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EFFECT OF SOLAR COLLECTOR GEOMETRY ON DRYING TIME AND NUTRITIONAL PROPERTIES OF LEVANT QUALITY HAZELNUTS

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Abstract: This study examines the impact of drying Levant quality hazelnut samples, including husk and shell, using hot air heated by solar panels at a constant speed of 6 m/s. The study also investigates the impact of collector irradiation absorption surface geometries on hazelnut drying time. A solar collector with four types of air duct geometry was used to dry hazelnuts. The radiation-absorbing surface of the air duct was manufactured flat, and three different trapezoidal geometries (30, 45 and 60 angles) were used. The mass losses of hazelnuts were measured and determined at regular intervals. In addition, the total phenolic content, the DPPH radical scavenging activity, the FRAP, the free fatty acid content, the peroxide value and the moisture content were measured. For the purpose of comparison, some of the products have been dried by means of unheated air at ambient temperature. The pre-drying process (withering process) to separate the hazelnuts from husk, only took 1.5 days (14 h excluding night). In these systems, the shelled fresh hazelnuts, separated from the husk, fell below the equilibrium moisture content of 6% in 2 days (except for 18 h at night). It was found that the most suitable collector geometry for all the parameters studied in the drying of hazelnuts with solar collectors was 45 degrees, and that other geometries could be used in terms of food properties.

Keywords: Drying, Solar collector, Hazelnut traits, Husk

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1. Introduction

Hazelnut (*Corylus avellana* L.) is classified as hard-shelled fruits and is cultivated in countries with temperate climates. Türkiye is considered as the homeland of hazelnut because it has been cultivated for many years and is home to the highest quality varieties (Özçağıran et al., 2014). Approximately 68% of the world's hazelnut production is carried out on the Black Sea coast of Türkiye, which is the most suitable area in terms of ecological conditions (TUIK, 2021). In the Black Sea region, hazelnuts are grown up to 60 km inland from the coast and up to 750 m altitude (Köksal, 2002). Of these areas, those between 0-250 m altitudes are called the coastal part, those between 251-500 m altitudes are called the middle part, those at altitudes higher than 500 m are called the high part, and the hazelnut variety grown according to altitude varies (Turan and Islam, 2018). Generally, Tombul, Palaz, Kara, Sivri, Uzunmusa, Çakıldak, and Foşa hazelnut varieties are grown in the region and many varieties are produced together in the same garden, especially in the gardens located in the coastal area. These varieties differ in terms of physical and chemical fruit characteristics and are named according to their quality. Considering the quality parameters, hazelnuts in Türkiye are classified as Giresun and Levant quality hazelnuts. While Giresun quality refers to Tombul hazelnut, Levant quality refers to the dominant varieties and the mixture of these varieties in the city where cultivation is carried out. In Ordu, where hazelnut production is the highest, Kalınkara, Sivri, Palaz, Uzunmusa, and Çakıldak hazelnuts are called Levant quality (Uzundumlu et al., 2019).

Threshing is the process of drying harvested hazelnuts using various methods. Threshing machines are used to sort hazelnuts with high moisture content after withering for 3-5 days. The sorted nuts are typically laid on soil, concrete, or grass and sun-dried for 5-15 days. Harvest in central and upland areas tends to coincide with late summer and mid-autumn, exposing these areas to high rainfall and mist. Rain can make the hazelnuts difficult to harvest and thresh and can also affect the quality of the nuts. During the drying process, hazelnuts can be damaged in terms of quality parameters, depending on the duration of the process and climatic factors. If hazelnuts are dried in the sun, there is a risk of contamination with pathogens, microbial spoilage, formation of aflatoxins, deterioration of antioxidants and fatty acids, as well as loss of quality and yield (Kontaş, 2022). Hazelnuts contain secondary metabolites with antioxidant properties, such as phenolic acids, flavonoids, water and fat-soluble vitamins and tannins, in addition to the main components of fat, carbohydrates and protein. The harvesting and drying conditions determine the presence of these properties.

