***Original Research Article***

# Exergy and Energy Analysis of Forced Convective Thin-Layer Solar Drying of Tiger Nuts(*CyperusEsculantus L.*)

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## ABSTRACT

**Aims:** To study the exergy and energy analysis for thin-layer solar drying of tiger nuts; and also to determine the drying kinetics for the thin-layer solar drying of tiger nuts.
**Study design:**Yellow variety of tiger nuts were dried in a forced convection solar dryer to determine the exergy and energy indices.
**Place and Duration of Study:**Federal University of Technology, Owerri, Nigeria between October, 2022 to March, 2023.
**Methodology:**The experiment was conducted at three different air velocities of 1.5, 2.5, and 3.5 m s-1 and two different loads of 70 and 140 g. The tiger nuts were dried from average initial moisture content of 52% (wb) to final moisture content of 10.2% (wb), at an average temperature range of 50.5 to 51.2 ºC. Energy utilization, exergy loss rate, exergy efficiency, improvement potential, and sustainability index were determined.
**Results:**The results of energy utilization, exergy loss rate and improvement potential ranged from 2.1 to 5.09 W, 0.25 to 0.93 W and 0.08 to 0.54 W respectively; however, these values increased with increasing air velocities and loads. The results of exergy efficiency and sustainability index ranged from 41.8 to 68.49% and 1.72 to 3.17 respectively; these values increased with decreasing air velocities and loads.Graphical plots of moisture content with drying time showed that the moisture content of the tiger nuts decreased with increasing drying time. The characteristic nature of the curve is indicative of the fact that there was an initial higher rate of drying, which gradually declined with drying time.The results also showed that the drying rates of the tiger nuts ranged from 6.03 to 8.44 %MC/hr; and these values varied with the different air velocities and loads.
**Conclusion:**The results from this research will serve as a guide in reduction of energy costs for the optimum design of convective dryers.

*Keywords: Air velocity; convective dryers; forced convection; load; moisture content.*

## 1. INTRODUCTION

Tiger nuts (*Cyperusesculantus L.*) are crops belonging to the family cyperacae, which is cultivated throughout the world [1]. The tubers contain a significant amount of dietary fiber; they also contain minerals such as potassium, phosphorus, calcium, magnesium, zinc, copper, vitamins C and E, essential fatty acids like myristic acid and Linoleic acid [2]. The black, brown and yellow varieties of this nut are in existence. Okafor et al. [3] stated that only the yellow and brown varieties are readily available in the Nigerian market; and that the yellow variety is preferred to all other varieties because of its qualities like its bigger size, colour and fleshier body. Tiger nuts can be eaten raw or be made into a refreshing beverage called tiger nut milk [4].

The main purpose of drying agricultural products is to improve food stability and minimize chemical and physical changes during storage [5]. The conventional methods of crop drying include open sun drying, drying in the fireplace, and the use of mechanical dryers. These methods are faced with some limitations such as inadequate heat transfer to the food materials, high drying energy consumption, low overall efficiency, longer drying time, and poor dried product quality [6, 7]. The solar drying method, which has gained good popularity in the crop drying industry in recent years is a good replacement for the conventional dryers. The relatively low operating requirements and the low cost of running a solar dryer justifies its economic usage in the rural farming environment of Nigeria. The use of solar dryer in Nigeria is justified because of the renewable nature of solar energy, low operating cost, and the abundance of sunshine available in Nigeria throughout the year.

One of the major challenges encountered in drying operations is to seek the reduction in the costs associated with energy sources in order to increase efficiency in drying facilities, while also leading to high quality dried products [8]. Golpour et al. [9] established that thermodynamic analysis plays a pivotal role when analyzing the energy utilization efficiency in industrial processes; and that exergy analysis in particular has proven as an essential instrument to the design, analysis and optimization of thermal systems. Exergy analysis aims at evaluating the energy available at different points of the system and offers useful information that allows choosing appropriate operating conditions and parameters to design engineering systems [10].

Several research have been done both in the determination of drying kinetics of tiger nuts and exergy and energy analysis of agricultural products. Research by Abano et al. [4] revealed that temperature and the state of the tiger nuts affected their drying kinetics; and that the Midilli et al model was best apt for predicting the thin-layer drying performance of tiger nuts. It is reported in the literature that different agricultural products as potato slices, okra, chili pepper pieces, eggplant, and mulberry displayed that the exergy and energy indices changed with varying drying temperatures, air velocities and loads [9, 11, 12, 13, 8].

