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Thermodynamic analysis of a sustainable hybrid dryer

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ABSTRACT

In this study, an energy and exergy analysis of the drying process of corn was developed for a hybrid dryer coupled with a PV system. The differential of the dryer is the fact that the PV system was used to feed an electrical heater and fans and also to preheat the drying air through the use of the PV panel rear side as heat exchanger, increasing the air temperature before the inlet of the solar collector. The performance of solar drying processes is extensively investigated in the literature, but usually the drying chamber is used as control volume in the analysis. The main contribution of this work is the assessment and comparison of the performance of the dryer using three different control volumes in the thermodynamic analysis: only the drying chamber, the drying chamber and the solar collector, referred to as solar dryer and the complete drying set, corresponding to the drying chamber, the solar collector and the PV module. The results indicated that the efficiency values found are greatly affected by the control volume used, with variations of the exergy efficiency ranging from 22.2% to 45.0%, depending on the control volume used. It was found that the higher efficiencies were found selecting the drying chamber as control volume (as usually chosen by most works from literature). For the complete drying set, the individual contributions of the exergy rates were evaluated. It was concluded that the main contribution to the input and output exergy are the heat transfer and the outflow exergy rates, respectively.

1. Introduction

Drying is a highly energy-intensive process. Solar radiation is a free source of energy which can be harnessed for drying (Poblete and Painemal, 2020). In open or natural sun drying, the products are exposed directly to sunlight. It is widely used because it is cheap, easy and convenient (Aghbashlo et al., 2013). Nevertheless, the products are subject to degradation of quality due to the intermittence of climatic conditions and to the action of insects and animals (Kumar et al., 2016). Solar dryers are interesting alternatives to minimize losses from open sun drying and are subject of relevant research (Azaizia et al., 2020; Bhardwaj et al., 2019; Essalhi et al., 2018; Shrivastava and Kumar, 2016; Vengsungnle et al., 2020). An extensive review of solar dryers for agricultural products in Africa and Asia has been developed (Udomkun et al., 2020). However, solar dryers may present reduction of the quality of the dried product due to intermittent availability of solar energy, seasonal fluctuations and unexpected rain (Abubakar et al., 2018; Lakshmi et al., 2018). Hybrid solar dryers can overcome some of these drawbacks by utilizing an additional source of heat energy or thermal energy storage (Lamidi et al., 2019; Vásquez et al., 2019), allowing the drying to be completed without stopping and saving the products without spoilage (Amer et al., 2018; Ssemwanga et al., 2020). Also, the use of hybrid dryers enhance thermal performance and increase energetic and exergetic efficiency of the process (Sansaniwal et al., 2018). Huge effort should be carried out to enhance and promote solar drying, and implementing hybrid systems coupling solar dryers to other energy concepts could be an efficient solution especially for isolated regions (El Hage et al., 2018).

Additional sources for hybrid dryers can be liquefied petroleum gas (Murali et al., 2020), biomass (Abunde Neba and Jiokap Nono, 2017; Hamdani et al., 2018), geothermal (Sandali et al., 2019), electric (Huenulaf P, 2014) or a photovoltaic system (Chauhan et al., 2018; Daghigh et al., 2020; Eltawil et al., 2018a, 2018b; Fterich et al., 2018; Tiwari and Tiwari, 2016). Photovoltaic thermal collectors were successfully used (Daghigh et al., 2020; Fterich et al., 2018), showing increased efficiency and viability. It can be concluded that drying can be sustainably achieved when little or no fossil fuel input is used (Lamidi et al., 2019).

Usually, drying processes are inefficient operations (Boulemtafes-

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Nomenclature

c_p	specific heat at constant pressure, Jkg^{-1} K^{-1}
E_{inflow}	energy rate supplied to the dryer, W
$\dot{E}_{xd}$	destroyed exergy rate, W
$E_{xinflow}$	exergy supplied to the dryer, W
$E_{xoutflow}$	exergy leaving the dryer, W
gz	specific potential energy, Jkg^{-1}
h	specific enthalpy, Jkg^{-1}
m_i	initial mass of the product, kg
m_x	instantaneous mass of the product, kg
$\dot{m}$	air mass flow rate, kgs^{-1}
$\dot{m}_{da}$	mass flow rate of the dry air, kgs^{-1}
$(\dot{m}_{da})_{in}$	mass flow rate of the dry air at the inlet of the device, kgs^{-1}
$(\dot{m}_{da})_{out}$	mass flow rate of the dry air at the outlet of the device, kgs^{-1}
$\left(\dot{m}_{st_{H_2O}}\right)_p$	mass flow rate of the humidity of the product, kgs^{-1}
$\dot{m}_{wa}$	mass flow rate of the wet air, kgs^{-1}
$\dot{Q}$	useful energy, W
T	local temperature, K
T_S	surface temperature, K
T_∞	reference condition temperature, K
$\frac{1}{2}v^2$	specific kinetic energy, Jkg^{-1}
ω	air absolute humidity, $kgkg^{-1}$
ω_i	initial moisture content of the product, $kgkg^{-1}$
ω_{in}	air absolute humidity at the inlet of the device, $kgkg^{-1}$
ω_{out}	air absolute humidity at the outlet of the device, $kgkg^{-1}$
ω_x	instantaneous moisture content of the product, $kgkg^{-1}$
η_I	thermal efficiency
η_{II}	exergy efficiency

Boukadoum and Benzaoui, 2011), and research must be developed to increase the performance. Energy analysis is carried out to study performance of the process (Sansaniwal et al., 2018); however, it does not distinguish the quality of energy (Aghbashlo et al., 2013; Aviara et al., 2014). In drying processes, it is desirable to use as less energy possible for the maximum moisture removal for the required final conditions of the products. Consequently, energy quantity and quality should be investigated, therefore, the drying processes should be based both on energetic and exergetic balances of the process (Celma and Cuadros, 2009). The exergy analysis is an effective tool to investigate the quality of the drying (Vijayan et al., 2020). There is also a correlation between exergy and sustainable development since exergy is consumed or destroyed due to irreversibilities (Maia et al., 2013).

