18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0189
PERFORMANCE EVALUATION OF AN INDIRECT SOLAR DRYER FOR CORN DRYING

Gisele Mol da Silva
Pontifícia Universidade Católica de Minas Gerais, Av. Dom José Gaspar, 500. Belo Horizonte, MG
Centro Federal de Educação Tecnológica de Minas Gerais, Av. Amazonas, 7675, Belo Horizonte, MG
g.mols@cefetmg.br, g.mols@hotmail.com

André Guimarães Ferreira
Rogério Morouço Coutinho
Centro Federal de Educação Tecnológica de Minas Gerais, Av. Amazonas, 7675, Belo Horizonte, MG
agferreira@cefetmg.br, rogeriomorouco@yahoo.com.br

Cristiana Brasil Maia
Pontifícia Universidade Católica de Minas Gerais, Av. Dom José Gaspar, 500. Belo Horizonte, MG
cristiana@pucminas.br

Abstract. *The importance of reducing postharvest losses and preservation of food products has been increasing worldwide. Drying is considered as an efficient way to increase the store agricultural products, with reduced risk of deterioration. However, the drying process affects the final quality of the dried products. In the present work, experimental investigations carried out on drying of corn kernels in an indirect solar dryer and open sun drying are presented. Results showed that the, for an average solar radiation of 652 W/m2 and ambient temperature of 30.4 °C, the dryer reduced the moisture content of the products from 22.5% to 12.8% in 7 h, with a drying efficiency 6.1%. The open sun drying did not succeed to obtain the final desired moisture content of 13.0% in 24 h.*

Keywords: *Drying efficiency, solar dryer, open sun drying*

1. INTRODUCTION

Inadequate preservation techniques and poor storage provisions lead to deterioration in the quality of agricultural products. Drying is a processing technique used to reduce postharvest losses and food product preservation (Lingayat et al. 2020). In tropical countries, conventionally, the drying of agricultural products has been carried out in the open sun drying (Lakshmi et al. 2019). The disadvantages of open sun drying are uncontrolled heat transfer to the product, slow drying rate, requirements of more yard space, and possible contamination with dust, dirt, rainfall, insects and microorganisms, which lead to losses of quality (Ssemwanga, Makule, and Kayondo 2020; Pochont et al. 2020; Lakshmi et al. 2018).

The limitations of open sun drying have led to the development of more advanced techniques of food drying. The hot drying airflow can be obtained using several energy sources, but solar energy is a renewable and cheap energy source. Solar dryer is a device which exploits solar energy to add significant amount of heat to a product and extract humidity from it without affecting its quality (El Hage et al. 2018). A comprehensive review of the status of solar drying technologies in developing countries is presented in paper (Vijayavenkataraman, Iniyan, and Goic 2012). The various designs of solar dryers, its types and performance analysis are reviewed.

The comparison of solar drying and open sun drying was performed in several works. The drying behavior of grapes was evaluated in an indirect solar dryer in Morocco (Essalhi et al. 2018). The solar dyer consists of a solar collector, a heat exchanger, a water storage tank and a drying chamber. The drying of red pepper grown in the North of Tunisia was studied in a mixed mode solar greenhouse dryer with forced convection (EL khadraoui et al. 2019). The drying behavior of Indian red chilli was assessed in a solar hybrid greenhouse dryer (Pochont et al. 2020). To the best knowledge of the authors, only a few works were developed on the drying of corn (Rahmanian-Koushkaki et al. 2017; Khanali, Khakpour Giglou, and Rafiee 2018; Wei et al. 2019), all developed under different conditions than those evaluated in this paper.

In this work, it is evaluated a sustainable indirect solar dryer used to dry corn kernels. The dryer consists of a solar collector, a drying chamber, a PV system and an electric heater. The electric heater is used when the drying air temperature is lower than ambient temperature. The sustainable characteristic is given by the use of a PV system to feed the fans and the electric heater. This study is conducted to experimentally compare the drying behavior of corn kernels dried in the dryer and open sun drying respectively.

2. MATERIALS AND METHODS

2.1 Description of the drying system

The drying system under study is a sustainable mixed active solar dryer. The system consists of three main parts, which are a PV system, a solar collector, and a dryer chamber. The sustainable characteristic is the use of the PV system (composed of a PV module, batteries, and a charge controller) to feed the fans and an electric heater. The scheme of the drying system is shown in Fig. 1.

