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Study of a solar energy drying system—Energy savings and effect in dried food quality

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Abstract

It is estimated that in Portugal per year, 132 kg/person of food is wasted due to imperfections in weight, shape and due to their perishability, resulting in foods that cannot be marketed. Solar drying can be used to extend food life. However, it usually does not meet the current productivity and quality requirements of the dried product. Solar energy is renewable, very available in Portugal, which can make an important contribution to reducing the specific energy consumption and carbon footprint intensity associated with drying. This work aims to optimize the drying process using a solar dryer with electric support. The conditions of temperature and humidity in the dryer and their influence on the physical and chemical properties of blueberries and raspberries were studied, namely the ash, protein, fat, sugars, total phenolic compounds content and antioxidant capacity.

It was concluded that the blueberries and raspberries, after drying underwent slight changes in some chemical parameters, namely the reduction of fats and phenolic compounds. The results of the drying tests showed a strong dependence on atmospheric conditions. Under the most favorable conditions, it was possible to record reductions in electricity consumption of 35%.

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Keywords: Circular economy; Food drying; Food waste; Renewable energy; Solar dryer; Solar energy

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1. Introduction

Drying is usually defined as an operation that converts a liquid, solid, or semi-solid material into a solid material with lower moisture content relative to the initial state. According to Erbay and Icier [1], despite its great importance, drying is one of the most complex and least-understood processes at the microscopic level, because of the difficulties and deficiencies in mathematical descriptions. In addition, the drying of food materials is further complex since physical, chemical, and biochemical transformations may occur during drying. Although the study of drying theory and its mathematical description is very relevant, experimental developments proved to be of great importance [2].

In the food industry, at physical, chemical and sensorial levels, the advantages of drying are the ease of the conservation process itself and the protection against microbiological, enzymatic and oxidative degradation [3,4]. The main deterioration factors of dehydrated vegetables and fruits are enzymatic and non-enzymatic reactions, lipid and vitamin oxidation reactions and pigment degradation, which are considered critical quality parameters [5].

Drying is responsible for the consumption of 10 to 15% of all energy in the current industry in developed countries [6]. Solar energy, despite being the source of thermal energy traditionally used for drying, is often not able to meet the productivity and quality of the dried product [7,8]. However, it has enormous potential to reduce the consumption of other types of energy and, therefore, reduce greenhouse gases emissions [9]. Moreover, solar energy is renewable, widely available in southern European countries, such as Portugal, which can make an important contribution to reducing the specific energy consumption and the carbon intensity associated with the food industry.

This work aims to optimize a food drying process using a solar dryer with electric support, with a previous evaluation of the fruits drying curves under different drying conditions. The effect of the operational conditions on dried food quality is also assessed.

2. Materials and methods

For this work, some products from the agro-industry were selected for which drying has a strong interest, once the companies have a high quantity of fruits that do not meet the required quality for marketing in the fresh chain and therefore generate waste and economic losses for the farmer. Based on the information collected from companies in this sector, blueberry (*Vaccinium myrtillus*) and raspberry (*Rubus idaeus*) were studied.

2.1. Drying tests

The selected products were subjected to a drying process with controlled relative humidity and temperature conditions. The drying curves, equilibrium moisture content and the period to reach equilibrium determination were performed to 40, 50 and 60 °C and 10% of relative humidity, therefore close to the conditions found in real drying conditions.

All tests were performed in triplicate and the mass of the samples was monitored until constant mass, allowing the determination of the drying curves.

A field test for energy-saving evaluation was carried with 7.5 kg of spinach. The first field test was done with a food product more abundant and with lower cost, due to the larger amounts needed. The solar dryer used was model Avatar (CHATRON) with a capacity of 800 liters. Has a solar power of 560 W and integrates an electrical resistance of 1 kW to compensate for the insufficiency or absence of solar energy. It is built with sandwich panels connected by zinc/steel profiles. The vertical thermal solar panel has useful dimensions of 90 × 69 cm, and it has also a photovoltaic panel with 32 × 25.5 cm, incorporated in the center of the thermal panel, to feed the operation of the inflation fan that does not have any electrical power. The dryer was instrumented with a pyrometer on the outside surface, thermocouples and hygrometers inside and with an electric energy accumulator meter. The electrical resistance is thermostatically controlled and a minimum temperature of 45 °C has been imposed.