Various studies have been reported in literature on energy (Goud et al., 2019; Lingayat et al., 2020a) and exergy analysis of drying (Amjad et al., 2016; Fudholi et al., 2014; Karthikeyan and Murugavelh, 2018; Maia et al., 2017; Şevik et al., 2019; Tiwari and Tiwari, 2017). The thermal performance of a passive mixed solar dryer for tomato slices was evaluated in Mexico (Erick César et al., 2020). An analysis of energy efficiency of a forced convection mixed mode horizontal solar cabinet dryer was performed to the drying of black ginger (Ekka et al., 2020). An energy and exergy analysis was developed for a low-cost wind powered active solar dryer integrated with glycerol as thermal storage (Ndukwu et al., 2020). Most works from literature, however, use the drying chamber as control volume when assessing the exergy efficiency of the dryers. In this case, only a portion of the set is evaluated, which can weaken the analysis. An experimental investigation of the drying of stevia leaves in India was developed (Lakshmi et al., 2019). The authors performed the exergy analysis only in the drying chamber. The evaluation of the exergy efficiency of the drying of banana and bitter gourd was also developed in the drying chamber (Arun et al., 2020). The solar collector was selected in the analysis of the drying of medicinal herbs in a solar dryer incorporating sensible and phase change materials in Western Himalayan region (Bhardwaj et al., 2019). To the best knowledge of the authors, the influence of the control volume on the assessment of the exergetic and energetic performance indicators of the drying process was not evaluated in the literature. In the present work, three control volumes were used to assess the performance of the dryer when applying the thermodynamic analysis: only the drying chamber, the drying chamber and the solar collector (or absorber plate), referred to as solar dryer and the complete drying set, corresponding to the drying chamber, the solar collector and the PV module.

In our paper, the analysis was performed for the drying of corn inside a forced-ventilation solar-cabin hybrid dryer. Among the cereal grains, corn is the leading crop in terms of worldwide production and consumption (de Lima et al., 2017; Serna-Saldivar and Perez Carrillo, 2018). It is one of the most valuable livestock feed (Rahmanian-Koushkaki et al., 2017) and it is gaining economic importance with its use as biofuel. Only a few studies concerning corn drying are presented in the literature (Khanali et al., 2018; Rahmanian-Koushkaki et al., 2017; Wei et al., 2019), all developed under different conditions than those evaluated in this paper. A hot air-infrared dryer was used to evaluate the grain moisture variation (Rahmanian-Koushkaki et al., 2017), a plug flow fluidized bed dryer was used to dry shelled corn (Khanali et al., 2018). Corn kernel was dried using hot air to obtain experimental data to validate drying models (Wei et al., 2019). Recently, it was described an experimental analysis of corn drying in a hybrid dryer (da Silva et al., 2020). The main objectives of the present work are to perform a thermodynamic analysis of the drying process of corn inside a sustainable hybrid solar dryer. A PV system was used to feed the electrical heater and the fans, ensuring that the dryer can be used in locations without access to the power grid, as suggested by the literature. A PV operated system is preferred for forced convection in solar dryers (Lingayat et al., 2020b, 2020a). In the present work the PV module was also used to preheat the drying air in an innovative approach, increasing the temperature of the air at the inlet of the solar collector, reducing the absorption area required. An energy and exergy analysis was conducted, assessing the influence of the control volume on the evaluation of the performance of the device, comparing the results for three different control volumes. Also, for the complete drying set, the contribution of exergy rates was evaluated.

2. Materials and methods

2.1. Energy and exergy analysis

In a steady flow process, the mass conservation equations for the dry air and water can be written as:

$$\left(\dot{m}_{da}\right)_{in} = \left(\dot{m}_{da}\right)_{out} = \dot{m}_{da} \tag{1}$$

$$\omega_{in}\dot{m}_{da} + \left(\dot{m}_{st_{H_2O}}\right)_p = \omega_{out}\dot{m}_{da} \tag{2}$$

where $\dot{m}_{da}$, $(\dot{m}_{da})_{in}$, $(\dot{m}_{da})_{out}$ *and* $\left(\dot{m}_{st_{H_2O}}\right)_p$ represent, respectively, the mass flow rate of the dry air, of the dry air at the inlet and outlet of the device, and of the humidity of the product. ω_{in} and ω_{out} represent the air absolute humidity at the inlet and outlet of the device, respectively. Although the process is unsteady, quasi-steady conditions were

