Numerical Simulation of the Drying Kinetics of Red Onions (Allium cepa) to Prevent the Growth of Aspergillus niger and the Design of a Tray Dryer for Small-Scale Setting

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ABSTRACT: Red onions are commonly grown crops in the Philippines. The country's favorable climate and soil conditions make it an ideal environment for cultivating these onion varieties. The high moisture content of onion makes it susceptible to fungus growth, particularly *Aspergillus niger*, which causes spoilage and agricultural losses. To extend the shelf-life of onions, drying is a technique that reduces water activity and moisture content (MC). Drying onions until the MC is 5% inhibits the growth of microorganisms and ultimately increases their longevity. This research attempts to predict the optimum temperature and shortest drying time to achieve 5% MC in red onions. Three mathematical models, the Laplace Transform Model, Page Model, and Non-linear Decomposition Model, were examined to describe the drying behavior of thinly sliced red onions at 50, 60, and 70°C using a tray dryer. The Page model gave the best fit for red onions with the least total error and highest coefficient of determination. The optimum temperature was observed to be 70°C, which was efficient in producing quality onions without any fungal growth at the shortest drying time of 67.27 minutes. A tray dryer was designed to dry 100 kg of red onions for a small-scale setting using 40 trays with dimensions 1.4 x 0.8 x 1.7 m and a heating requirement of 13.77 kW with solar heat as the primary source of energy and a recirculating mechanism of air as innovations.

Keywords: *Aspergillus niger*, drying kinetics, mathematical model, moisture content, onions, tray dryer

Abbreviations: MC, moisture content; MR, moisture ratio; PSA, Philippine Statistics Authority; DA, Department of Agriculture; PHP, Philippine peso; PGH, panel generation factor

I. INTRODUCTION

Onion (Allium cepa) is extensively cultivated in 22 provinces in the Philippines. Red onion is one of the most grown onion varieties [1]. The favorable climate and soil conditions create an ideal environment for cultivating these species of alliums in the country [2]. Onion is a staple in Filipino cuisine as a flavor enhancement in various dishes [3]. The demand for onions in the country is high, wherein the country consumes approximately 17,000 metric tons of onions every month [4]. However, the government relies on onion importation to meet domestic demand [5]. According to the Philippine Statistics Authority, 12.45% of the country's total supply in 2022 came from importation [6].

Upon harvesting, fresh red onions' initial moisture content (MC) is 87.80% [6]. Due to the onion's high MC, it has a shorter shelf life and is susceptible to black mold caused by the fungi *Aspergillus niger* [7]. In 2022, the highest post-harvest loss due to spoilage of freshly harvested onions was recorded at 45.06%, a deficit of PHP 1.96 billion in the Philippines [8]. In the same year, farmers in Occidental Mindoro experienced significant losses in onion production due to poor agricultural methods, heavy rainfall, and a lack of post-harvest facilities. These challenges resulted in farmers being forced to throw or burn their harvest [9]. Food preservation, such as drying, extends the storage life of various crops. Water removal is needed to eliminate the microorganism's negative effect that increases food deterioration [10].

Drying is a unit operation for reducing the MC of fruits and vegetables to a level required to prolong the shelf-life of agricultural products that will inhibit microorganism growth [11]. In food and pharmaceutical industries, a tray dryer, operated in batch operation, is commonly used to remove the moisture in the samples. It is an insulated chamber consisting of multiple stacks of trays with adequate spacing in between. Hot air, supplied by the fan and heated by the heating unit, is circulated throughout the chamber, and the moisture carried by the air is exhausted from the outlet. Generally, a tray dryer is used for drying onions at 50 - 70°C as it is efficient and consumes less energy. Additionally, it is suitable for small-scale drying of vegetables like onions since drying onions operates at relatively low temperatures [12].

Drying onion slices up to 4-5% MC inhibits microorganism reproduction that causes spoilage [13]. The main objective of this study is to prolong the shelf-life of red onions through drying.

Specific objectives are:

- to determine the suitable mathematical model that describes the drying kinetics of red onions.
- to predict the optimum temperature and drying time to attain 5% moisture content (MC).
- to produce quality dried onions without the growth of *Aspergillus niger*; and
- to design a tray dryer that applies to a small-scale onion farm in the Philippines.

