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Energy and exergy analyses of okra drying process in a forced convection cabinet dryer

Abiodun Okunola, Timothy Adekanye*, Endurance Idahosa

Department of Agricultural and Biosystems Engineering, College of Engineering, Landmark University, Omu-Aran, Nigeria

**Corresponding author: adekanye.timothy@lmu.edu.ng*

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Abstract: A forced convection automatic cabinet dryer integrated with a data logger was designed and fabricated. The okra samples were dried in the dryer at drying temperatures of 50, 60, and 70 °C and at three different load densities of 200, 300, and 400 g at a continuous air velocity of 0.7 $m \cdot s^{-1}$. Energy and exergy analyses of the drying process were performed. The obtained results showed that the energy efficiency, energy utilisation, and utilisation ratio increased from 26.59 to 68.24%, 5.47 to 114.36 W, and 0.36 to 0.71 as the temperature increased to 70 °C, respectively. The inflow, outflow, and exergy losses were in the range of 7.02 to 26.14 W, 4.43 to 14.16 W, and 2.59 to 11.98 W, respectively, while exergy efficiency varied from 49.15 to 63.47%. The findings show that exergy efficiencies decrease with an increase in the drying temperature, but increase with a lower load rate. The index of sustainability varies from 2.14 to 2.77, the value increases as the load density decreases while it decreases with a temperature increment.

Keywords: agriculture; food processing; force drying; tray dryer

Okra (*Abelmoschus esculentus* L. Moench) is an annual plant growing 0.91 to 1.82 m tall and belongs to the Malvaceae family (Ume et al. 2016). It is an essential vegetable grown in the tropics and subtropics for its valuable food nutrients, vitamins, proteins and carbohydrates for the growth and repair of body tissue, as well as for disease prevention (Semon et al. 2005). The dried seeds are used for the preparation of vegetable curds, or roasted and ground to be used as a coffee additive or as a substitute; the leaves are known to be good feed for cattle, and also useful in confectionery (Akoroda 2011).

The worldwide okra production is estimated to be six million tonnes per year (Iheke 2010). In West Africa, it is estimated to be 500 000 to 600 000 t per year (Ngbede et al. 2014). The total area under cultivation has increased over the years. India is the world's largest producer of okra followed by Nigeria and Sudan (Varmudy 2011). During the lean season, the okra fruits are produced in low quantities, are scarce and expensive to get (Iheke 2010). In the peak season, it is produced in large quantities much more than what the local populace can consume. The adequate processing, preservation, marketing and utilisation of okra are necessary to arrest the wastage being experienced during the peak season.

Fruit and vegetable drying is one of the oldest forms of food preservation known to man. Drying is the removal of moisture from a product, usually to some predetermined moisture content while dehydration is the rapid removal of moisture, usually to a very low level. Drying has been regarded by humans as probably the most important and oldest food preservation method and it entails a complex thermal process in which a simultaneous heat and mass transfer occur (Ojediran and Raji 2010). During the drying of a wet agricultural product, two phenomena occur simultaneously; the transfer of heat energy to the product and the movement of the internal moisture to the surface of the product where it is evaporated. The three major drying processes based on heat transfer are; conduction, convection, and radiation (Liu et al. 2019).

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Some of the drying technologies which have been used for agricultural products include; sun drying, hot air convection drying, vacuum drying, microwave drying, infrared drying and their mixtures (Kaveh et al. 2018; Omari et al. 2018). Hot air drying, which has two major important facts related to it; the efficient removal of the surface water and a low operating cost. Hot air drying involves blowing heated air over food materials to remove moisture, which has been used frequently in food dehydration (Omari et al. 2018; Ojediran et al. 2020). However, the dehydration of vegetables and other food crops by traditional methods of open-air sun drying is not satisfactory, because the products deteriorate rapidly (Adekanye et al. 2019). Furthermore, traditional methods do not protect the products from contamination by dirt, debris, insects, or germs and, as a result, various methods have been developed over the years to improve the drying operations which grew into the fabrication of various types of food dryers.

Many other research scholars have used different drying systems to perform energy and exergy studies on the moisture reduction and removal of several food and agricultural products. Akpinar (2007) examined the energy and exergy of using a tray dryer to dry strawberry slices, whose measurement revealed that the tray dryer's exertional output varied from 24.81–100%. The drying process' exergy efficiency improved as the drying time decreased, the air velocity improved, and the temperature increased. Hancioglu et al. (2010) claimed that the exergy efficiency of an entire dehydration system based on cycle efficiency was 3.6% at a 50 °C air-drying temperature, 1m·s^{-1} air velocity and 14.7 °C dead-state temperature. The authors added that the drying temperature had a critical impact on the exergy efficiency during the dehydration cycle. Although increasing the air velocity did not show an extreme effect on the exergy efficiency of the drying process. Erbay and Koca (2012) examined the exergy analysis of cheese using a pilot scale dryer, the results indicated that, the exergy efficiency during the dehydration process declined as the drying temperature increased. Maria et al. (2018) asserted that, the exergy efficiency declined as the temperature increased for an onion drying process using a convection dryer. there are almost little or no reports on the analyses of energy and exergy for okra drying using a tray dryer. The main objective of this study was, therefore, to determine the energy and exergy analyses of okra dehydration in a fabricated automated tray dryer equipped with inbuilt sensors and a data logger.