2.2. Dried food chemical characterization

For the evaluation of the drying effect in the food products, the levels of ash, fat, protein, total phenolic compounds were determined, and the antioxidant capacity was also assessed. All analyses were done in triplicate. The samples were frozen at the time of receipt until the moment of analysis to preserve their characteristics. The ash content was determined by gravimetric means in a muffle oven (DINKO D-62D) at a controlled temperature of

550 °C [10]. The fat content followed the Weende method [10]. The protein was quantified according to the Kjeldahl method [10], using a conversion factor of 6.25 [11]. The samples were submitted to digestion in a BEHROTEST K20 digester and distilled in a Selecta Pro-Nitro II automatic distillator quantifying the nitrogen by titration with HCl 0.1 N [8]. The phenolic compounds and the antioxidant activity was done after extraction with acidified water. The phenolic compounds were determined by the Folin Ciocalteu method [12]. The quantification of antioxidant activity was performed following the DPPH• (2,2-diphenyl-1-picrylhydrazyl) free radical inhibition method [13]. The total sugars were determined by the phenol-sulphuric method and the redutors by the DNS method (acid dinitrosalicilic) [14].

3. Results and discussion

3.1. Drying curves

Two seasonal products of the agri-food industry were selected for which drying has a potential interest in valuing waste streams from food value chains. The fruits were submitted to a complete drying process, to determine the initial moisture content, and to a drying process with controlled conditions, to determine the drying curves and equilibrium moisture content. In terms of drying curves, Fig. 1 shows fresh blueberries and raspberries drying curves at 10% relative humidity (RH) and at 40 °C, 50 °C and 60 °C temperature (T). An expected shape of the drying curves was achieved, with a low drying rate in the first period of adaptation to the test temperature and relative humidity. After that, the drying curves present a nearly constant rate of drying with a significant decrease of moisture content, ending with a falling rate drying period until reaching the equilibrium moisture content.

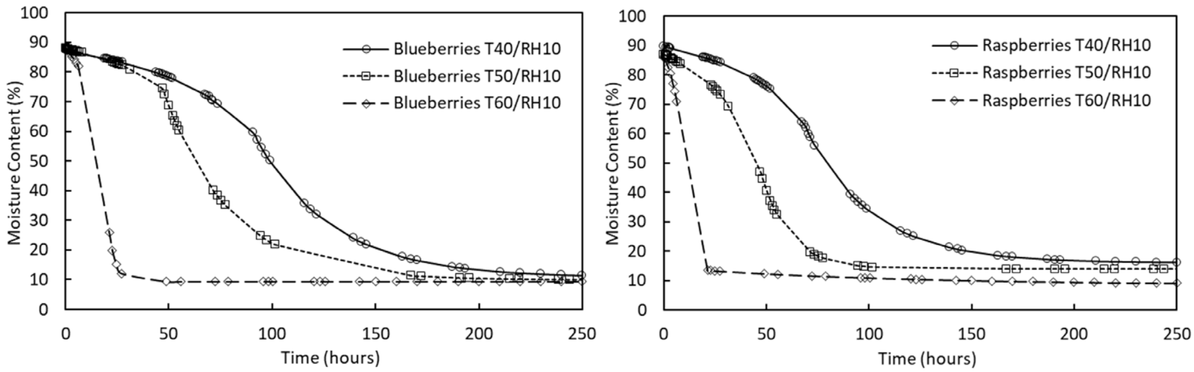

Fig. 1. Blueberries and raspberry's drying curves at 10% relative humidity and 40 °C, 50 °C and 60 °C.

Table 1 shows the main drying curves parameters: the initial moisture, the equilibrium moisture and the period to reach equilibrium. As expected, for both fruits, the equilibrium moisture and the time to reach it decrease with increasing temperature. The effect of temperature in the equilibrium moisture is more evident in raspberries than in blueberries. Raspberries reach the equilibrium moisture content faster than blueberries. For blueberries and raspberries, the initial moisture was between 86% and 90%. The equilibrium moisture for blueberries was between 10.8% at 40 °C and 9.4% at 60 °C, and for raspberries between 16.0% at 40 °C and 8.4% at 60 °C.

Table 1. Blueberries and raspberries drying curves parameters.

Fruits	Relative humidity [%]	Temperature [°C]	Initial moisture content - Wet basis [%]	Equilibrium moisture content - Wet basis [%]	Equilibrium time [h]
Blueberries	10	40	87.5	10.8	320.0
		50	88.0	9.9	267.7
		60	87.8	9.4	178.8
Raspberries		40	89.7	16.0	270.0
		50	87.0	13.8	167.0
		60	85.9	8.4	120.3

Considering the energy requirements, low drying temperatures require less energy, but on the other hand, require more time to reach the desire dryness state. If time is not a requisite, the lower drying temperatures to obtain the same final product can by easier supported by solar energy.

