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Comparison of kinetics, energy consumption, and *GHG* analysis of Santa Maria variety pear chips processed by microwave and hot air-assisted microwave drying systems

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Abstract: This study, evaluated the effects of microwave-*MD* and hybrid-*MACD* (hot air + microwave) drying systems on drying rate (*DR)*, moisture content (*MR)*, effective moisture diffusion (D_{eff}), specific moisture absorption rate (*SMER)*, specific energy consumption (*SEC)*, and greenhouse gas emission (*GHG)* properties in the production process of '*Santa Maria'* variety pear fruit chips. Microwave method (except 360 W) dried the products in a shorter time than the hybrid method. The *DR* values of the *MD* method were higher than *MACD*. The D_{eff} values of the drying processes varied between 2.54 × 10^{-9} and 1.01 × 10^{-8}. The average *SMER* values for the *MD* method varied between 0.006917 - 0.002803 kg/kWh and the *SEC* values varied between 356.8205 - 144.5714 kWh/kg. For *MACD* method, the average *SMER* values varied between 0.0037 - 0.0016 kg/kWh and *SEC* values between 6261.5 - 2693.6 kWh/kg. The increase in energy consumption increased the *GHG* values. The lowest *GHG* values were determined in the drying process performed at *MD* - 720 W power value.

Keywords: Pear fruit, drying processes, effective moisture diffusion, energy analyses, greenhouse gas

Mikrodalga ve sıcak hava destekli mikrodalga kurutma sistemleriyle işlenen Santa Maria çeşidi armut cipslerin kinetik, enerji tüketimi ve sera gazı analizinin karşılaştırılması

Öz: Bu çalışmada, mikrodalga (*MD)* ve hibrit (*MACD)* (sıcak hava + mikrodalga) kurutma sistemlerinin, '*Santa Maria'* çeşidi armut meyve yongalarının üretim sürecinde kurutma hızı (*DR)*, nem içeriği (*MR)*, etkili nem difüzyonu (D_{eff}), özgül nem çekme oranı (*SMER)*, özgül enerji tüketimi (*SEC)* ve sera gazı emisyonu (*GHG)* özellikleri üzerine etkileri incelenmiştir. Kurutma prosesleri arasında mikrodalga yöntemi (360 W hariç) hibrit yönteme göre ürünleri daha kısa sürede kurutmuştur. *MD* yönteminin *DR* değerlerinin *MACD* yönteminden daha yüksek olduğu bulunmuştur. Kurutma proseslerinin D_{eff} değerleri 2.54 × 10^{-9} ile 1.01 × 10^{-8} arasında değişmiştir. *MD* yöntemi için ortalama *SMER* değerleri 0,006917 - 0,002803 kg/kWh arasında, *SEC* değerleri ise 356,8205 - 144,5714 kWh/kg arasında değişmiştir. *MACD* yöntemi için ortalama *SMER* değerlerinin 0,0037 - 0,0016 kg/kWh arasında, *SEC* değerlerinin ise 6261.5 – 2693.6 kWh/kg arasında değiştiği belirlenmiştir. Enerji tüketimindeki artış *GHG* değerlerini artırmıştır. En düşük *GHG* değerleri *MD* - 720 W güç değerinde gerçekleştirilen kurutma prosesinde belirlenmiştir.

Anahtar kelimeler: Armut meyvesi, kurutma işlemleri, efektif nem difüzyonu, enerji analizleri, sera gazı

1. Introduction

Drying is the process of removing moisture from solid or semi-solid material by evaporation technique (Aghbashlo et al., 2008). The process of removing water from products/dehydrating them to preserve for human food is one of the oldest known methods (Antonio et al., 2008). Minimium nutritional losses, quick drying, and low energy consumption are the desired standards for achieving this goal (Afzal et al., 1999). For this reason, drying methods and techniques have been developed.