A number of techniques have been developed to prevent the hazelnuts from being damaged by the threshing conditions and to dry them quickly and efficiently with a minimum of energy input. Traditional dryers are commonly used for this, with the flow rate, temperature, and humidity of the mass transfer fluid being adjusted to achieve optimum results. Recent advancements in drying systems have led to the increasing popularity of new technologies such as infrared, microwave, heat pump, LED dryers, and hybrid dryers, which combine two or more drying systems (Akgün et al., 2018; Aksüt et al., 2023; Kian-Pour, 2020; Huang et al., 2021; Fenandes et al., 2024).

Drying and storage are required for nuts such as hazelnuts, walnuts, almonds, and peanuts. Sun drying is more challenging for hazelnuts than for other fruits as they are typically grown in rainy and humid regions. As a result, there has been a need for eco-friendly drying systems that preserve fruit quality, minimize energy costs, and are affordable for growers (Danso-Boateng, 2013; Topdemir, 2019). Recently, there has been an increasing focus on drying methods that use energy from solar panels and the design of such systems (Mohana et al., 2020; Memur, 2022).

The aim of using solar energy as a renewable energy source in the drying sector is to increase energy efficiency and minimize damage to the environment. These systems use the sun as the dryer source, resulting in low operating costs (Yıldız and Gökayaz, 2019). Numerous studies have employed solar collectors for drying purposes to enhance energy efficiency and speed. These studies have explored various food types and emphasized the importance of improving collector efficiency (Reddy, 1987; Shariah et al., 2002; Aktaş, 2003; Ceylan et al., 2006; Saleh and Gatea, 2010; Behera et al., 2022; EL-Mesery et al., 2022; Harini et al., 2022).

The drying of Levant hazelnuts harvested in their shells before and after patching is the subject of this experimental study. The effects of air heated by solar collectors at different drying temperatures on the drying times and the characteristics of the nuts are being studied.

2. Materials and Methods

This study focuses on Levant of *Corylus avellana* L, which is extensively cultivated in the Perşembe district of Ordu province, located in the coastal region of the Black Sea in Türkiye. The initial moisture content of the hazelnuts is between 27.3% and 32.2%, while the initial moisture content of the hazelnut shells is between 72.2% and 77.6%.

The shelled hazelnuts of the Levant have a size of 14-22 mm. The hazelnuts used in this study have not been sized. Hazelnuts were harvested by hand from the branches of plants of Levant quality cultivars. The hazelnut harvest in the coastal area takes place between 5-20 August, during which time the Black Sea coast experiences humidity and rainfall. Hazelnuts have unique characteristics that require them to be sun-dried by laying them on the ground to separate them from their husks. Depending on the climate, the drying time for hazelnuts varies from 3 to 7 days. Hazelnuts are dried in the sun until they reach 6% humidity. This process can take 3-12 days, and unfavorable drying conditions can lead to the formation of aflatoxins.

2.1. Drying Equipment

In the drying process, 5 air type solar collectors designed and manufactured by us were used as heat source (Figure 1). The radiation absorption surface of solar collector 1 given in Figure 1 is flat, the radiation absorption surface of the collector 2 is closed for drying at ambient temperature, the radiation absorption surface of the collector 3 is 30 degrees trapezoidal, the radiation absorption surface of the collector 4 is 45 degrees trapezoidal and the radiation absorption surface of the collector 5 is 60 degrees trapezoidal. The channel heights are taken equal in order to ensure equal air flow rates through the collectors.

The radiating surface of the collectors measures 1 m^2. Adjustable fans for air flow rate were placed at each collector inlet. The air velocity was measured at the inlet of the hazelnut drying box using a thermo-anemometer. The air temperature was measured in a time-dependent manner at the inlet and the outlet of the collector. The heated and accelerated air passes through the collector and is discharged into the environment through the spiral pipe, which is located above the nuts that are laid on the net in the box.