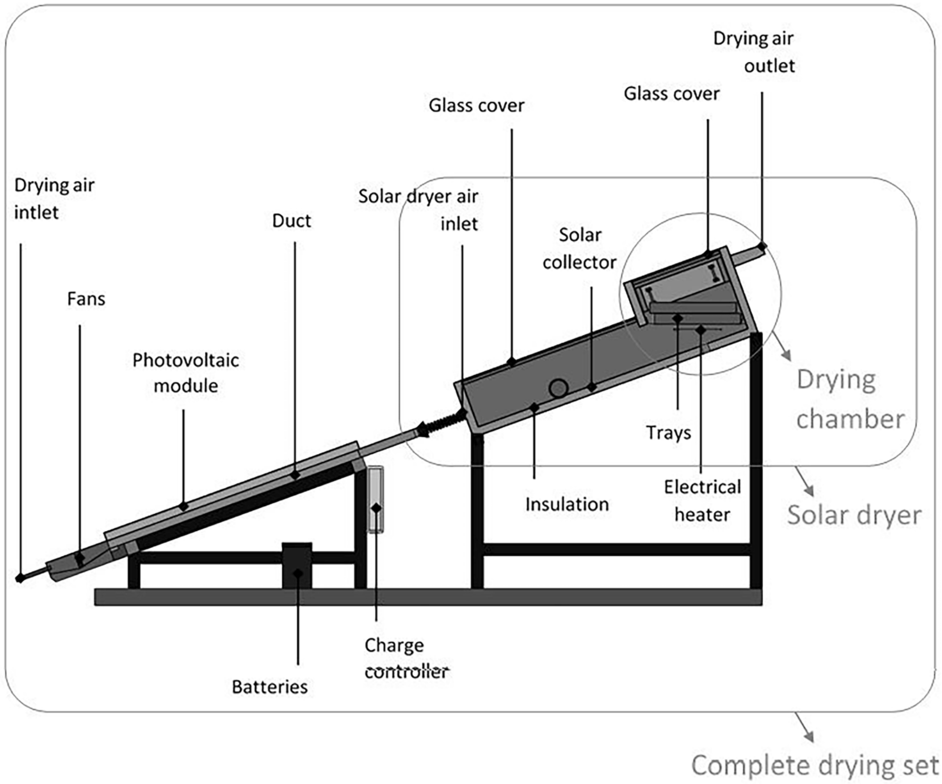

Fig. 1. Schematics of the dryer.

assumed, and the equations for steady state are valid (Medina, 1999).

The energy conservation equation is given by:

$$\dot{Q} = \sum_{out} \dot{m}\left(h + \frac{1}{2}v^2 + gz\right) - \sum_{in} \dot{m}\left(h + \frac{1}{2}v^2 + gz\right) \tag{3}$$

where $\dot{Q}$ is the useful energy gained by the airflow, $\dot{m}$ is the air mass flow rate, h is the specific enthalpy, $\frac{1}{2}v^2$ is the specific kinetic energy, and gz is the specific potential energy.

The second law of Thermodynamics can be written as:

$$\dot{E}_{xd} = E_{xinflow} - E_{xoutflow} = \left\{\dot{m}_{wa}\left(\frac{1}{2}v^2 + gz\right) + \left[\sum\left(1 - \frac{T_\infty}{T_s}\right)\dot{Q}\right] + \left[\sum \dot{m}_{wa}\left(c_p T_\infty\left(\frac{T}{T_\infty} - 1 - ln\frac{T}{T_\infty}\right)\right)\right]\right\}_{in} - \left\{\dot{m}_{wa}\left(\frac{1}{2}v^2 + gz\right) + \left[\sum \dot{m}_{wa}\left(c_p T_\infty\left(\frac{T}{T_\infty} - 1 - ln\frac{T}{T_\infty}\right)\right)\right]\right\}_{out} \tag{4}$$

where $\dot{E}_{xd}$ is the destroyed exergy rate, given as the difference between the inlet and outlet exergy rates, $E_{xinflow}$ and $E_{xoutflow}$. $\dot{m}_{wa}$ represents the mass flow rate of the wet air and T, T_∞ and T_S, the local temperature, the reference condition (ambient) temperature, and the surface temperature, respectively, and C_p represents the specific heat at constant pressure.

The mass flow rate of the wet air is given by

$$\dot{m_{wa}} = \dot{m_{da}}(1 + \omega) \tag{5}$$

where ω is the air absolute humidity.

The thermal efficiency η_I is defined as the ratio of the useful heat gained ($\dot{Q}$) to the energy supplied to the dryer (E_{inflow}), which refers to the solar radiation on the PV system, absorber plate, and drying chamber.

$$\eta_I = \frac{\dot{Q}}{E_{inflow}} \tag{6}$$

The exergy efficiency η_{II} is defined as the ratio of the exergy destroyed in the drying process (E_{xd}) to the exergy supplied to the dryer ($E_{xinflow}$) (Vijayan et al., 2020).

$$\eta_{II} = 1 - \frac{E_{xd}}{E_{xinflow}} \tag{7}$$

The exergy efficiency was determined considering three different situations: only the drying chamber, the solar collector and the drying chamber (referred to as solar dryer), and the complete drying set. Most works from literature evaluate only the drying chamber, and the results can be different according to the control volume used.

A drying curve usually plots the moisture content of the product versus the drying time. The instantaneous moisture content of the product ω_x can be expressed as (Mewa et al., 2019; Vijayan et al., 2020)

$$\omega_x = 1 - \left[\frac{m_i}{m_x}(1 - \omega_i)\right] \tag{8}$$

m_i and m_x are the initial and instantaneous mass of the product and ω_i is the initial moisture content of the product. To determine the initial moisture content of the product, a sample was placed inside a stove for 24 h at 105.0 °C.

Fig. 2. The hybrid dryer.

2.2. Materials

In this work, 16 kg of corn were dried inside a forced-ventilation solar-cabin hybrid dryer. A sample of the product was dried at 105.0 °C in a stove for 24 h to determine the initial moisture content.

The dryer was designed combining a PV system (composed of a polycristalline PV module, batteries, and a charge controller), a solar collector, and a drying chamber, as shown in Fig. 1. The air is forced by the fans (CPU cooling fans, of direct current and voltage of 24 V) and enters the dryer through a rectangular screened opening, exchanges heat with the lower part of the PV module and is directed to the solar collector, in which is heated by the incident solar radiation. The heated air enters the drying chamber, removes humidity from the products and leaves the device.

The PV system feeds the fans and an electric heater. The fans operate 24 h a day to ensure the airflow to the operation of the dryer. The drying process only occurs during the day. At night or when the solar irradiance is low enough, if the air temperature drops below ambient temperature, the electric heater works and heats the airflow, minimizing the probability of humidity reabsorption from the products. In preliminary tests, it was performed a drying test without the electrical heater and it was observed that, at night, the ambient temperature was always higher than the drying air temperature. When the electrical heater was put back on the system, the drying air was maintained higher than ambient temperature, which avoided the moisture reabsorption by the products.