The most commonly used drying methods are conventional (tray, tunnel, and drum etc.), microwave and microwave-assisted (oven, vacuum etc.) hybrid techniques (Kutlu et al., 2015). The most widely used drying technique in the fruit and vegetable drying

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industry is hot air-drying systems. These systems, transmit hot air to the drying medium, and constitute > 85% of the drying devices used in the drying field (Moses & Authority, 2014). Hot air-drying systems have the advantage of not being affected by climatic conditions. However, the long drying process causes nutritional losses (Guan et al., 2024). Understanding of good drying has improved with the development of innovative drying systems. This has revealed the importance of sustainable food systems (Calín-Sánchez et al., 2020). However, the drying time has decreased by an average of 26%, the process efficiency has increased, and the energy consumption has decreased by approximately 80% (Chojnacka et al., 2021). Microwave drying ovens are one of the innovative drying systems used in the drying processes developed by utilizing microwave energy (Fan et al., 2024). Microwave energy penetrates the moisture in the fresh product and heat is produce by the principle of ionic contact and polar rotation (Li et al., 2023). Junqueira et al. (2017) dried the pumpkin to compare the convective and microwave drying systems. The microwave method dried the product earlier than the convective drying system. Although microwave drying systems have advantages over many other methods, there are still some quality losses in the product due to high heat towards the final stage of drying (Shen et al., 2020). Microwave-assisted drying methods have been developed to eliminate the problems that occur in microwave drying methods. The quality of food materials is better when compared to the drying systems used together (hybrid). For this reason, researchers have focused on investigating the properties, effects and advantages of microwave-assisted hybrid drying methods (Zielinska et al., 2020). There are some studies in the literature on the production of dried pear fruit by applying microwave and different drying techniques. For example, Önal et al. (2021) dried Rocha variety pear fruit using ultrasound and microwave pretreatment hot air-drying technique. Drying kinetics, color and phytochemical properties were examined in the study. The quality characteristics of microwave pretreatment samples caused higher losses compared to the quality characteristics of control and ultrasound samples. Marzec et al. (2020) investigated the effect of hot air and microwave-assisted hot air-drying techniques on the quality of ‘Conference’ and ‘Alexander Lucas’ variety dried pear fruits. It was determined that drying methods affected the varieties, but there was no significant difference between the varieties in terms of general quality characteristics. There are many studies on drying different varieties of pear fruits using microwave technique; Fumagalli and Silveira (2007; ‘Packham's Triumph’ pear), Li et al. (2021; ‘Balsam’ pear), Zhang et al. (2023; ‘Dangshan’ pear), Tepe & Tepe (2024; ‘Deveci’ pear), Coşkun-Topuz et al. (2022; ‘Mellaki’ pear), Kian-Pour (2023; ‘Santa Maria’ pear), Onwuzuruike et al. (2022; ‘African’ pear) etc. However, it has been seen that the number of studies on drying ‘Santa Maria’ pear fruits is still insufficient.

In this study, the drying rate - *DR*, moisture rate - *MR*, effective moisture diffusion D_{eff}, color, specific moisture absorption rate - *SMER*, specific energy consumption - *SEC*, and greenhouse gas emission - *GHG* values of *Santa Maria* variety pear fruit dried with microwave and hot air assisted microwave methods were compared.

2. Materials and Methods

2.1. Raw fruit

Fresh ‘Santa Maria’ fruits were purchased from a local market in Tokat province. The fruits were first washed with chlorinated tap water and sliced crosswise into circular slices for chips. An average of 140 g of sample was used in thermal treatments.

2.2. Drying devices

Microwave drying (MD): Fresh ‘*Santa Maria’* fruits were used in a Vestel brand and MD-GD23 model microwave oven. The microwave oven has a total output power of 900 W and its dimensions are 305 mm × 508 mm × 385 mm in height × width × depth, respectively. The products were placed on a glass plate and dried on the rotating glass tray in the oven at 360, 540, 720, and 900 W power values.

Microwave-assisted convective drying (*MACD*): Fresh fruits was dried by Ariston Hotpoint Brand MWHA 33343 model 2450 MHz (Italy). This dryer is a device with both hot air and microwave features. The AND brand GF-300 model precision balance (0.01 g) was used to follow the weight change of the samples in the drying processes.