2.2. Method

Hazelnuts harvested from the orchard were weighed without separation and placed in Polyfoam boxes, with 4 kg per treatment. To prevent the collector outlet temperatures from getting too high and affecting the quality of the hazelnuts, the air speed through the collectors has been increased. The air velocity passing over the hazelnuts was 6 m/s costant.

Moisture losses were measured by weighing the samples at regular intervals during the drying process. Once the moisture losses of the samples with husks reached a constant level, they were manually sorted and separated from the husks. The moisture content of each sample was then measured. The fresh hazelnut samples were sorted, weighed, and placed in polyfoam boxes with a weight of 1.5 kg per treatment.

Figure 1. Five solar collectors used in the drying system.

Table 1. Measurement tools

Measureme	Measurement	Tool	Range	Precision
Temperature	K-type thermocouple	Vert	-220 – 1370 °C	0.1 °C
Temperature	Infrared thermometer	Fluke-62 Max	-30 – 500 °C	0.1 °C
Air speed	Hot wire anemometer	Cem Dt-8880	0.1 – 25 m/s	0.01 m/s
Weight loss	Digital scale	Necklife Agt S2	0 – 6 kg	0.1 g
Moisture	Moisture analyzer	Precisa-XM60	0.02 –124 g	0.001 g

During the drying process, the mass loss of hazelnuts was measured at regular intervals (every hour) with an electronic balance. The purpose of this weighing is to determine whether the hazelnut has reached 6% equilibrium moisture. When the hazelnut reached the equilibrium moisture, the drying experiment was terminated. Air temperature was measured at the inlet and outlet of each panel. In sun drying, the surface temperature of the hazelnut was measured with an infraret thermometer. Air velocity was measured by telescopic hot wire anamometer in both panel drying and sun drying. Hazelnut wet and dry moisture values were determined by infraret moisture measuring device. The instruments used and the sensitivity values for the measurements performed in the experiments are shown in Table 1.

2.2.1. Hazelnut oil extraction

Hexane was used as a solvent for cold-extracting oil from homogenised hazelnut samples. The extraction process was carried out by stirring the samples on a MR-12 Rocker-Shaker (Biosan, Latvia) at 50 rpm for 2 hours at room temperature. The resulting supernatant was obtained by centrifugation (Nüve 800R, Türkiye) at 4500 rpm for 10 minutes and then decanted. The hexane-oil mixture was then subjected to rotary evaporation (Heidolph Laborota 4000, Germany) at 45°C to remove the hexane. The free fatty acidity and peroxide value of the obtained oil were analyzed (Akgün and Akgün, 2023).

2.2.2. Free fatty acids (FFA)

Hazelnut oils (2 g) were weighed to an accuracy of 0.01 g and treated with 12 mL of a neutral mixture of diethyl ether:ethanol (1:1, v:v). The titration was then carried out using a 0,01 N solution of potassium hydroxide in ethanol with 1 % of phenolphthalein as an indicator. The results for free fatty acids (FFA) are presented as a percentage of oleic acid (AOAC, 1990).

2.2.3. Peroxide value (PV)

The oil sample was weighed in a glass jar using a precision balance. Then, 10 mL of chloroform and 15 mL of acetic acid were added and mixed. Next, 1 mL of saturated potassium iodide solution was added to the mixture and kept in the dark for 5 minutes. Titration was carried out with 0.002 N sodium thiosulphate solution followed by the addition of 75 mL distilled water and 1 mL 1% starch solution. The PV was calculated as meq O_2/kg (according to AOAC, 1990).