MATERIAL AND METHODS

Description of the drying system and mode of operation. The drying machine utilised for performing the experiment was an automated tray dryer. The pictorial representation of the automated tray dryer is shown in Figure 1. The component parts of the automated dryer include the drying chamber which consists of two drying trays, the heating chamber which consists of two heating elements (1 800 W each), and a control device for reading and storing the data (data logger) as well controlling the chamber temperature by the method of using a relay. A temperature sensor (DS18B20), a relative humidity sensor (DHT11), and a load sensor (5 kg load cell) were the sensors embedded in the drying machine. The temperature and relative humidity sensors were fixed at the air inlet and outlet of the dryer while the load sensor was attached to the trays. The dryer was insulated with fibreglass to reduce the heat loss. It also has a blower that is powered by an electric motor. The trays have a perforated bottom (wire mesh) depending on the size of the crop and as the hot drying air circulates from the bottom to the top, as the drying process takes place on the trays loaded with fresh product. While the drying process is ongoing, the data logger stores

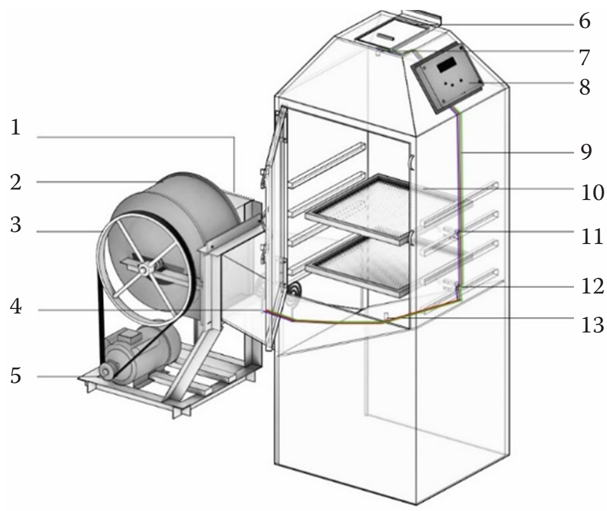

Figure1. The automated cabinet tray dryer

1 – air inlet; 2 – blower; 3 – pulley; 4 – heating elements; 5 – electric motor; 6 – top vent; 7 – temperature and humidity sencor; 8 – data logger; 9 – data cable; 10 – trays; 11 – upper load sensor; 12 – lower load sensor; 13 – temperature and humidity sencor

https://doi.org/10.17221/48/2020-RAE

the data on each ongoing activity in the drying chamber. The data logger is programmed to store data on the weight loss on each tray, the inlet and outlet relative humidity and air temperature as well as the ambient temperature with regards to the drying time.

Sample preparation and experimentation. Fresh samples of okra were obtained from the Landmark University Research Farm. The okra was washed with clean water to expel particles that may antagonise the exploratory results. This study adopted the experimental procedure used by Aviara et al. (2014) for drying local starch (cassava) in a tray dryer. 8–10 mm thickness samples of the okra at different load densities of 200, 300, and 400 g at different temperatures of 50, 60 and 70 °C, were placed in the tray dryer, respectively, at a continuous air velocity of 0.7 m·s^{-1}. The fan was turned on for each experimental run for the load density and drying temperatures. Prior to the drying operation, the dryer was used to heat the drying air to a relative humidity of 55 ± 0.35% and a dry bulb temperature of 27 to 70 °C for 1 h to properly stabilise the drying environment. The dryer ran void for 60 min to enable it to reach a balanced level at the predetermined air conditions before the analysis started. The initial moisture content was recorded and weighed using an electronic weighing balance (Contech, India) (88% w.b.). The samples were spread in a thin layer and placed in the trays, and changes in the weights of the okra samples were recorded by the data logger which recorded the data on a memory card. The LCD screen was observed at every hour interval after 4 h of consistent drying and, when three successive readings gave the same weight, the drying procedure was terminated. The drying experiment was carried out in three replicates and the mean was subsequently used.