II. MATERIALS AND METHODS

A. Sample preparation

Firm, fresh, medium-sized, and mold-free red onions were procured from a local market in Balintawak, Quezon City. The onions were wiped, peeled, and sliced to a thickness of 4 to 5 millimeters (mm) using a sharp kitchen knife [14] as shown in Fig. 1. The size of sliced onions was measured using a vernier caliper to monitor its uniform thickness.

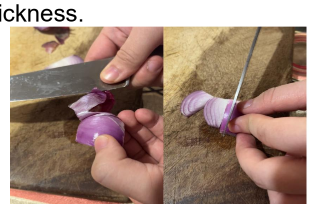

Fig. 1. Peeling and slicing of onions

B. Drying experiment

The drying experiment was done by batch using a tray dryer. Before the drying experiment, the dryer system was pre-heated to achieve a desirable steady state condition of temperature and constant air velocity. Single layers of thinly sliced red onions were arranged evenly in a static tray (see Fig. 2) and were heated in the tray dryer at 50°C. The onions were weighed every 5 minutes until constant weight was achieved. The drying procedure was conducted in triplicate and was repeated at 60°C and then at 70°C [15].

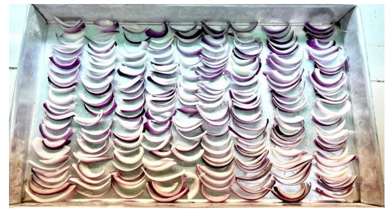

Fig. 2. Onion sample before drying

C. Determination of moisture ratio

The moisture ratio (MR) in red onions during drying was calculated using Eq. 1:

$$MR = \frac{M-M_e}{M_e} \quad (1)$$

D. Numerical simulation of drying curves

Many drying kinetic models have been used to evaluate the drying processes involved in food engineering. Three mathematical models were used to simulate the drying kinetics of red onions, namely, the Page, Laplace Transform, and Non-linear Decomposition models. These models were tested for the best fitting of the drying curves of red onions based on the highest coefficient of determination, R^2, and the least total error.

Page Model. The drying rate is related to the difference in moisture content between the material being dried and the equilibrium moisture content for the specific drying condition, according to the Page Model, which was developed from Newton's Law of Cooling. The equation of the Page Model is shown in Eq. 2.

$$MR = ae^{-kt^n} \quad (2)$$

The drying rate equation of the Page Model was linearized, which is shown in Eq. 3.

$$ln(MR) = lna - kt^n \quad (3)$$

Laplace Transform Model. The overall material balance generated through the drying system served as the basis for the Laplace Transform Model. It is done by subtracting the input from the system's output and equating that result with the accumulation rate, as shown in Eq. 4.

$$\tau \frac{dM}{dt} = M_e - M \quad (4)$$

Eq. 4 is transformed into a Laplace Transform Model, integrated, and simplified to create Eq. 5, which is used to simulate the features of the drying rate of the slices of red onions.

$$M = M_e - M_e e^{-\frac{t}{\tau}} + M_i e^{-\frac{t}{\tau}} \quad (5)$$

Nonlinear Decomposition Model. The Non-linear Decomposition Model is based on the differential equation of batch decomposition given in Eq. 6, where n is not equal to one.

$$\frac{dMR}{dt} = -k \cdot MR^n \quad (6)$$

The equation of the Non-linear Decomposition Model was linearized, which is shown in Eq. 7.

$$\frac{1}{MR^{(n-1)}} = (n-1)kt + \frac{1}{MR_0^{(n-1)}} \quad (7)$$

Eq. 7 is adjusted and expressed as the moisture ratio, as shown in the equation below.

$$MR = \left[\frac{MR_0^{(n-1)}}{(n-1)ktMR_0^{(n-1)}+1}\right]^{\frac{1}{n-1}} \quad (8)$$

E. Determination of the suitable model

The experimental and predicted drying data (MR vs. t) at 50, 60, and 70°C were fitted into the three mathematical models: Page Model, Laplace Transform Model, and Non-linear Decomposition Model. Values of the time constant, for the Laplace Transform Model; correlation coefficient, R^2, for Page Model and Non-linear Decomposition Model; and the total error for the three models were computed. These models were tested for the best fitting of the drying curves of red onions based on the highest coefficient of determination, R^2 and least total error. The selection of the best-fit model was further confirmed by visual inspection among the graphs.

