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# DRYING KINETICS OF SWEET POTATO SLICES WITH INFRARED AND AIR CONVECTION HEATING

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***Abstract***

*In this study, the combined infrared-hot air dryer develops and optimize in Agricultural Engineering laboratory, faculty of agriculture, Tanta University, Egypt. Thin-layer modelling of sweet potato slices drying under infrared (IR) and hot-air drying (HAD) were used to estimate the drying coefficients. The initial moisture content of the freshly harvested sweet potato was 79 – 81 % (w. b.). Three different levels of sweet potato slices thickness (1, 3, 5 mm), were pre-treated by dipping into a solution of 0.5 % sodium meta-bisulphite and 1% citric acid for 30 min. Four different levels of infrared radiation (0.861, 0.973, 1.039 and 1.161 kW.m-²) and three different levels of air-drying temperature (45,55 and 65°C) with a constant air velocity of 1.2 m. $s^{-1}$ were using. The experimental measurements included sweet potatoes slices moisture content, air temperature, radiation intensity, and quality changes of the dried sweet potato. Three different thin layer drying models (Lewis's model and Henderson & Pabis's and Logarithmic model) were examined for describing the changes of moisture content during the drying process. The results show that, the Coefficient of determination $R^2$ and Standard error, SE. for The Logarithmic model recorded $R^2$= 0. 99 and SE= 0.122 were considered more proper for describing the drying kinetics and predicting the changes in moisture content of sweet potatoes more than the Henderson and Pabis's were model recorded $R^2$= 0.94 and SE= 0.51 and Lewis's model were recorded $R^2$= 0.96and SE = 0.241. The results show that, the moisture ratio of sample slices decreased when the radiation intensity and the drying air temperature increased. Meanwhile, the drying constant of Logarithmic model ($k_{Log}$) increased with the increasing of radiation intensity and air-drying temperature and the decreasing of slice thickness. The diameter and thickness shrinkage percentage occurred with all treatments, while slightly increasing with infrared radiation. The rehydration ratio ranged from 3.95 to 5.53.*

***Key words***: *sweet potatoes, moisture ratio, rehydration, thin layer, infrared, hot-air drying.*

## INTRODUCTION

Fresh fruits and vegetables are perishable and difficult to preserve because of their high moisture content. For example, fresh sweet potatoes have a short shelf life because of their high moisture content, and they are susceptible to rotting and microbial spoilage by microorganisms and external adverse conditions even at refrigerated conditions [32].
Therefore, drying treatment is one of the important processing methods for sweet potatoes for solving these problems and increasing their shelf life. Dehydrated sweet potatoes can be used as noodles, soups, beverages, bakery and confectionery products snacks. In addition, the transportation cost can be reduced dramatically due to the obvious reduction in sweet potatoes weight [31].
Sweet potatoes (*Ipomoea batatas L. (Lam.)*) are important tuber crops rich in β-carotene (precursor of vitamin A), vitamin B, C, and E as well as, polysaccharides, potassium, copper, manganese, iron, and low in fat and cholesterol with anti-carcinogenic and cardiovascular disease prevention functions [25].
In 2019 sweet potato world production exceeded 100 million tonnes, and the major producers include China, Malawi, Nigeria, Tanzania, Uganda, Indonesia, Ethiopia and Angola. The total area harvest and production of sweet potato in Egypt is 35,002.39 faddan and 454,041 tonnes, respectively [11].

Several pre-treatments and blanching are applied prior to drying of sweet potato to improve nutritional and sensory qualities of the final product. It also prevents undesirable changes during drying and increases shelf life of the final product during storage [5].

In these studies, sodium and potassium hydroxide, potassium carbonate, potassium meta bisulfite, ethyl and methyl ester emulsions, citric and ascorbic and were mostly used as pre-treatment solutions [2].

Pretreatments prior to drying are desired to increase the drying rate by removing the surface resistance as well as relaxing tissue structure of fruits and vegetables. It can also incapacitate enzymes, thus preventing color changes and produce a desirable dried product. For example [22] for sweet potatoes, [17] for potato and [21] for Mango.

The most popular and efficient way to preserve food by reducing its moisture content is convective drying. However, there are many problems such as low energy efficiency, long drying times and the problem of case hardening etc. during the falling rate period. The use of high drying temperatures results in degradation of the quality parameters of the product such as color, nutritional value and taste etc. [3].

Infrared drying, which is the part of the electromagnetic spectrum in the wavelength range 0.78-1,000 μm, is employed for thermal processes involving food such as drying and pasteurization and for determining the quality and safety of agricultural products [4].

IR drying technology has a number of advantages over traditional drying technology, including high energy efficiency, short drying time, uniform heating of materials, easy control of material temperature, good quality of the final products and low energy costs [16].

The combination of infrared with hot air provides an efficient drying process. When infrared radiation strikes a material's surface, it penetrates it. The increased molecular vibration due to absorption of radiation generates heat in the material both at surface and inner layers simultaneously [29].

[30] Compared the hot air drying and infrared drying characteristics of garlic slices. With decreasing air flow velocity and increasing IR radiation intensity, the drying rate increased and decreased at the time of drying.

In a vacuum infrared drying system, the effect of drying behaviour on the drying rate and qualitative attributes of potato slices was investigated. [14]. The drying time decreased, while drying rates increased with infrared radiation power increase. The rehydration process at 100ºC yielded the highest rehydration capacity at the power level of 200 W, vacuum 80 mmHg and thickness of 1 mm.

The effect of infra-red radiation and ultraviolet radiation on protein, trypsin inhibitor and total microbial count in cowpea seeds as pre- conditioning approaches before storage. Five exposure times of (3-6-9-12-15 min) and five irradiation intensity (804.255, 882.67, 964.74, 1,050.45, 1,139.8 W/m$^2$) were used for infra-red treatments. For ultraviolet treatment four exposure times (10-20-30-40min) and three irradiation intensity (7.077 – 3.538 – 2.359 mW/cm$^2$) were used.

The IR conditioning approach recommend to an irradiation intensity of 882.67 W/m$^2$ and a 15-minute exposure time. This level of radiation intensity and exposure time, showed total microbial count of 2.3 Log CFU/g., protein content 28.88 %, trypsin inhibitor 1.148 TIU/mg and moisture content 8.13 % of cowpea seeds Meanwhile, for UVC irradiation pre-treatment, a 3.538 mW/cm$^2$ irradiation intensity at a 40-minute exposure time is indicated to achieve a total microbial count of 2 Log CFU/g., protein content 28.15%, trypsin inhibitor 0.57 TIU/mg and moisture content 10.95% [12].

Specific energy consumption was lower and thermal efficiency was higher for the Infrared-Hot air setting when compared to both Infrared-Cold air and Hot air settings. The rehydration ratio, shrinkage and color properties of apples dried under Infrared-Hot air conditions were better than for either Infrared-Cold air or Hot air [10].

The application of infrared heating of legumes (Cowpea seeds) is gaining importance due to its inherent advantages over conventional heating. Pre-treatment with infra-red of cowpea seeds or ultra-violet radiation and storage of cowpea seeds in hermetic bags (three or seven layers) showed a safe storage result in terms of seeds quality and prevention of microorganisms and insect growth at the FIR and UVC optimum conditions. When using infra-red pre-treatment for cowpea seeds, the irradiation intensity of 882.67 w/m$^2$ at exposure time of 15 min get total microbial count 2.3 log cfu/g., and moisture content 8.13 % of cowpea seeds [13].

Mathematical modelling of thin layer drying is important for optimum management of optimising operational and predicting the drying system's performance.

Thin layer drying equations are used to predict drying kinetics and to generalise drying curves for a variety of items. Modelling the drying process and kinetics is a process control technique that is required to select the optimum drying method for specific product [23].

The main aims of the research were:

-To evaluate and examine the drying behavior of sweet potato slices by drying rate using a combination of the infrared radiation heating method.

-Studying the effect of air temperature, thickness of slices and initial chemical treatment with 0.5% sodium meta bisulfate solution and 1% citric acid for 30 minutes on the drying properties of sweet potato slices.

## MATERIALS AND METHODS

Sweet potatoes, (*Ipomoea batatas* L.) available in a local market was selected for experimental work during December 2020. The raw sweet potatoes had an initial moisture content of 380- 420% (d. b.).

Sweet potatoes preparation included washed with tap water to remove any dirt or dust particles attached to the surface, and peeling followed by slicing of the sweet potatoes with thickness of 1, 3 and 5mm using digital Vernier caliper.

