicate that no comprehensive study has been conducted on the production of kiwi powder using a hybrid microwave (microwave + hot air) drying method with maltodextrin and lactose as carrier agents, while simultaneously evaluating drying kinetics, energy analysis, flow properties, and bioactive compound content of the resulting powder. Therefore, this study is considered to be original. The aim of this research is to convert kiwi purees into powder using a hybrid dryer at constant microwave power (350 W) and different air temperatures (50, 60 and 70 °C) with the addition of 2.5 % maltodextrin and lactose, and to investigate the effects of the drying process on drying kinetics parameters (*DR*, *MR*, D_{eff}), energy performance indicators (*SMER*, *SEC*, Q_w, *EE*, *EXE*), thermal properties, physical powder properties (Color, *HR*, *CR*, *GPE*), and bioactive compounds (total phenolic content, total flavonoid content, and total antioxidant capacity).

2. Material and method

2.1. Preparing kiwi puree

For the production of kiwi fruit powder, the fruits were stored at +4 ± 0.5 °C until the end of the study. First, the kiwis were washed with chlorinated tap water, peeled, and subjected to a permanent homogenized puree formula for approximately 1 min with the addition of 20 % water in a Beko brand 2166 model (700 W) food processor. High amounts of maltodextrin addition can lead to undesirable taste formation when mixed with fruit juice or puree. Therefore, minimizing maltodextrin use is considered a critical parameter, especially in terms of supporting healthy life or distributing powdered beverages as parts of daily consumption [25]. 2.5 % maltodextrin and lactose were used for the encapsulation of the kiwi powder material [26]. The products with added maltodextrin and lactose were processed in a food processor to make them completely homogeneous.

2.2. Drying processes

Drying processes were carried out in an Ariston Hotpoint brand MWHA 33343 model 2450 MHz (Italy) hybrid microwave (microwave + hot air) dryer at 350 W + 50 °C, 350 W + 60 °C and 350 W + 70 °C combinations, respectively. An average of 40 g of prepared kiwi puree sample was used for drying processes. Drying experiments were carried out in three parallel stages.

2.3. Determining moisture content

The initial moisture content of kiwifruit purees was determined by drying them in an oven at 70 °C until weight changes became constant [27]. Eq. 1 was used to calculate the initial moisture content of kiwifruit purees. During the weighing process, the product may absorb moisture from outside. These moisture levels are ignored.

$$N_{d.b.} = \frac{M_i - M_l}{M_l} \, x\, 100 \tag{1}$$

Here; M_i: Initial weight (g), M_l: final weight (g), $N_{d.b}$: moisture content based on dry basis (g moisture/g dry matter).

2.4. Drying kinetics

Drying rate (DR): Equation number 2 was used to determine the drying rate values of kiwi powder [28].

$$DR = \frac{M_t - M_{(t+dt)}}{dt} \tag{2}$$

Here; M_t: amount of moisture (g water/ g dry matter.minute), d_t: time (minute).

Moisture ratio (MR): Equation number 3 was used to determine the moisture content of the drying processes [29].

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \tag{3}$$

Here: M; Instantaneous moisture content of the product (g water/g dry matter), M_e; Equilibrium moisture content of the product (g water/g dry matter), M_0; Represents the initial moisture content of the product (g water/g dry matter).

Effective moisture diffusion (D_{eff}): Equation number 4 was used to calculate the effective moisture diffusion values of moisture moving away from kiwi puree samples [30].

$$lnMR = ln\frac{8}{\pi^2} - \frac{\pi^2 \bullet D_{eff\bullet t}}{4L^2} \tag{4}$$

Here; D_{eff}: Effective diffusion value (m^2/s), L: Half of the thickness value (m) of the product, t: drying time.

2.5. Energy parameters

Specific moisture extraction rate (SMER): Equation number 5 was used to calculate the specific moisture extraction ratios (*SMER*) of the drying processes. [31].

$$SMER = \frac{Moisture\ removed\ during\ drying\ process\ (kg)}{Energy\ consumed\ by\ the\ dryer\ (kWh)} \tag{5}$$

Specific energy consumption (SEC): Equation number 6 was used to calculate the specific energy consumption (*SEC*) values of the drying processes. [32].

$$SEC = \frac{E_t}{m_w} \tag{6}$$

Here: E_t; total energy consumed (kWh), m_w; amount of moisture removed (kg).

Evaporation energy (Q_w): In the production of powder obtained from dried kiwi purees, the calculations of the latent heat of evaporation related to the drying process were carried out using equation number 7. [33].

$$Q_w = h_{fg} \times m_w \tag{7}$$

$$h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3 \times (T_d - 273.16)$$

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

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

$$338.72 \le T_d(K) < 533.16$$

Here: h_{fg}; latent energy of evaporation (kJ/kg), m_w; amount of evaporated moisture (kg), T_d; drying temperature (°K).

Energy Efficiency (EE): Equation number 8 was used to calculate the energy efficiency (*EE*) in drying kiwi puree [33].

$$n_e = \frac{Q_w}{E_t} \tag{8}$$

Here: Q_W: Evaporation energy, E_t: Total energy consumed.