2.3. Moisture content

Equation number 1 was used to determine the moisture content of fresh fruits on a dry basis (Yağcıoğlu, 1999).

$$N_{d.b.} = \frac{M_i - M_S}{M_S} \times 100 \quad (1)$$

Here: Mi; Initial weight (g), Ms; Final weight (g).

2.4. Drying rate (DR)

Equation number 2 was used to determine the drying rates of dried fruits (Doymaz et al., 2006).

$$DR = \frac{M_{t-M(t+dt)}}{dt} \quad (2)$$

Where: M_t; Moisture content (g moisture/g drying matter), d_t; minutes, DR; Drying rate (g moisture/g drying matter minutes).

2.5. Moisture rate (MR)

To determine the rate of moisture removed from the dried fruits, equation number 3 was used (Maskan, 2000).

$$MR = \frac{M-M_e}{M_0-M_e} \quad (3)$$

Where: MR: Moisture content, M; Instantaneous moisture content of the product (g moisture/g dry matter), M_e; Equilibrium moisture content of the product (g moisture/g dry matter), M_o; Initial moisture content of the product (g moisture/g dry matter).

2.6. Effective moisture diffusion (D_{eff})

Equation number 4 was used to calculate the effective moisture diffusion values of dried fruits (Corzo et al., 2008).

$$\ln MR = ln\frac{8}{\pi^2} - \frac{\pi^2 \cdot D_{eff} \cdot t}{4L^2} \quad (4)$$

Where: D_{eff}: Effective diffusion value (m^2/s), L; half of the thickness value of the product (m).

2.7. Total energy consumption

A Polaxtor brand PLX-15366 model energy analyzer (± 0.02 kWh) was used to measure the energy consumption values of dried fruits.

2.8. Specific moisture absorption ratio ($SMER$)

Equation number 5 was used to calculate the specific moisture absorption ratio of dried fruits (Surendhar et al., 2019).

$$SMER = \frac{Evaporated\ moisture\ (kg)}{Consumed\ energy\ (kWh)} \quad (5)$$

Where: SMER: Specific moisture removal rate (kg/kWh).

2.9. Specific energy consumption (SEC)

Equation number 6 was used to calculate specific energy consumption values in dried fruits (Motevali et al., 2012).

$$SEC = \frac{P \times t \times 10^{-6}}{m_w} \quad (6)$$

Where: SEC: Specific energy consumption (kWh/kg), P: Microwave power value (W), t: Drying time, mw; amount of moisture removed (kg).

2.10. Greenhouse gas emissions (GHG)

The amount of GHG released into the atmosphere during drying processes was determined according to the methods of Nazari et al. (2010) and (Kaveh et al., 2021). Energy consumption values were by multiplying the specified coefficients with the consumed energy consumption values. Energy production method - Consumed energy raw material source - GHG were calculated according to the principle. Calculations were made without considering regional GHG emission differences or any other factors as variables.

2.11. Statistical analysis

SigmaPlot10 was used to create the drying kinetics of the dried samples ($p<0.05$). Duncan multiple comparison test (p<0.05) was performed in SPSS17 to statistically evaluate the findings obtained within the scope of the study.

3. Results and Discussion

3.1. Moisture rate and drying rate

The humidity and drying rate curves of the drying processes are given in Figure 1. The moisture content of the samples on a wet basis was reduced from 86% to < 7%. The decrease in the drying times of the products progressed inversely proportional to the increase in the microwave power value. The average duration of the drying processes in the microwave dryer varied between 15.5 - 54 minutes and between 34 - 36 minutes in the hybrid dryer. Alibaş et al. (2021) investigated the effects of drying methods on the drying kinetic parameters of ‘Deveci’ pear. The initial moisture content of the product was dried from 83.95 ± 0.01% (5.24 ± 0.003 kg moisture kg dry matter^{-1}) to a final moisture content of 11.40 ± 0.06% (0.13 ± 0.001 kg moisture kg matter^{-1}). It was dried by hot air-drying method at 60, 80, and 100 °C for 11150, 437, 252, and 148 min, respectively. Nguyen et al. (2006) studied the estimation of effective diffusion of pear tissue and cuticle by means of numerical water diffusion model. The MR was determined as a function of time in the weight loss of a pear slice at 1 °C and 20 °C and 80-90% relative humidity. Initially, it was observed that the curves decreased at 1 °C and this decrease was due to the temperature and evaporation of excess water from the free surface of the samples. Kılıç (2014) studied the determination of drying characteristics of vegetables and fruits dried under convective conditions. The decrease in the time to reach equilibrium humidity provided an increase in the dimensionless humidity ratio and drying air temperature in drying under natural convective conditions. It was observed that the moisture content of the products decreased significantly in the first 100 minutes of drying. The times to reach equilibrium humidity were 330, 250, and 210 minutes at 60, 70, and 80 °C, respectively.