3.2. Chemical analysis

The effect of the drying conditions on the chemical characteristics of the fruits under study is described in Table 2. The variation relative to fresh fruits are presented. A more detailed study about the fresh characteristics of these fruits was previously presented [15].

Table 2. Variation of the chemical parameters of the dried fruits (dry basis).

Fruit	Drying Conditions	Fat [%]	Ashes [%]	Protein [%]	Antioxidant activity [mg AAE/100 g sample]	Total phenols [mg GAE/100 g sample]	Total Sugars [%]
Raspberries	Fresh	3.8	6.24	8.64	430	1229	5.40
	T40/RH10	0.38	6.58	11.1	308	930	10.9
	T50/RH10	0.24	3.96	9.24	213	180	8.10
	T60/RH10	0.61	4.91	9.19	223	566	6.80
Blueberries	Fresh	1.45	2.13	4.95	685	2594	12.4
	T40/RH10	0.32	2.09	6.0	290	822	12.7
	T50/RH10	0.16	1.74	3.74	235	313	8.80
	T60/RH10	0.36	1.99	4.24	244	681	9.90

AAE — Ascorbic Acid Equivalents; GAE — Gallic Acid Equivalents.

The results in Table 2 provide information on the nutritional value, the mineral content and bioactive components of the raspberries and blueberries before and after the drying process. Fruits may have a wide range of ash content. It is possible to acknowledge that this is not significantly influenced during drying procedures. It is expected that the high temperature may influence the protein losses, due to denaturation processes. It was verified that there were fluctuations in the protein content that was higher in the fruits treated with lower temperature, suggesting the temperature increases affect the protein degradation probably because of lipid oxidation. The influence of temperature on fats translates into an increase in the phenomenon of lipid oxidation, which results in the smell and taste of rancid food and the change in the texture of protein foods. In lipid oxidation, oxygen reacts with unsaturated fatty acids, producing free radicals that destroy fat-soluble vitamins and decrease the nutritional value of proteins [5]. However, due to the low content of lipids in these products, this is not a reaction with great influence for these fruits.

Phenolic compounds are substances that exist mainly in plants, but which may also arise from the catabolism of amino acids [12]. These compounds are antioxidants through the elimination of free radicals, in addition to inhibiting lipid oxidation and fungal proliferation and are also responsible for the color, astringency and aroma of several foods [16]. It was observed globally, regardless of the drying condition, that phenolics were degraded, and the loss of these compounds increases when the products are subjected to drying conditions above 50 °C. According to Efraim et al. [17], the higher the temperature and humidity, the greater the oxidation of the polyphenols.

Food antioxidant activity is one of the most appreciated characteristics due to its benefits in health. Among the compounds with antioxidant capacity are found the phenolic compounds [18]. Before drying, the greater antioxidant power of blueberries may be related to the higher content of phenolic compounds compared to raspberries. Drying causes a decrease in the antioxidant activity that may be related to the decrease observed in the content of phenolic compounds after drying. The effect of the decrease in antioxidant activity with increasing drying temperature is evident from 40 °C to 50 °C, with practically no change to the temperature of 60 °C. The parameters analyzed to highlight the effect of drying temperature on the reduction of fats, phenolic compounds and antioxidant activity. The values of ash, as expected, remain similar before and after drying. The drying conditions that affect the chemical properties less was drying at 40 °C, with a relative humidity of 10%.

3.3. Field test with solar drier

The field test in the solar drier allowed to study the potential of energy saving when the drying process is performed in real conditions, using solar energy as the main energy source. This test was the first evaluation of the real dryer operation. The food product used was spinach and the dryer set point was the interior temperature of 45 °C. The test was conducted until the spinach mass remains constant, indicating the release of all the water. The monitoring of mass loss consisted of regular weighing of these samples, using a digital balance with an uncertainty of 0.1 g. The drying test was considered finished when the total mass of the samples varied less than 0.1 g between each weighing in at least 3 consecutive weighings, in an interval of not less than 24 h. Whenever the temperature decreases below the setpoint, the electrical resistance automatically turns on. In this first evaluation of this dryer, it was not considered the operating conditions previously evaluated in the climate chamber. Table 3 shows the variation of the chemical characteristics of spinach after drying. Only the antioxidant activity and the phenols content were dramatically reduced, as expected by the oxidant conditions they were submitted, with the former decreasing 10 times. Once more should be emphasized that the drying process decreases the amount of bioactive compounds in the food, and therefore, their nutritional richness.