Although a lot of work has been done on the exergy and energy analysis of agricultural materials, ~~however,~~ information on the exergy and energy analysis of tiger nuts is scarce in literature. Therefore, the objective of this work is to conduct the exergy and energy analysis for thin-layer solar drying of tiger nut. The work will further explore the energy and exergy indices for drying tiger nuts as affected by dryer and crop parameters.

## 2. MATERIAL AND METHODS

The materials used in the experiment are the Solar dryer, yellow variety of tiger nut samples, Electronic weighing balance (OHAUS: PAJA 102; resolution: 0.01 g), digital thermometer/hygrometer (sensitivity: 0.01 ℃), Stop watch, hand-held pyranometer (Model: 4890.20; Frederiksen).

### 2.1 Sample Preparation

Large quantity of the yellow variety of tiger nuts were bought from Eke ukwu market in Owerri town, Imo state, Nigeria. The nuts were selected by close observation according to uniform size. ~~The mean diameter of the tiger nuts was determined as 8.52 ± 0.52 mm using a micrometer screw gauge~~. The nuts were washed and kept in a refrigerator at a temperature of 4 ºC to slow down the physiological and chemical changes.

## 2.2Description of the Equipment and Experimental Procedure

The dryer used in the research is a flat plate solar cabinet dryer (Fig. 1). The top of the dryer was covered with plain glass. A dark-coloured galvanized steel plate acts as the absorber plate, which overlay a thermal storage base. The drying chamber consists of two drying trays. The axial flow fan that was used was equipped with a microprocessor-controlled speed regulator; this allowed air velocity values of choice to be entered on the keypad and the values will be displayed on the digital display unit. The fan was powered by a 20 watts capacity solar cell, that was connected to a 12 Volts direct current (DC) battery for power storage. The experiment was designed as a 3×2 factorial in a completely randomized design in three replications with factors: air flow velocity (1.5, 2.5, and 3.5 m s-1); and load (70 and 140 g). At the beginning of the experiment, the solar dryer was switched on, a fan speed was selected, then the dryer was allowed to run at the preset conditions until the dryer reached equilibrium conditions. The tiger nut samples were then placed on drying trays, weighed and placed inside the dryer. The initial moisture content of the samples was determined as 52% (wb) in accordance with the standards of [14]. The sample masses, the dryer and exhaust air relative humidity, as well as both the ambient and dryer temperatures at intervals of 30 minutes were also taken and recordedusing the electronic weighing balance and the digital thermometer/hygrometer.The solar radiation intensities (insolation) incident on the surface of the dryerwere taken at hourly intervals, using a hand-held pyranometer (Model: 4890.20; Frederiksen).The experiment continued until equilibrium moisture content of the tiger nut samples was reached. This point was characterized by three equalconsecutive mass readings. The procedure was repeated for all the experimental treatments. The drying experiment was done at Federal University of Technology, Owerri, Nigeria (latitude 5° 27' North, longitude 7° 2' East and altitude of 90.91 m above sea level)

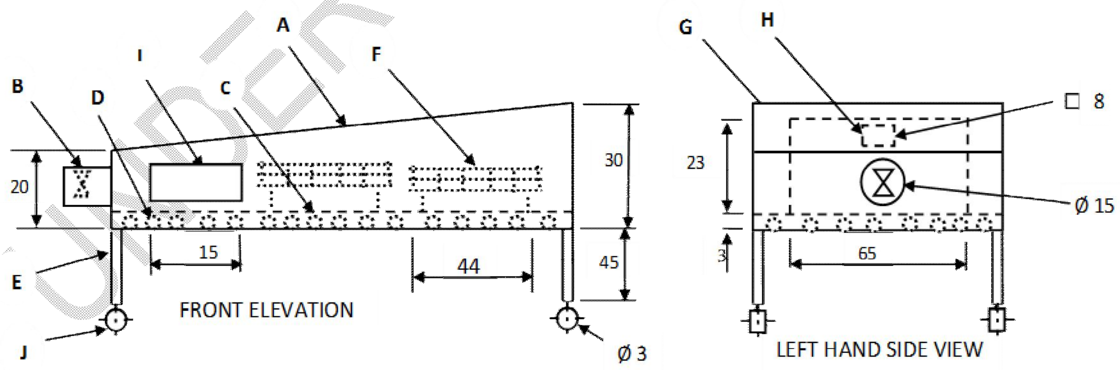


**Fig. 1a. Schematic representation of the equipment**

Where A- Glass ~~surface~~, B- Fan, C - Absorber plate, D - Thermal storage, E - Stand, F - Drying rack, G - Loading/unloading door, H - Exit hole for moist air, I - Access door, J – ~~Rollers~~Wheels.