2.6. Exergy analysis (EXE)

Exergy energy can be calculated to determine the energy losses in drying processes and the success of converting the energy provided to the dryer into work. Eqs. 9–16 were used for exergy energy [34,35]. The exergy analysis was carried out under the assumptions of steady-state operation, negligible heat and pressure losses and ideal gas behavior of moist air. Kinetic and potential energy changes, as well as chemical exergy effects, were considered insignificant.

$$\Sigma \boldsymbol{Ex_{in}} - \Sigma \boldsymbol{Ex_{out}} = \Sigma \boldsymbol{Ex_{des}} \tag{9}$$

$$\Sigma \boldsymbol{Ex_{loss}} = \Sigma \boldsymbol{Ex_{in}} - \Sigma \boldsymbol{Ex_{out}} \tag{10}$$

$$\boldsymbol{Ex_{in}} = \boldsymbol{C_{air}}\left[(T_{out} - T_0) - T_0.ln\left(\frac{\boldsymbol{T_{in}}}{\boldsymbol{T_0}}\right)\right] \tag{11}$$

$$\boldsymbol{Ex_{out}} = \boldsymbol{C_{air}}\left[(T_{out} - T_0) - T_0.ln\left(\frac{\boldsymbol{T_{out}}}{\boldsymbol{T_0}}\right)\right] \tag{12}$$

$$\boldsymbol{Ex_{evop}} = \left[1 - \left(\frac{\boldsymbol{T_0}}{\boldsymbol{T_{in}}}\right)\right].\bar{Q}_{evop} \tag{13}$$

$$\bar{Q}_{evop} = \frac{Q_{evop}}{d_t} \tag{14}$$

$$\eta_{drying} = \frac{Ex_{evop}}{Ex_{in}} \tag{15}$$

$$\eta_{dryer} = \frac{Ex_{out}}{Ex_{in}} \tag{16}$$

Here: Ex_{in}; exergy inlet flow in the dryer (J/s), Ex_{out}; output exergy (J/s), Ex_{des}; exergy loss, Ex_{loss}; exergy lost energy, C_{air}; specific heat of air, T_{out}; dryer internal temperature, T_0; ambient temperature (K°), Ex_{evop}; evaporated exergy (J/s), $\bar{Q}_{evop}$; evaporating energy (J/s), Q_{evop}; constant coefficient (2257 KJ/Kg), t; time (s), η_{drying}; exergy of the drying process, η_{dryer}; exergy of the drying chamber.

2.7. Thermal properties

Thermophysical properties such as density, specific heat, thermal conductivity and thermal diffusivity of kiwi puree were calculated depending on the moisture content on a dry matter basis; the thermal conductivity value was determined by equation number 17 defined in the literatüre [36].

$$k = 0.49 - 0.44\ \exp(-0.206X) \tag{17}$$

Here: k; thermal conductivity (W/mK), X; Dry-based moisture content (kg moisture/kg dry matter).

Equation number 18 was used to calculate the specific heat value of kiwi puree, which is a drying product [37].

$$C_{p=837+3348\left(\frac{X}{1+X}\right)} \tag{18}$$

Here: C_p; specific heat (J/kgK).

To calculate the thermal diffusivity value of kiwi puree, equation number 19 was used [36].

$$\propto = \frac{k}{p.C_p} \tag{19}$$

Here: ∝; thermal diffusivity (m^2/s), p; Density (kg/m^3).

Equation number 20 was used to calculate the density of kiwi purees [38,39].

$$P_p = 147.95\frac{X}{X_0} + 691.46 \tag{20}$$

Here: P_p; density (kg/m^3), X_0; initial dry-based moisture content (kg moisture/kg dry matter).

2.8. Powder characterization

Dried kiwi purees were ground for approximately 2 min using an Arçelik brand 6134 TK model blender with a power of 350 W and turned into powder form. The powder samples obtained were packaged in ziplock bags to prevent moisture and stored in a dry and controlled environment.

Grinding process efficiency (GPE): The grinding process efficiency of kiwi fruit powder was calculated using equation number 21.

$$GPE = \frac{Kiwi\ fruit\ powder\ weight\ (g)}{total\ dry\ matter\ weight\ (g)} \times 100 \tag{21}$$

Here: GPE; Grinding process efficiency (%).

Tapped-bulk density: Tapped-bulk density is a volume weight parameter that has critical importance in the storage and packaging processes of functional food powders. In this study, the tapped density and bulk density values of the kiwi powders produced were determined by making a small adaptation to the method described by Sejali and Anuar [35]. Tapped density (*Pt*) value was calculated by measuring the total mass of kiwi powder filled into a 100 mL glass measuring tape three times. In the measurement of bulk density (*Pb*), 10 g of kiwi powder sample was transferred to a 100 mL glass measuring tape in three replicates and the density value was obtained by determining the average volume occupied by the powder [40].

Flow properties: Flow properties of fruit powders play an important role in the pulverization, transportation and storage processes. Two basic indicators are generally used to evaluate the flow behavior of powdered products: Carr index (*CI*) and Hausner ratio (*HR*). Carr index reflects the free flow ability of the powder, i.e. pourability; Hausner ratio expresses the degree of cohesion between particles, i.e. stickiness tendency. In this study, eqs. 22 and 23 were used to calculate the Carr and Hausner indexes of the kiwi powders obtained, respectively [41].

$$CI = \frac{Pt - Pb}{Pt} \times 100 \tag{22}$$

1) % 5 < CI < % 15.
The pourability of kiwi powder is very good.
2) % 15 < CI < % 25.
The pourability of kiwi powder is normal.
3) % 25 ≤ CI.
The pourability of kiwi powder is very poor.

$$HR = \frac{Pt}{Pb} \tag{23}$$

1) HR > 1.40.
Kiwi powder has high stickiness (level C).
2) 1.40 > HR > 1.25.
The stickiness of kiwi powder is medium (C-A level).
3) 1.25 > HR > 1.
Kiwi powder has low stickiness (level A).

Here: CI; carr index (%), HR; hausner index, Pt; tapped density (g/ml), Pb; bulk density (g/ml).