F. Determination of the drying time to attain 5% moisture content

Lagrange interpolation was used to calculate the drying time to achieve the desired 5% MC in red onions. This method produces polynomials of nth order that traverse (n+1) points. These polynomials assume that the relationship between the data is curved to create interpolation values with greater precision. Eq. 9 serves as a representation of its general equation, while the other three versions are Eq. 10 - 12.

$$f_n(x) = \sum_{i=0}^{n} L_i(x) f(x_i) \quad (9)$$

First-Order version:

$$f_1(x) = \frac{x-x_1}{x_0-x_1} f(x_0) + \frac{x-x_0}{x-x_0} f(x_1) \quad (10)$$

Second-Order version:

$$f_2(x) = \frac{(x-x_1)(x-x_2)}{(x_0-x_1)(x_0-x_2)} f(x_0) + \frac{(x-x_0)(x-x_2)}{(x_1-x_0)(x_1-x_2)} f(x_1) + \frac{(x-x_0)(x-x_1)}{(x_2-x_0)(x_2-x_1)} f(x_2) \quad (11)$$

Third-Order version:

$$f_3(x) = \frac{(x-x_1)(x-x_2)(x-x_3)}{(x_0-x_1)(x_0-x_2)(x_0-x_3)} f(x_0) + \frac{(x-x_0)(x-x_2)(x-x_3)}{(x_1-x_0)(x_1-x_2)(x_1-x_3)} f(x_1) + \frac{(x-x_0)(x-x_1)(x-x_3)}{(x_2-x_0)(x_2-x_1)(x_2-x_3)} f(x_2) + \frac{(x-x_0)(x-x_1)(x-x_2)}{(x_3-x_0)(x_3-x_1)(x_3-x_2)} f(x_3) \quad (12)$$

G. Quality of dried onion slices

The dried red onion slices were stored in sealed containers made from low-density polyethylene at an ambient temperature of 28°C. The dried samples were set aside for four weeks to check for the growth of *Aspergillus niger* or black mold fungus.

H. Design of a tray dryer

Using 100 kg of red onions per batch in a tray dryer with an initial MC of 87.80% [6], the amount of moisture removed (kg), M_W, to attain 5% MC, can be calculated using Eq. 13 [16].

$$M_W = M_P \cdot \frac{(x_0-x_f)}{(1-x_f)} \quad (13)$$

The quantity of heat required to remove the moisture in red onions, E_a, is computed using Eq. 14 [16].

$$E_a = M_P(C_P)(T_f - T_i) + M_W(L_V) \quad (14)$$

Where C_p of onion is 3.37 kJ/kg °C and L_v is 2257 kJ/kg [16,17]. The blower or fan in a tray dryer supplies the energy to transport the air to the chamber; the horsepower, bhp, and power, P_h, of the blower are calculated using Eq. 15 and 16, respectively [16]. A vane-axial fan will be used in the design due to its excellent maintenance of a consistent airflow pattern.

$$bhp = \frac{V_a * static\ pressure}{6356 * industrial\ fan\ efficiency} \quad (15)$$

The vane-axial fan's static pressure is taken as 3 in WC (water column) and industrial fan efficiency is 0.85 [17]. Using the calculated bhp from the previous equation, power of fan, P_f, is computed using Eq.16 [16].

$$P_f = \frac{bhp * 746}{industrial\ fan\ efficiency} \quad (16)$$

Heating coils heat the air supplied by the fan, and its required power, P_h, is given by Eq. 17 [16]. The drying time, t_D, in Eq. 17 is obtained from the drying experiment at optimal temperature.

$$P_h = \frac{E_a}{t_D} \quad (17)$$

The efficiency of the dryer, η_D, is computed using Eq.18 [16].

$$\eta_D = \frac{M_w(L_v)}{P_F + P_h} \quad (18)$$

Trays are used to hold the dried onion samples inside the chamber; the number and dimensions of trays must be specified to hold 2.5 kg per tray. The number of trays can be calculated using Eq. 19 where ρ_p is 970 kg/m³ [18].