Table 3. Variation of the chemical parameters of spinach before and after drying (dry basis).

Condition	Fat [%]	Ash[%]	Protein [%]	Antioxidant activity [mg AAE/100 g sample]	Total phenols [mgAE/100 g sample]	Total sugars [%]
Fresh	1.4	9.7	17.8	1616	25.3	0.5
Dried	1.3	23	20.2	160.8	11.8	1.2

Fig. 2 shows the profile of the global horizontal irradiation (dot lines) and the average electric power consumption (continuous line) during the field test, in the absence of solar energy, ensuring that the product is not damaged. The atmospheric conditions were not the most favorable during the seven days it took for the product to be dried. It is possible to evaluate the night and daily periods when the solar radiation it is null. The end of the process was considered when the spinach achieved the constant mass. The moisture content of the spinach, in the end, was about 8%. However, it is possible to verify that, during sunny periods, there is a reduction in the average electrical power that reaches 35%. Although it is a primary evaluation, considering this reduction of electrical power need for the drying process, and the characteristics of the greenhouse gases (GHG) emission related with the electrical power, it can be expected a reduction of CO_2 emissions. In Portugal, the specific emissions of the energetic sources for electrical production, in 2019, was 253 gCO_2/kWh [19]. Considering the operation of 54.5 h under solar radiation and the consequent reduction of 2.3 kWh of electrical energy consumed, it can be estimated a reduction in CO_2 emissions of 1.4 kg/h of solar radiation.t product. This data is obtained for the specific conditions of this test and cannot be generalized to all conditions.

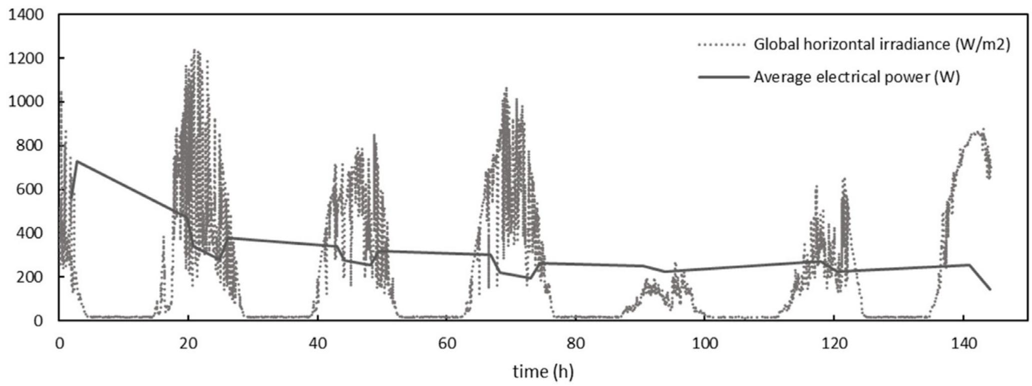

Fig. 2. Global horizontal irradiance (dot lines) and Average electrical power (continuous line) during the field test.

4. Conclusion

For the products under study, the drying curves and the equilibrium moisture content were determined using three different air-drying conditions. The analysis of the results shows the importance of drying temperature during the process: the increase in temperature decreases the drying time, as well as the equilibrium moisture content reached. Additionally, it can be verified the influence of the structure and morphology of the product, both in the drying progress and time. Raspberry takes less time to start the constant drying phase and to reach the equilibrium moisture than blueberries.

The products studied, when submitted to the drying process, change their chemical characteristics. The parameters were analyzed to highlight the effect of temperature on the reduction of fats, phenolic compounds and antioxidant activity. The most favorable drying test was verified at 40 °C and at 10% of relative humidity.

The evolution of fats, proteins, phenolic compounds and antioxidant activity in drying products are related, but further studies are needed to be better understand the transformations occurring on a molecular level.

The field test with a solar drier demonstrated the importance of using solar energy in drying processes. A significant reduction in electricity consumption was observed with the utilization of solar energy and consequently, a reduction in CO_2 emissions. Further tests will be performed to better understand and evaluate the advantages of the use of solar energy as the main energy for high-quality food drying.

CRediT authorship contribution statement

C. Catorze: Conceptualization, Methodology, Project administration, Funding acquisition, Writing – original draft. **A.P. Tavares:** Investigation. **P. Cardão:** Investigation. **A. Castro:** Investigation. **M.E. Silva:** Data curation, Writing – review & editing. **D.W. Ferreira:** Data curation, Writing – review & editing. **S. Lopes:** Conceptualization, Methodology, Data curation, Writing – review & editing. **I. Brás:** Methodology, Writing – original draft, Resources, Validation, Writing – review & editing.