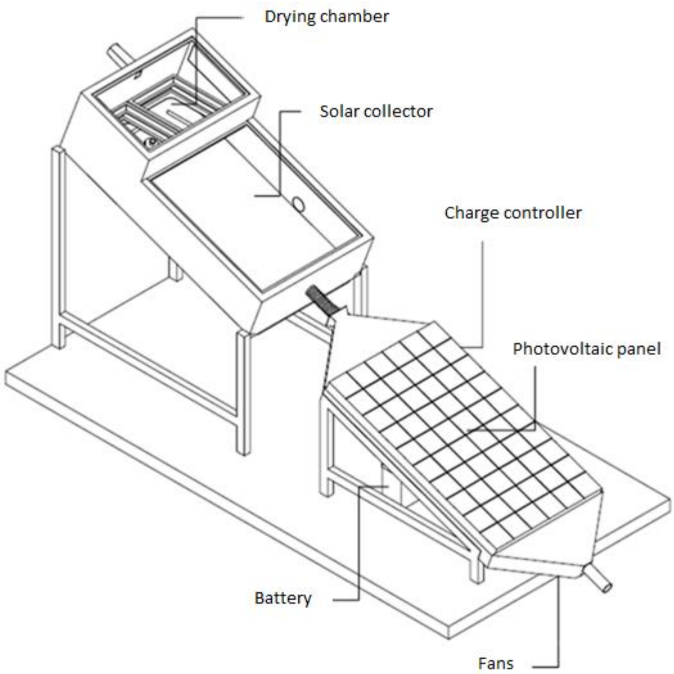

Figure 1. Solar drying system

The drying system consists of the solar dryer and some complementary equipment. The solar dryer consists of the solar collector, responsible for heating the air flow, and the drying chamber, where the trays are positioned. The solar absorber is made of galvanized steel sheet painted in matte black to maximize radiation absorption. The cover is made of 8mm tempered glass. The dryer is 1000 mm wide, 1800 mm long and 500 mm high. The internal structure of the dryer is made of wood. The dryer is covered internally and externally by galvanized steel sheets. The thermal insulation is made of glass wool.

The complementary equipment are fans, battery, photovoltaic panel and charge controller. The equipment allows the system to operate autonomously, in direct current.

The drying system was installed on the roof of the Materials Engineering Department, on Campus I of CEFET-MG, in the city of Belo Horizonte (latitude of 19°55'S). The location is flat, with no interference of elements that may generate shading on it and supported by a metallic structure that prevents its contact with the moisture of the floor. The drying system was positioned according to the works of (Villalva, Marcelo Gradella; Gazoli 2012; Duffie and Beckman 2013), who suggest that the collector should be facing the opposite hemisphere with a slope equal to latitude. The drying system was then positioned with an inclination angle of 20° to maximize the incident radiation throughout the year (Duffie and Beckman 2013).

The airflow is forced by the fans to cross a duct below the PV module. When the PV module is operating, it dissipates energy and the airflow is heated when in thermal contact with its lower surface. The power output generated by the PV module is used to feed the fans and the remaining energy is stored in the batteries. The energy stored is also used to feed the fans when there is no incidence of solar radiation. After crossing the duct, the airflow enters the dryer and is heated by the solar collector surface. At the end of the collector, the airflow enters the drying chamber, where the trays with the corn grains are positioned and removes moisture from the products. Then, the wet airflow leaves the dryer.

The operating scheme of the drying system is shown in Fig. 2.