2.9. Color properties

A CR400 model/Japan color measuring device was used to measure the brightness *L*, red/green *a*, and yellow/blue *b* values of fresh and dried kiwi puree. The measured values are laboratory measurement values. Chroma and total color change values were calculated using these values. While the chroma (*C*) value indicates the color tone of the product, low values are calculated for pale products, while high values are calculated for brightly colored products. The total color change value (*ΔE*) shows the total change of color pigments that are degraded by heat (non-enzymatic) during drying processes. Eqs. 24 and 25 were used to calculate these values [42,43].

$$C = \left(a^2 + b^2\right)^{1/2} \tag{24}$$

$$\Delta E = \sqrt{\left(L - L^*\right)^2 + \left(a - a^*\right)^2 + \left(b - b^*\right)^2} \tag{25}$$

Here: L^*, a^* ve b^* values show the brightness, redness/green, yellowness/blue color values of kiwi powder.

2.10. Bioactive properties

Total Phenolic Content (TPC): TFC was determined according to the method of Singleton and Rossi [44]. Kiwi samples (1 g) were extracted with a buffer (acetone, water, acetic acid; 70:29.5:0.5 *v*/v) for three days. The obtained extract was mixed with Folin-Ciocalteu reagent, water and 7 % sodium carbonate and incubated at room temperature for 2 h. Absorbance was measured at 750 nm using a UV–vis spectrophotometer (T60U, PG Instruments). Gallic acid was used as standard and the results were expressed as μg GAE g^{-1} per dry weight (ka) and fresh weight (ta).

Total Flavonoid Content (TFC): TF content was analyzed according to the method of Zhishen et al. [45]. To 1 mL of extract, 5 mL of distilled water and 0.3 mL of 5 % $NaNO_2$ were added. After five minutes, 0.3 mL of 10 % $AlCl_3$ was added and after five minutes, 2 mL of 1 M NaOH was added. The mixture was diluted to 10 mL with distilled water and the absorbance was measured immediately at 510 nm. The results were expressed as mg catechin equivalent (KE) L^{-1} per dry weight (ka) and fresh weight (ta).

Total Antioxidant Activity (TAA): Total antioxidant activity was determined by Ferric Ion Reduction Capacity (FRAP) analysis. FRAP was carried out according to the method developed by Benzie and Strain [46]. Firstly, acetate buffer solution (30 mM) was prepared by dissolving 2.4 g of sodium acetate with 14.5 mL of glacial acetic acid, completing the volume to 1 L with distilled water and adjusting the pH to 3.6. Iron (III) chloride solution (20 mM) was obtained by dissolving 324 mg $FeCl_3$ in 80 mL of distilled water and completing the volume to 100 mL. TPTZ solution (10 mM) was prepared by dissolving 312 mg of 2,4,6-Tris(2-pyridyl)-*s*-triazine (TPTZ) in 80 mL of distilled water, adding 0.330 mL of HCl and making the volume up to 100 mL. The prepared stock solutions were stored in dark bottles and used within 7–10 days. The FRAP working solution was obtained by mixing acetate buffer, $FeCl_3$ and TPTZ solutions at a ratio of 10:1:1. The prepared mixture was light brown and could be used for 1–2 h. A standard curve was created using 1 mM Trolox or ascorbic acid to determine the antioxidant capacity of the samples and the analyses were carried out spectrophotometrically at 593 nm. The results were reported as μmol Trolox Equivalent (TE) g^{-1} per dry weight (ka) and fresh weight (ta).

2.11. Program used and statistical analysis

Statistical analysis of the parameters of the samples was performed using SPSS22 software and Duncan multiple comparison test with a significance level of $p < 0.05$. SigmaPlot10.0 program was used to create kinetic and 3D graphs of the drying processes.

3. Results and discussion

3.1. Drying and moisture rates

Curves reflecting the drying kinetics of the samples subjected to the drying process for the purpose of kiwi powder production are presented in Fig. 1. Drying rate has a direct impact on drying time and energy consumption and is a key parameter that determines the efficiency of the process and equipment design [47]. Additionally, proper drying speed plays a critical role in maintaining the product's color, structure and bioactive compound stability [48].

Drying temperatures and carrier agents affected the drying rates and

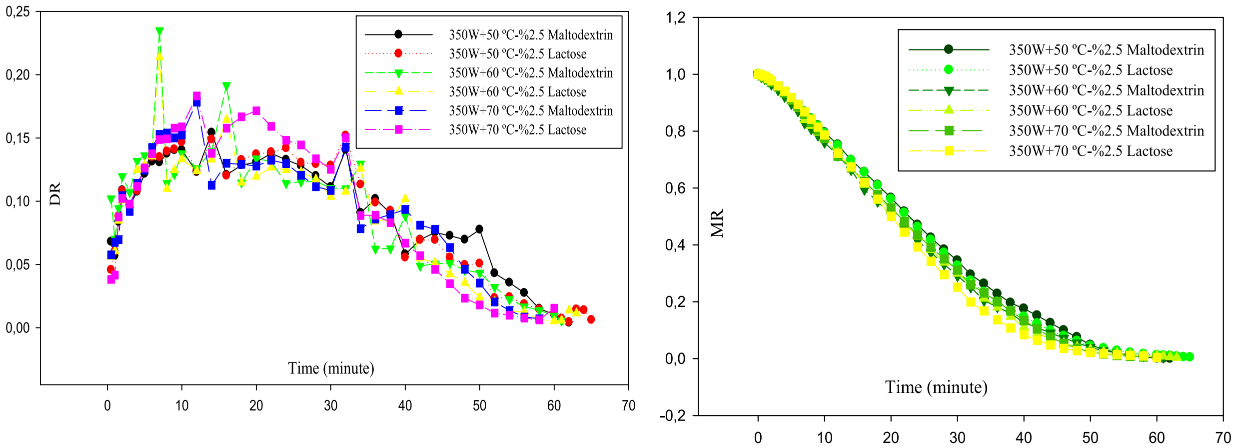

Fig. 1. Drying rate and moisture content of kiwi purees subjected to drying process.