**Fig. 1b. Pictorial view of the equipment**

The samples were oven-dried by standards of [14] for moisture content determination. The moisture content (wb) of the samples was determined using Equation (1).

$$M_{wb} = \frac{m_{ws}-m_{ds}}{m_{ws}} \qquad (1)$$

Where: $M_{wb}$ – Moisture content (%),$m_{ws}$ - Mass of the wet sample (g), $M_{ds}$- Mass of the dry sample (g)

## 2.3 Energy Analysis

The energy analysis for the drying experiment was done by using the equation utilized by Davishi*et al*. [8]. The conservation of mass for the drying air is mathematically expressed in Equation (2) as

$$\sum M_i = \sum M_0 \qquad (2)$$

Where $M_i$ - Inlet mass flow rate of air (kg $s^{-1}$), $M_o$ = Outlet mass flow rate of air (kg $s^{-1}$)
The conservation of energy is mathematically expressed as

$$\sum E_i = \sum E_0 \qquad (3)$$

Where$E_i$ and $E_o$ are the input and output energy values (J) respectively.
Equation (3) is further expanded as

$$Q - W = \sum M_o\left(h_o + \frac{V_o^2}{2}\right) - \sum M_i\left(h_i - \frac{V_i^2}{2}\right) \qquad (4)$$

Where $h_i$ - Air enthalpy at the temperature entering the dryer (J kg$^{-1}$), $h_o$ - Air enthalpy at the temperature leaving the dryer (J kg$^{-1}$), Q - Inflow of heat energy (W), $W$ - Mechanical work production rate (W), $V_i$, $V_o$ - Velocities of air into and out of the dryer (m s$^{-1}$).

$\frac{V_o^2}{2}$ and $\frac{V_i^2}{2}$ have been eradicated from Equation (4) because of no resulting mechanical movement in the drying process. Therefore, Equation (4) can be represented as

$$Q = \sum M_o h_o - \sum M_i h_i \tag{5}$$

Assuming uniformity of mass, $M_a = M_i = Mo$

$$Q = M_a(h_o - h_i) \tag{6}$$

The enthalpy of the drying air (h) was determined according to Nazghelichi*et al*. [15] and expressed in Equation (7) as

$$h = C_{pa}T_{da} + Wh_{sat} \tag{7}$$

Where $C_{pa}$ - Specific heat capacity of dry air (kJ kg$^{-1}$K$^{-1}$), $T_{da}$ - Temperature of air during drying (℃), $W$ - Humidity ratio during drying (kg $H_2O$/kg of dry air), $h_{sat}$ - Saturated vapour's enthalpy (kJ kg$^{-1}$).
The values of $W$ were obtained from the psychrometric chart using the values of temperature and relative humidity. The specific heat capacity of dry air ($C_{pa}$) is mathematically expressed as per [11] and expressed in Equation (8).

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

The mass of air required for drying was determined by the energy balance equation according toBalbine et al. [16] and expressed as Equation (9).

$$M_{ar}C_{pa}(T_{da} - T_{\infty}) = M_w L_v \tag{9}$$

Where $M_{ar}$ – Mass of air required for drying (kg) $T_{\infty}$ - Ambient temperature (℃), $M_w$ - Mass of water used for the drying process (kg), $L_v$ - Latent heat of vaporization of water (kJ kg$^{-1}$).
The mass flow rate of air, $M_a$ (kg s$^{-1}$) was mathematically expressed as Equation (10).

$$M_a = \frac{M_{ar}}{t} \tag{10}$$

Where t - drying time (secs).
The mass of water utilized for the drying process ($M_w$) was estimated according to Ehiem et al. [17] and represented in Equation (11) as

$$M_w = M_o\frac{(MC_i - MC_f)}{(100 - MC_f)} \tag{11}$$

Where $M_o$ - Initial mass of sample (kg), $MC_i$ - Initial moisture content of sample (%), $MC_f$ - Final moisture content of sample (%). Energy usage ($EU$) is mathematically expressed as

$$EU = M_a(h_{ai} - h_{ao}) \tag{12}$$

Where $h_{ai}$ and$h_{ao}$ are enthalpies of inlet and outlet air respectively
Energy efficiency ($\eta_E$) is mathematically expressed as

$$\eta_E = \frac{E_i - E_o}{E_i} = \frac{M_a(h_{ai} - h_{ao})}{M_a h_{ai}} \times 100\% \qquad (13)$$