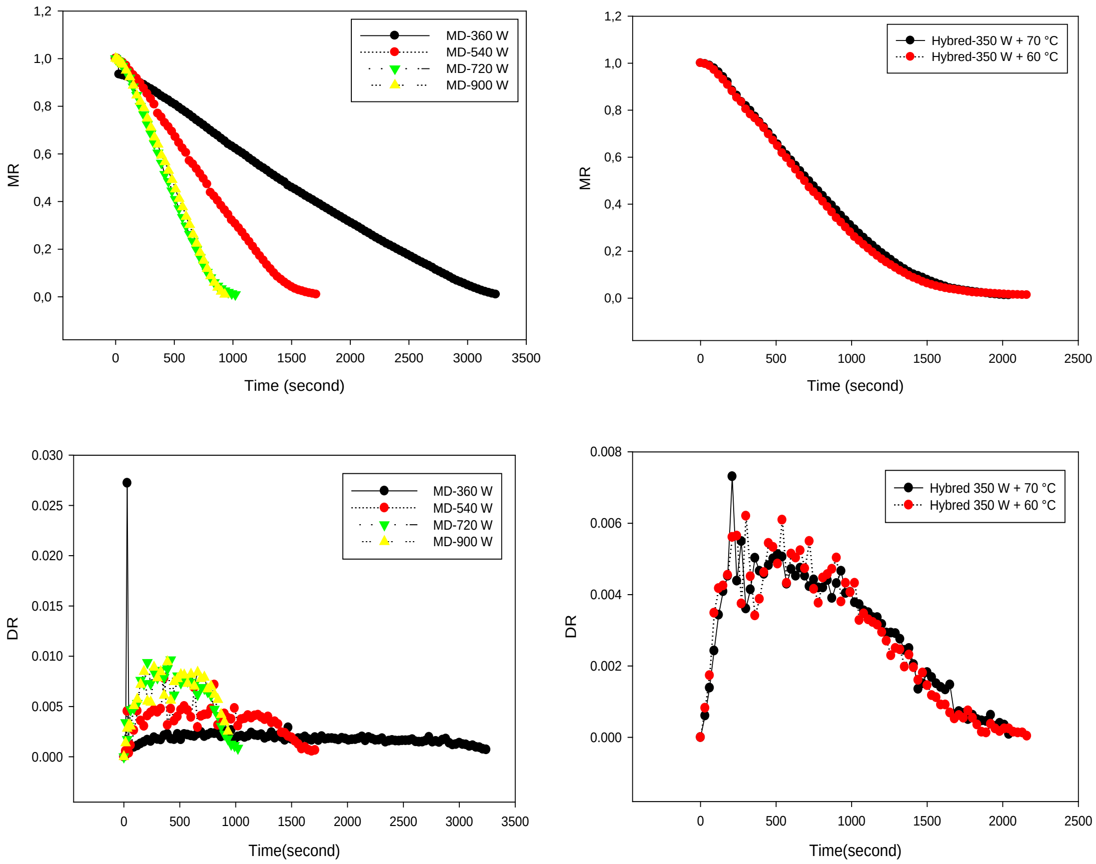

Figure 1. Drying kinetics.