After that, sweet potato slices were pre-treated by dipping into a solution of 0.5: 1 % sodium metabisulphite and citric acid for 30 min [27], the concentration of sodium metabisulphite in solution was reduced from 1 to 0.5% because of the risk of allergy [24].

The sweet potato was distributed uniformly as a single layer of 800: 300g for each sample on a perforated tray which was then placed directly inside the drying chamber at a distance of 20 cm from the two ceramic Infrared heaters. The output from the weighing balance, indicated as weight changes of the samples which were recorded every 15 min along the first two hours and every 30 min along the next two hours, and every 60 min up to the end of the run for the slices. Each run was reproduced three times in order to reduce experimental errors, and the average was used. Initial moisture content was measured before the drying process by taking (5 g) of sample in three replicates and using drying in an air oven for 24 hours at 105°C as recommended by [1].

The samples were initially weighed using an electronic balance having a sensitivity of 0.01 g. The average initial moisture content was found to be 79-81% (wet basis).

To weight the periodical changes of samples masses, throughout the experimental runs using 5kg Load Cell with HX711 Amplifier.

A Load cell is made from an aluminium-alloy and is capable of reading a capacity of 5kg. (Rated Output: 1.0±0.15mV/V, Operation temp. range -20~+60°C, Combined error (%RO) : < ±0.03)

Thermocouple K Type Temperature Sensor was used to measure the temperature of the air passing over the samples.

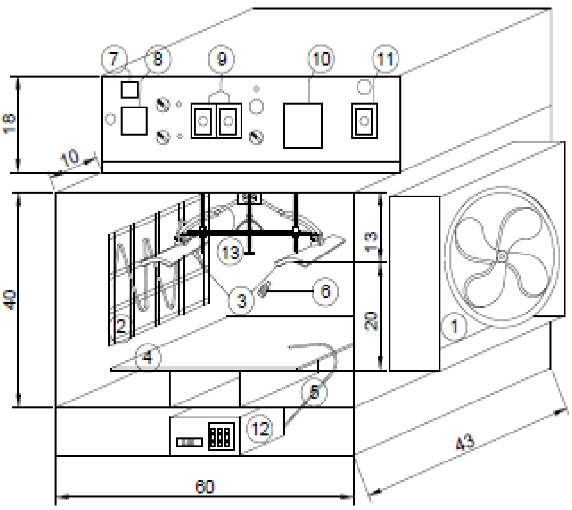
General LCD digital Anemometer (model DCFM 700) was used for measuring the air velocity. The unit is a self – contained direct reading portable instrument.

The dryer was used for conducting the experimental work for drying sweet potatoes at the Agricultural Engineering Department, Faculty of Agric. Tanta University.

The combined infrared-hot air dryer used for the experimental set up. The dryer, it consists of a box-type drying chamber, an electric heater, a centrifugal fan, two ceramic Infra-red heaters, a drying tray, a load cell, two control panels and a personal computer. The exterior of the box-type dryer is made of stainless steel. The drying air velocity was measured using a Thermo-Anemometer. The air velocity was kept constant at1.2 m. s-1 as recommended by [6].

The drying bed consists of three drying shelves. Each shelf was (60* 43 *40) cm (L * W* H). The drying trays which were made of stainless-steel wire net were situated at 20 cm from each IR lamp [9] For infrared heating process, two Elstein Germany Ceramic Infrared Emitter (wavelength of 2-10 µm; length of 24.5 cm/width of 6 cm/max power of 1,000W/ up to 750°C each ceramic Infra-red heaters were fixed over two iron blades and assembled into the ceiling of each drying chamber facing the drying shelves at constant distance of 20 cm, using two screw rods welded to the iron blades. To control the radiation intensity of the infra-red heaters, a set of dimmers were used as shown in Figure1

**No.** **Part name**




| | |
|---|---|
| 1 | Axial flow fan |
| 2 | Electric heater |
| 3 | Infrared heaters |
| 4 | Sample tray |
| 5 | Temperature sensor |
| 6 | Temperature & Humidity sensor |
| 7 | Led ampir |
| 8 | Thermostat |
| 9 | Dimmer |
| 10 | Electric meter |
| 11 | Fan speed control |
| 12 | Load cell |
| 13 | Lifter |

Fig. 1. Schematic diagram of the experiment
Source: Author's own illustration.

An electric heater was also used for air heating of the drying chambers. The heating circuit of each chamber consists of two (1 kW-Turki) were connected to a thermocouple type (T) to control and measure air temperature. Electric heaters fixed over the surface of an iron net in order to increase the area of air contact with the heating source.

An analogue thermostat was used for temperature control of air passed over the drying trays at drying chamber. Each Details about digital thermostat (AUTONICS – Korean), connected to the electric circuit for stopping and connecting the heater and keeping the pre-adjusted temperature relatively constant throughout each experimental run.

Moisture ratio (MR) was calculated using the following formula [1]:

MR=(Mt-Mf)/(Mo-Mf) ………....................(1)

where:
MR, The moisture ratio, Mt, Moisture content at a specific time, (d. b.). Mf, The Final moisture content, (d. b.). Mo, The initial moisture content, (d. b.).

The drying rate (DR) of sweet potatoes slices was calculated using the following equation:

DR = $(M_t - M_{t+\Delta t}) / \Delta t$, …............................(2)

where:
$Mt+\Delta t$ is moisture content at $t + \Delta t$ (kg water/kg dry matter) and $t$ is time (min), according to [2].

**Drying Models for Simulating the Drying Data**

The obtained data of the laboratory experiments was employed to examine the applicability of three thin layer drying models (Lewis's, Henderson and Pabis's and Logarithmic equations) on describing and simulating behavior of sweet potato slices satisfactory as indicated from the higher coefficient of determination for the three models.

The drying models that were investigated may be summarized as follows:

**1. Lewis's model**

Lewis's model [19] was applied to fit the drying data of the sweet potato slices. It based on Newton's law of cooling in heat transfer and is often used to explain the mass transfer in thin layer drying as follows:

$MR=\exp^{(-k_L t)}$ ……........................................(3)

where:

M: Instantaneous moisture content during the drying process, % (d. b). Mf: Final moisture content of sweet potato slices representing the equilibrium moisture content, % (d. b).

Mo: Initial moisture content of sweet potato slices, % (d. b). t: Time, min $K_L$: Drying constants, min-1

**2. Henderson and Pabis's model**

Henderson and Pabis's model [15] were applied to fit the drying data of the sweet potato slices. The form of the model could be presented as follows:

$MR = A \exp^{(-k t)}$ ……..................................(4)

where:

A: Drying constant, dimensionless. $K_L$: Drying constant, min -1

The equation was modified to the exponentially form and the constants (k and A) were calculated.

**Calculation of drying constants ($k_H$, A) for Henderson and Pabis's equation**

The values of Henderson and Pabis's drying constants ($k_H$) and (A) can be calculated using the linear relationship between Ln (MR) and drying time (t) as follows:

$\text{Ln}_{MR} = \text{Ln } A^{-K_H t}$ …. ....................(5)

where:

the slope of the drying curve represents the drying constant ($k_H$) while the constant (A) could be calculated from the intercept.

**Logarithmic model**

To simulate and characterize the observed drying curves and analyze the relationship between the drying constants and the investigated drying parameters, a mathematical analysis of the experimental data and a calculation of the drying constants ($K_{log}$), ($A_o$), and (c) were performed.

The values of drying constants ($K_{log}$), ($A_o$) and (c) for the Logarithmic equation, could be obtained using a developed computer program based on MATLAB.

$MR=A_o \exp^{(-kt)+c}$ ..……….................(6)

where:

$A_0$ and c: Drying constant, dimensionless.

K: Drying constant, min -1, according to [28]

General comparison was also conducted between the three models based on the statistical analysis between the observed and the calculated values of moisture ratio to assess the most proper model for describing the drying behaviour of sweet potatoes slices. In addition to high value of correlation coefficient (r), various statistical parameters such as; reduced chi-square ($x^2$), mean bias error ($MBE$) and root mean square error ($RMSE$) were computed.

The correlation coefficient ($R^2$), the reduced chi-square ($x^2$), and the root mean square error were used to assess the quality of fit of the tested mathematical models to the experimental data (RMSE), according to [26]. The better the fit, the higher the $R^2$ values and the lower the $x^2$ and RMSE values. The following formulas can be used to determine the reduced chi-square and RMSE:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{obs.,i} - MR_{calc.,i})^2}{N-n} \quad ………..... (7)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(MR_{calc.,i} - MR_{obs.,i}) \quad ………… (8)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{calc.,i} - MR_{obs.,i})^2\right]^{1/2} \quad . (9)$$

where:

$MR_{obs}$: The observed moisture ratio, dimensionless.