## 2. 4 Exergy Analysis

The exergy of the system was determined according to the second law of thermodynamics. Generally, the exergy of a heat transfer system under steady state flow is mathematically expressed as per [18] and represented in Equation (14).

$$EX = M_a C_{pa}\left[(T - T_\infty) - T_\infty ln\frac{T}{T_\infty}\right] \qquad (14)$$

Where $EX$ - Exergy of the system (kW), $T$ - Temperature (˚C),$T_\infty$ - Ambient temperature (˚C)
The inflow exergy ($EX_i$) is mathematically expressed as

$$EX_i = M_a C_{pa}\left[(T_{ai} - T_\infty) - T_\infty ln\frac{T_{ai}}{T_\infty}\right] \qquad (15)$$

Where $T_{ai}$- Temperature of air at the entrance of the dryer (˚C).
The outflow exergy ($EX_o$) is mathematically expressed as

$$EX_o = M_a C_{pa}\left[(T_{ao} - T_\infty) - T_\infty ln\frac{T_{ao}}{T_\infty}\right] \qquad (16)$$

Where $T_{ao}$ - Temperature of the ambient air at the outlet (˚C).
The exergy loss ($EX_L$) is given according to [10] as:

$$EX_L = EX_i - EX_o \qquad (17)$$

The exergy efficiency ($\eta_{EX}$) is determined as per [10] and expressed as

$$\eta_{EX} = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow} = 1 - \frac{Exergy\ loss}{Exergy\ inflow}$$

$$\eta_{EX} = 1 - \frac{EX_L}{EX_i} \qquad (18)$$

The rate of improvement potential ($IP$) is determined according to Khanali et al. [19] as:

$$IP = (1 - \eta_{EX})(EX_i - EX_o) \qquad (19)$$

The drying process sustainability index ($SI$) is determined as per [20] as:

$$SI = \frac{1}{1 - \eta_{EX}} \qquad (20)$$

# 3. RESULTS AND DISCUSSION

## 3.1 Experimental Drying Data

The results of temperature and relative humidity values for the thin-layer solar drying of tiger nuts are summarized in Table 1.

**Table 1. Mean values of temperature, relative humidity and insolation for the thin-layer solar drying of tigernuts**

| Load(g) | Velocity | Temperature (˚C) | Relative humidity (%) | Insolation |
|---|---|---|---|---|

|  | (m/s) | Ambient | Dryer | Air exit | Ambient | Dryer | Air exit | $(W/m^2)$ |
|---|---|---|---|---|---|---|---|---|
| 70 | 1.5 | 32.1 | 51.2 | 45.2 | 68.05 | 25.94 | 30.5 | 475.5 |
|  | 2.5 | 31.9 | 50.5 | 46.4 | 66.9 | 22.95 | 28.2 | 468.3 |
|  | 3.5 | 32.1 | 51.1 | 47.4 | 67.46 | 24.97 | 27.5 | 469.1 |
| 140 | 1.5 | 32.1 | 51.2 | 43.8 | 68.05 | 25.94 | 31.5 | 472.7 |
|  | 2.5 | 31.9 | 50.5 | 44.6 | 66.9 | 22.95 | 30.2 | 470.7 |
|  | 3.5 | 32.1 | 51.1 | 46.2 | 67.46 | 24.97 | 28.5 | 472.5 |

### 3.2 Effect of Air Flow Velocity and Load on Energy Usage

A graphical plot of energy usage versus air flow velocity for the varying loads is shown in Fig. 2. It is evident from Fig. 2. that the energy usage increased with increasing air flow velocities and increased with increasing load.However, for the load of 70 g, the effect of air flow velocity on the energy usage is negligible. This behaviour could be attributed to the low value of load used.The phenomenon of the energy usage increasing with load could be attributed to the fact that at higher load, more energy is utilized per unit time in water removal during the drying process. Furthermore, the increase in thermal energy usage with increasing air flow velocities could be attributable to the fact that higher air flow velocities facilitates faster moisture removal, thus leading to increased energy utilization. This characteristic behavior of the energy usage with respect to load and air flow velocity is in agreement with research work by Okunola *et al*. [11] and Akpinaret *al*. [21], for the thin layer drying of okra and potato slices respectively.