2.2.4. Extraction procedure of bioactive components

To extract the hazelnut samples, a mixture of 80% methanol and 20% distilled water was added to one gram of defatted hazelnut. The mixture was then subjected to extraction on an MR-12 Rocker-Shaker (Biosan, Latvia) at 50 rpm for 6 hours at room temperature. After extracting, the mixture was centrifuged for 10 min at 5000 rpm and the supernatant was decanted. The procedure was repeated for the residue and the combined extracts were analyzed for the total phenolic content and antioxidant activity (according to DPPH, ABTS and FRAP assays).

2.2.5. Total phenolic content

An aliquot of the sample extract was mixed with FC reagent and a 20% w/v solution of sodium carbonate in a test tube and the total volume was adjusted to 5 ml with distilled water according to the Folin-Ciocalteu test (Singleton et al., 1999). After 30 minutes at room temperature, the absorbance of the prepared mixtures was recorded at 760 nm using a UV mini-1240 spectrophotometer (Shimadzu, Japan). Using a gallic acid standard curve, the results are expressed as milligrams of gallic acid equivalent (GAE) per 100 g dry weight.

2.2.6. Antioxidant activity assays

The hazelnut samples' antioxidant activity was determined by calculating µmol trolox-equivalent (TE)/g dry weight using three different in vitro antioxidant assays: DPPH, ABTS, and FRAP.

To determine DPPH, 100 µl of the sample extract was mixed with 0.1 mM DPPH solution (2.9 ml) in a test tube. After incubating the mixtures at 30 °C for 30 min, the absorbance was measured at 517 nm (Brand-Williams et al., 1995).

The determination of ABTS was carried out according to the protocol developed by Re et al. (1999). In order to allow the formation of radical cations, a 7 mM ABTS stock solution containing 2.45 mM potassium persulfate was kept in the dark for 12 h. The resulting radical mixture was then diluted with ethanol until the absorbance at 734 nm was 0.700±0.02, yielding the ABTS test solution. Next, 100 µl of the sample extract was added to the test tube and reacted with the diluted ABTS test solution (2900 µl) for 6 minutes. The absorbance was read at 734 nm and recorded.

For FRAP analysis, the FRAP reagent was prepared by mixing TPTZ (10 mmol/L), $FeCl_3.6H_2O$ (20 mmol/L) and acetate buffer (0.3 mol/L, pH 3.6) solutions in appropriate volumetric ratios (1:1:10 v/v). Absorbance values of the mixture prepared with the sample extract and FRAP reagent were measured at 593 nm in a spectrophotometer after incubation at 37 °C for 4 minutes (Benzie and Strain, 1996).

The statistical analysis of all values obtained from the study was conducted using the One-Way ANOVA method in the SPSS 25 software package (Genç and Soysal, 2018).

3. Results and Discussion

This section presents the results of the study in two parts: the hazelnut drying process and the resulting changes in kernel quality characteristics.

3.1. Hazelnut Drying

Figure 2 shows the ambient temperature change of Levant during pre-drying (withering process) to remove hazelnuts from the husk. It took 1.5 days to complete the pre-drying process. The moisture contents of the shelled hazelnuts were as follows: Sample 1 (21.3%), Sample 2 (25.6%), Sample 3 (20.8%), Sample 4 (20.0%), and Sample 5 (21.2%). These measurements were taken after 14 hours of operation, excluding nighttime.

The temperature at night, when the system was not operated, was not measured, and is represented as intermittent on the graph. Sample 4 experienced a higher moisture loss due to the higher ambient temperature (46.3 °C) compared to the other samples, despite having the same flow rates. In system no. 2, the humidity value was high as expected since the air flow was at ambient temperature (max. 30.1 °C). At the end of the pre-drying process, the humidity of the solar collectors at the end of the drying process was close to each other and lost about 30% more moisture than the drying directly at ambient temperature. This finding is consistent with earlier research (Demirtaş, 1996).

The objective of the drying process following pre-drying is to reduce the moisture content of the shelled hazelnuts to below 6% equilibrium moisture. This drying process lasted 18 hours.