final moisture contents of kiwi puree samples. A similar result was obtained by Dursun et al. [49] in their blackberry powder production study. The average drying rates of the samples dried by adding 2.5 % maltodextrin to kiwi puree in the hybrid microwave dryer at 350 W + 50 °C, 350 W + 60 °C, 350 W + 70 °C were determined as 0.0920, 0.0899, 0.0945 g moisture/g dry matter.min, respectively. The average drying rates of kiwi puree dried by adding 2.5 % lactose in the same methods were determined as 0.0874, 0.0840, 0.0948 g moisture/g dry matter.min, respectively. The drying rate was higher in samples dried at 50 °C than in samples dried at 60 °C. This can be explained by the non-homogeneous distribution among the samples used for moisture determination. Taşova et al. [50] obtained powder by drying Viking variety aronia fruit purees in hybrid microwave and microwave dryers. As a result of the study, they calculated that the drying rates varied between 0.0595 and 0.292 g moisture/g dry matter.min. The findings obtained within the scope of this study were found to be compatible with the literature. Dursun et al. [49] produced fruit powder by adding different carrier agents (corn starch, powdered sugar and maltodextrin) and ratios (5 % and 10 %) to blackberry purees and drying them with convective and hybrid microwave dryers. As a result of the study, they determined that the drying rate was between 0.0057 and 0.0477 g moisture/g dry matter.min. Better results were obtained in this study compared to the studies in the literature. This situation can be explained by considering that the initial moisture of the fruits used in the studies was different and the carrier agents were used in different ratios.

3.2. Effective moisture diffusion

The effective diffusion coefficient is a key parameter that determines the rate of moisture transport from the food matrix during the drying process and is of critical importance in understanding the drying mechanism and modeling studies [51]. Effective moisture diffusion values of the drying processes for kiwi powder production are given in Table 1.

When Table 1 is examined, drying temperatures and carrier agents affected the effective moisture diffusion values of the drying processes of kiwi purees. The moisture diffusion values of the kiwi purees dried by adding lactose were calculated higher than the samples dried by adding maltodextrin, except for the 350 W + 50 °C method. The reason for this is that the maltodextrin added to the samples to be dried in the 350 W + 50 °C method is less homogenized with the kiwi puree, and this is thought to be due to the fact that the diffusion event occurs more aerosol in this method. Çalışkan et al. [23] obtained powder by drying kiwi purees by freezing and hot air method. As a result of the study, they determined the effective mass diffusion coefficient of the drying processes as 7.3 × 10^{-10}. It was observed that better results were obtained in this study compared to the study in the literature. The reason for this is thought to be due to the working principle of the hybrid microwave dryer used in this study.

Table 1
Effective moisture diffusion values of drying processes.

Method	Carrier agents	Effective moisture diffusion (m^2/s)	R^2
Hybrid microwave 350 W + 50 °C	Maltodextrin	3.71×10^{-7}	0.753
	Lactose	3.06×10^{-7}	0.931
Hybrid microwave 350 W + 60 °C	Maltodextrin	3.07×10^{-7}	0.911
	Lactose	3.22×10^{-7}	0.935
Hybrid microwave 350 W + 70 °C	Maltodextrin	3.10×10^{-7}	0.892
	Lactose	3.32×10^{-7}	0.939

3.3. SMER, SEC, evaporation energy and energy efficiency values

Energy performance parameters SMER, SEC, evaporation energy, and overall energy efficiency are critical for the engineering design and energy optimization of drying systems. Low SEC and high SMER values increase the economic efficiency of the process by reducing energy consumption and also contribute to the preservation of bioactive compounds by shortening the time food is exposed to thermal spoilage [52]. Q_w, EE and total energy consumption values are given in Table 2.

According to Table 2, the highest evaporation energy and energy efficiency values were determined in kiwi puree samples dried in the hybrid microwave 350 W + 50 °C method. It is estimated that the reason for this is that the total energy consumption value is less energy consumed compared to other methods. Dursun et al. [53] produced Jerusalem artichoke chips in convective and microwave dryers by

Table 2
Q_w, EE and total energy consumption values.

Method	Carrier agents	Evaporation energy (kWh)	Energy efficiency (%)	Total energy consumption (kWh)
Hybrid microwave 350 W + 50 °C	Maltodextrin	3.95	5.2	0.763
	Lactose	3.93	4.9	0.796
Hybrid microwave 350 W + 60 °C	Maltodextrin	3.76	4.8	0.783
	Lactose	3.62	4.5	0.806
Hybrid microwave 350 W + 70 °C	Maltodextrin	3.72	4.2	0.892
	Lactose	3.86	4.2	0.915

applying ethyl oleate pretreatment. As a result of the study, they determined the evaporation energy as 2.38–2.79 kWh. It was observed that better results were obtained in this study compared to the literature. It is estimated that the reason for this is that more moisture evaporated due to the pureeing of kiwis for kiwi powder production in this study. Taghinezhad et al. [54] sliced kiwi slices in different thicknesses (4, 6, 8 mm) and dried them in a hybrid (hot air + infrared) dryer by applying ultrasound pretreatment. As a result of the study, they found that the energy efficiency values varied between 1.54 and 11.09 %. The 3D representation of the time-dependent SMER and SEC values of the kiwi puree drying processes is given in Fig. 2.