Energy analysis. An energy analysis of is a typical and fundamental way to deal with assessing the different energy transformation processes. The energy utilisation, utilisation ratio and efficiency were calculated throughout the okra drying process using models proposed by Dincer (2002), Akpinar (2005) and Aviara et al. (2014).

The conservation of mass for the dry air:

$$\sum m_{\mathrm{i}} = \sum m_{\mathrm{o}} \tag{1}$$

where: m_{i} – inlet rate of the mass flow (kg·s^{-1}); m_{o} – outlet rate of the mass flow (kg·s^{-1}).

The conservation of the mass of the humidity is given by:

$$\sum\left(m_{\mathrm{hi}} + m_{\mathrm{hi}}\right) = \sum m_{\mathrm{ho}} \tag{2}$$

where: h_{i} – air enthalpie of the temperature entering the dryer (J·kg^{-1}); h_{o} – air enthalpie of the temperature exiting the dryer (J·kg^{-1}).

The conservation of energy:

$$Q - W = \sum m_{\mathrm{o}}\left(h_o + \frac{V_0^2}{2}\right) - \sum m_{\mathrm{i}}\left(h_{\mathrm{i}} - \frac{V_{\mathrm{i}}^2}{2}\right) \tag{3}$$

where: Q – inflow of the heat energy (KJ·s^{-1}); W – mechanical work production rate (J·s^{-1}); V_{i} – velocities of the air entering the dryer (m·s^{-1}); V_{o} – velocities of the air exiting the dryer (m·s^{-1}).

$\frac{V_{\mathrm{o}}^2}{2}, \frac{V_{\mathrm{i}}^2}{2}$ have been eradicated from Equation (3) as there is no resulting movement in the drying process and Equation (4) results:

$$Q = \sum m_{\mathrm{o}} h_{\mathrm{o}} - \sum m_{\mathrm{i}} h_{\mathrm{i}} \tag{4}$$

Assuming the uniformity of the mass flow rate of the air (i.e., $m_{\mathrm{a}} = m_{\mathrm{i}} = m_{\mathrm{o}}$), Equation (4) is reduced to Equation (5).

$$\dot{Q} = \dot{M}_{\mathrm{a}}\left(h_{\mathrm{o}} - h_{\mathrm{i}}\right) \tag{5}$$

$$\dot{M}_{\mathrm{a}} = \rho_{\mathrm{a}} V_{\mathrm{a}} \tag{6}$$

where: ρ_{a} – dry air density (kg·m^3); V_{a} – volumetric rate of the flow for the air utilised during the drying; (m^3·s^{-1}); $\dot{M}_{\mathrm{a}}$ – mass flow (kg·s^{-1}).

$$h = C_{\mathrm{pa}} T_{\mathrm{da}} + W h_{\mathrm{sat}} \tag{7}$$

where: C_{pa} – dry air specific heat (J·kg^{-1}); T_{da} – temperature of the air during the drying (°C); W – ratio of the humidity during the drying (kg·H_2O·kgDA); h_{sat} – saturated vapour's enthalpy (J·kg^{-1}).

$$C_{\mathrm{pa}} = 1.0029 + 5.4 \times 10^{-5} T_{\mathrm{da}} \tag{8}$$

$$EU = M_{\mathrm{a}}\left(h_{\mathrm{ai}} - h_{\mathrm{ao}}\right) \tag{9}$$

where: EU – energy usage.

The energy usage ratio during the drying process was found from the equation given by (Akpinar 2005).

https://doi.org/10.17221/48/2020-RAE

$$EUR = \frac{M_a(h_{ai} - h_{ao})}{M_a(h_{ai} - h_{a\infty})} \quad (10)$$

where: EUR – the energy usage ratio for the drying chamber.

$$\eta_E = \frac{E_i - E_o}{E_i} = \frac{M_a(h_{ai} - h_{ao})}{M_a h_{ai}} \times 100\% \quad (11)$$

where: η_E –energy efficiency (%); E_i – inlet energy; E_o – outlet energy.

Exergy analysis. The exergy analysis for the drying process of the okra sample was performed on the basis of the second law of thermodynamics, which holds that the energy has an attribute and volume, adding that the actual procedure occurs with regard to the declining energy quality (Aviara et al. 2014). The mathematical definitions used to evaluate the exergy analyses for the dryer are as shown in Equation (12–22) as proposed by Dincer (2002) and Aviara et al. (2014).

$$EX = C_p\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \quad (12)$$

where: T – temperature; T_∞ – ambient temperature.