The batteries accumulate the energy produced by the PV module and allow the fans to operate when there is no incidence of solar radiation and feed the electrical heater. The charge controller protects the PV module and batteries from eventual energy overloads and controls the charge and discharge status of the batteries. Fig. 2 presents a photograph of the device.

The structure of the dryer is made of wood and covered with galvanized steel sheets and thermal insulation (glass wool with 50 mm of thickness). The absorber plate is made of galvanized steel, painted in black, and covered by a glass cover (1.051 m × 0.853 m × 3.2 mm of length, width and thickness, respectively). The trays, of 520 mm × 420 mm, are made of galvanized wire mesh painted in black. The solar collector and the PV panel had an inclination of 20°, equal to the local latitude angle.

The experiments were performed in Belo Horizonte, Brazil (20°S latitude and 44°W longitude), at the beginning of the Spring. A sample of corn was put inside the dryer, and another sample was dried under the open sky, in the process referred to as natural sun drying. The samples have the same initial conditions (initial moisture content) and were exposed to the same ambient conditions (ambient temperature and solar radiation). Also, both the trays have similar areas and mass of products. The temperature measurements of the airflow inside the dryer and at the walls were made from K-type thermocouples. The temperature and humidity at the dryer inlet and outlet were measured using thermo-psychrometer sensors (AKSO, AK174 model). The velocity of the air at the outlet and inlet was measured with ICEL (AN-4870) anemometers. The incident solar radiation was measured with a pyranometer (Hukseffux thermal sensor, SR05, DA2 model). The samples of corn were weighted with a digital electronic balance (Toledo, 9094 model, 6 kg of capacity). It was developed an uncertainty analysis (Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG1), 2008). Fig. 3 shows the position of the sensors. The specification of the dryer and the equipment are shown in Tables 1 and 2, respectively.

The thermocouples are represented by numbers 3–6 and 9; the thermo-psychrometer sensors are represented by numbers 2 and 8, the anemometers are represented by numbers 1 and 10 and the pyranometer is represented by number 7.

3. Results and discussions

The drying test was performed at the beginning of the Spring in the southern hemisphere in 2018. The sky was cloudless, as shown in Fig. 4. The tests started at 7:30 a.m. The solar radiation intensity varied from a minimum of 40 to 1020 W/m^2, with an average of 684 W/m^2. The highest value was reached at around noon. The mass flow rate obtained was 0.0103 kg/s. The ambient temperature and ambient relative humidity are shown in Fig. 5. As expected, these parameters showed opposite trends: while the temperature increased from 22.8 °C to 33.9 °C, the relative humidity decreased from 57% to 28%.

The temperatures of the airflow inside the solar dryer ranged from 22.8 °C, at the inlet of the dryer, to 68.9 °C, at the inlet of the drying chamber, as seen in Fig. 6. The air enters the dryer at ambient temperature through a duct, as shown in Figs. 2 and 3. The duct is located under the lower surface of the PV module. Since the temperature of the PV module surface is higher than ambient temperature due to the dissipated heat, the drying air increases its temperature. After the PV module, the air is heated by the absorber and reaches its maximum value. In the drying chamber, the air temperature decreases when it removes water from the products. The maximum temperature was observed at the absorber plate, which reaches a maximum value of 101.4 °C.

The moisture content of the corn as a function of the drying time is presented in Fig. 7. The moisture content decreased from 23% to 13% after 8.5 h of drying inside the dryer, while natural sun drying failed to reach this value in 24 h.

The performance of the dryer can be assessed by thermal and exergy efficiencies. When the thermodynamic analysis is performed, it is essential to accurately define the control volume used. In this work, three different control volumes were evaluated: only the drying chamber, the solar collector and the drying chamber (referred to as solar

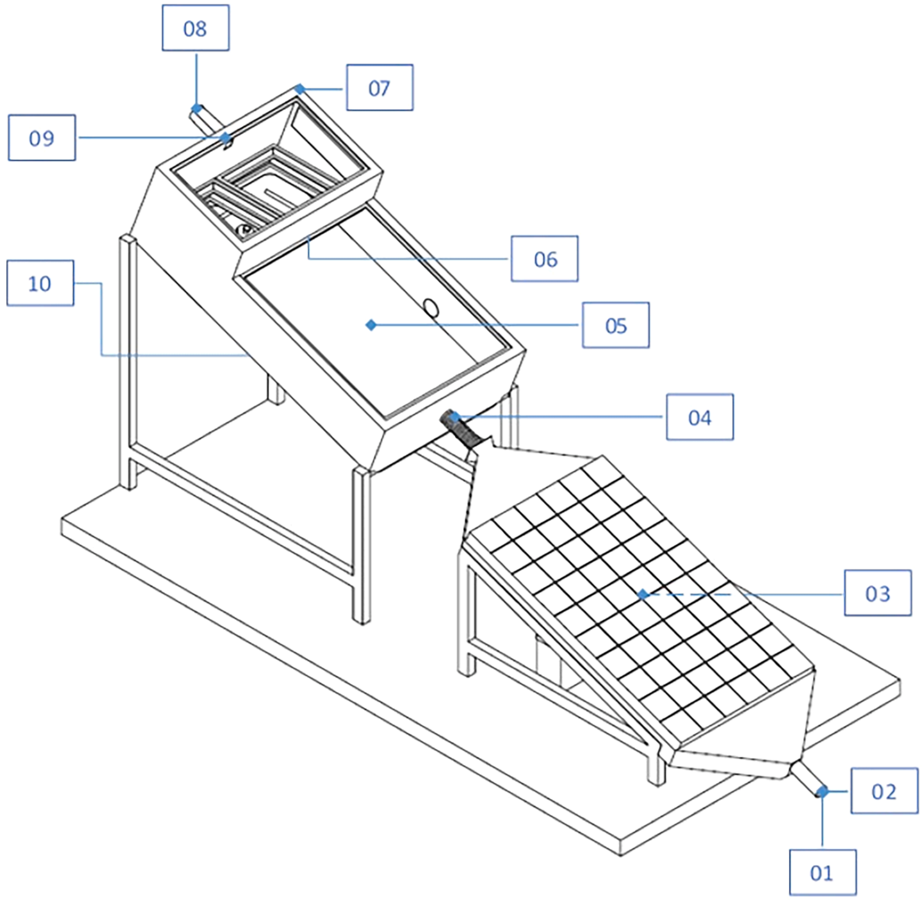

Fig. 3. Position of the sensors.