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.

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References

[1] Erbay Z, Icier F. A review of thin layer drying of foods: Theory, modeling and experimental results. Crit Rev Food Sci Nutr 2010;50(5):441–64.
[2] Baker Christopher GJ. Industrial drying of Foods. Wantage, UK: Blackie Academic & Professional; 1997.
[3] Machado AM, de Souza MC, Saraiva SH, Teixeira LJQ. Cinéticas de secagem. In: Enciclopédia biosfera, Vol. 8, no. 15. Goiânia: Centro Científico Conhecer; 2012, p. 428–37.
[4] Buckner B, Fischler C, Gustafson E, Reilly J, Riccardi G, Ricordi C, et al. Food waste: Causes, impacts and proposals. Italy: Barrilha Center for Food Nutrition; 2012.
[5] Celestino SMC. Princípios de secagem de alimentos. Plenaltina DS, Brasil.: Emprapa Cerrados; 2010.
[6] Strumiłło C, Jones PL, Zyłła R. Energy aspects in drying. In: Mujumdar AS, editor. International handbook of industry drying. 1st ed.. CRC Press; 2014, p. 1075–102. http://dx.doi.org/10.1201/b17208-59.
[7] Vlachos N, Karapantsios T, Balouktsis A, Chassapis D. Design and testing of a new solar dryer. Drying Technol 2002;20. http://dx.doi.org/10.1081/DRT-120004050.
[8] Tiwari A. A review on solar drying of agricultural produce. J Food Process Technol 2016;9. http://dx.doi.org/10.4172/2157-7110.1000623.
[9] Eswara AR, Ramakrishnarao M. Solar energy in food processing—a critical appraisal. J Food Sci Technol 2013;50:209–27. http://dx.doi.org/10.1007/s13197-012-0739-3.
[10] AOAC. In: Horwitz William, editor. Official methods of analysis of AOAC international. Gaithersburg, Maryland.; 2002.
[11] Galvani F, Gaertner E. Adequação da Metodologia Kjeldahl para determinação de Nitrogênio Total e Proteína Bruta. Circ Téc 2006;4:1–9, Avaiable in: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/812198/adequacao-da-metodologia-kjeldahl-para-determinacao-de-nitrogenio-total-e-proteina-bruta.
[12] Ferreira D, Guyot S, Marnet N, Delgadillo I, Renard CMG, Coimbra MA. Composition of phenolic compounds in a Portuguese pear (Pyrus communis L. Var. S. Bartolomeu) and changes after sun-drying. J Agric Food Chem 2002;50(16):4537–44.
[13] Brand-Williams W, Cuvelier ME, Berset C. Use of a free radical method to evaluate antioxidant activity. LWT Food Sci Technol 1995;28:25–30.
[14] Santos AA, Deoti JR, Müller G, Dário MG, Stambuk BU, Junior SLA. Microwell plate-based method for the determination of reducing sugars with the dns reagen. Braz J Food Technol 2017. http://dx.doi.org/10.1590/1981-6723.11315.

[15] Tavares A, Brás I, Silva ME. Valorização de produtos alimentares sazonais. Parte I - Caraterização físico-química de framboesa, mirtilo e salicórnia fresca cultivada em Portugal. 2020, p. 143–9. http://dx.doi.org/10.29352/mill0207e.16.00375, Millenium, 2 (ed espec n°7).
[16] Soares SE. Ácidos fenólicos como antioxidantes. Rev Nutr 2002;15(1):71–81. http://dx.doi.org/10.1590/S1415-52732002000100008.
[17] Efraim P, Pezoa-García NH, Jardim DCP, Nishikawa A, Haddad R, Eberlin MN. Influência da fermentação e secagem de amêndoas de cacau no teor de compostos fenólicos e na aceitação sensorial. Ciênc Tecnol Aliment 2010;30:142–50. http://dx.doi.org/10.1590/S0101-20612010000500022.
[18] Fernandes PAR, Ferreira SS, Bastos R, Ferreira I, Cruz MT, Pinto A, et al. Apple pomace extract as a sustainable food. Ingred Antioxid 2019;8(6):189. http://dx.doi.org/10.3390/antiox8060189.
[19] Direção geral de Energia. Indicadores energéticos. 2021, p. 1995–2019, Avaiable in: https://www.dgeg.gov.pt/pt/estatistica/energia/indicadores-energeticos.