$$No.\ of\ trays\ = \frac{M_P(\frac{1}{\rho\ \ p})}{V_{tray}} \qquad (19)$$

The solar panel tilt depends on the latitude of the location of the solar panel. Considering the lack of cold storage for onions that causes the onion to rot, Occidental Mindoro, Philippines that is situated in Southern Luzon is a potential location for the design of tray dryer to promote post-harvest practices, preventing the farmers from throwing or burning their harvest [9]. Given the latitude location of Occidental Mindoro, which is 13.1024°, solar angle tilt, β, can be computed using Eq. 20 [16]. For other locations, values are found in Geoportal Philippines [19].

$$\beta = 10^\circ + Latitude\ of\ Location \qquad (20)$$

The power requirement of a solar photovoltaic system, PV, to supply the required power of dryer is computed using Eq. 21 where panel generation factor, PGF, in the Philippines is 3.43 [16,20].

$$PV = \frac{(P_h+P_f)\,(t_D)}{PGF} \qquad (21)$$

Batteries with 12V and 400Ah capacity were used for energy storage. For a battery, the minimum allowable capacity is 0.90 [16]. To store the required power from solar panels for 4 cycles in 2 days, the required number of batteries is calculated using Eq. 22 where both depth of discharge, DoD, and battery efficiency, η_B, is 0.85 as the healthy range for both parameters is 0.85 to 1 [20].

$$No.\ of\ batteries\ = \frac{\frac{(P_h+P_f)(t_D)\left(\frac{1\,hr}{3600s}\right)(4\ cycles)(2\ days)}{12V(DoD)(\eta_B)}(0.9)}{400\ Ah} \qquad (22)$$

III. RESULTS AND DISCUSSION

A. Analysis of drying behavior

The drying behavior of red onion slices is significantly affected by temperature. Higher temperatures result in a faster drying rate. As shown in Fig. 3, the highest drying temperature of 70°C gave the shortest drying time of 125 minutes to reach equilibrium moisture content in red onions. Meanwhile 60°C and 50°C required a drying time of 170 and 290 minutes, respectively.

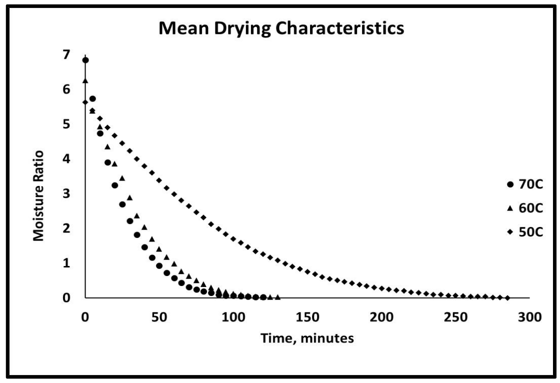

Fig. 3. Mean drying characteristics of dried red onion slices at different temperatures.

B. Determination of best fit model and optimum drying temperature

The MR data of red onion slices were fitted into the three different models and the coefficient of determination, $R^{2,}$ for the Page and Laplace Transform Models, residence time, , for the Laplace Transform Model and the total error for the three models were recorded and presented in Table 1. The Page model exhibited the least total error and highest coefficient of determination at 70°C drying temperature. The Page Model yielded notable accuracy, precisely modeling the data series of red onion slices and predicting its future behavior. By visual inspection, the Page Model also provided the best fit to the experimental data at 70°C, as shown in Fig. 4, compared to the graphs of the Laplace Transform Model and Non-linear Decomposition model, as shown in Fig. 5 and Fig. 6, respectively. Therefore, the Page Model may be assumed to represent the thin-layer drying behavior of red onion slices with an optimum drying temperature of 70°C. Additionally, the Page model is commonly used for food samples [21, 22], while the Laplace Transform and Non-Linear Decomposition models are more suitable for thin materials like wood. This finding is consistent with a study conducted by Demiray et al., who also reported that the Page model represents the drying kinetics of onion slices [23]

Table 1: Summary of Results

Temperature (°C)	Page Model			Laplace Transform Model		Non-linear Decomposition Model		
	n	R^2	Total Error		Total Error	n	R^2	Total Error
50	1.69	0.997	0.080	59.76	0.206	0.69	0.999	0.078
60	1.57	0.998	0.021	29.00	0.296	0.69	0.998	0.069
70	1.21	0.999	0.004	24.84	0.126	0.86	0.999	0.040