Table 1
Specifications and parameters of the dryer.

Drying chamber (Length × width × height)	557 mm × 910 mm × 560 mm
Absorber plate (Length × width)	1113 mm × 910 mm
PV module (Length × width)	1650 mm × 992 mm
PV module (nominal power)	270 W
Electrical heater capacity	60 W
Fans capacity	2, of 5 W each
Quantity of corn	16 kg
Initial moisture content of the corn	23% (wet basis)

Table 2
Uncertainty analysis.

Measured variable	Expanded uncertainty
Temperature (k-type thermocouple)	±2.2 °C
Temperature (Thermo-psychrometer)	±0.5%
Relative humidity	±3% RH
Solar radiation	±1%
Mass	±1 g
Velocity	±3%
Initial moisture content	±1%
Instantaneous moisture content	±2%
Mass flow rate	±4.5%

dryer), and the complete drying set. Most works from literature evaluate only the drying chamber.

Fig. 8 presents the thermal efficiency as a function of time. The higher the solar radiation, the higher the thermal efficiency. It is defined as the ratio of the energy expended (represented mainly by the enthalpy increase) to the energy supplied. The higher thermal efficiency was obtained when the control volume included only the drying chamber since the air enthalpy increases more significantly when it removes water from the products. The lower thermal efficiency was obtained for the complete drying set. The higher values found for the entire dryer, solar dryer, and drying chamber were, respectively, 30.5%, 51.3%, and 92.1%. In indirect solar dryers, the products are not directly exposed to solar radiation, and the hot drying air is produced by the collector (Vijayan et al., 2020). Hatami et al. (2020) presented a model for the energy and exergy of an indirect solar dryer. For solar radiation levels ranging from 650 W/m^2 to 1050 W/m^2, and average outlet temperatures from 40 °C to 53 °C, the maximum energy efficiency was close to 18%. Also, in a comprehensive review of the thermal efficiency of solar dryers, a range of efficiencies between 21% and 69% was found (Lingayat et al., 2020b).

The exergy efficiency as a function of time is presented in Fig. 9 for the three control volumes. It was defined as the ratio of exergy outflow rate in the drying to the exergy rate of the drying air supplied to the device. Regardless of the control volume considered, the exergy efficiency showed the same behavior. During the early stages of the drying process, at the beginning of the day, exergy efficiency was low due to the utilization of more energy for the removal of surface moisture (Amjad et al., 2019). During the day, the exergy efficiency increased when the quantity of moisture of the products decreased. The ranges for the values were calculated as 8.9–22.2%, 10.5–26.2%, and 15.5–45.0% for the complete drying set, solar drying, and drying chamber, respectively. The higher exergy efficiencies were found for the drying chamber selected as control volume, as occurred for the thermal efficiency. Similar values were found in the literature. An exergy efficiency of 49% was found in a mixed mode forced convection solar tunnel dryer (Karthikeyan and

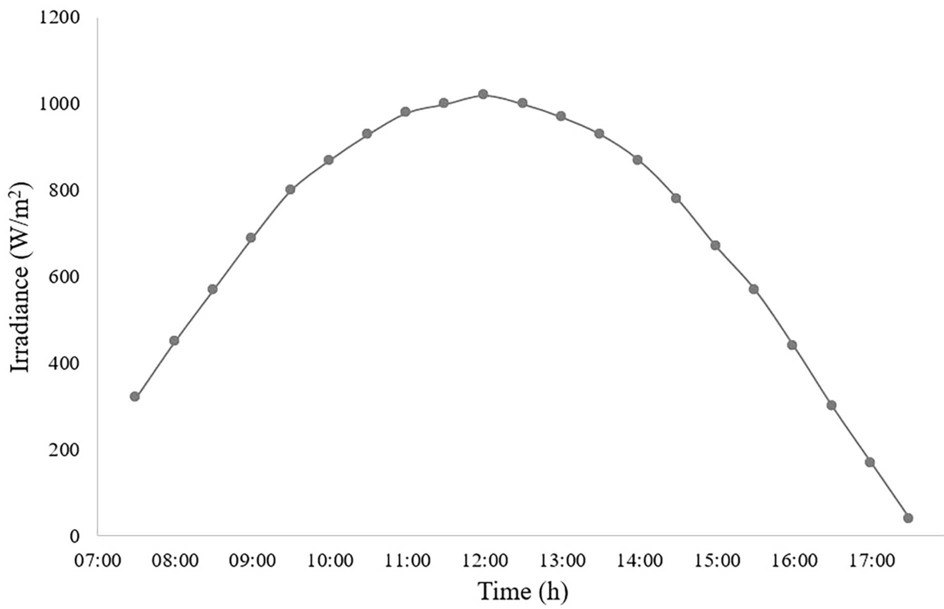

Fig. 4. Solar irradiance.