The above expression can be used to calculate the inflow and outflow of exergy depending on the drying chamber's inlet and outlet temperatures. As a result, the exergy loss is calculated as follows:

$$\text{Exergy loss} = \text{Exergy inflow} - \text{Exergy outflow} \quad (13)$$

$$\sum EX_L = \sum EX_i - \sum EX_o \quad (14)$$

where: EX_L, EX_j, EX_o – loss of exergy, exergy of the inflow and outflow and outlet, respectively (J·s^{-1}).

$$EX_i = C_p\left[(T_{ai} - T_\infty) - T_\infty \ln\frac{T_{ai}}{T_\infty}\right] \quad (15)$$

Substituting Equation (8) with Equation (15) gives EX_i as:

$$EX_i = 1.0029 + 5.4 \times 10^{-5} T_{ai}\left[(T_{ai} - T_\infty) - T_\infty \ln\frac{T_{ai}}{T_\infty}\right] \quad (16)$$

The exergy outflow can be evaluated using Equation (17):

$$EX_o = 1.0029 + 5.4 \times \times 10^{-5} T_{ao}\left[(T_{ao} - T_\infty) - T_\infty \ln\frac{T_{ao}}{T_\infty}\right] \quad (17)$$

where: T_{ao} – the temperature of the ambient dry air at the outlet.

$$\text{Exergy efficiency} = \frac{\text{Exergy inflow} - \text{Exergy loss}}{\text{Exergy inflow}} \quad (18)$$

$$\text{Or Exergy efficiency} = 1 - \frac{\text{Exergy loss}}{\text{Exergy inflow}} \quad (19)$$

Equation (22) can be stated as follows:

$$\eta_{EX} = 1 - \frac{EX_L}{EX_i} \quad (20)$$

where: η_{EX} – exergy efficiency (%).

The rate of the improvement potential (IP) in J·s^{-1} is given by:

$$IP = (1 - \eta_{EX})(EX_i - EX_o) \quad (21)$$

The drying process sustainability index (SI) is given by

$$SI = \frac{1}{1 - \eta_{EX}} \quad (22)$$

RESULTS AND DISCUSSION

Drying temperature and its effect on the exergy loss rate. Figure 2 illustrates the drying chamber's rate of the exergy loss variability with the examined variables for the thin-layer drying of the okra slices in the dryer. It shows that the exergy loss increases respectively with load density augmentation at air temperatures of 50–60 °C. At a drying

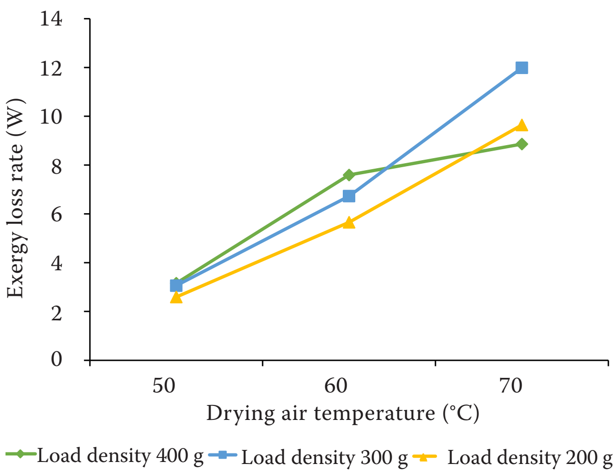

Figure 2. The rate of the exergy loss variation with the temperature and load density

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air temperature of 70 °C and a load density of 300 g, the maximum exergy loss value was 11.98 J·s^{-1}, demonstrating that a huge portion of the delivered exergy was utilised for drying. At a 50 °C air temperature and a 200 g load density, a minimal value of 2.59 W of exergy was attained. Similarly, Colak et al. (2008) determined that the loss of exergy increased when drying mint leaves in a heat pump dryer with an increase in the temperature. Furthermore, Aviara et al. (2014) stated that the loss of exergy increased with increasing temperatures.

Drying temperature and its effect on the exergy efficiency. The effect of the drying air temperature and load density on the exergy efficiency is illustrated in Figure 3. It was observed that the load density is proportional to the exergy output. This may be as a result of the growth in the total heat transfer coefficient. Additionally, at a lower load density, an increase in the output exergy is observed when compared with the input air exergy. Hence, the maximum exergy efficiency values were 63.47, 60.22 and 58.92% at an air temperature of 50 °C and a load density of 200, 300 and 400 g, respectively. Maria et al. (2018) obtained values close to 63% at a 50 °C drying temperature and an air velocity of 1m·s^{-1}. Likewise, Maria et al. (2018), observed that the output of the exergy decreases as the temperatures increase when drying onions with a convection dryer. Rabha et al. (2017) obtained similar results. However, Ranjbaran and Zare (2013) concluded that the exergy efficiency increases with an increase in the temperature due