$MR_{calc}$: The calculated moisture ratio, dimensionless.

N: number of observations.

n: The model's total number of constants.

**Determination of shrinkage**

This diameter shrinkage and thickness shrinkage can be measured by the Archimedes principle or by a number of displacement techniques; it was calculated by the following equation:

Diameter shrinkage of dried sweet potato slices = $(D_0-D)/D_0$ % …….. ..................(10)

Thickness shrinkage of dried sweet potato slices = $(Th_0-Th\ d)/Th_0$ % ……………...(11)

Where $Th_d$ and D are the thickness and diameter of the dried sample, respectively. While $Th_0$ and $D_0$ represent the initial values of the thickness and diameter of the sample before drying, respectively.

**Determination of rehydration rate**

Generally, it found that the greater the drying, the slower and less complete is the degree of rehydration [20].

[18] showed that dried sweet potato slices were rehydrated in water at 25°C (±1°C). About 5 g of the dried products were added to 200 ml distilled water. Weight of the sample was measured after 180 min. Subsequently, the samples were drained, with absorbent paper to eliminate excess water on its surface, and weighed. The following formula was calculated the rehydration ratio (RR):

RR = Weight after rehydration/Weight before rehydration.

**Variables under study were:**

- Four radiation intensity (0.861, 0.973, 1.093 and 1. 161kW.m$^{-2}$).
- Three hot air temperature (45, 55 and 65 ºC), at constant air velocity (1.2 m. s$^{-1}$)

## RESULTS AND DISCUSSIONS

**Influence of drying parameters on the change of sweet potatoes moisture ratio**

Four different levels of infrared radiation intensity including 0.861, 0.973, 1.093 and 1.161 kW. m$^{-2}$ were applied to determine the effect of infrared radiation intensity on the drying kinetics of sweet potatoes. The variation of the moisture ratio versus drying time for the experimental data are shown in Figure 2, 3 and 4.

Changing the radiation intensity from 0.861 to 1. 161kW.m$^{-2}$ and a minimum air temperature of 45°C, the drying time decreased from 165 to 90 min for 1mm slice thickness. While, at 5 mm thickness, the drying time decreased from 630 to 330 min.

However, changing the radiation intensity from 0.861 to 1.161 kW.m$^{-2}$ at the maximum air temperature of 65°C, the drying time decreased from 105 to 60 min for 1mm slice thickness. While, at 5 mm thickness, the drying time decreased from 450 to 240 min.

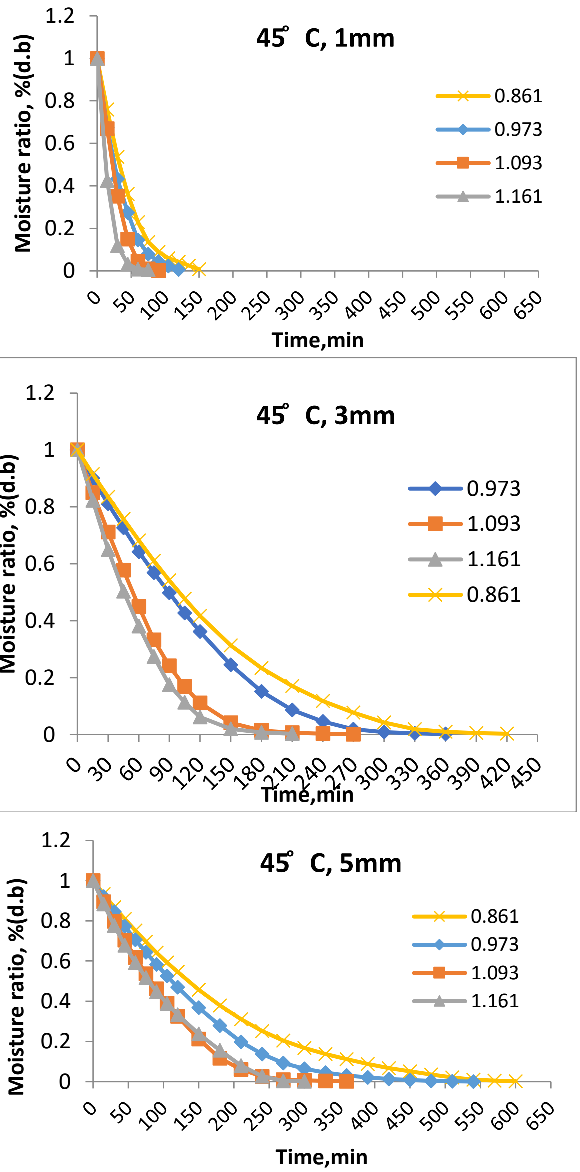
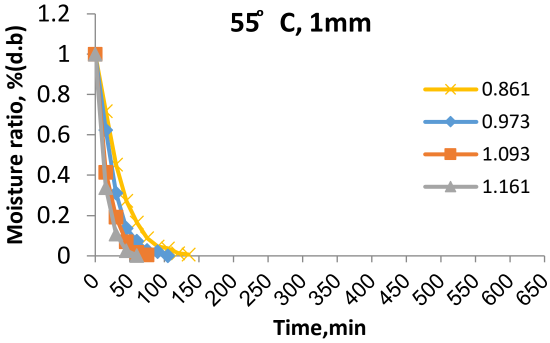
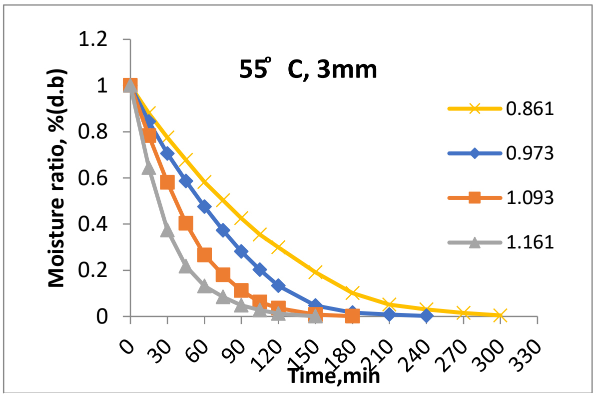



Fig. 2. Sweet potatoes moisture ratio as related to drying time for different levels of radiation intensity and slices thickness ( 1mm, 3mm, 5mm ) at drying air temperature of 45°C.
Source: Authors' determination.



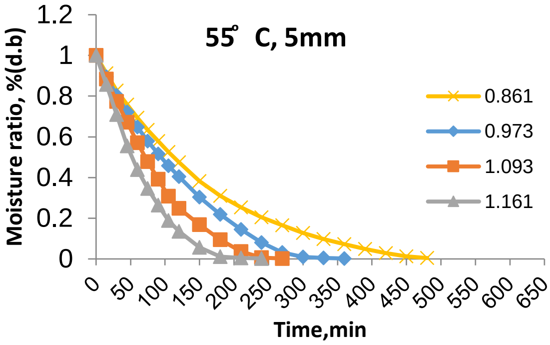
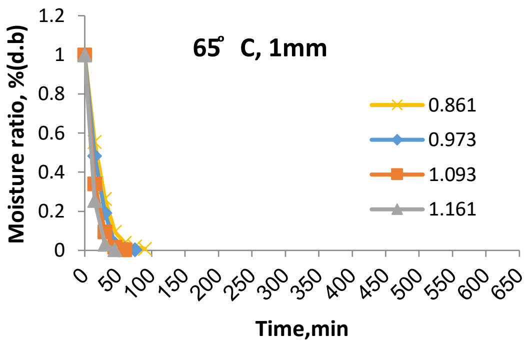
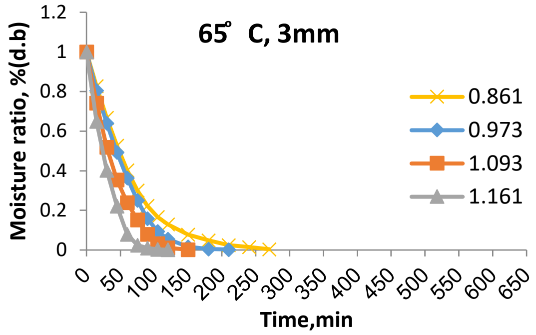




Fig. 3. Sweet potatoes moisture ratio as related to drying time for different levels of radiation intensity and slices thickness ( 1mm, 3 mm, 5mm)at drying air temperature of 55°C.
Source: Authors' determination.