3.2. Effective moisture diffusion

The effective moisture diffusion of the drying processes was affected by the microwave and hybrid power values (Table 1). The effective moisture diffusion values in the microwave dryer varied between 9.13×10^{-9} - 1.01×10^{-8} m^2/s and in the hybrid dryer between 5.58 - 5.58×10^{-9} in drying processes. The highest effective moisture diffusion value was determined as 1.01×10^{-8} m^2/s in the microwave dryer. This situation is thought to be the result of energy produced by the microwave system directly affecting the heat conversion within the product. Doymaz and Aktaş (2018) observed that the effective moisture diffusion value was positively affected by increasing the drying temperature. The reason for this was that the increase in the drying rate in the product affected the easier evaporation of moisture. Nguyen et al. (2006) worked on the estimation of the effective diffusion of pear tissue and cuticle by means of a numerical water diffusion model. Diffusion coefficient values were greater in late collected pear samples (inner cortex: 123.0 ± 48.0). This is because pears picked late are riper than those picked early. Since cell membrane deterioration is seen in products picked late, diffusion coefficients increase. Silva et al. (2016) studied three-stage intermittent drying of pears considering shrinkage and variable diffusion coefficient. In the results of the study, considering the amount of shrinkage in the samples, diffusion coefficients varying between 2.5×10^{-9} m^2/s and 6.0×10^{-11} m^2/s at 40 °C and 2.4×10^{-9} m^2/s and 1.9×10^{-10} m^2/s at 50 °C were observed. In the drying performed at 50 °C, a 28.7% decrease in the total time was obtained. This result determined that air temperature had a greater effect on drying kinetics than air flow rate. Effective moisture diffusion values of drying processes are given in Table 1.

3.3. Energy consumption values

The energy consumption curves of the drying processes are given in Figure 2.

Table 1. Effective moisture diffusion values of drying processes.

Microwave power	Effective diffusion (m^2/s)	R^2
360 W	2.54×10^{-9}	0.8407
540 W	5.83×10^{-9}	0.8637
720 W	1.01×10^{-8}	0.8766
900 W	9.13×10^{-9}	0.8012
350 W + 60 ºC	5.58×10^{-9}	0.9470
360 W + 70 ºC	5.58×10^{-9}	0.9691

It was observed that the average *SMER* values of *MD* drying processes varied between 0.006917-0.002803 kg/kWh and *SEC* values varied between 356.8205-144.5714 kWh/kg. It was observed that the average *SMER* values of hybrid drying processes varied between 0.0037-0.0016 kg/kWh and *SEC* values varied between 6261.5-2693.6 kWh/kg. Alibaş et al. (2021) investigated the effects of drying methods on the drying kinetics parameters of 'Deveci' pear. In the study, it was determined that the method with the highest total energy consumption in the hot air-drying method was 60°C. The increase in drying temperature was the determining factor in the increase in total energy consumption and the decrease in specific energy consumption. Kaveh et al. (2023) investigated the comparative evaluation of GHG emissions and specific energy consumption of different drying techniques in pear slices. For CV, IR, and MW the highest *SEC* values were obtained with the values of 267.61, 204.64, and 87.03 MJ/kg for 6 mm thickness at 50 °C, 500 W, and 270 W, respectively, while the lowest *SEC* values were 94.54, 85.36, and 28.33 MJ/kg for a 2 mm sample thickness at 70 °C, 1000 W, and 630 W, respectively. In the study, it was obtained that the *SEC* value decreased with increasing temperature-power and decreasing sample thickness. It was determined that the shrinkage values were higher at low sample thicknesses and temperature powers.

3.4. Greenhouse gas emission (*GHG*)

The *GHG* values in drying processes are given in Table 2.