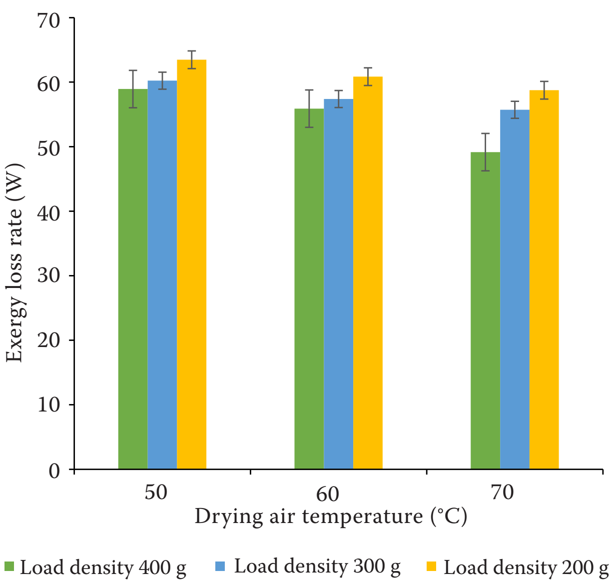

Figure 3. Effect of drying air temperature and load density on exergy efficiency

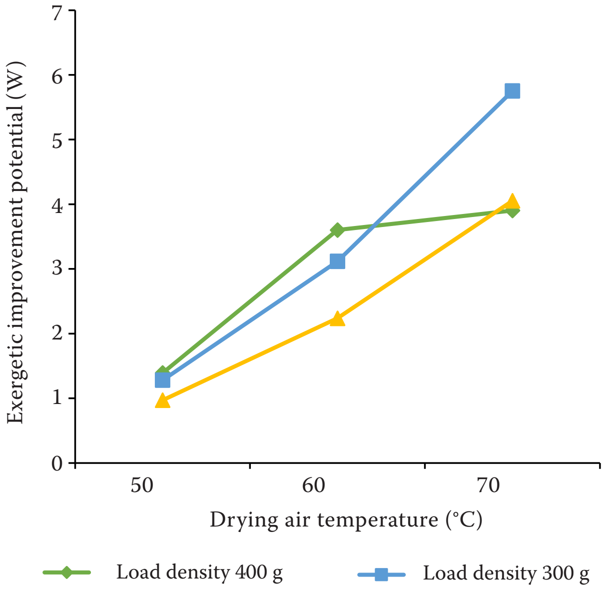

Figure 4. Effect of the drying air temperature on the okra's drying capacity

to the saturated surface of the moisture for which more heat was required to evaporate the free water.

Drying temperature and its effect on the exergetic improvement potential. Figure 4 illustrates the effect of the drying air temperature on okra's drying capacity for the exertional improvement in a tray dryer. It is obvious that the rate of improvement potential increases directly with the drying air temperature. Aghbashlo et al. (2012) and Erbay and Icier (2011) published similar findings on the drying of encapsulated fish oil and olive leaves, respectively.

The values of the improvement potential changed from 0.97 to 5.75 W under the operating conditions, which is comparable to the results recorded by Colak and Hepbasli (2007) for the green olive tray drying process (10.3–14.2 W). The levels of the improvement potential of the variables examined accounted for 13.10–22% of the overall inlet exergy, suggesting that the exergy output of the okra drying process can be ameliorated. Aghbashlo et al. (2012) identified the rates of the improvement potential to be within the range of 13.28–33.07% of the total input exergy for the fluidised spray drying of fish oil. Consequently, the okra drying process offers the potential for growth in the exergy efficiency.

Drying temperature and its effect on the sustainability index of the drying chamber. The impact of the temperature and load density on the drying chamber's sustainability index is presented in Figure 5. Although the sustainability index ranges

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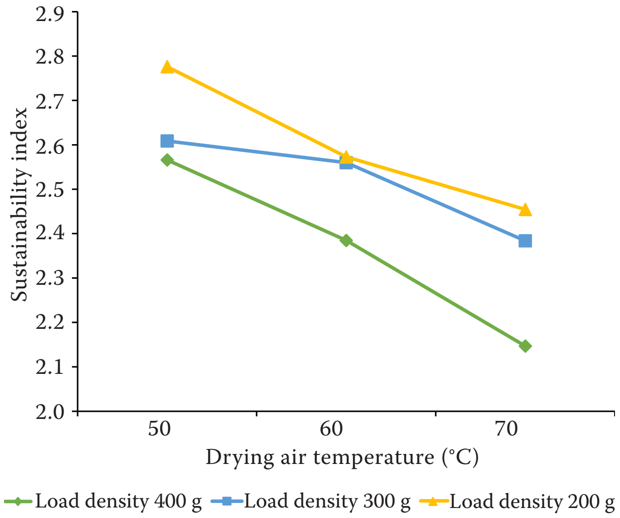