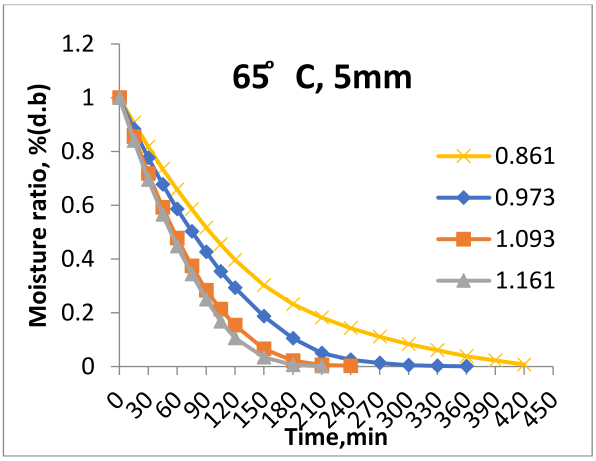




Fig. 4. Sweet potatoes moisture ratio as related to drying time for different levels of radiation intensity and slices thickness (1mm, 3mm, 5mm) at drying air temperature of 65°C
Source: Authors' determination.

**Influence of drying parameters on the change in sweet potatoes drying rate**

Figures 5, 6 and 7 show the changes in drying rate as a function of moisture content at the same temperatures.

It is clear that the moisture content and drying rate decrease endlessly with drying time.

During the beginning phases of the drying process, the rate of drying was fast, but it became quite slow throughout the drying method.

Comparison between drying data at various conditions revealed that the drying time of slices at higher IR power or less thickness permissible limits must be determined.

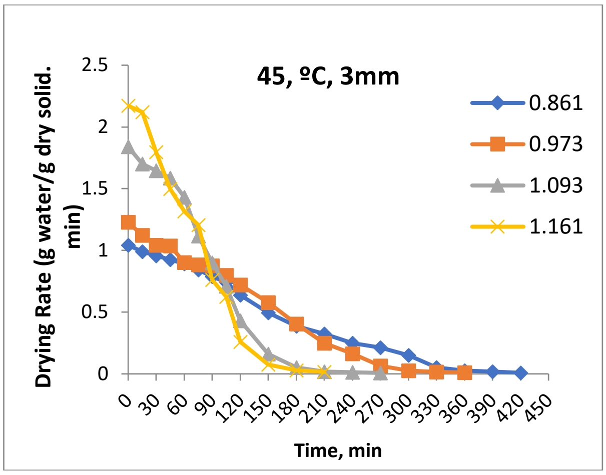



Fig. 5. Drying rate of sweet potato slices as related to drying time for different levels of radiation intensity and slices thickness (3mm) at drying air temperature of 45°C
Source: Authors' determination.

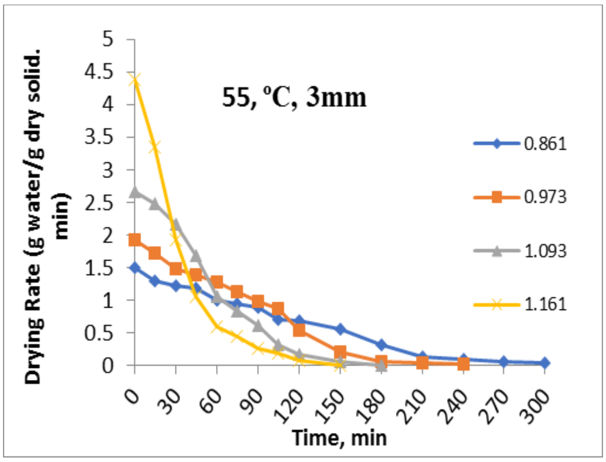



Fig. 6. Drying rate of sweet potato slices as related to drying time for different levels of radiation intensity and slices thickness (3mm) at drying air temperature of 55°C.
Source: Authors' determination.

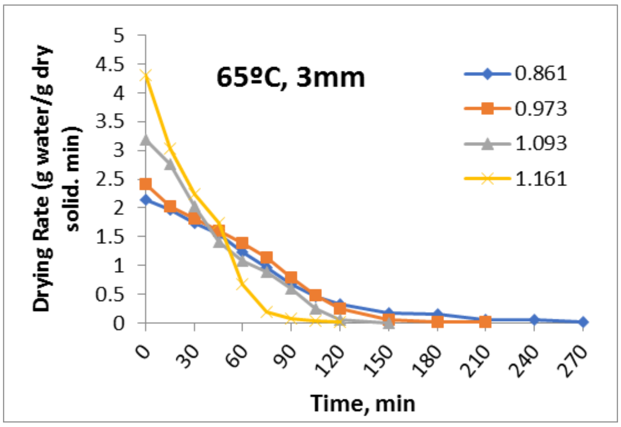



Fig. 7. Drying rate of sweet potato slices as related to drying time for different levels of radiation intensity and slices thickness (3mm) at drying air temperature of 65°C.
Source: Authors' determination.

## Analysis Of Thin Layer Drying Of Sweet Potato

### Analysis of thin layer drying of sweet potato using Lewis's model

The values of drying constant ($k_L$) for the Lewis's model could be obtained from the exponential relationship between the moisture ratio (MR) of the tested sample versus drying time (t).

As shown in Table 1, the drying constant ($K_L$) increased with the increase of drying air temperature and the increase of radiation intensity. However, it was decreased with the increase of slice thickness.

A multiple regression analysis was also performed to correlate the investigated parameters (I, T, and Th) with the drying constant ($k_L$). The following equation could be used to express the nature of dependence:

$$K_L = 0.100663I + 0.000958\ T - 0.01233\ T_h - 0.08353 \quad \text{………}\ \text{.......}(12)$$

and r = 0.898636, $R^2$ = 0.807547 and S. E= 0.012687.

Table 1. Drying constant ($k_L$) of Lewis's model at different levels of radiation intensity (I), air temperature (T) and slice thickness ($T_h$).

| Air temp. ºC | Thickness of slices, mm | Radiation intensity, kW.m$^{-2}$ | | | |
|---|---|---|---|---|---|
| | | 0.861 | 0.973 | 1.093 | 1.161 |
| 45 | 1 | 0.028 | 0.036 | 0.057 | 0.073 |
| | 3 | 0.011 | 0.014 | 0.023 | 0.025 |
| | 5 | 0.007 | 0.011 | 0.015 | 0.016 |
| 55 | 1 | 0.033 | 0.046 | 0.066 | 0.088 |
| | 3 | 0.015 | 0.022 | 0.031 | 0.039 |
| | 5 | 0.008 | 0.013 | 0.017 | 0.022 |
| 65 | 1 | 0.053 | 0.076 | 0.091 | 0.125 |
| | 3 | 0.018 | 0.026 | 0.035 | 0.051 |
| | 5 | 0.009 | 0.016 | 0.021 | 0.025 |

Source: Authors' determination.

### Analysis of sweet potatoes drying using Henderson and Pabis's model:

To simulate and describe the obtained drying curves and to assess the relationship between the drying constants and the studied drying parameters, a mathematical analysis of the experimental data and a calculation of the drying constants ($K_H$ and A) were performed.

The drying constants ($K_H$) and (A) for Henderson and Pabis's model could be calculated from using the exponential relationship between the moisture ratio (MR) of the tested samples and the drying time (t).

The drying constant ($K_H$) was found to be dependent on the drying air temperature (T), radiation intensity (I), and the thickness of the slices ($T_h$). The drying constant ($K_H$) increased with increasing of drying air temperature and radiation intensity, but it was decreased with increasing slice thickness, as shown in Table 2.

Table 2. Drying constant ($K_H$) of Henderson and Pabis' model at different levels of radiation intensity (I), air temperature (T) and slice thickness ($T_h$).

| Air temp. °C | Thickness of slices, mm | Radiation intensity, kW.m$^{-2}$ | | | |
|---|---|---|---|---|---|
| | | 0.861 | 0.973 | 1.083 | 1.161 |
| 45 | 1 | 0.03 | 0.04 | 0.065 | 0.074 |
| | 3 | 0.013 | 0.017 | 0.026 | 0.029 |
| | 5 | 0.008 | 0.012 | 0.018 | 0.019 |
| 55 | 1 | 0.036 | 0.049 | 0.069 | 0.094 |
| | 3 | 0.017 | 0.025 | 0.036 | 0.044 |
| | 5 | 0.009 | 0.016 | 0.021 | 0.026 |
| 65 | 1 | 0.055 | 0.082 | 0.096 | 0.134 |
| | 3 | 0.019 | 0.03 | 0.042 | 0.058 |
| | 5 | 0.01 | 0.018 | 0.025 | 0.032 |

Source: Authors' determination.