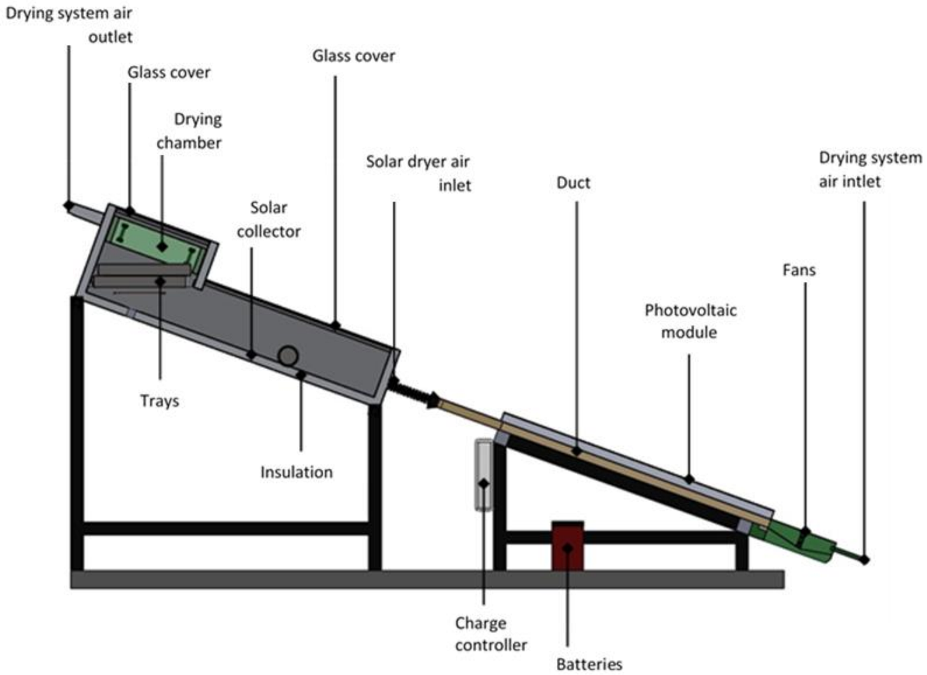

Figure 2. Operation diagram of the drying system

The drying load was 16 kg of corn, distributed directly on four trays arranged in two different levels, in order to allow the airflow of move between the grains of the product.

The drying system worked with forced air flow using two fans positioned at the entrance of the duct under the PV module. The desired final moisture content of the corn was 13.5%. Below this value, most of the fungi that attacks the grain practically interrupt their development.

2.2 Experimental procedure

Measurements of solar radiation, air temperature, relative humidity and instant moisture content of the product were made on a wet basis. The measurement period comprised the time from 7:30 am to 5:30 pm (solar time). The measurements were performed at every 30 minutes, according to the procedure adopted by the paper (Celma and Cuadros 2009). The determination of the initial moisture content of the product was performed 24 hours after the beginning of the tests, using a drying oven at 105° C.

The tests were performed on September 27, corresponding to early Spring. In this month, historically, the city shows little rain and a significant increase in solar irradiation compared to the rest of the year (Tiba 2000).

The ambient and airflow parameters were measured with calibrated instruments. The uncertainty analyzes were performed according to Joint Committee for Guides in Metrology (Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG1) 2008).

Solar radiation was measured using a pyranometer (Hukseflux thermal sensors, model SR05-DA2). The thermo-psychrometer (model AKSO, AK174) was used to measure air humidity and drying air temperature at the inlet and outlet of the dryer. The flow velocity was measured with an anemometer (ICEL AN-4870). Digital electronic scale (Toledo, model nº 9094), with a capacity of 6 kg, with an accuracy of ± 1 g, was used to weigh the corn.

3. MODELING OF THE DRYING SYSTEM

The drying efficiency is defined by the ratio of the energy used to evaporate the product moisture and the energy supplied to the control volume (Fudholi et al. 2014). This refers to the solar radiation on the photovoltaic module, the absorber and the drying chamber.

The drying efficiency can be calculated by

$$\eta = \frac{m_{H_2O} L}{\int (A_m + A_a + A_c)\, G\, dt}\ x\ 100 \quad (1)$$

where η, m_{H2O}, L, G, A_m, A_a e A_c are the drying efficiency [%], the product's evaporated water mass [kg], the latent heat of water vaporization at the average air inlet and outlet temperature [kJ/kg], solar irradiation [kW/m²] and the surface areas of the photovoltaic panel, the glass cover on the solar collector and the glass cover on the drying chamber, respectively [m²].

The moisture content of corn can be expressed on a dry or wet basis. For agricultural products it is usual for moisture to be determined on a wet basis. Equation (2) defines how the moisture content of the product on a wet basis is calculated (Belessiotis and Delyannis 2011).

$$W_{sp} = \frac{(m_{sp})_i - (m_{sp})_e}{(m_{sp})_i}\ x\ 100 \quad (2)$$

where W_{sp}, $(m_{sp})_i$ e $(m_{sp})_e$ are the total moisture content of the sample on a wet basis [%], the initial mass of the sample (wet) and the final mass of the sample (dry), respectively [kg].