Figure 3 shows the time-dependent ambient temperature of shelled hazelnuts that were separated from the husk and dried again. It is clearly seen that sample 1 and the air velocity without heated drying will dry more slowly than the others. The temperature curve of sample 2 shows that the hazelnuts can be dried in a shorter time by increasing the temperature of the air. This is clearly seen when compared with the temperature curve of sample 1. To prevent hazelnuts from spoiling in rainy regions, it is recommended to heat them slightly above atmospheric air and pass them under cover, this will also shorten the drying time.

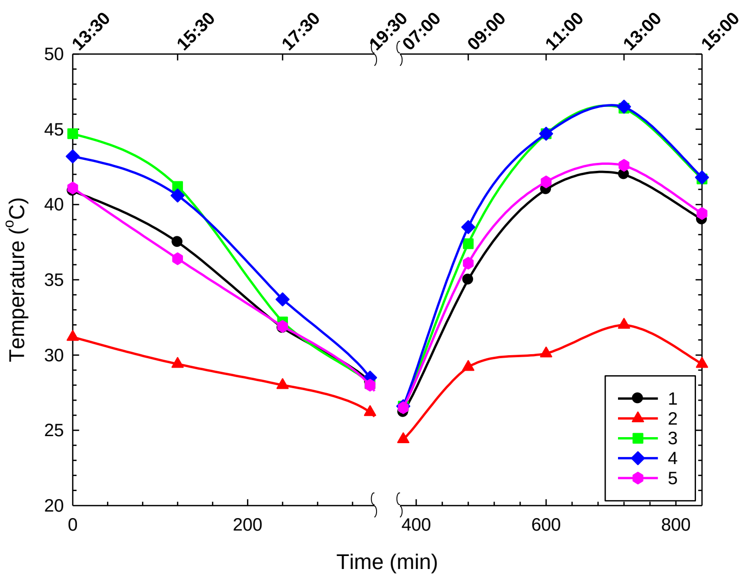

Figure 2. The variation of in-husk hazelnut drying ambient temperature over time.

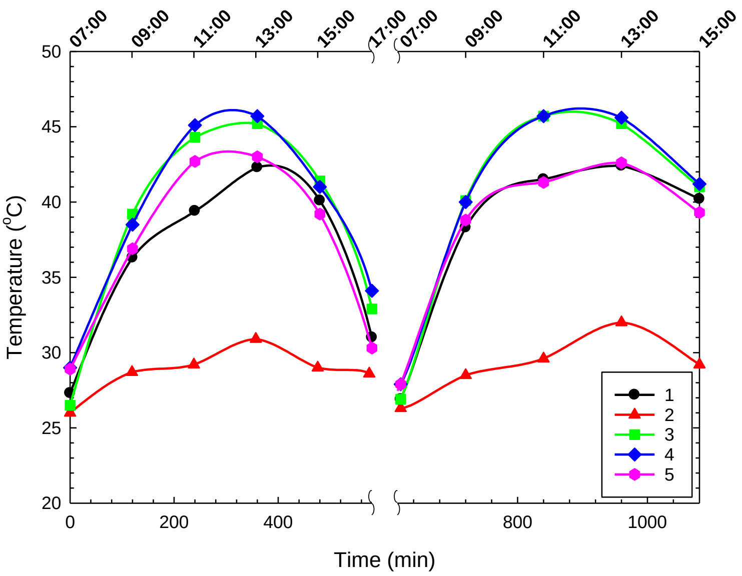

Figure 3. The variation of hazelnut without husk drying ambient temperature over time.

The drying process was completed in 18 hours. However, despite the humidity dropping below 6% in the solar collectors (Sample 2), the process continued for an additional 8 hours at ambient temperature.