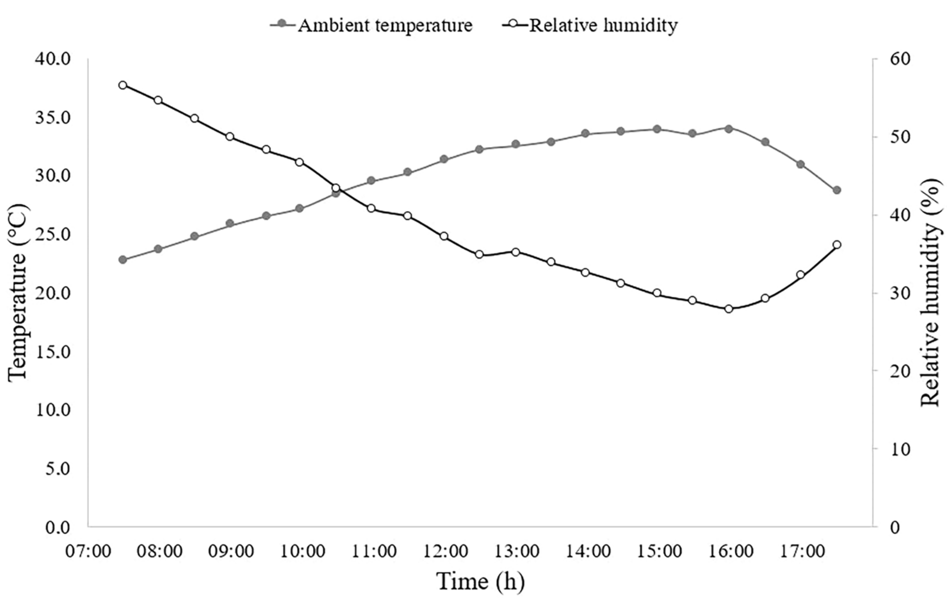

Fig. 5. Ambient temperature and relative humidity.

Murugavelh, 2018), and 49%, 59% and 69% were found for the drying of apples and mint (Şevik et al., 2019).

The behavior of the exergy efficiency can be explained when the individual terms of exergy rates are evaluated. This analysis was performed using the complete drying set as control volume. The contribution of kinetic, potential, and inflow rates on the input exergy rates can be neglected because the device was in thermal equilibrium with the environment and its properties were the same properties of the dead state. Therefore, the main contribution to the input exergy is from the heat transfer.

The input heat transfer can be divided into the heat transfer on the PV module, absorber plate, and drying chamber, as shown in Fig. 10. The most significant part is due to the absorber plate, followed by the drying chamber and by the PV module. The higher temperatures are found at the absorber plate surface (Fig. 6), resulting in higher exergy rates, since the exergy rates are related to the heat transfer at the surface.

The output exergy rates are presented in Fig. 11, divided into the contributions. The heat transfer exergy rate was neglected since the solar dryer is thermally insulated. The potential and kinetic exergy rates are not representative, and the most significant part is the outflow exergy rate. The higher the airflow temperature, the higher the exergy rate.

The destroyed exergy is the difference between the input and output exergy rates, and the higher the destroyed exergy, the lower the exergy efficiency, as shown in Fig. 12. The destroyed exergy is higher when the energy used inside the dryer is higher, which is calculated based on the temperature difference (Amjad et al., 2019). At the beginning of the drying process, the dryer and the temperatures of the products were close to ambient temperature, resulting in low heat transfer rates. Therefore, both the input and output exergy rates were close, resulting in high exergy efficiency, as described by the literature (Rabha et al., 2017). When the solar radiation and ambient temperature increased, the

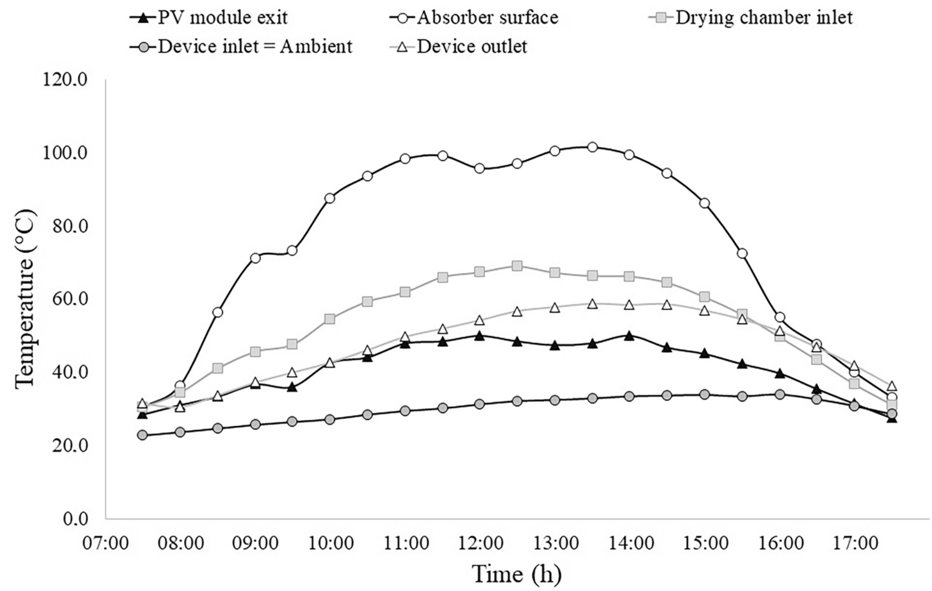

Fig. 6. Temperatures of various elements of the dryer.