When Fig. 2 is examined, it is seen that the drying methods and the carrier agents used affect the acid SMER and SEC values in the drying processes. The average SMER values of the drying processes were

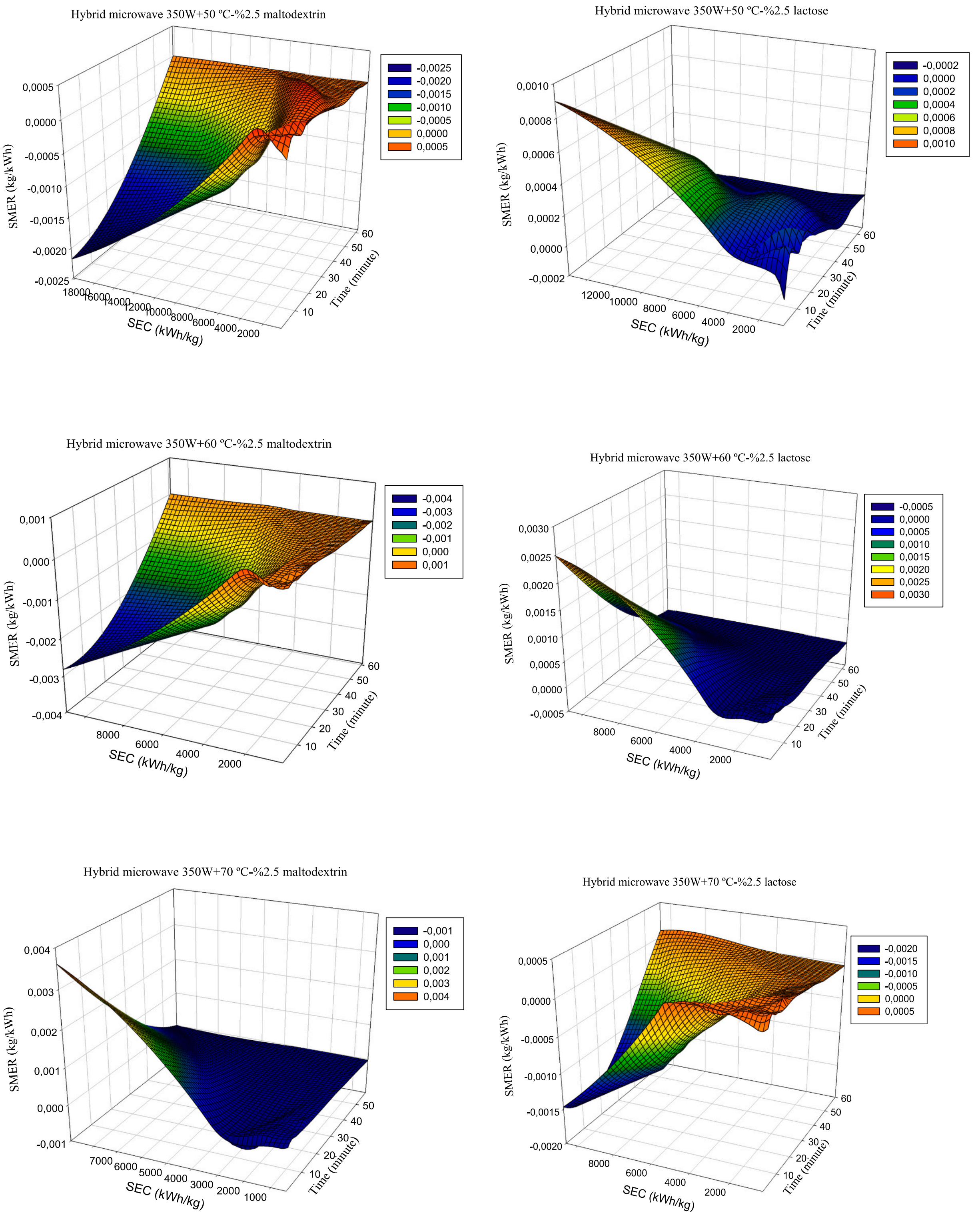

Fig. 2. SMER and SEC values of drying processes depending on time.

determined as 0.00131, 0.00127, 0.00111 kg/kWh in the samples dried by adding maltodextrin in the hybrid microwave dryer at 350 W + 50 °C, 350 W + 60 °C, 350 W + 70 °C methods, respectively. The SMER values of the samples dried by adding lactose in the same methods were calculated as 0.00125, 0.00124, 0.00109 kg/kWh, respectively. In the drying processes carried out in the hybrid microwave dryer, the average SEC values obtained in samples dried with 350 W microwave power at 50 °C, 60 °C, 70 °C, respectively, and with maltodextrin addition were determined as 763.50, 786.90, 897.13 kWh/kg. The average SEC values obtained in samples dried with 350 W microwave power at 50, 60 and 70 °C temperatures and with lactose carrier agent were calculated as 799.73, 808.98, 918.09 kWh/kg, respectively. Lower SMER and SEC values were determined at low temperatures. This can be explained by the lower energy consumption values at low temperatures. Darvishi et al. [7] dried kiwi slices at different power values (200, 300, 400, 500 W). As a result of the study, they found that SEC values vary between 2.16 and 4.50 kWh/kg. Mohammadi et al. [55] dried kiwi slices in a heat pump-supported convective dryer. They worked at different circulation rates (0, 50, 100 %) and constant temperatures (45, 55, 65 °C) while using the dryer with the heat pump on and off. As a result of the study, they found the SMER values to be 0.049–0.15 kg/kWh on average. It was seen that the study findings in the literature obtained better results than the findings of this article. It is thought that the reason for this is that the carrier agents used in this study rapidly absorb the moisture in the kiwi puree, making moisture transfer difficult, thus negatively affecting the SMER and SEC values.