The moisture content of the sample, on a wet basis, is obtained by

$$W_x = 100 - \left[\frac{(m_p)_i}{(m_p)_x}\ x\ (100 - W_{sp})\right] \quad (3)$$

where W_x, W_{sp}, $(m_p)_i$ e $(m_p)_x$ are the instant moisture content of the product on a wet basis [%], the total moisture content of the sample on a wet basis [%] and the initial mass and instantaneous mass of the product, respectively [kg].

The comparison of the performance of the solar dryer in relation to the drying time with drying in the sun using (Fudholi et al. 2014)

$$S = \frac{t_{sun} - t_{sd}}{t_{sun}}\ x\ 100 \quad (4)$$

Where S, t_{sun} e t_{sd} are the reduction in drying time [%], the duration of drying of the product in the sun until the required moisture content is reached [h] and the duration of drying of the product in the solar dryer until the content of required humidity is reached [h].

4. RESULTS AND DISCUSSION

The drying system operated on September 27 for the drying of corn kernels. Some of the characteristics of the drying process are shown in Tab. 1.

Table 1. Performance summary of the loaded drying system.

Parameter	Value
Initial product weight [kg]	16.000
Final product weight [kg]	14.220
Initial moisture content - wet basis [%]	22.5
Final moisture content - wet basis [%]	12.8
Average drying time until 13% moisture content is reached [h]	9.0
Average solar radiation [W / m²]	652
Average ambient temperature [° C]	30
Average drying chamber temperature [° C]	54
Average relative humidity of the air at the entrance of the drying system [%]	38
Average relative humidity of the air at the exit of the drying system [%]	26
Average drying efficiency [%]	6.1

During the experiment, the day was sunny, with clouds appearing at 13:30 hours. The rest of the day remained clear, with an average clearness index of 70%. The average solar irradiation in the period (7:30 am to 5:30 pm) was (652 ± 11) W/m² and the maximum solar irradiation recorded was (990 ± 11) W/m² at 12: 00h and 12: 30h, as can be seen observed in Fig. 3. The ambient temperature during the test ranged from 22.9 ° C to 35.2 ° C.

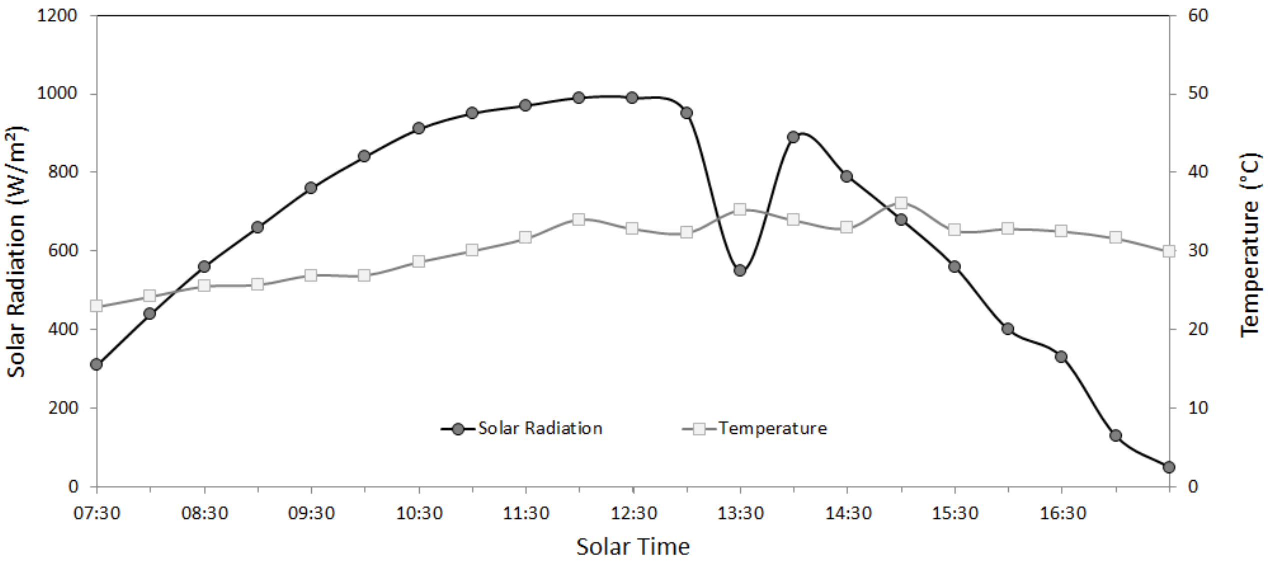

Figure 3. Solar irradiation and ambient temperature

To evaluate the performance of the drying process, it is essential to obtain the drying curve. It is possible to determine the instant moisture content, the time necessary to reach the required humidity, as well as to compare the performance of the drying process carried out in the solar dryer with natural open sun drying. The corn drying curve is shown in Fig. 4. 2.