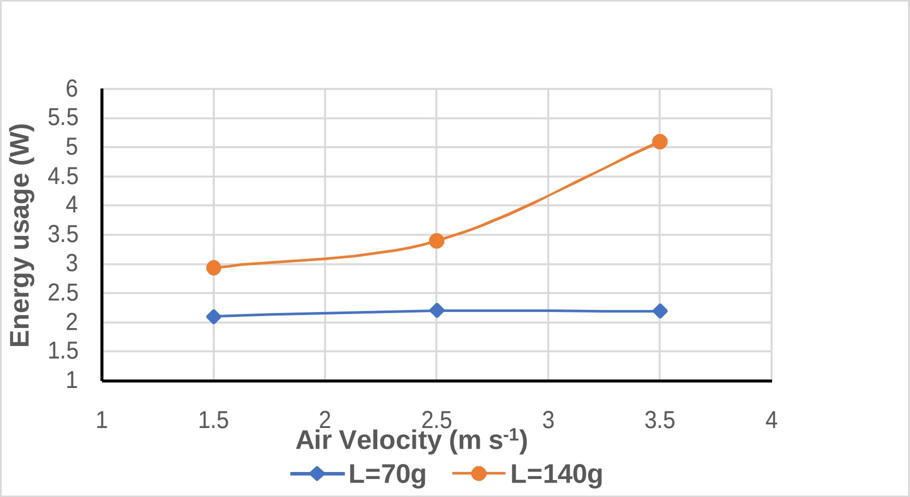
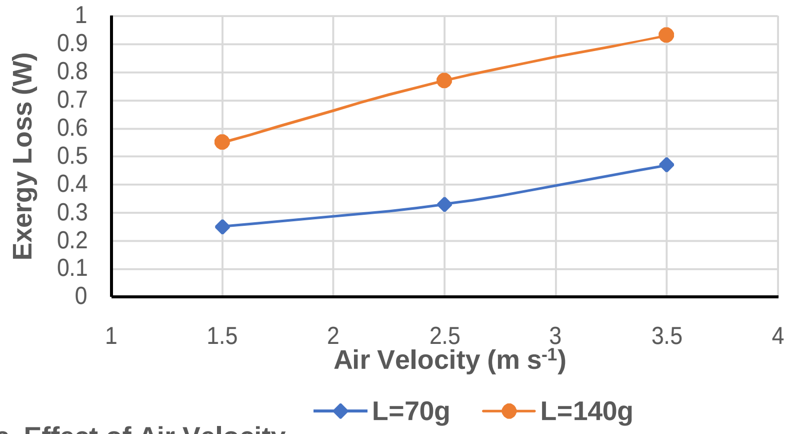


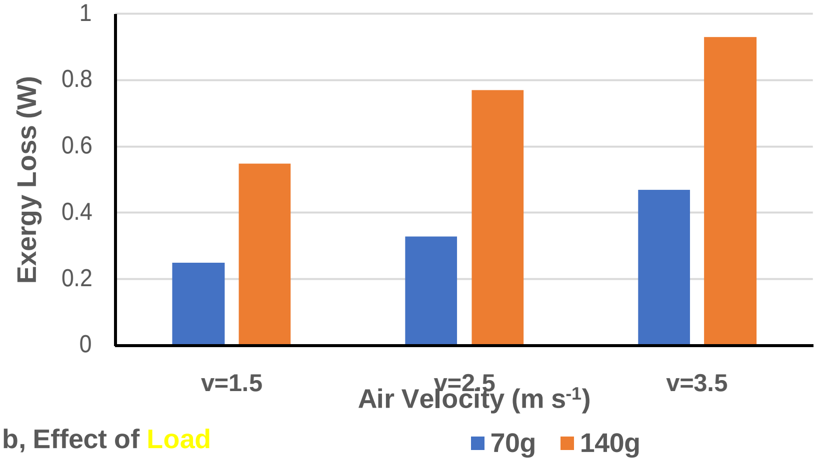
**Fig. 2. Effect of air velocity and load on the energy usage of tiger nuts**