After the hazelnuts were dried, their moisture content was measured and recorded as follows: Sample 1 (5.3%), Sample 2 (7.4%), Sample 3 (5.1%), Sample 4 (5.4%), and Sample 5 (5.2%). Although sample 4 has the highest average temperature (Figure 3), it also has a higher humidity level compared to samples 3 and 5. Hazelnut size is mainly responsible for the variation in moisture content during the same process. Drying slows down as the size increases, and moisture diffuses more slowly from the interior to the hazelnut shell. Sample 2 was not completely dry by the end of the experiment. It was therefore dried separately until it reached an equilibrium moisture content of 6%.

3.2. Hazelnut traits

The study investigated the effect of different drying rates on oxidation parameters. Both free fatty acid and peroxide levels were found to be significant (P<0.05) by statistical analysis.

Table 2 presents the TPC, and antioxidant capacity of hazelnut samples dried using various methods. The utilization of different drying methods significantly affected the TPC and antioxidant capacity of the hazelnut samples (P<0.01). The TPC of the hazelnut samples ranged from 312.79-449.19 mg GAE/100 g. The highest TPC was observed in hazelnuts dried using 45° and Flat solar collectors (SCs), while hazelnuts dried with 30° SC had the lowest TPC (P<0.05). In this study, the continuous system had the lowest drying temperature (26-32°C), but the longer drying time compared to other methods had a negative effect on the bioactive properties. A similar trend to TPC results was also observed for antioxidant activity assays. The highest values (P<0.05) for all three antioxidant activity assays were presented by 45° and Flat SCs, while the antioxidant capacity of the hazelnuts dried by the SC system with 30° tilt angle was the lowest (P<0.05). Previous studies have shown a positive correlation between TPC and antioxidant capacity in hazelnut samples, which is in agreement with our findings Yılmaz et al. (2019). The TPC and antioxidant activity findings were consistent with previous studies on hazelnuts (Yılmaz et al., 2019; Balık et al., 2021; Çelik et al., 2023; Yaman et al., 2023). However, some researchers reported lower values (Ghirardello et al., 2013; Karaosmanoğlu, 2022; Akgün and Akgün, 2023). Yılmaz et al. (2019) determined the DPPH and FRAP values of hazelnuts of different sizes to be 31.60-44.18 mmol/kg and 33.48-58.83 mmol/kg, respectively. Balık (2021) reported TPC, DPPH and FRAP values for different Turkish hazelnuts in the range of 280.35-1130.06 mg GAE/100 g, 1.22-2.54 mmol TE/kg, and 2.9-26.99 mmol TE/kg, respectively. The hazelnut's bioactive component content and antioxidant capacity vary depending on agricultural factors, variety, size, processing method, extraction procedure, and storage conditions (Ghirardello et al., 2013; Simsek et al., 2017; Yılmaz et al., 2019; Karaosmanoğlu, 2022). Additionally, the bioactive properties of hazelnuts are significantly affected by the drying method used. In their study, Özcan and Uslu (2023) found that drying hazelnuts using different methods (room temperature, conventional oven, and microwave) increased the total phenolic content (TPC) and the antioxidant activity (measured by DPPH). They recommended the use of conventional oven drying over the other methods.

Table 3 presents the FFA (%oleic acid) and PV (meq O_2/kg) values of hazelnuts dried using different methods. The hazelnut oils were found to have FFA and PV values in the range of 0.21-0.23% and 0.26-0.37%, respectively. The FFA and PV values of hazelnut samples dried using different methods were similar (P>0.05). Therefore, the drying methods used in this study did not have a significant (P>0.05) effect on the oxidation parameters of hazelnuts. Similarly, Kashaninejad et al. (2003) found no significant difference between the FFA values of pistachios dried by different methods. However, in the present study, all samples had FFA values below the threshold value (≥1%) accepted as an indicator of quality deterioration (Turan, 2018b). Our results were lower than the values found in previous studies (Celik et al., 2023; Akgun and Akgun, 2023), but similar to those reported by Turan (2018a, 2018b). Previous studies (Ghirardello et al., 2013; Turan, 2018a, Turan, 2018b; Mokhtarian and Tavakolipour, 2019) have shown that the FFA and PV of nuts can vary depending on environmental factors, drying, processing, storage, and packaging conditions. In order to prevent oxidation, Turan (2018b) emphasized that hazelnuts should be dried at a maximum temperature of 45 °C for a short time. Mokhtarian and Tavakolipour (2019) found that pistachios dried using conventional solar drying systems with air recycling had a lower peroxide value than those dried without air recycling, due to the longer drying time associated with the latter method. A study conducted by Akgün and Akgün (2023) found that hazelnuts preserved their oxidative quality better when dried using a solar collector with an air flow rate of 3.00 m/s, compared to sun drying.