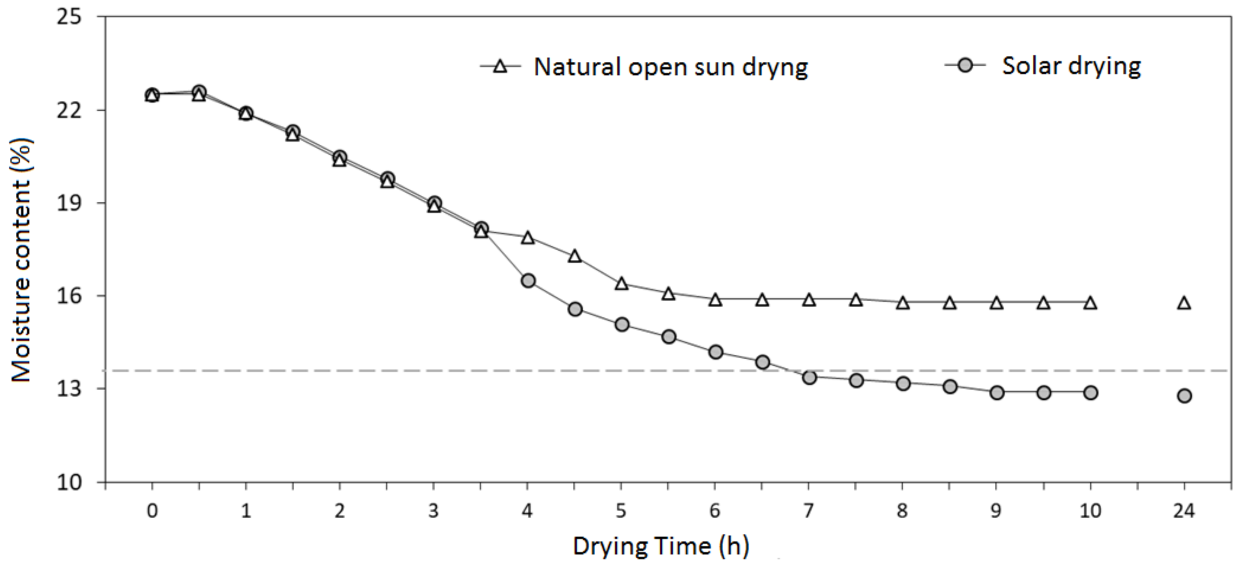

Figure 4. Drying curves

Natural open sun drying failed to achieve the desired moisture content (13.5%) in 24 hours, while in solar drying the desired moisture content was achieved in approximately 7 hours. A lower drying speed was observed in the natural process, after the corn reached about 16% humidity (around 13: 00h). This is due to the fact that the corn had reduced humidity, requiring a higher heat rate to continue the removal of moisture. However, it is noteworthy that at 13:00h the solar radiation was still high (950 ± 10) W/m², but the ambient temperature was much lower than that of the airflow in the dryer.

There is no guarantee that natural open sun drying will reach the necessary humidity. Once the product is in equilibrium with the ambient air, the drying process is interrupted, as explained by (Ekechukwu and Norton 1999). Normally it is close to 12:00 the next day, when the irradiation is maximum, that the moisture content decreases again, because for lower temperatures, the corn will possibly be in equilibrium with the ambient air. Similarly, (Selvaraj and Natarajan 2017), when studying the drying kinetics of saffron, observed that when the equilibrium humidity between the sample and the drying air was reached, there was no further change in the sample mass.

To assess the drying duration, two analyzes were performed. The first considered the final moisture content of corn equal to 15.8% (minimum value achieved in natural open sun drying). In this case, the natural open sun drying time was 44% longer than drying using the dryer. The second analysis assumed, at best, that dry corn would naturally reach a moisture content of 13.5% with 32 hours of drying (at 15: 30h of the day after the start of the test). Considering this premise, the natural open sun drying time would be 78% longer than when drying using the solar dryer.

The initial and final moisture content of the corn, on a humid basis, are recorded in Table 2.

Table 2. Corn moisture content (wet basis).