Figure 5. Effect of the drying temperature on sustainability index of the drying chamber

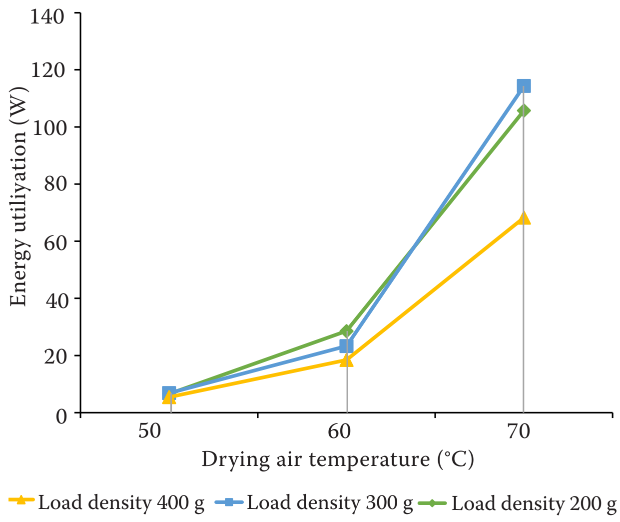

Figure 7. Variation in the use of the energy in the drying of okra using hot-air temperatures

from 2.14 to 2.77 under the studied operating conditions, it has been found that its value is proportional to the load density and inversely proportional to an increase in temperature. Beigi et al. (2017) obtained values ranging from 1.48 and 3.11. It is crucial to remember that the highest index values for sustainability indicate a small effect on the environment. Hence, the exergy efficiency should be improved to reduce this effect.

Drying temperature and its effect on the exergy inflow and outflow. Figure 6 shows the variation in the exergy inflow and exergy outflow at the drying

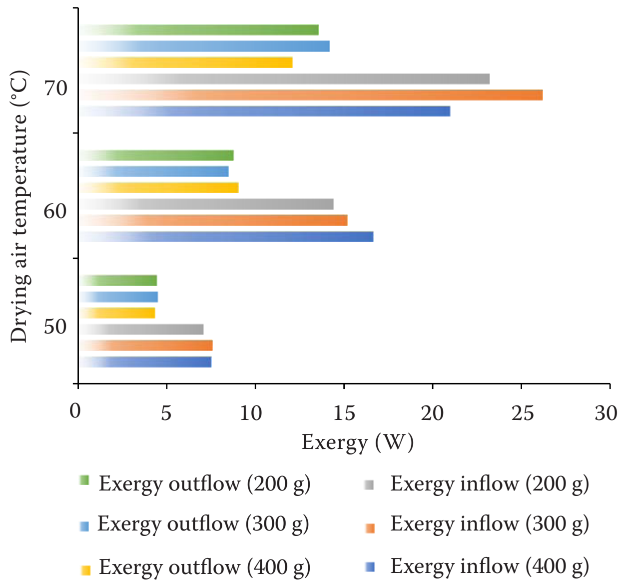

Figure 6. Variation in the exergy inflow and outflow at the drying air temperatures in the dryer

air temperatures in the dryer. The exergy inflow and outflow falls from 7.02 to 26.14 W and 4.43 to 14.16 W, with air temperatures increasing from 50 to 70 °C. Findings have been recorded for the drying procedure of pistachios using a solar dryer (Midilli and Kucuk 2003), eggplant drying in a cyclone style dryer (Akpinar 2005) and the encapsulation of fish oil by means of a spray dryer (Aghbashlo et al. 2012). Motevali and Minaei (2012) reported a decrease in the exergy loss with increases in the temperature and time in the thin layer of the microwave drying of pre-treated sour grenade arils and Akpinar (2011) noted a decrease in the exergy inflow and exergy outflow as parsley leaves were dried using a solar drying system.

Drying temperature and its effect on the energy utilisation. Figure 7 shows the variation in the use of the energy in the drying of okra using hot-air temperatures between 50–70 °C. Figure 7 reveals that the energy usage increased as the drying temperature increased from 5.47 to 114.36 W. In a similar study, Aviara et al. (2014) obtained an energy utilisation range from 1.93 to 5.51 W. Akpinar et al. (2005) and Erbay and Icier (2011) published similar findings on potato slices drying in a cyclone dryer and olive leaves drying in a tray dryer, respectively. The maximum energy utilised was 114.36 W at 70 °C and a load density of 300 g, while the minimum energy utilisation was 5.47 W at 50 °C and a load density of 200 g. However, at 60 °C the energy utilisation increased with an increasing load density.