3.4. *Exergy analysis*

Exergy analysis is a critical tool in engineering for minimizing energy losses and increasing system efficiency in drying processes, and from a biological perspective, it plays an important role in process optimization for preserving product quality and bioactive compounds [56,57]. Drying processes and exergy analyses of the dryer are given in Table 3.

According to Table 3, it was observed that there was an increase in Exin values with increasing temperatures. However, the Exout values at the intermediate temperature value of 60 °C were lower than the other methods. The reason for this is that the ambient temperature was measured higher during the drying experiments compared to the other methods. The highest Exevap value was determined as maltodextrin in the hybrid microwave 350 W + 70 °C method. This can be explained by the shorter drying time. Taşova et al. [58] turned waste tomatoes into puree and added maltodextrin at different rates (%5 and 10) and dried them in convective, temperature-controlled microwave, hybrid microwave and vacuum dryers, and turned them into powder. As a result of the study, they determined the Exin and Exout values of the hybrid microwave drying processes as 4.21 and 3.13 J/s, respectively, while the Exevap value was determined as 13.97 kJ/kg. The differences between the two studies are thought to be due to the differences in the initial moisture and maltodextrin concentrations of the materials used for powder production affecting the drying time, and the different drying temperatures and ambient temperatures. The highest drying process exergy was found in the samples dried by adding maltodextrin in the hybrid microwave 350 W + 50 °C method. The reason for this is that the Exin values were calculated lower than the other methods. The highest dryer exergy was determined in the 350 W + 50 °C method. This is related to the reason that the drying process exergy was high in the same method. Heydari [59], dried different fruits (apple, banana, kiwi and quince) in a hybrid dryer with a solar air heater and auxiliary heating system. As a result of the study, they calculated the exergy efficiency of the kiwi fruit drying process as 0.76. It is estimated that the reason why the findings of the study in the literature are better than the findings in this study is due to the differences in dryers, parameters such as energy and time required for the materials to reach the desired final moisture values, and the physical differences of the kiwis used for drying (in this study, the kiwis were in puree form, while in the literature they were in slices). Saygı et al. [60] obtained fruit powder in a spray dryer by adding maltodextrin to cranberry purees at different rates (40, 50, 60 % of the weight of the purees). As a result of the study, they determined the ergies of the spray dryer in the range of 27–39.1. They also stated that maltodextrin rates did not have a significant effect on performance. The reason why the findings in the literature are better than the findings in this study is thought to be due to the differences in dryers and the use of carrier agents at different rates.

Table 3
Energy analysis values.

Method	Carrier agents	Ex_{in} (J/s)	Ex_{out} (J/s)	Ex_{evap} (kJ/kg)	$Ŋ_{drying}$	$Ŋ_{dryer}$
Hybrid microwave 350 W + 50 °C	Maltodextrin Lactose	1.45	0.28	0.056 0.054	0.039 0.037	0.19
Hybrid microwave 350 W + 60 °C	Maltodextrin Lactose	1.82	0.13	0.063 0.061	0.035 0.034	0.07
Hybrid microwave 350 W + 70 °C	Maltodextrin Lactose	3.85	0.59	0.095 0.091	0.025 0.024	0.15

3.5. *Thermal properties*

Thermal properties determined during drying processes (especially thermal conductivity, diffusivity, specific heat, and density) play a critical role in optimizing heat transfer and the engineering design of dryers; accurate determination of these parameters directly contributes to improving processing time, energy consumption, and system efficiency. Furthermore, controlling temperature distribution underscores the importance of thermal modeling in maintaining biological quality, preserving product microstructure, and ensuring bioactive compound stability [61]. The calculated average thermal properties of the drying processes are given in Table 4.

Drying temperatures and the carrier agents used were found to have a significant impact on the thermal properties of kiwifruit puree. Taşova [26], obtained similar results in his study on orange powder produced by drying with the microwave-assisted foam mat method. Although the thermal property parameters of the products obtained after drying exhibited similar values, it was determined that different drying characteristics led to various changes in the kiwifruit puree during the process. Aksüt et al. [62] In the drying study using hybrid dryer, they determined the thermal conductivity values in the range of 0.05–0.31 W/mK, specific heat values in the range of 837.00–851.03 J/kgK, thermal diffusivity values in the range of 8.79×10^{-8}-4.34×10^{-7} m^2/s, and density values in the range of 691.93–839.74 kg/m^3. Taşova et al. [63] in their study on microwave dryer, found that thermal conductivity, specific heat, thermal diffusivity and density values varied between 0.08 and 0.41 W/mK, 838.21–871.62 J/kgK, 2.344×10^{-7}-5.649×10^{-7} m^2/s and 697.93–839.41 kg/m^3, respectively. It was observed that the findings of this study and the findings of the studies in the literature were compatible.

3.6. *GPE, physical and flow property values*

Grinding success and powder bulk and tapped density are critical engineering parameters for powder flowability, packability, and processability, while Carr and Hausner ratios quantify the powder's flow properties, directly impacting production efficiency and product homogeneity [64]. Optimizing these parameters supports biological quality, particularly in terms of preserving nutritional value and ensuring microbial stability, while also ensuring precision in process control [65]. Some flow properties and grinding process efficiency of the produced kiwi powders are given in Table 5.

Table 4
Thermal properties.

Method	Carrier agents	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Thermal diffusivity (m^2/s)	Density (kg/m^3)
Hybrid microwave 350 W + 50 °C	Maltodextrin	0.22	846.10	3.23×10^{-7}	762.16
	Lactose	0.20	845.37	3.04×10^{-7}	756.55
Hybrid microwave 350 W + 60 °C	Maltodextrin	0.21	845.47	3.11×10^{-7}	759.72
	Lactose	0.20	844.84	2.95×10^{-7}	756.95
Hybrid microwave 350 W + 70 °C	Maltodextrin	0.22	846.09	3.25×10^{-7}	764.69
	Lactose	0.21	845.88	3.14×10^{-7}	760.47

Table 5
Flow properties and grinding process efficiency values of kiwi powders.