A multiple regression analysis was also proceeded to relate the studied parameters ($I$, $T$ and $T_h$) with the drying constant ($K_H$). The following equation might be used to explain the nature of dependence:

$$K_H = 0.112347I + 0.001042\,T - 0.0127\,Th - 0.09526 \quad (13)$$

and r= 0.90576, $R^2$= 0.820406 and S.E = 0.012838.

## Calculation of drying constant (A)

The drying constant (A) was determined for various combinations of drying air temperature, radiation intensity, and slice thickness as indicated in Table 3.

Table 3. Drying constant (A) of Henderson and Pabis' model at different levels of radiation intensity (I), air temperature (T) and slice thickness ($T_h$).

| Air temp. °C | Thickness of slices, mm | Radiation intensity, kW.m$^{-2}$ | | | |
|---|---|---|---|---|---|
| | | 0.861 | 0.973 | 1.083 | 1.161 |
| 45 | 1 | 1.273 | 1.3442 | 1.739 | 1.0689 |
| | 3 | 1.6826 | 1.8897 | 1.75 | 1.6946 |
| | 5 | 1.5084 | 1.6803 | 1.8199 | 1.9924 |
| 55 | 1 | 1.1904 | 1.22 | 1.2247 | 1.3142 |
| | 3 | 1.5851 | 1.8296 | 1.8569 | 1.565 |
| | 5 | 1.3854 | 1.9108 | 1.9477 | 1.8678 |
| 65 | 1 | 1.1654 | 1.4139 | 1.266 | 1.3496 |
| | 3 | 1.2275 | 1.6561 | 1.9397 | 1.7711 |
| | 5 | 1.253 | 1.6131 | 1.8358 | 2.3164 |

Source: Authors' determination.

The drying constant (A) was varied from 1.0689 to 2.3029 with an average value of constant (A).

**Analysis of thin layer drying of sweet potatoes using Logarithmic model**

The values of drying constants ($K_{Log}$), ($A_o$) and (c) for the Logarithmic equation could be obtained using the computer program (MATLAB).

The drying constant ($K_{Log}$) was discovered to be dependent on the drying air temperature

The drying constant ($k_{log}$) was discovered to be dependent on the drying air temperature (T), radiation intensity (I), and the thickness of the slices (Th). The drying constant ($k_{Log}$) increased with increasing drying air temperature and radiation intensity, but it was decreased with increasing slice thickness, as shown in Table 4.

A multiple regression analysis was also proceeded to relate the studied parameters ($I$, $T$ and Th) with the drying constant ($k$Log). The following equation might be used to explain the nature of dependence:

$$K_{Log} = 0.06489\,I + 0.000684\,T - 0.00995\,Th - 0.04969 \quad (14)$$

and r= 0.8856, $R_2$= 0.7844 and S. E = 0.010411.

Table 4. Drying constant ($k_{Log}$) of Logarithmic model at different levels of radiation intensity (I), air temperature (T) and slice thickness (Th)

| Air temp. °C | Thickness of slices, mm | Radiation intensity, kW.m$^{-2}$ | | | |
|---|---|---|---|---|---|
| | | 0.861 | 0.973 | 1.093 | 1.161 |
| 45 | 1 | 0.0215 | 0.0265 | 0.0383 | 0.0595 |
| | 3 | 0.0073 | 0.0095 | 0.0118 | 0.0153 |
| | 5 | 0.0031 | 0.0064 | 0.0069 | 0.0091 |
| 55 | 1 | 0.0261 | 0.0360 | 0.0560 | 0.0704 |
| | 3 | 0.0089 | 0.0124 | 0.0169 | 0.0216 |
| | 5 | 0.0059 | 0.0089 | 0.0092 | 0.0121 |
| 65 | 1 | 0.0417 | 0.0487 | 0.0705 | 0.0875 |
| | 3 | 0.0155 | 0.0160 | 0.0267 | 0.0291 |
| | 5 | 0.0092 | 0.0111 | 0.0117 | 0.0128 |

Source: Authors' determination.

A comparison study for the three drying models (Lewis's-Henderson and Pabis's and Logarithmic models). Figures (8 to 16) also show the measured and predicted moisture content values at a 45-degree chart for the minimum and maximum levels of drying air temperature, radiation intensity, and slices thickness.

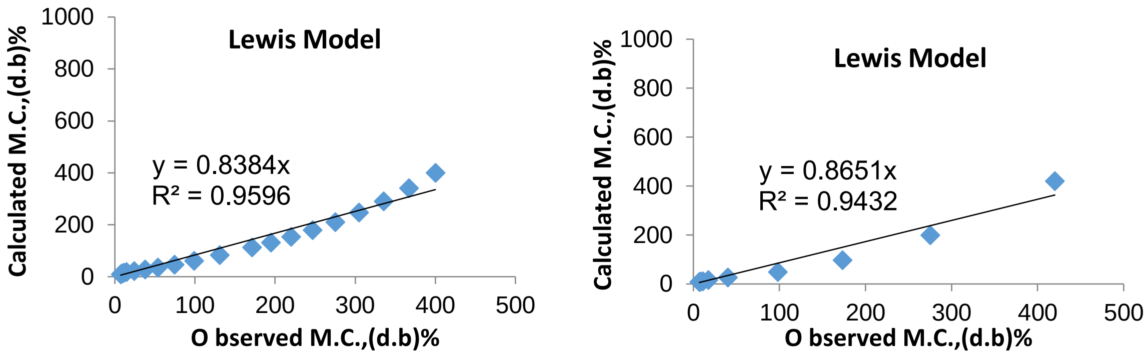



Fig. 9. Observed and calculated values of sweet potatoes slices moisture content using Lewis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 3 mm slices thickness
Source: Authors' determination.

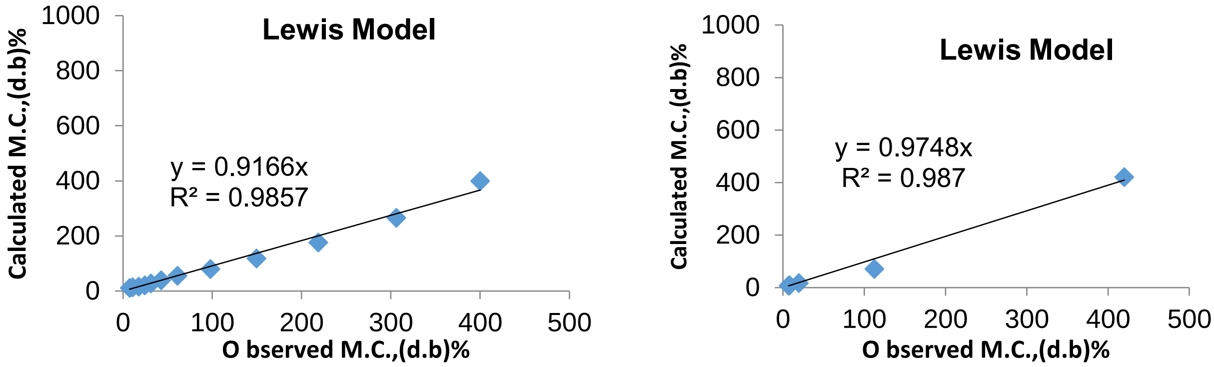



Fig. 9. Observed and calculated values of sweet potatoes slices moisture content using Lewis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 3 mm slices thickness
Source: Authors' determination.

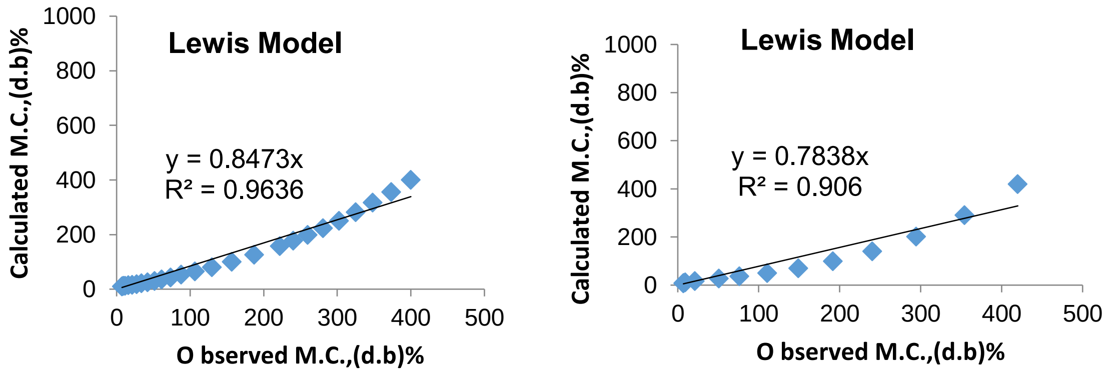



Fig. 10. Observed and calculated values of sweet potatoes slices moisture content using Lewis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 5 mm slices thickness
Source: Authors' determination.