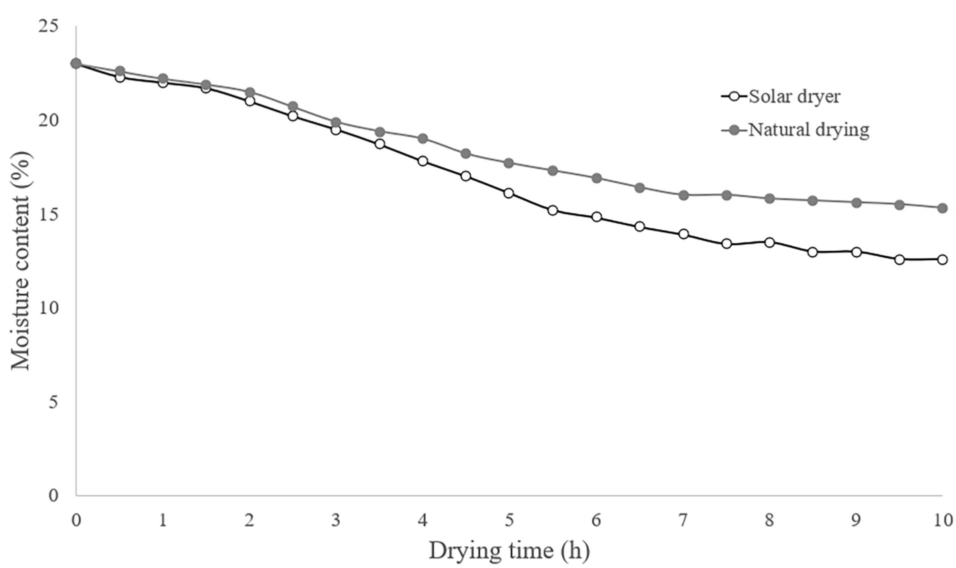

Fig. 7. Drying curves.

input exergy rates increased. Still, the thermal losses became more significant and the output exergy rates decreased, and the exergy efficiency decreased. In the afternoon, the solar radiation started to reduce, resulting in lower input exergy rates. Nevertheless, the temperature inside the dryer was not reduced at the same time, due to the thermal inertia. Consequently, with low input exergy rates and high output exergy rates, the exergy efficiency was high. Furthermore, with the end of the drying process and the reduction of the moisture content of the products, the outlet temperature increased, increasing the exergy efficiency.

4. Conclusions

Energy and exergy analysis of the corn drying inside a sustainable hybrid dryer coupled to a PV system was focused on this study. The drying material (16 kg) was dried from an initial moisture content of 23% to 13% under two drying modes: natural sun drying and drying inside the proposed dryer. The performance of the dryer was evaluated using three different control volumes, unlike most works from the literature. For the complete drying set selected as control volume, the contributions of the exergy rates were evaluated. The following conclusions have been drawn based on present analysis:

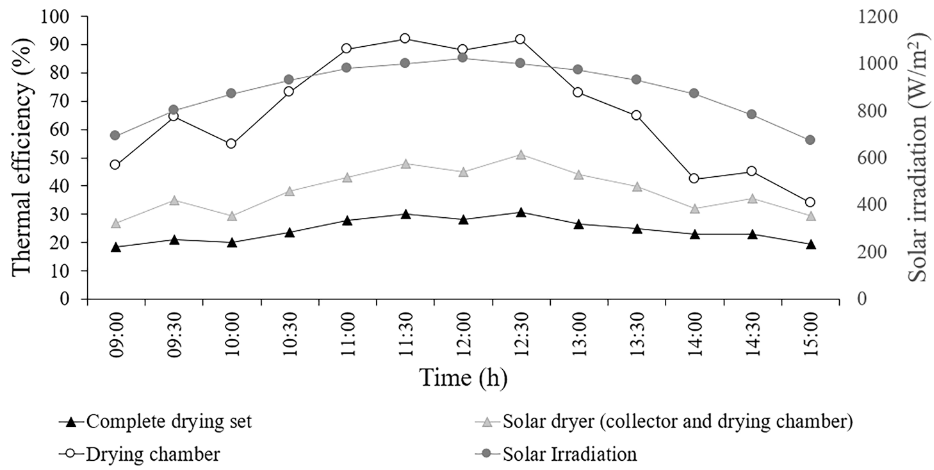

Fig. 8. Thermal efficiency.

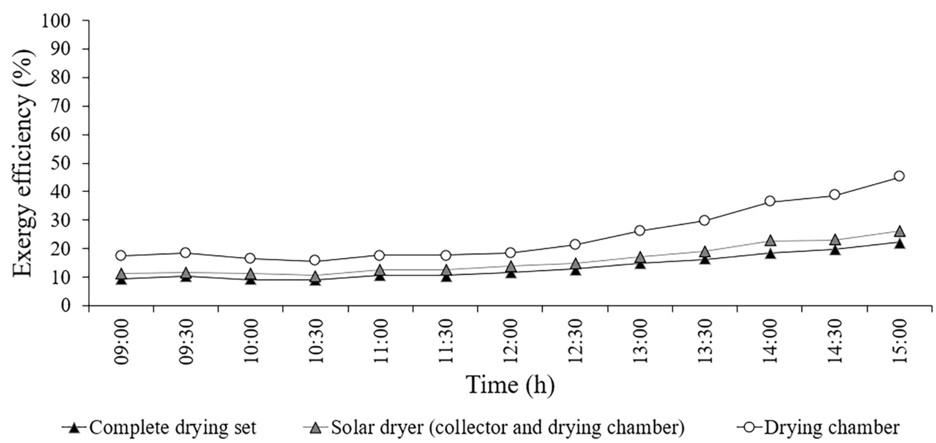

Fig. 9. Exergy efficiency.