	Corn moisture content (%)	
	Initial	Final
Solar dryer	22.5	12.8
Natural open sun drying	22.5	15.8

Corn mass measurements for the determination of the moisture content were carried out between 7:30 am and 5:30 pm and interrupted until 7:30 am the next day, when a final product moisture assessment was carried out. It was observed that there was no moisture absorption during the night by the dry corn in the dryer, nor naturally, since the moisture content remained the same. This stability of the moisture presented by the corn, mainly in natural drying, was attributed to the low relative humidity of the air that remained below (62.4 ± 1.9)%, presenting an average of 49% at night (17: 30h to 7: 30h).

Another fundamental point of the drying process is the control of the air flow temperature, which should not exceed 90° C in order to preserve the physical integrity and nutritional quality of the corn kernels, that is, the quality achieved by the product. The drying air temperature did not exceed 90 ° C at any time during the day. The airflow and ambient temperature values obtained for the drying air are shown in Fig. 5.

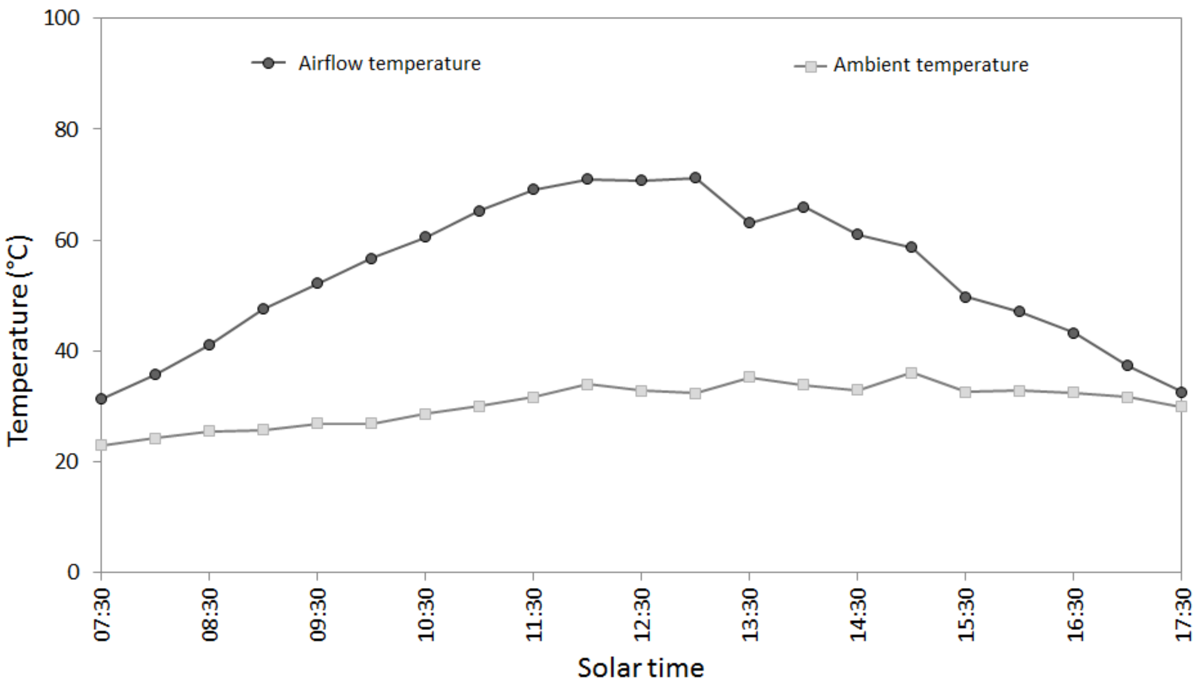

Figure 5. Drying temperature and ambient temperature

It can be seen (Figs. 3 and 5) that the airflow temperature varies according to solar irradiation. This effect can be seen at 1:30 pm, when there is a sudden drop in solar radiation and, as a consequence, in the air temperature in the dryer. In addition, the airflow temperature in the dryer reaches up to 38.9°C higher than the ambient temperature.