Method	Carrier agents	Tapped density (g/ml)	Bulk density (g/ml)	Carr indeks (%)	Hausner indeks	*GPE* (%)
Hybrid microwave 350 W + 50 °C	Maltodextrin	2.52^a	1.72^a	41.06^a	1.18^a	94.48
	Lactose	2.42^a	1.60^a	41.90^a	1.27^a	96.66
Hybrid microwave 350 W + 60 °C	Maltodextrin	1.79^a	1.38^a	27.74^a	1.11^a	92.54
	Lactose	2.08^a	1.45^a	42.15^a	1.07^a	95.88
Hybrid microwave 350 W + 70 °C	Maltodextrin	2.44^a	1.64^a	42.72^a	1.19^a	97.95
	Lactose	2.07^a	1.55^a	27.32^a	1.23^a	97.43

The findings in Table 5 show that the physical properties and flow behavior of kiwi powder do not have a statistically significant ($p < 0.05$) effect depending on the drying method, temperatures and type of carrier material. The highest tapped and bulk density values were determined in kiwi powders produced by adding maltodextrin in the hybrid microwave 350 W + 50 °C method. It is estimated that this is due to the better preservation of organic matter properties in kiwi purees during drying processes. Dirim et al. [22] determined the bulk and tapped density values of their kiwi powders as 0.32 and 0.42 g/ml, respectively. The lowest CR value was determined in kiwi powders produced by adding lactose in the hybrid microwave 350 W + 70 °C method. It is thought that this is due to the less agglomeration event in this method. The lowest Hausner index was determined in kiwi powders produced by adding lactose in the hybrid microwave 350 W + 60 °C method. Çalışkan et al. [23] determined the Carr and Hausner index values of kiwi powders as 38 (pourability of the powder is very poor) and 1.60 (stickiness of the powder is high), respectively. While Pt, Pb, HR values were obtained better results compared to the studies in the literature, CI values were found to be compatible with the literature. The highest grinding process efficiency was calculated as 97.95 % in kiwi powders produced by adding maltodextrin in the hybrid microwave 350 W + 70 °C method. Pui et al. [41] determined the grinding process efficiency of the fruit powders they produced by spray drying by adding maltodextrin to Cempedak fruit as values ranging from 42.8 to 62.4 %. Better results were obtained in this study according to the literature.

3.7. Color values

Color properties of dried powder products are a critical parameter both as a biological quality indicator affecting consumer acceptance and from an engineering perspective for the control and optimisation of the drying process [66]. Color values of fresh and produced kiwi powders are given in Table 6.

According to the data in Table 6, the applied drying methods could not preserve the *L* and *a* color parameters of fresh kiwi puree at a statistically significant level ($p < 0.05$). Domin et al. [67] reported that there was an increase in the a values of the kiwis they dried. It was observed that the samples dried by adding maltodextin had a statistically significant ($p < 0.05$) effect on *L*, *a* and *ΔE* values at different temperatures, but had no effect on *b* and *C* values. Drying methods and carrier agents caused an increase in the *L* and *a* color parameters of fresh kiwi puree. This can be explained as the carrier agents added to the purees affecting the color values. In terms of yellow/blue and chroma color values, kiwi powders produced by adding lactose in the hybrid microwave 350 W + 70 °C method were statistically ($p < 0.05$) protected compared to fresh and the lowest ΔE value was determined. Yi et al. [68] stated that lower total color change (*ΔE*) values indicate the closeness of the product to its fresh form and can be associated with minimal color deterioration. Çalışkan et al. [23] determined the *L, a, b* values of fresh kiwi puree as 47.3, −0.67, 17.5, respectively, while the color values of kiwi powders produced by adding maltodextrin in the freeze-drying method were determined as 78.12, −6.53, 22.08, respectively. The differences in the color values of the fresh kiwi puree samples used in the studies can be associated with the storage period after harvest, while the differences in the color values of kiwi powders after drying are thought to be due to the dryers. It is estimated that the drying method used in this study breaks down more color pigments than the freeze-drying method in the literature.

3.8. Bioactive properties of fresh and kiwi powders

While the bioactive compound content of dried fruits turned into powder is of biological importance in terms of preserving their functional properties that contribute to human health, optimizing the

Table 6
Color values.

Method	Carrier agents	*L*	*a*	*b*	*C*	*ΔE*
Fresh kiwi puree	–	39.14 ± 0.98^f	-6.03 ± 1.05^e	14.73 ± 0.82^d	15.95 ± 0.70^d	–
Hybrid microwave 350 W + 50 °C	Maltodextrin	51.05 ± 0.77^b	3.82 ± 0.25^d	18.50 ± 0.23^{ab}	18.89 ± 0.20^{ab}	36.45 ± 0.65^b
	Lactose	51.48 ± 1.54^b	4.63 ± 0.25^c	17.86 ± 0.77^{bc}	18.45 ± 0.71^{bc}	36.96 ± 1.09^b
Hybrid microwave 350 W + 60 °C	Maltodextrin	49.76 ± 1.71^c	4.87 ± 0.38^{bc}	18.49 ± 1.14^{ab}	19.12 ± 1.13^a	35.15 ± 1.13^c
	Lactose	48.13 ± 0.78^d	5.12 ± 0.21^b	17.34 ± 0.59^c	18.08 ± 0.58^c	34.11 ± 0.48^d
Hybrid microwave 350 W + 70 °C	Maltodextrin	52.73 ± 0.67^a	5.01 ± 0.17^{bc}	18.53 ± 0.36^a	19.20 ± 0.33^a	37.72 ± 0.49^a
	Lactose	45.10 ± 0.85^e	6.83 ± 0.19^a	$\mathbf{14.30 \pm 0.51^d}$	$\mathbf{15.85 \pm 0.49^d}$	$\mathbf{32.43 \pm 0.59^e}$

The dark data specified in the table shows the most appropriate value in terms of color value.

process to preserve the thermal stability of these compounds is also a critical engineering requirement [69]. Bioactive properties of fresh kiwi puree and kiwi powders are given in Table 7.