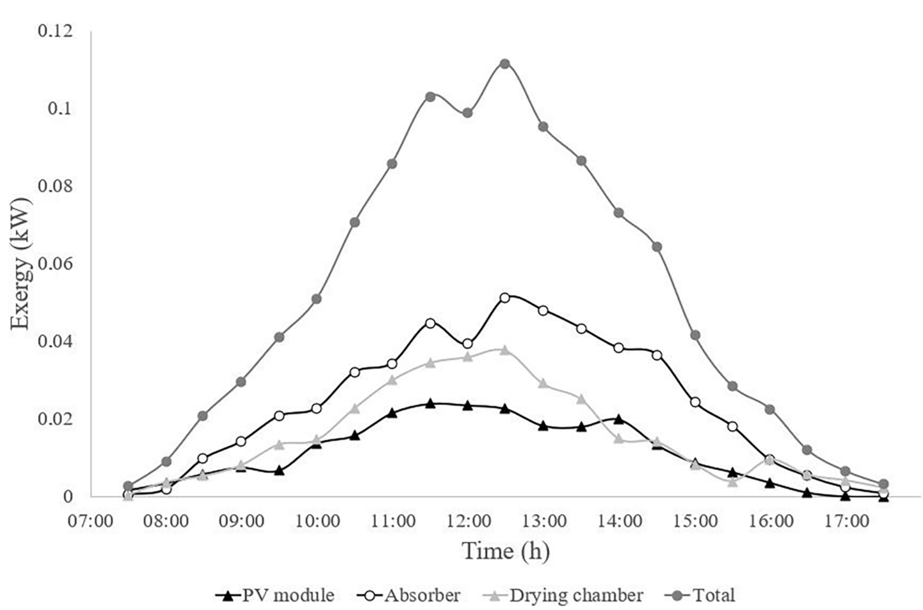

Fig. 10. Exergy rates of the various elements of the dryer.

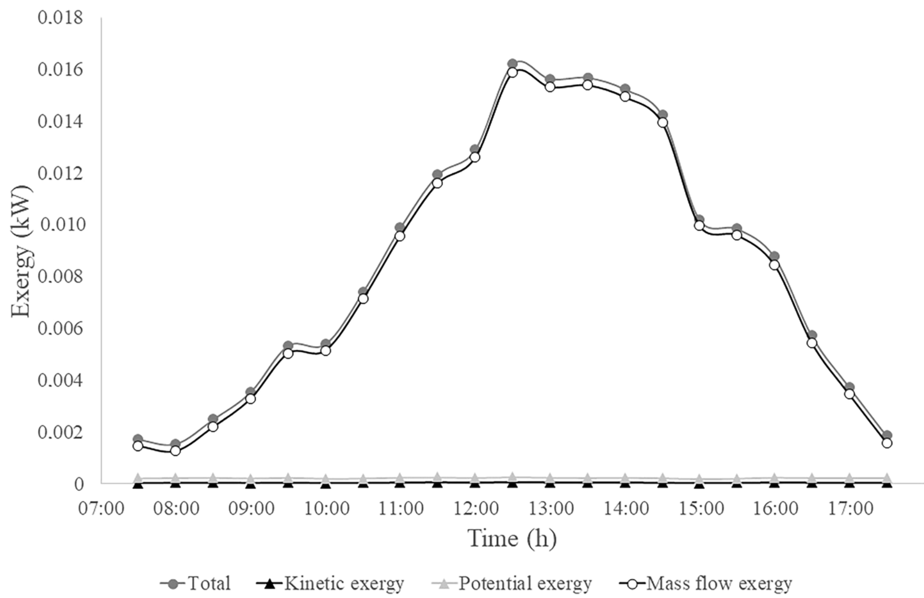

Fig. 11. Output exergy rates.

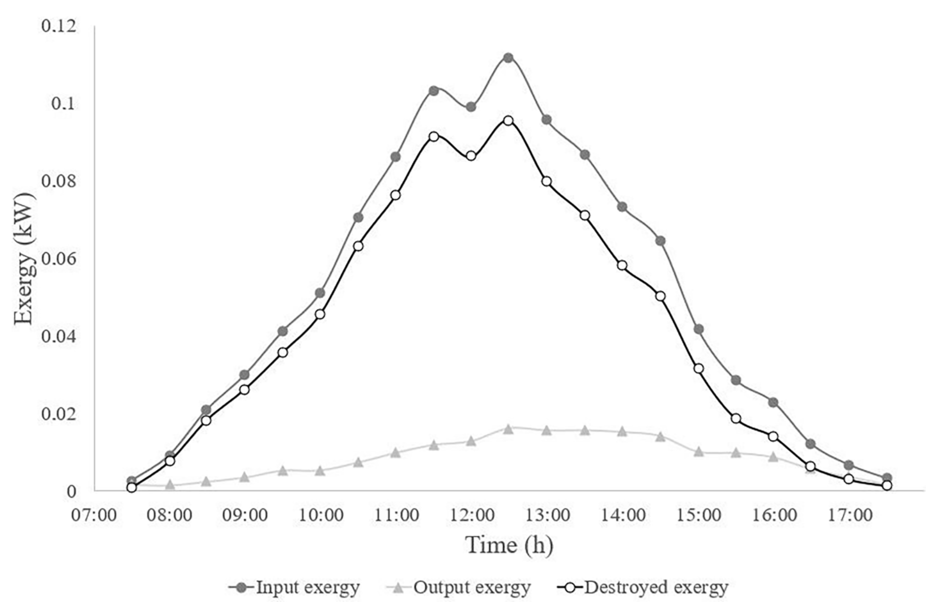

Fig. 12. Destroyed exergy rates.

- It was found that the hybrid dryer was able to successfully dry the corn in 8.5 h, while natural sun drying failed to achieve the final desired moisture content in 24 h.
- The PV system significantly increased the air temperature at the inlet of the solar collector. It was observed that the airflow reached a maximum increase of 19 °C after exchanging heat with the PV module, reaching 50 °C, to a subsequent rise of 14 °C in the absorber plate. It might reduce the absorber plate area required for the airflow to achieve the desired temperature in the drying chamber.
- The most significant input exergy rate is due to the absorber plate, followed by the drying chamber and by the PV module.
- The control volume used in the analysis significantly affects the obtained values for thermal and exergy efficiencies. From the literature, it is found that the drying chamber is the most common choice for the control volume. In this situation, lower solar radiation levels are considered, resulting in lower input energy rates and higher efficiencies, which can weaken the analysis. When compared the exergy efficiency obtained for the drying chamber and the complete drying set, the maximum values were, respectively, 45.0% and 22.2%.

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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