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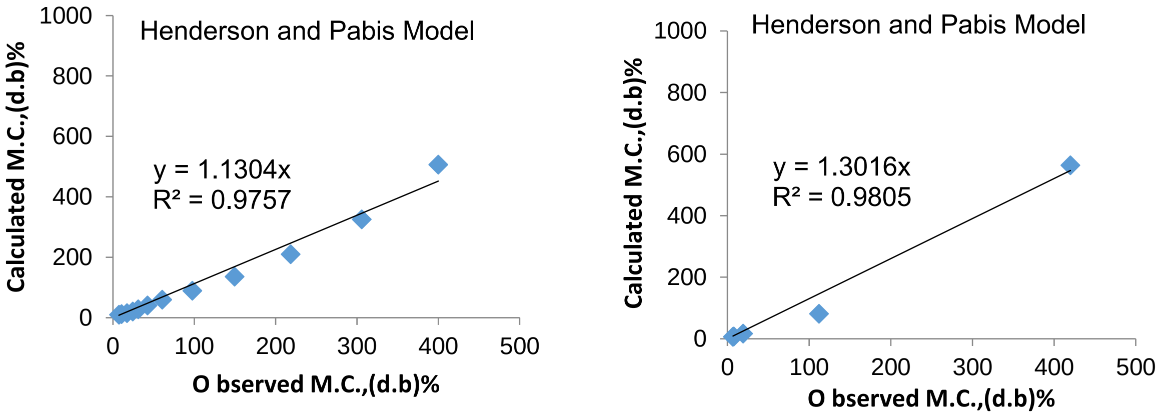


Fig. 11. Observed and calculated values of sweet potatoes slices moisture content using Henderson and Pabis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 1 mm slices thickness
Source: Authors' determination.

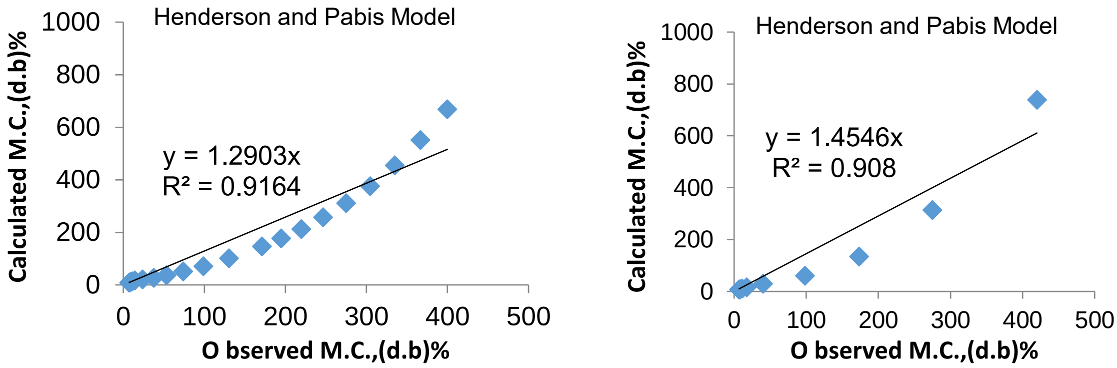


Fig. 12. Observed and calculated values of sweet potatoes slices moisture content using Henderson and Pabis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 3 mm slices thickness
Source: Authors' determination.

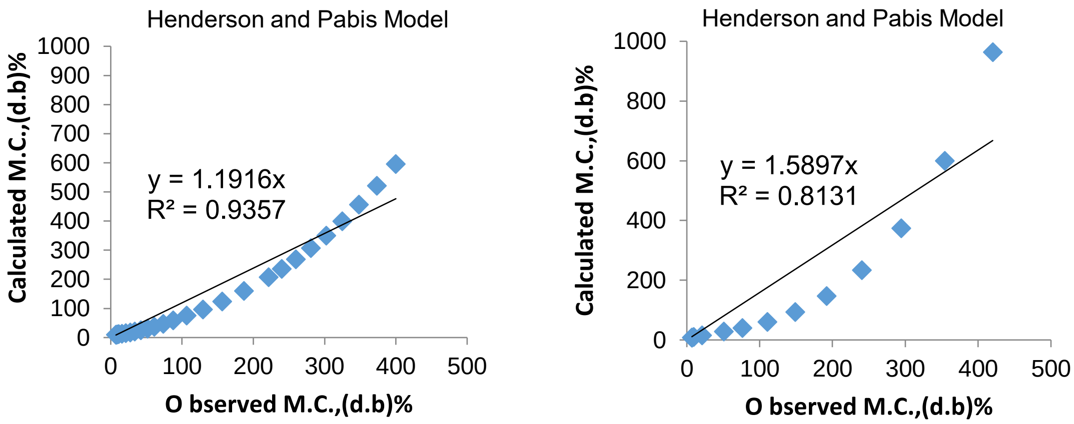


Fig. 13. Observed and calculated values of sweet potatoes slices moisture content using Henderson and Pabis's model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 ºC and 1.161 kW/m$^{-2}$ at 5 mm slices thickness
Source: Authors' determination.

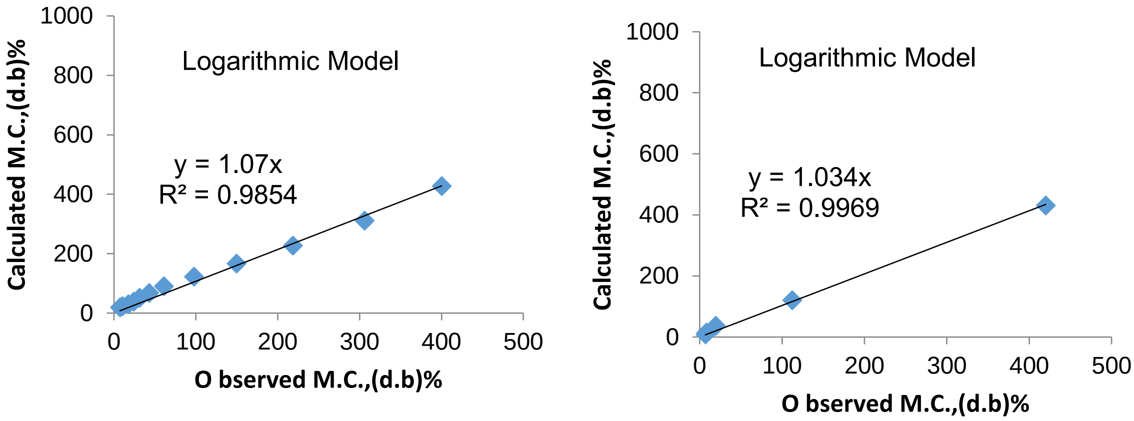


Fig. 14. Observed and calculated values of sweet potatoes slices moisture content using Logarithmic model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 oC and 1.161 kW/m$^{-2}$ at1 mm slices thickness
Source: Authors' determination.

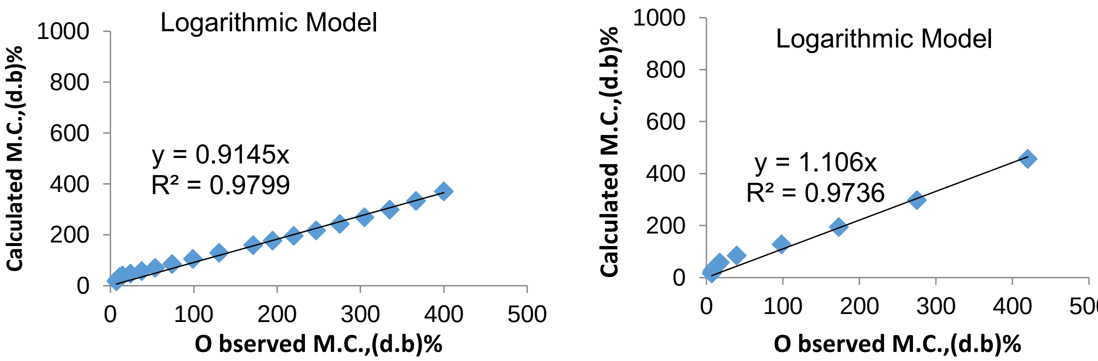


Fig. 15. Observed and calculated values of sweet potatoes slices moisture content using Logarithmic model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 oC and 1.161 kW/m$^{-2}$ at 3 mm slices thickness
Source: Authors' determination.