The data obtained in the study revealed that the applied drying method, temperature level, and carrier agent type had significant effects on the bioactive properties of kiwi powders (Table 7). When evaluated in terms of total phenolic content (TPC), drying processes generally increased the phenolic content compared to the fresh sample ($p < 0.05$). It was observed that especially the samples prepared with lactose carrier agent had significantly higher TPC values compared to the samples containing maltodextrin in all temperature groups. The highest total phenolic content was measured in the sample prepared with lactose addition under hybrid microwave 350 W + 70 °C conditions and this value was determined as 5171.1 ± 134.3 μg GAE/g. This finding suggests that lactose may have an effect on increasing the extraction or stability of phenolic compounds. A temperature-dependent enhancement in TPC was particularly evident in the lactose group, suggesting a potential interaction between lactose and heat in phenolic compound retention. Similarly, it is seen that lactose-added samples stand out in terms of total flavonoid content (TFC). At all temperature levels, samples with lactose carrier showed higher flavonoid content than samples with maltodextrin carrier. The highest TFC value was again determined in the sample dried with lactose under hybrid microwave 350 W + 70 °C condition (702.96 ± 41.24 mg KE/L) and this value was found to be well above the fresh sample. The possible interaction of lactose with flavonoid compounds may positively affect the preservation and analyzability of these compounds. The interaction between temperature and carrier type became apparent in TFC results, where lactose consistently led to higher flavonoid content, particularly at elevated temperatures. However, when the total antioxidant activity (TAA) values are examined, a different trend from the TPC and TFC results is observed. Samples using maltodextrin carrier showed higher antioxidant activity compared to lactose added groups at all temperatures. These results suggest that maltodextrin may be more effective in preserving especially antioxidant components. However, it was observed that the TAA value in the sample prepared with lactose carrier at 70 °C decreased significantly compared to fresh fruit (56.83 ± 1.43 μmol TE/g). This decrease shows that high temperature causes degradation of antioxidant components and lactose cannot provide sufficient protection under these conditions. In addition, lactose may have contributed to this situation by entering into Maillard reactions at high temperatures and forming products that can reduce free radical scavenging capacity. This inverse trend in TAA compared to TPC and TFC suggests that antioxidant activity responds differently to temperature–carrier interactions, and that the protective efficacy of carrier agents is compound-specific and condition-dependent.

In conclusion, the findings obtained in the study reveal that high phenolic and flavonoid contents cannot always be directly associated with high antioxidant activity; the type of carrier agent and the temperature factor can have different effects on both the amount and functional activities of bioactive compounds. Therefore, both the amount of bioactive components and biological activity should be evaluated together in functional product development processes.

Table 7
Bioactive values.

Method	Carrier agents	*TPC (μg GAE/g)*	*TFC (mg KE/L)*	*TAA (μmol TE/g)*
Fresh kiwi puree	–	1298.3 ± 112.6^{e}	332.78 ± 29,00^{d}	64.16 ± 0.19^{c}
Hybrid microwave 350 W + 50 °C	Maltodextrin	2897.8 ± 52.39^{d}	465.92 ± 3,70^{c}	**75.93 ± 0.56^{a}**
	Lactose	4517.8 ± 154.3^{b}	617.78 ± 22,22^{b}	67.77 ± 1.15^{b}
Hybrid microwave 350 W + 60 °C	Maltodextrin	3081.1 ± 127.0^{d}	502.96 ± 20,62^{c}	**75.64 ± 0.29^{a}**
	Lactose	4034.5 ± 63.33^{c}	606.67 ± 11,11^{b}	69.63 ± 0.55^{b}
Hybrid microwave 350 W + 70 °C	Maltodextrin	3164.5 ± 97.01^{d}	454.81 ± 3,70^{c}	**74.66 ± 0.48^{a}**
	Lactose	**5171.1 ± 134.3^{a}**	**702.96 ± 41,24^{a}**	56.83 ± 1.43^{d}

4. Conclusion

In this study, the effects of different temperatures and carrier agents on kiwi powder production using hybrid drying method were investigated. Drying methods and carrier agents affected the kinetics of drying processes, energy parameters, some physical and flow, bioactive and quality properties of the produced powders. When the drying kinetics, energy parameters, and flow properties of kiwifruit powders were evaluated, drying with maltodextrin added at 350 W microwave power and 50 °C was determined to be the most suitable condition in terms of process efficiency. However, drying with lactose at 350 W and 70 °C was found to be more advantageous in terms of color and bioactive compound preservation. These findings reveal that carrier type and drying conditions are determinants of both product quality and process efficiency. The results obtained show the effectiveness of the hybrid drying method in the production of functional fruit powders and are promising to prove that similar studies can be conducted with different fruits. For further studies, it is recommended to investigate the effects of different drying methods and carrier agent mixtures or encapsulation on rehydration, sensory properties and energy parameters.

CRediT authorship contribution statement

Samet Kaya Dursun: Writing – original draft, Software, Resources, Project administration, Methodology, Investigation. **Muhammed Taşova:** Writing – review & editing, Validation, Supervision, Methodology. **Osman Nuri Öcalan:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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