### 3.3 Effect of Air Flow Velocity and Load on Exergy Loss

The graphical plot of Exergy loss versus air flow velocity (Fig. 3a) shows that exergy loss increased with increasing air flow velocity for all the loads. Graphical plots of exergy loss versus load (Fig. 3b) showed that the exergy loss increased with increasing loads for the various air flow velocities. The maximum exergy loss of 0.93 W was recorded forload of 140 g and air flow velocity of 3.5 m $s^{-1}$, while the least exergy loss of 0.25 W was recorded for load of 70 g and air flow velocity of 1.5 m $s^{-1}$. This characteristic behavior of exergy loss with respect to load and air flow velocity, demonstrates that a greater portion of the delivered exergy was utilized in the drying process. This trend in exergy loss with air flow velocities and loads is in agreement with previous research findings by Golpour*et al*. [9] for potato slices, Okunola *et al*. [11] for okra. However, the exergy loss values obtained in this study are slightly less than the values obtained in the research by [9] and [11]. This variation in values could be attributed to the lower loads used and the nature of crop dried in this research.



**a, Effect of Air Velocity**



**b, Effect of Load**

**Fig. 3. Effect of air velocity and load on exergy loss of tiger nut**

## 3.4 Effect of Air Flow Velocity and Load on Exergy Efficiency

Graphical plots of Exergy efficiency versus air flow velocity (Fig. 4) show that the exergy efficiency decreased with increasing air velocities and loads. The maximum exergy efficiency of 68.49% was obtained for air flow velocity of 1.5 m $s^{-1}$ and load of 70 g, while the least exergy efficiency of 41.8% was obtained for air flow velocity of 3.5 m $s^{-1}$ and loadof 140 g. This characteristic behavior could be attributed to the fact that higher loads of crop being dried is normally associated with greater mass of moisture to be removed. This implies that more of the input exergy was utilized (lost) in removing this moisture mass. The higher air flow rates facilitate the effective removal of this moisture, which leads to increased exergy loss and thus a reduction in exergy efficiency. This trend in the variation of exergy efficiency with load and air flow velocity is in agreement with previous research in literature [11, 9, 19].

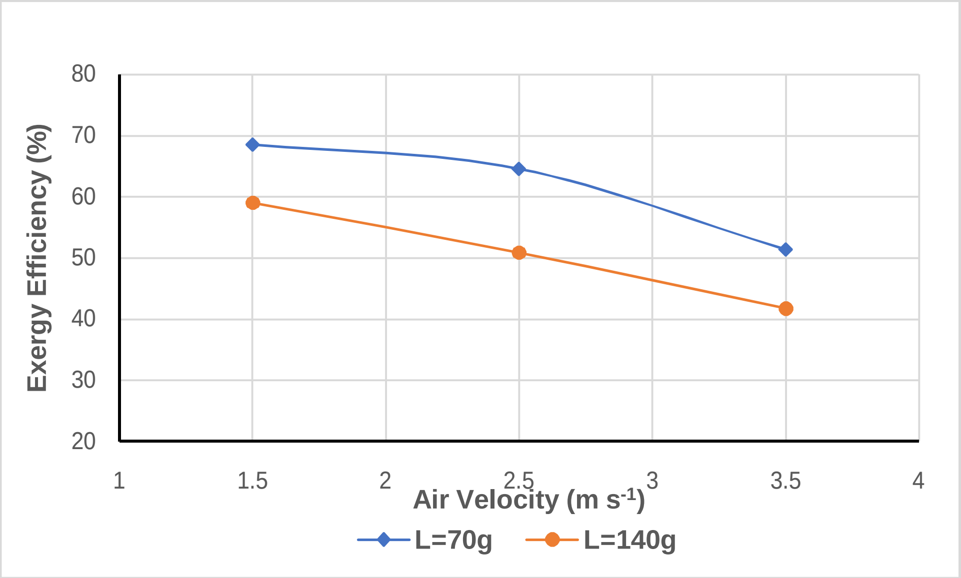


**Fig. 4. Effect of air velocity and load on the exergy efficiency of tiger nuts**

### 3.5 Effect of Air Flow Velocity and Load on the Sustainability Index

Fig. 5. describes how the air flow velocity and load affects the sustainability index for the thin layer drying of tiger nut. The obtained sustainability index values ranged from 1.72 to 3.17. It was evident from Fig. 5. that the sustainability index decreased with increasing values of air velocities and increasing load. These range of values and the characteristic behavior of sustainability index values with respect to load and air velocity are in agreement with research by Okunola et al. [11] and Beigi et al. [22]. High index values for sustainability indicate a small effect on the environment [11].