The drying efficiency of the system was calculated, obtaining the value of (6.1 ± 0.1)% for reducing the moisture content of the corn from 22.5% to 12.8%. It is worth noting that this same dryer, before the introduction of complementary equipment, was studied by other researchers, such as (SILVA 2014), who dried ore with an average drying efficiency of 2.5%. In (Oliveira 2014), bananas were dried under different conditions, with initial and final moisture levels around 78% and 58%, respectively, reaching an average drying efficiency of 4.1% and a maximum of 6%. The results of the first tests allowed the author to make adjustments to the process (maximum load and minimum mass flow), increasing the drying efficiency to 18.8%. In (Ferreira, Gonçalves, and Maia 2014), the same dryer was used to dry solid waste from the steel wire industry. The initial and final humidity of the product were 70% and 30%, respectively. The drying efficiency varied from 5.2% to 7.2% and, as stated by the authors, the efficiency achieved was of the same order of magnitude as similar solar dryers; although it has been stated that the comparison of dryer efficiencies is not relevant, since the operating conditions and product characteristics have a significant influence on drying efficiency and they were not similar.

It is worth mentioning that the greater the amount of dough and or the greater the moisture content of the product to be dried, the greater the drying efficiency. In the case of corn, the initial moisture content is relatively low when compared to other products, since it should only be harvested after reaching physiological maturity. At this stage, the corn is between 30 and 38% moisture content. However, the harvest must happen when the corn reaches between 18 to 25% of moisture if it is submitted to the drying process before being stored (Magalhães and Durães 2006).

5. CONCLUSIONS

In this study, an experimental analysis of the drying of corn grains in a sustainable mixed active solar dryer.

It was observed a direct relation between solar irradiation and ambient temperature.

The greater the drying temperature, the greater the air's ability to remove water from the product. As the product dries, less humidity is available to be eliminated making it more difficult to remove. At the beginning of the drying process, the moisture content of the product and the drying efficiency are high.

The drying process was compared to natural open sun drying. It was observed that the drying efficiency of the dryer was 6.1% and the duration of natural open sun drying was approximately 44% higher than drying with the dryer, for a final product moisture of 15.8%.

6. ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001. The authors are also thankful to FAPEMIG, CNPq, CEFET-MG and PUC Minas.

7. REFERENCES

Belessiotis, V., and E. Delyannis. 2011. “Solar Drying.” *Solar Energy* 85 (8): 1665–91. https://doi.org/10.1016/j.solener.2009.10.001.

Celma, A. R., and F. Cuadros. 2009. “Energy and Exergy Analyses of OMW Solar Drying Process.” *Renewable Energy* 34 (3): 660–66. https://doi.org/10.1016/j.renene.2008.05.019.

Duffie, John A., and William A. Beckman. 2013. *Solar Engineering of Thermal Processes: Fourth Edition*. *Solar Engineering of Thermal Processes: Fourth Edition*. https://doi.org/10.1002/9781118671603.

Ekechukwu, O. V., and B. Norton. 1999. “Review of Solar-Energy Drying Systems II: An Overview of Solar Drying Technology.” *Energy Conversion and Management*. https://doi.org/10.1016/S0196-8904(98)00093-4.

Essalhi, Hajar, Mohamed Benchrifa, Rachid Tadili, and M. N. Bargach. 2018. “Experimental and Theoretical Analysis of Drying Grapes under an Indirect Solar Dryer and in Open Sun.” *Innovative Food Science and Emerging Technologies*. https://doi.org/10.1016/j.ifset.2018.08.002.

Ferreira, André Guimarães, Lindomar Matias Gonçalves, and Cristiana Brasil Maia. 2014. “Solar Drying of a Solid Waste from Steel Wire Industry.” *Applied Thermal Engineering* 73 (1): 104–10. https://doi.org/10.1016/j.applthermaleng.2014.07.047.

Fudholi, Ahmad, Kamaruzzaman Sopian, Mohammad H. Yazdi, Mohd Hafidz Ruslan, Mohamed Gabbasa, and Hussein A. Kazem. 2014. “Performance Analysis of Solar Drying System for Red Chili.” *Solar Energy* 99: 47–54. https://doi.org/10.1016/j.solener.2013.10.019.

Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG1). 2008. “Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement.” *International Organization for Standardization Geneva ISBN* 50 (September): 134. https://doi.org/10.1373/clinchem.2003.030528.

Hage, Hicham El, Amal Herez, Mohamad Ramadan, Hassan Bazzi, and Mahmoud Khaled. 2018. “An Investigation on Solar Drying: A Review with Economic and Environmental Assessment.” *Energy* 157: 815–29. https://doi.org/10.1016/j.energy.2018.05.197.

khadraoui, Aymen EL, Ilhem Hamdi, Sami Kooli, and Amenallah Guizani. 2019. “Drying of Red Pepper Slices in a Solar Greenhouse Dryer and under Open Sun: Experimental and Mathematical Investigations.” *Innovative Food Science and Emerging Technologies*. https://doi.org/10.1016/j.ifset.2019.01.001.