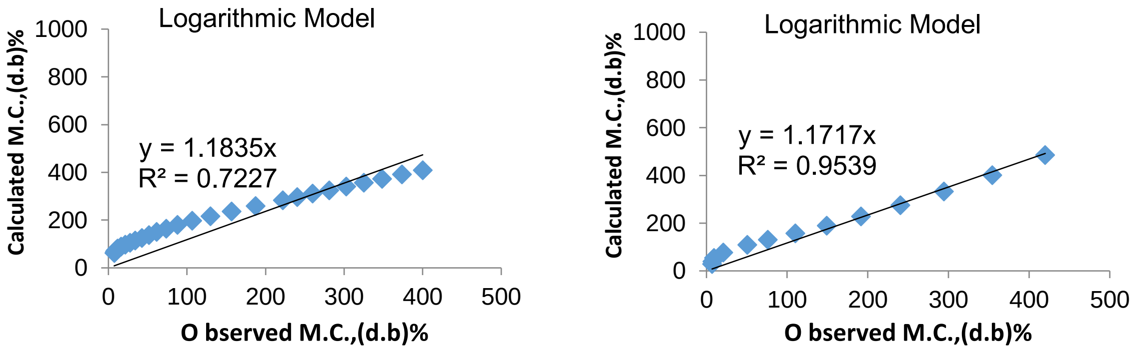


Fig. 16. Observed and calculated values of sweet potatoes slices moisture content using Logarithmic model at (T) 45°C, (I) 0.861 kW.m$^{-2}$ and 65 oC and 1.161 kW/m$^{-2}$ at 5 mm slices thickness
Source: Authors' determination.

**Comparative Evaluation Of The Studied Drying Models For Predicting The Changes Of Moisture Content Of Sweet Potatoes Slices**

A comparison study for the three drying models (Lewis's, Henderson and Pabis's and Logarithmic models) was conducted to assess the most appropriate drying model for simulating and describing the drying behavior of sweet potatoes under the studied range of experimental parameters.

Table 5 presents the overall average of the obtained coefficient of determination ($R^2$) and the standard error (SE) for the observed and the calculated moisture ratio of the studied model.

Table 5. The overall average of the obtained ($R^2$) and (SE) for three studied drying models

| The model | Coefficient of determination ($R^2$) | Standard error, (SE) |
|---|---|---|
| **Lewis** | 0.96383 | 0.24079 |
| **Henderson and Pabis** | 0.94090 | 0.50930 |
| **Logarithmic** | 0.99448 | 0.12193 |

Source: Authors' determination.

The computed values of chi-square ($x2$), mean bias error ($MBE$), root mean square error ($RMSE$) and correlation coefficient (r) are listed in Table 6 for the three models. The best model describing the thin-layer drying characteristics of sweet potatoes slices was chosen as the one with the highest $R2$ values and the lowest $\chi2$ and RMSE values. Statistical results from models are summarised in Table 6. The results from Table 6, the statistical parameter estimations showed that $\chi2$, and RMSE values were ranged from 0.00004 to 0.06767, and 0.00607 to 0.25131, respectively.

Table 6. Values of coefficient of correlation (r), chi-square ($\boldsymbol{x2}$), mean bias error ($\boldsymbol{MBE}$) and root mean square error ($\boldsymbol{RMSE}$) at three models

| IR | Ta °C | Th, mm | Lewis model | | | | Henderson and Pabis model | | | | Logarithmic model | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | r | $\chi^2$ | MBE | RMSE | r | $\chi^2$ | MBE | RMSE | r | X2 | MBE | RMSE |
| 0.861 | 45 | 1 | 0.99315 | 0.00323 | -0.03729 | 0.05438 | 0.98976 | 0.00494 | -0.04773 | 0.06729 | 0.99821 | 0.00323 | -0.03729 | 0.05438 |
| | | 3 | 0.98165 | 0.00950 | -0.05851 | 0.09501 | 0.96600 | 0.01228 | -0.07877 | 0.13919 | 0.99813 | 0.00055 | -0.01195 | 0.02354 |
| | | 5 | 0.98545 | 0.01006 | -0.07857 | 0.09833 | 0.97652 | 0.01578 | -0.09853 | 0.12318 | 0.99211 | 0.00701 | 0.07081 | 0.08209 |
| | 55 | 1 | 0.99574 | 0.00180 | -0.02574 | 0.04040 | 0.99362 | 0.00280 | -0.03397 | 0.05047 | 0.99859 | 0.00049 | 0.00996 | 0.02111 |
| | | 3 | 0.97652 | 0.01365 | -0.08653 | 0.11312 | 0.96370 | 0.02119 | -0.10924 | 0.14094 | 0.99830 | 0.00077 | 0.00864 | 0.02695 |
| | | 5 | 0.99370 | 0.00440 | -0.05360 | 0.06481 | 0.98787 | 0.00846 | -0.07452 | 0.08989 | 0.99987 | 0.00004 | -0.00138 | 0.00607 |
| | 65 | 1 | 0.99430 | 0.00210 | -0.02239 | 0.04283 | 0.99277 | 0.00275 | -0.02716 | 0.04905 | 0.99842 | 0.00062 | 0.01092 | 0.02326 |
| | | 3 | 0.99643 | 0.01964 | 0.11308 | 0.13538 | 0.99449 | 0.01393 | 0.09446 | 0.11402 | 0.99874 | 0.06767 | 0.21519 | 0.25131 |
| | | 5 | 0.99662 | 0.00083 | -0.02312 | 0.02807 | 0.99267 | 0.00286 | -0.04407 | 0.05213 | 0.99599 | 0.01682 | 0.10847 | 0.12642 |
| 0.973 | 45 | 1 | 0.99296 | 0.00313 | -0.03599 | 0.05307 | 0.98701 | 0.00593 | -0.05107 | 0.07304 | 0.99923 | 0.00886 | -0.03724 | 0.08932 |
| | | 3 | 0.96818 | 0.01668 | -0.08169 | 0.12550 | 0.94356 | 0.00976 | -0.04849 | 0.09602 | 0.99376 | 0.00292 | -0.00071 | 0.05250 |
| | | 5 | 0.97464 | 0.01432 | -0.08344 | 0.11715 | 0.96569 | 0.01910 | -0.09742 | 0.13528 | 0.99748 | 0.00120 | 0.01018 | 0.03388 |
| | 55 | 1 | 0.99408 | 0.00146 | 0.02424 | 0.03608 | 0.99127 | 0.00089 | 0.01584 | 0.02811 | 0.99804 | 0.00662 | 0.05930 | 0.07671 |
| | | 3 | 0.96812 | 0.01633 | -0.08945 | 0.12313 | 0.95261 | 0.02433 | -0.11100 | 0.15032 | 0.99667 | 0.00149 | 0.01505 | 0.03718 |
| | | 5 | 0.96879 | 0.01693 | -0.09384 | 0.12665 | 0.94285 | 0.03103 | -0.12943 | 0.17145 | 0.99421 | 0.00239 | -0.02464 | 0.04762 |
| | 65 | 1 | 0.98483 | 0.00473 | -0.01589 | 0.06366 | 0.97963 | 0.00800 | -0.04439 | 0.08282 | 0.99803 | 0.00110 | 0.01894 | 0.03067 |
| | | 3 | 0.97722 | 0.01045 | -0.06660 | 0.09823 | 0.96224 | 0.01759 | -0.08954 | 0.12742 | 0.99617 | 0.00179 | 0.02090 | 0.04061 |
| | | 5 | 0.97169 | 0.00281 | 0.03879 | 0.05156 | 0.95792 | 0.00134 | 0.01829 | 0.03558 | 0.99720 | 0.03660 | 0.16033 | 0.18592 |
| 1.093 | 45 | 1 | 0.96709 | 0.01386 | -0.06396 | 0.11012 | 0.95255 | 0.02019 | -0.07950 | 0.13291 | 0.99479 | 0.00277 | 0.02730 | 0.04926 |
| | | 3 | 0.97041 | 0.01434 | -0.07910 | 0.11569 | 0.95570 | 0.02123 | -0.09833 | 0.14076 | 0.99286 | 0.00401 | 0.04189 | 0.06114 |
| | | 5 | 0.96924 | 0.01670 | -0.09008 | 0.12561 | 0.94627 | 0.02876 | -0.11996 | 0.16476 | 0.99632 | 0.00157 | 0.00061 | 0.03847 |
| | 55 | 1 | 0.99110 | 0.01174 | 0.07648 | 0.10033 | 0.98869 | 0.00959 | 0.06880 | 0.09068 | 0.99747 | 0.02255 | 0.10739 | 0.13902 |
| | | 3 | 0.96996 | 0.00969 | -0.06535 | 0.09423 | 0.96415 | 0.01673 | -0.08781 | 0.12383 | 0.99529 | 0.00327 | 0.04169 | 0.05472 |
| | | 5 | 0.96996 | 0.01535 | -0.08503 | 0.11971 | 0.94359 | 0.03149 | -0.13102 | 0.17145 | 0.99819 | 0.00606 | 0.05775 | 0.07521 |
| | 65 | 1 | 0.99609 | 0.00167 | -0.01971 | 0.03736 | 0.99433 | 0.00250 | -0.02484 | 0.04560 | 0.99975 | 0.00018 | 0.00851 | 0.01233 |
| | | 3 | 0.97890 | 0.00958 | -0.06485 | 0.09333 | 0.96005 | 0.01817 | -0.09104 | 0.12851 | 0.99524 | 0.00177 | -0.02004 | 0.04017 |
| | | 5 | 0.97213 | 0.01011 | 0.08087 | 0.09690 | 0.95140 | 0.00650 | 0.06328 | 0.07767 | 0.99725 | 0.04479 | 0.17531 | 0.20393 |
| 1.161 | 45 | 1 | 0.99577 | 0.00143 | -0.01416 | 0.03500 | 0.99536 | 0.00159 | -0.01565 | 0.03696 | 0.99853 | 0.00058 | 0.01037 | 0.02233 |
| | | 3 | 0.97747 | 0.01090 | -0.06955 | 0.10031 | 0.96195 | 0.01860 | -0.09386 | 0.13102 | 0.99644 | 0.00171 | 0.01933 | 0.03974 |
| | | 5 | 0.96423 | 0.02093 | -0.11120 | 0.14007 | 0.94233 | 0.03363 | -0.14160 | 0.17755 | 0.99873 | 0.00164 | 0.03482 | 0.03921 |
| | 55 | 1 | 0.99705 | 0.00096 | -0.00474 | 0.02821 | 0.99506 | 0.00177 | -0.01482 | 0.03845 | 0.99995 | 0.01113 | -0.03817 | 0.09633 |
| | | 3 | 0.99609 | 0.00167 | -0.02707 | 0.03895 | 0.99032 | 0.00410 | -0.04341 | 0.06130 | 0.99948 | 0.00016 | 0.00516 | 0.01204 |
| | | 5 | 0.97332 | 0.01420 | -0.08378 | 0.11485 | 0.95377 | 0.02432 | -0.11165 | 0.15028 | 0.99727 | 0.00138 | 0.01486 | 0.03578 |
| | 65 | 1 | 0.99454 | 0.00263 | -0.02185 | 0.04586 | 0.99248 | 0.00373 | -0.02695 | 0.05462 | 0.99948 | 0.00040 | 0.01177 | 0.01795 |
| | | 3 | 0.97401 | 0.00943 | -0.05320 | 0.09211 | 0.96052 | 0.01332 | -0.05948 | 0.10948 | 0.99685 | 0.00424 | 0.05071 | 0.06178 |
| | | 5 | 0.95961 | 0.01251 | 0.09024 | 0.10747 | 0.92390 | 0.00869 | 0.07388 | 0.08954 | 0.99673 | 0.04553 | 0.17634 | 0.20501 |
| **Average** | | | **0.98142** | **0.00916** | **-0.03563** | **0.08510** | **0.96979** | **0.01300** | **-0.05252** | **0.10143** | **0.99722** | **0.00872** | **0.03670** | **0.06705** |