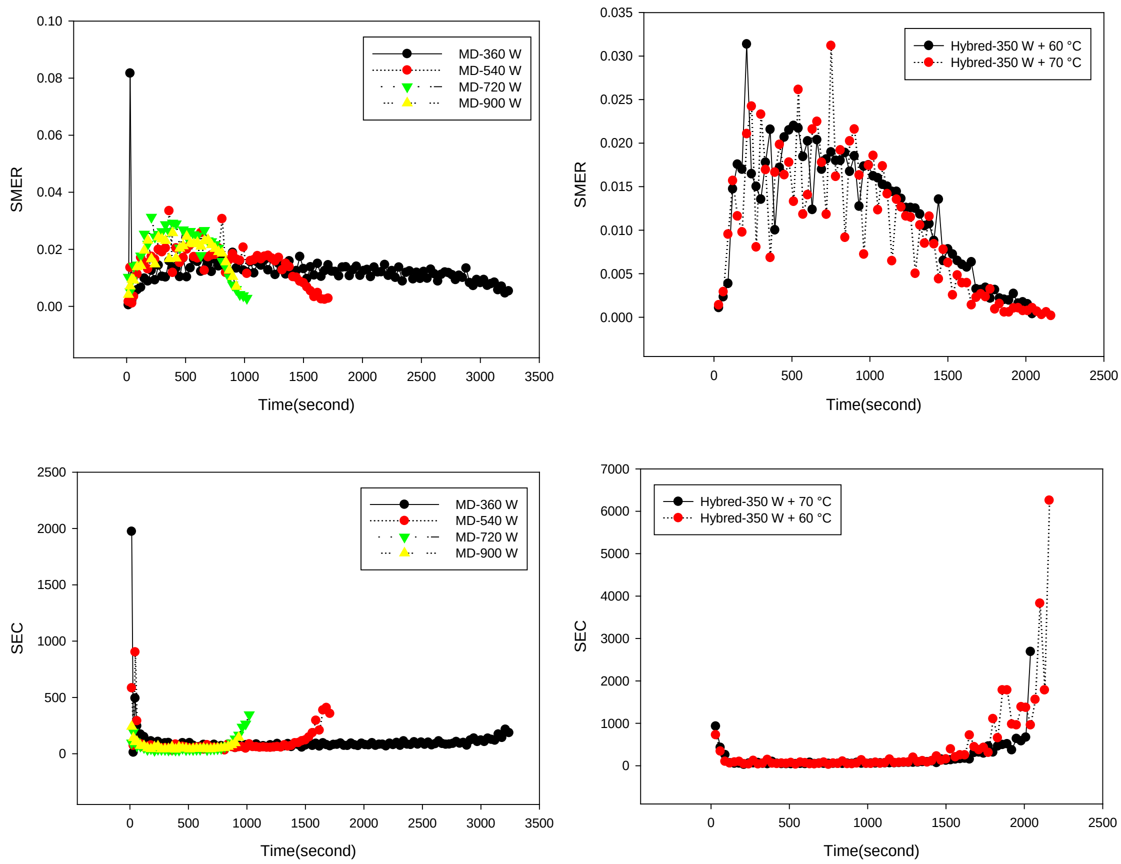

Figure 2. *SMER* and *SEC* curves of drying processes.

Table 2. GHG values.

Microwave power	Energy production methods	Fuel	NO_x (g)	SO_2 (g)	CO_2 (g)
360 W	Steam	Natural gas	1.32717	0	313.548
		Kerosene	1.24236	7.53304	505.325
	Gas turbine	Natural gas	0.94163	0	385.526
		Kerosene	2.85447	1.89312	516.664
	Combined cycle	Natural gas	1.45435	0	221.85
		Kerosene	1.86354	1.14376	306.646
540 W	Steam	Natural gas	1.11097	0	262.668
		Oil	1.04076	6.31064	423.325
	Gas turbine	Natural gas	0.78883	0	322.966
		Kerosene	2.39127	1.58592	432.824
	Combined cycle	Natural gas	1.21835	0	185.85
		Kerosene	1.56114	0.95816	256.886
720 W	Steam	Natural gas	0.84197	0	199.068
		Oil	0.78876	4.78264	320.825
	Gas turbine	Natural gas	0.59783	0	244.766
		Kerosene	1.81227	1.20192	328.024
	Combined cycle	Natural gas	0.92335	0	140.85
		Kerosene	1.18314	0.72616	194.686
900 W	Steam	Natural gas	0.8877	0	209.88
		Oil	0.8316	5.0424	338.25
	Gas turbine	Natural gas	0.6303	0	258.06
		Kerosene	1.9107	1.2672	345.84
	Combined cycle	Natural gas	0.9735	0	148.5
		Kerosene	1.2474	0.7656	205.26
350 W + 60 ºC	Steam	Natural gas	1.41225	0	333.9
		Oil	1.323	8.022	538.125
	Gas turbine	Natural gas	1.00275	0	410.55
		Kerosene	3.03975	2.016	550.2
	Combined cycle	Natural gas	1.54875	0	236.25
		Kerosene	1.9845	1.218	326.55
350 W + 70 ºC	Steam	Natural gas	1.77809	0	420.396
		Oil	1.66572	10.10008	677.525
	Gas turbine	Natural gas	1.26251	0	516.902
		Kerosene	3.82719	2.53824	692.728
	Combined cycle	Natural gas	1.94995	0	297.45
		Kerosene	2.49858	1.53352	411.142