Khanali, Majid, Asgar Khakpour Giglou, and Shahin Rafiee. 2018. “Model Development for Shelled Corn Drying in a Plug Flow Fluidized Bed Dryer.” *Engineering in Agriculture, Environment and Food*. https://doi.org/10.1016/j.eaef.2017.09.002.

Lakshmi, D. V.N., P. Muthukumar, Apurba Layek, and Prakash Kumar Nayak. 2018. “Drying Kinetics and Quality Analysis of Black Turmeric (Curcuma Caesia) Drying in a Mixed Mode Forced Convection Solar Dryer

Integrated with Thermal Energy Storage." *Renewable Energy*. https://doi.org/10.1016/j.renene.2017.12.053.
Lakshmi, D. V.N., P. Muthukumar, Apurba Layek, and Prakash Kumar Nayak, 2019. "Performance Analyses of Mixed Mode Forced Convection Solar Dryer for Drying of Stevia Leaves." *Solar Energy*. https://doi.org/10.1016/j.solener.2019.06.009.
Lingayat, Abhay Bhanudas, V. P. Chandramohan, V. R.K. Raju, and Venkatesh Meda. 2020. "A Review on Indirect Type Solar Dryers for Agricultural Crops – Dryer Setup, Its Performance, Energy Storage and Important Highlights." *Applied Energy*. https://doi.org/10.1016/j.apenergy.2019.114005.
Magalhães, Paulo Cesar, and Frederico O M Durães. 2006. "Fisiologia Da Produção de Milho." *Circular Técnica,76* d: 10. https://doi.org/ISSN 1679-1150.
Oliveira, Alexandre Melo. 2014. "Estudo Experimental Da Secagem de Banana Utilizando Secador Solar." CEFET MG.
Pochont, Nitin Ralph, Mohammad Noor Mohammad, Bodepu Thrinadh Pradeep, and P. Vijaya Kumar. 2020. "A Comparative Study of Drying Kinetics and Quality of Indian Red Chilli in Solar Hybrid Greenhouse Drying and Open Sun Drying." In *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2019.05.433.
Rahmanian-Koushkaki, H., A. Nourmohamadi-Moghadami, D. Zare, and G. Karimi. 2017. "Experimental and Theoretical Investigation of Hot Air- Infrared Thin Layer Drying of Corn in a Fixed and Vibratory Bed Dryer." *Engineering in Agriculture, Environment and Food*. https://doi.org/10.1016/j.eaef.2017.01.004.
Selvaraj, Karthikeyan, and Alagumurthi Natarajan. 2017. "Factors Influencing the Performance and Productivity of Solar Stills - A Review." *Desalination,* 2017. https://doi.org/10.1016/j.desal.2017.09.031.
SILVA, Sérgio Luiz Carvalho da. 2014. "Avaliação Da Eficiência Energética e Exergética de Um Secador Solar Industrial Na Secagem de Minério." Centro Federal de Educação Tecnológica de Minas Gerais.
Ssemwanga, M., E. Makule, and S. I. Kayondo. 2020. "Performance Analysis of an Improved Solar Dryer Integrated with Multiple Metallic Solar Concentrators for Drying Fruits." *Solar Energy*. https://doi.org/10.1016/j.solener.2020.04.065.
Tiba, Chigeru. 2000. "Atlas Solarimétrico Do Brasil: Banco de Dados Terrestres." *Atlas Solarimétrico Do Brasil* 1: 111. http://www.cresesb.cepel.br/publicacoes.
Vijayavenkataraman, S., S. Iniyan, and Ranko Goic. 2012. "A Review of Solar Drying Technologies." *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2012.01.007.
Villalva, Marcelo Gradella; Gazoli, Jonas Rafael. 2012. *Energia Solar Fotovoltaica: Conceitos e Aplicações*. *Creative Commons*.
Wei, Shuo, Zhenhua Wang, Fenghe Wang, Weijun Xie, Pengxiao Chen, and Deyong Yang. 2019. "Simulation and Experimental Studies of Heat and Mass Transfer in Corn Kernel during Hot Air Drying." *Food and Bioproducts Processing*. https://doi.org/10.1016/j.fbp.2019.08.006.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.