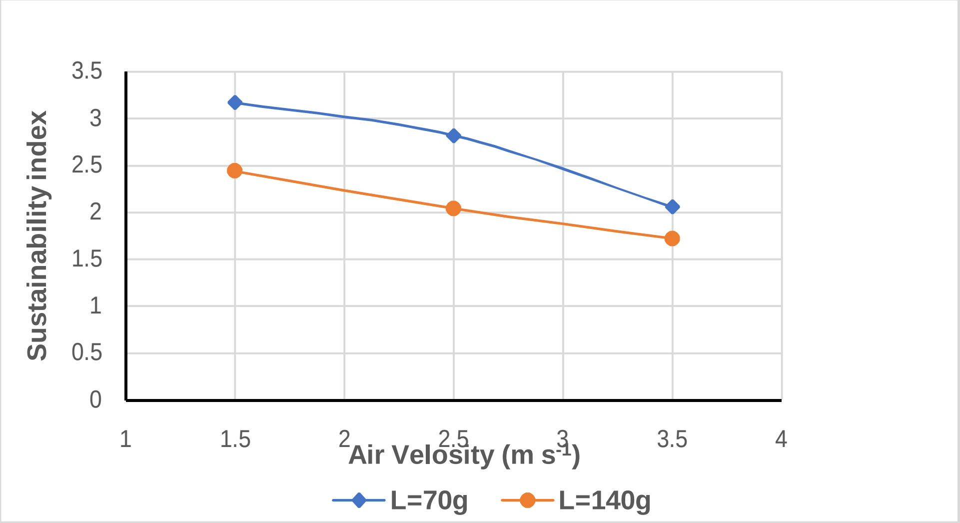


Fig. 5. Effect of air velocity on sustainability index

## 3.6 Effect of Air Flow Velocity and Load on the Improvement Potential

The effect of load and air flow velocity on the Improvement potential (IP) for the thin layer solar drying of tiger nuts is represented in Fig. 6. It is evident from Fig. 6. that the Improvement potential had a linear relationship with both the air flow velocities and drying loads.The IP values ranged from lowest value of 0.08 W, obtained for load of 70 g and air velocity of 1.5 m $s^{-1}$, to a maximum value of 0.54 W, obtained for load of 140 g and air flow velocity of 3.5 m $s^{-1}$. These values are slightly lower than the range of values of 0.97 W to 14.2 Wrecorded in literature for other agricultural materials [23, 11, 9]. This slight difference in values may be attributed to the range of loads used, the drying method applied, and the crop being dried. However, the values of Improvement potential increased with the increasing values of both the air flow velocity and load, which is in tandem with previous research findings [23, 11, 9].

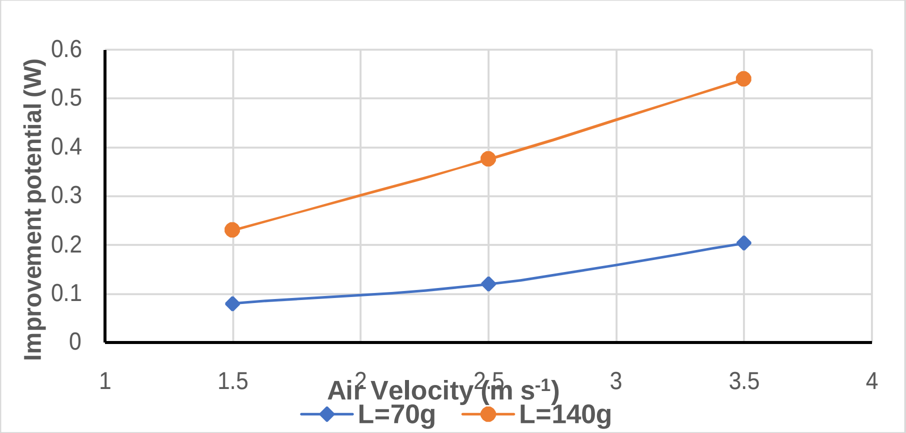
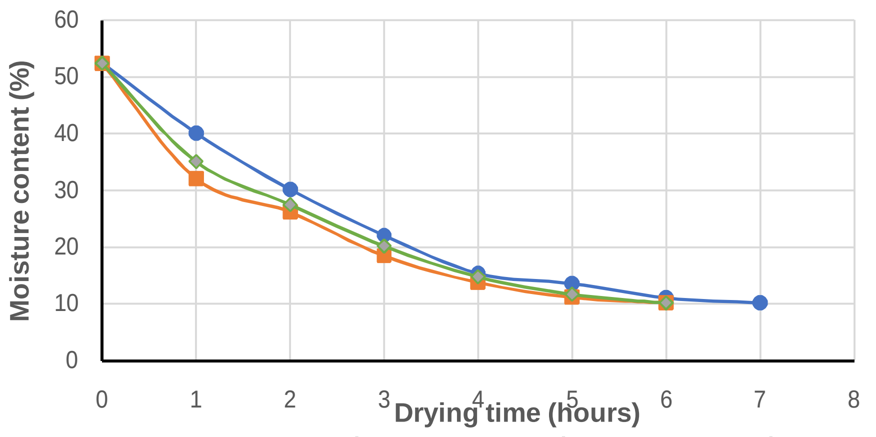