Table 2. Changes in total phenolics and antioxidant capacity of hazelnuts dried by various drying methods

Drying Method	TPC (mg GAE/100 g)	DPPH (μmol TE/g)	ABTS (μmol TE/g)	FRAP (μmol TE/g)
Flat-SC	431.84±2.82[a]	49.81±1.21[a]	15.63±0.52[ab]	25.83±1.70[a]
Continuous	360.10±12.39[c]	42.89±1.52[b]	14.11±0.44[bc]	22.18±0.73[b]
30° SC	312.79±8.22[d]	35.33±2.73[c]	10.78±0.65[d]	17.38±0.30[c]
45° SC	449.19±7.05[a]	50.01±1.22[a]	16.93±0.70[a]	26.70±1.99[a]
60° SC	389.94±16.55[b]	43.65±1.18[b]	13.91±0.34[c]	21.35±0.51[b]

SC= solar collector, TPC= total phenolic content, DPPH= DPPH antiradical activity, ABTS= ABTS antiradical activity, FRAP= ferric ion reducing antioxidant power, [(a-d)] Significant differences (Türkiye test; P<0.05) between means in the same column are indicated by different lowercase letters.

Table 3. Changes in FFA and PV values of hazelnuts dried by various drying methods

Drying Method	FFA (%)	PV (meq O_2/kg)
Flat-SC	0.22±0.02	0.33±0.08
Continuous	0.21±0.01	0.26±0.04
30° SC	0.21±0.01	0.28±0.14
45° SC	0.23±0.02	0.35±0.07
60° SC	0.23±0.01	0.37±0.08

SC= solar collector, FFA= free fatty acids, PV= peroxide value.

4. Conclusion

The study examined the effects of solar-heated air at different types solar collectors on the drying of Levant quality hazelnuts and drew the following conclusions:

1. In wet climates, it may be preferable to heat the hazelnuts slightly above the air temperature and dry them under cover to prevent spoilage and shorten the drying time.
2. Drying with air without heating took a long time. However, it allowed the hazelnuts to dry without spoiling.
3. At the end of the pre-drying process, the humidity of the solar collectors at the end of the drying process was close to each other (Sample 1, 3, 4, and 5) and lost about 30% more moisture than the drying directly at ambient temperature (Sample 2).
4. In the pre-drying stage, as expected, the shortest drying time was achieved with a Sample 4 (45 trapezoidal angle).
5. The drying time decreases as the heat of the air increases when a solar collector is used for the drying process.
6. It is seen that the most suitable collector geometry for TPC, DPPH, ABTS and FRAP values of hazelnut in hazelnut drying with solar collectors is 45 degrees.
7. The results indicate that the geometry of the collector does not have a statistically significant effect on the FFA and PV values of hazelnuts during solar drying.

Solar collectors are recommended for drying hazelnuts due to their environmentally friendly nature, lack of energy costs, and ability to preserve food properties.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	M.A.	C.A.	M.A.	E.T.
C	25	25	25	25
D	25	25	25	25
S	25	25	25	25
DCP	25	25	25	25
DAI	25	25	25	25
L	25	25	25	25
W	25	25	25	25
CR	25	25	25	25
SR	25	25	25	25
PM	25	25	25	25
FA	25	25	25	25

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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