The highest amount of energy consumption was observed at the beginning of the drying experi-

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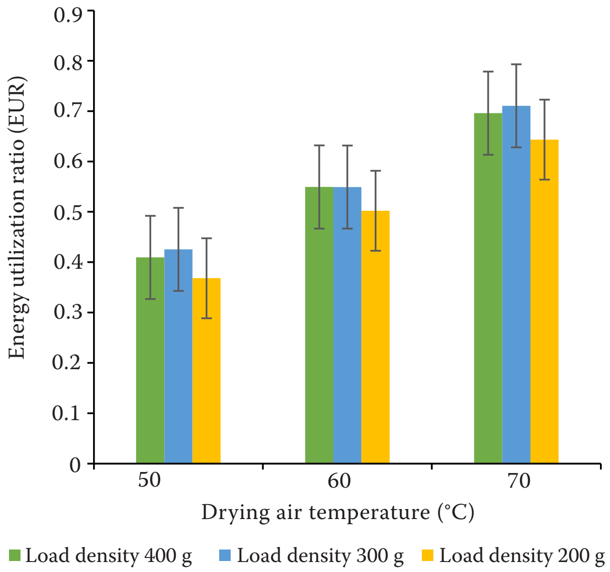

Figure 8. Effect of the drying temperatures on the energy utilisation

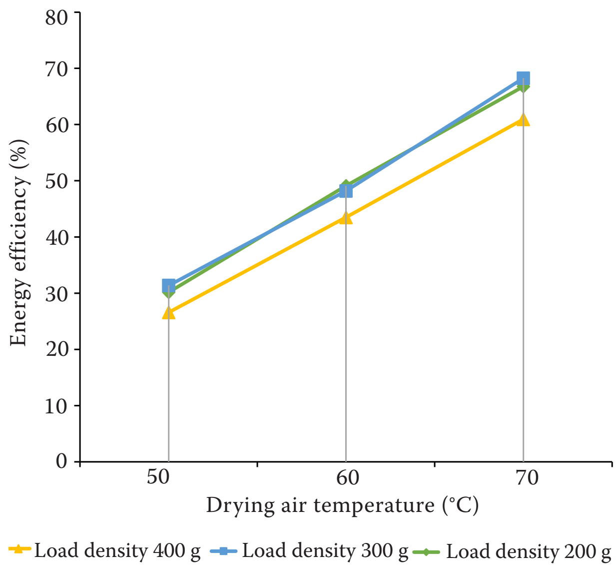

Figure 9. Effect of the drying temperatures on the energy efficiency

ment, and that level decreased over time due to the faster moisture transfer. Increasing the dryer air temperature resulted in the increased enthalpy of the inputs and increased heat and mass transfer resulting in a higher energy consumption, and a higher amount of moisture from the product was taken up. These findings are similar to those obtained by Azadbakht et al. (2017) for the thin layer drying of potatoes in a fluidised bed dryer.

Effect of drying temperature on the energy utilisation ratio (EUR). The effect of the drying temperature on the energy utilisation during the drying of okra in a tray dryer is shown in Figure 8. It was observed that the ratio of energy consumption increased from 0.36 to 0.71, as the temperature rose from 50 to 70 °C. Furthermore, the maximum EUR was 0.71 at 70 °C nd a load density of 300 g, while the minimum value (0.36) was obtained at 50 °C and a load density of 200 g. However, the EUR decreases with a decreasing load density at air temperatures of 50–70 °C, but only in correspondence with load densities of 200 to 300 g. Similarly, Abbaspour-Gilandeh et al. (2019) showed that air temperature increases with respect to the EUR when quince was dried in a hot air dryer. Akpinar et al. (2005) reported that the EUR decreases with a substantial increase in the temperature and air velocity while performing the energy and exergy analyses in a cyclone type dryer for potato slices.

Effect of drying temperature on the energy efficiency. Figure 9 shows that efficiency of the energy of the drying chamber increases from 26.59 to 68.24% as the temperature increases from 50 to 70 °C. Aviara et al. (2014) obtained similar results for starch (cassava) drying. Furthermore, Figure 9 also shows the maximal energy efficiency was 68.24% at 70 °C and a load density of 300 g, while the minimum energy efficiency was equal to 26.59% at 50 °C and a load density of 200 g. In addition, the energy efficiency decreases as the load density decreases.