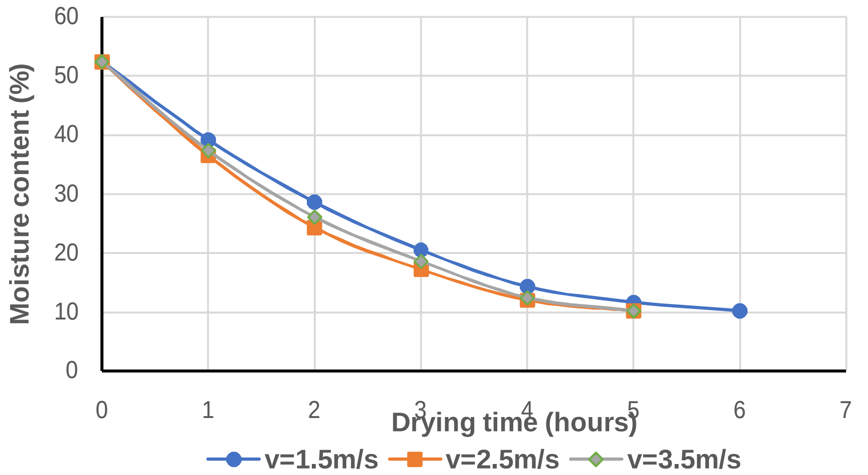
Fig. 6. Effect of air velocity and load on the improvement potential of tiger nuts

## 3.7 Drying Kinetics of Tiger Nut

Graphical plots of moisture content with drying time (Fig. 7), produced exponential curves which sloped from the left to the right side of the graph.It was evident from the graph that the moisture content of the tiger nuts decreased with increasing drying time. The characteristic nature of the curve is indicative of the fact that there was an initial higher rate of drying, which gradually declined with drying time. This characteristic behavior is attributed to the various forms and levels in which water is present in food materials [24]. It also represents the adhesive force with which the water molecules are held to the food matrix at a given stage of the drying process.This characteristic behavior has been reported in literature for other agricultural materials like rossale, cassava noodles, tomato slices; and has been attributed to the various forms and levels at which water is present in food materials [24, 25, 26].The drying rates of the tiger nuts ranged from the least value of 6.03 % MC/hr obtained for the samples dried at air velocity of 1.5 m/s and load of 140 g; to the highest value of 8.44 % MC/hr obtained for the samples dried at air velocities of 2.5/3.5 m/s and load of 70 g. The results revealed that the drying rates of the tiger nuts increased with decreasing drying loads and increasing air velocities. Research by [9] and [11] obtained similar results in their research. This research showed that beyond the air velocity of 2.5 m/s, the air velocity had no effect on the drying rate of the tiger nuts.



a, For samples at load density of 140g



**b, For samples at load density of 70g**

**Fig. 7. Moisture desorption curves for the thin-layer drying of tiger nut**

## 4. CONCLUSION

The aim of this research is to study the effect of air flow velocity and load on the energy and exergy analysis of thin layer solar drying of tiger nuts. In the course of the study, it was observed that the energy and exergy indices viz: energy usage, exergy loss, exergy efficiency, sustainability index, and exergy improvement potential, all varied with both the air flow velocity and load. The research revealed that the energy usage, exergy loss and improvement potential, all increased with increasing values of air flow velocity and load density; while the exergy efficiency and sustainability index decreased with increasing values of air flow velocity and load density. The trend in the relationship of the energy and exergy indices with the air flow velocity and load are in agreement with previous related research in literature. It was evident from the research that the drying rate of the tiger nuts increased with increasing air velocity and decreasing drying loads, which is in agreement with previous related research. It is recommended that this research should further be conducted for tiger nut, using other sources of heat and at varying temperatures.

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