** The value of 0 (Zero) indicates that the SO2 gas released into the atmosphere during energy production using natural gas fuel with steam, gas turbine and combined cycle methods is not at a significant level.

Çeşmeli and Pençe (2020) reported that GHG emissions exceed the capacity of our world to renew itself, leading to serious consequences such as ozone layer depletion, global warming and the decrease in food resources. In addition, GHG are one of the biggest factors in the formation of the ecological footprint. For the world to be more livable and sustainable, biomass areas and the ecological footprint must be kept in balance. To achieve this balance, the future status of greenhouse gas emissions must be predicted accurately. According to Table 2, it was determined that the *GHG* values decreased with the increase in microwave power values. This is because the drying time of the product decreased at high microwave power values, and the amount of energy consumed by the dryer also decreased. This caused the GHG values to decrease. Kaveh et al. (2023) investigated the comparative evaluation of GHG emissions and specific energy consumption of different drying techniques in pear slices. As seen in the microwave drying process, the highest CO_2 levels were recorded in SP-HO (89.21 kg/kg water) and GT-GO (91.21 kg/kg water) plants drying at 270 W with a sample thickness of 6 mm. The lowest CO_2 level was 12.75 kg/kg water in CC-NG plant with 630 W power and 2 mm sample thickness. The highest NO_x emissions (0.50 kg/kg water) were found in the GT-GO plant with 270 W and 6 mm thickness. The lowest NO_x (0.05 kg/kg water) was in the GT-NG plant with 2 mm sample thickness and drying at 630 W. In addition, increases in MW power led to a decrease in CO_2 and NO_x emissions, while an increase in sample thickness led to an increase in CO_2 and NO_x emissions. This high MW power required less energy to remove moisture from pear samples, which resulted in a decrease in greenhouse gas emissions. Kaveh et al. (2021) conducted a green pea drying study. In this study, they determined the highest and lowest CO_2 greenhouse gas emission values as 225.80 and 29.70 g/kg moisture.

The values in literature are higher than the values in this study. The reason for this is that the drying processes were carried out in industrial type convective dryers. Motevali and Koloor (2017) investigated the *GHG* values of different drying systems. They found the lowest CO_2 and NO_x greenhouse gas emissions in the microwave dryer as 38.55 g and 1.54 g. In this study, it was seen that the *GHG* values obtained with the microwave dryer were compatible with the GHG values obtained with the microwave dryer in the literature.

4. Conclusion

It was observed that microwave power values affected the drying kinetics, energy consumption and *GHG* values of pear chips. With the increase in power values, the moisture content of the samples also increased. NO_x gas emission was determined as 2.85 g at the highest power value of 360 W. SO_2 gas emission was determined as 6.31 g at the highest power value of 360 W. CO_2 gas emission was determined as 516.66 g at the highest power value of 360 W. The drying processes of the samples were affected by effective moisture diffusion, microwave and hybrid power values. In the pear chip study, it is thought that the energy produced by the microwave system directly affects the heat conversion within the product. The highest *SMER* and lowest *SEC* values were determined in the drying processes performed in the microwave dryer at 900 W power value and in the hybrid dryer at 350 W – 60 ºC.

Conflict of interest

The authors declare no conflicts of interest.

Authorship contribution statement

M.T: Planning, data processing, article writing, editing.
S.A: Laboratory work, data processing.

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