Drying curves of okra at different temperatures in both the upper and lower tray of the dryer

Figure 10 (A, B and C) shows the differences in the moisture content of the okra over time as the drying occurs at various temperatures within the scope of 50 to 70 °C and a load density in the range of 200 to 400 g. The drying temperatures and moisture content decreases as the time increases before a dynamic equilibrium moisture content was reached. Similarly, the moisture content decreases as the load density decreases. With regards to the upper tray, the drying time and moisture content for the dynamic equilibrium decreases from 660 to 360 min, 480 to 300 min, 420 to 180 min and 1.5 to 1%, 2.66 to 2%, 3 to 4% (w.b.) at 400, 300 and 200 g, respectively, when increasing the drying temperature from 50 to 70 °C, while for the lower tray, the drying time and moisture content for the dynamic equilibrium decreases from 600 to 300 min, 480 to 210 min, 360 to 300 min and 1 to 0.5%, 2 to 2%, 3 to 2% (w.b.) at 400, 300 and 200 g, respectively. Ojediran et al. (2020) and Aviara et al. (2014) obtained similar results when drying yam slices and drying native cassava starch, respectively .

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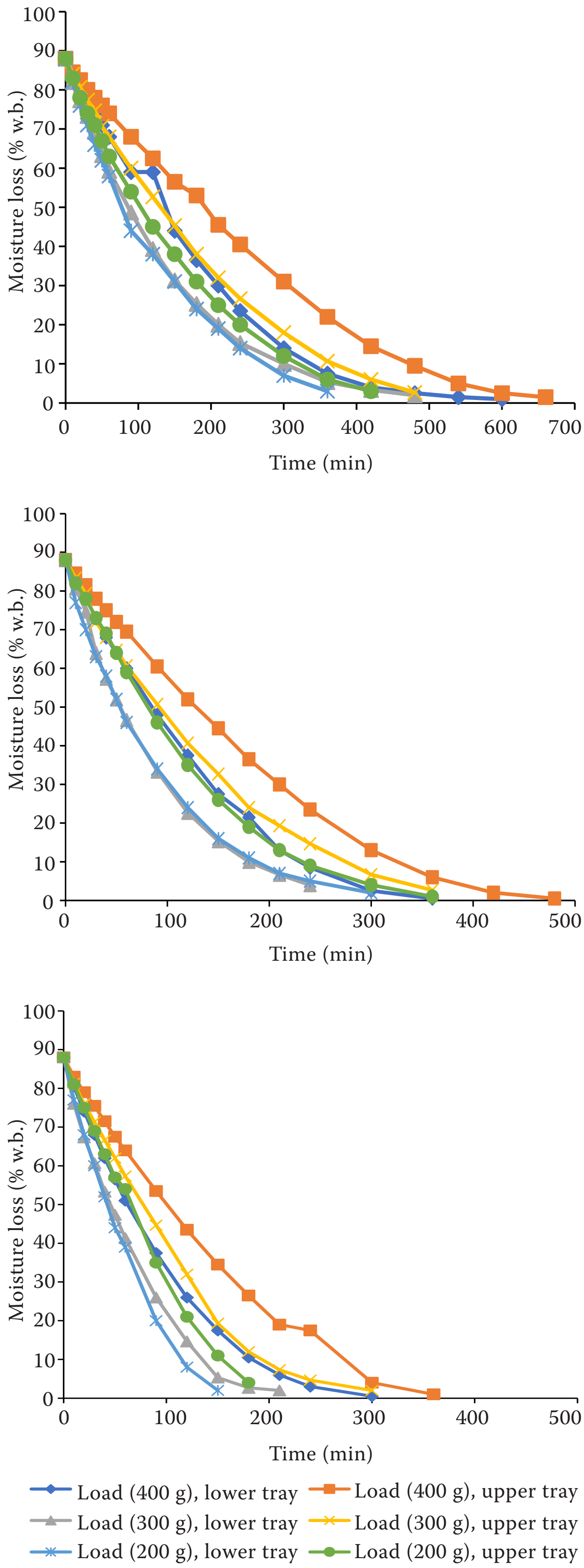

Figure 10. Drying temperature at (A) 50 °C, (B) 60 °C, and (C) 70 °C effect on the moisture loss

CONCLUSION

The energy and exergy analyses of okra dehydration in an automated tray dryer was investigated at three different drying air temperatures. The results showed that the amount of energy utilised increases directly with an increase in the temperature from 5.47 to 114.36 W. Although there was a decrease in the energy utilisation ratio with a decreasing load density at an air temperature 50–70 °C, but only in correspondence with a 200 to 300 g load density. The maximal energy efficiency was 68.24% at 70 °C and a load density of 300 g. At a temperature 70 °C and load density of 300 g, the maximum rate of the exergy loss value was 11.98 W, demonstrating that, for the drying process, a huge portion of the energy supplied was used. The maximum exergy efficiency values were 63.47 at the drying air temperature of 50 °C and load density of 200 g. The rate of improvement potential of the analysed parameters accounted for 13.10–22% of the total inlet exergy, which indicates that the efficiency of the exergy for the drying process of okra can be enhanced. The sustainability index varies from 2.14 to 2.77 under the studied operating conditions.

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