Source: Authors' determination.

**Quality of the dried sweet potatoes:**

Effect of air-drying temperature and infrared radiation on the sweet potato slices shrinkage shows. In that, with increase of air-drying temperature the diameter and thickness shrinkage percentage were decreased and with increase of infrared radiation, the diameter shrinkage percentage was increased, as shown in Figures 17 and 18.

The rehydration ratio increased with increasing of drying air temperature and radiation intensity, while rehydration ratio decreased with increase of slice thickness as shown in Table 7.

Table 7. Effects of drying temperature, infrared and thickness on rehydration ratio of dried sweet potatoes

| Radiation intensity, $kW.m^{-2}$ | Slices thickness, mm | Air drying temperature, °C | | |
|---|---|---|---|---|
| | | 45 | 55 | 65 |
| 0.861 | 1 | 2.86 | 3.35 | 3.43 |
| | 3 | 2.60 | 2.87 | 3.04 |
| | 5 | 2.46 | 2.64 | 2.90 |
| 0.973 | 1 | 3.75 | 3.81 | 3.84 |
| | 3 | 3.25 | 3.28 | 3.24 |
| | 5 | 2.72 | 2.73 | 2.64 |
| 1.093 | 1 | 3.74 | 4.00 | 4.05 |
| | 3 | 3.26 | 3.28 | 3.35 |
| | 5 | 2.55 | 2.95 | 3.00 |
| 1.161 | 1 | 3.95 | 4.15 | 4.16 |
| | 3 | 3.03 | 3.29 | 3.48 |
| | 5 | 2.60 | 2.73 | 3.13 |

Source: Own calculation.

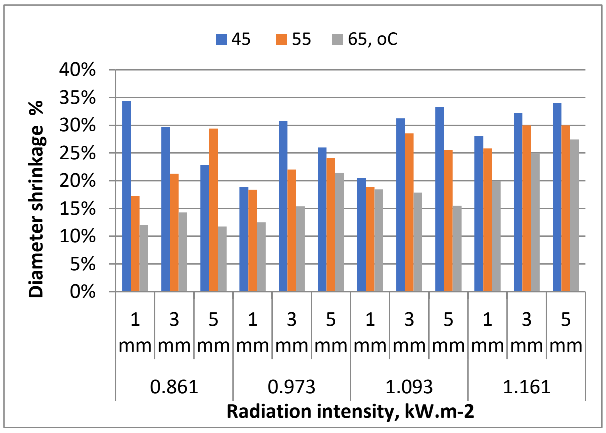


Fig. 17. Effect of air-drying temperature and infrared radiation on the diameter shrinkage percentage of sweet potato slices.
Source: Authors' determination.

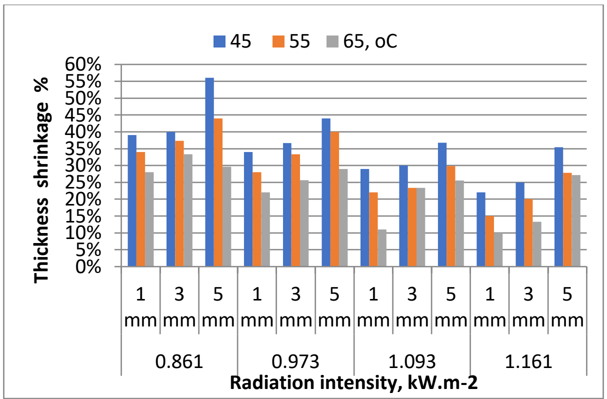


Fig. 18. Effect of air-drying temperature and infrared radiation on the thickness shrinkage percentage of sweet potato slices.
Source: Authors' determination.

The highest rehydration ratio of 4.16 were obtained at drying air temperature of 65°C, and the minimum rehydration ratio of 2.46 was obtained for 45°C.

## CONCLUSIONS

The intensity of infrared radiation and drying air temperature had a significant effect on the moisture ratio of sweet potato slices. The moisture ratio of sample slices decreased when the radiation intensity and the drying air temperature increased. The drying constant ($k_L$), ($k_H$) and ($k_{Log}$) increased with the increase of the drying air temperature and radiation intensity. However, it was decreased with the increase of slices thickness An exponential relationship was found between the drying constant ($k_L$), ($k_H$) and ($k_{Log}$) and the radiation intensity at all levels of air temperature and slice thickness. The drying constant (A) showed no direct relation with the experimental variable, while all the drying process occurred during the falling rate-drying period. Models (Lewis's model, Henderson and Pabis's model and Logarithmic model) could describe the drying behavior of sweet potato slices satisfactory.

Logarithmic model could be considered more proper model for describing the drying behavior of sweet potato slices and predicting the change in moisture content during the laboratory drying process due to simplicity of calculations.

- The final moisture content of the dried sweet potato slices under the studied conditions almost reached the recommended range of the dried sweet potato 4-8% (d. b).
- The rehydration ratio ranged from 3.95 to 5.53 for the sweet potato slices.
- The diameter shrinkage percentage of sweet potato slices ranged from 12% to 34%, while the thickness shrinkage percentage of slices ranged from 10% to 56%.

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