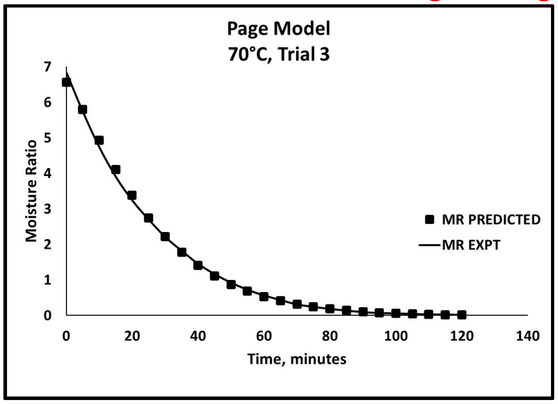

Fig. 4. Comparison of Predicted and Experimental Moisture Ratio Values of Red onions Using Page Model (70°C, Trial 3).

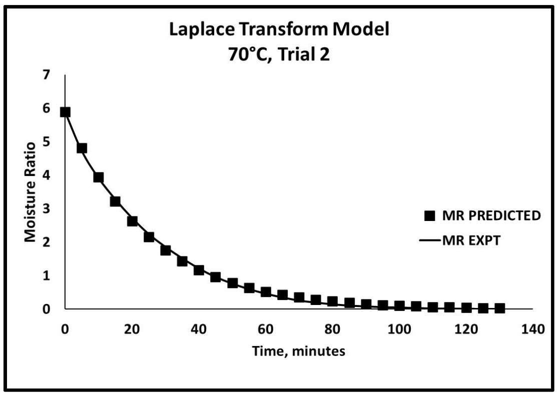

Fig. 5. Comparison of Predicted and Experimental Moisture Ratio Values of Red onions Using Laplace Transform Model (70°C, Trial 2).

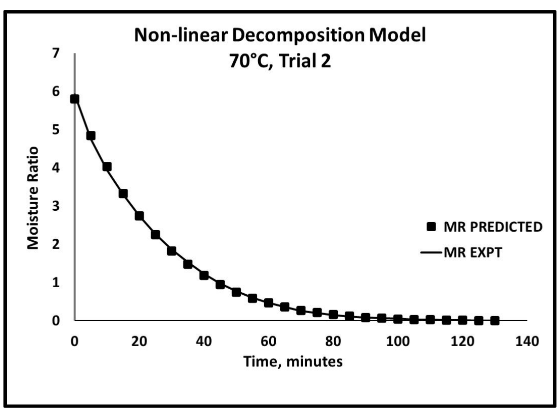

Fig. 6. Comparison of Predicted and Experimental Moisture Ratio Values of Red onions Using Non-Linear Decomposition Model (70°C, Trial 2).

C. Analysis of dying time

As predicted by the Page Model, Table 2 shows the calculated drying time using the third-order Lagrange interpolation for the red onion slices to attain the desired MC of 5%, at which the growth of microorganisms is unlikely to occur. The drying time was significantly affected by the drying temperature. The average drying time to reach 5% MC from the initial MC of 87.80% was 157.41, 82.61, and 67.27 minutes at drying temperatures of 50, 60, and 70°C, respectively, making 67.27 minutes the shortest drying time to attain a 5% MC in the red onion slices at the optimum drying temperature.

Table 2: Calculated Drying Time to Attain 5% Moisture Content as predicted by Page Model using Lagrange Interpolation

Trial No.	Temperature		
	50°C	**60°C**	**70°C**
1	159.76	82.61	71.69
2	157.41	90.16	68.66
3	188.14	111.84	67.27

D. Aspergillus niger analysis

The growth of *Aspergillus niger* or black mold fungus was monitored by visual inspection after red onions were heated, utilizing the predicted results from the drying experiment and numerical simulations. Red onion slices were heated at 70°C for 67.27 minutes. After four weeks of storage at room temperature with one-week intervals of monitoring, Fig. 7 shows no signs of the growth of *Aspergillus niger* or black mold fungus. Fig. 8 shows the black mold growth in freshly sliced onions after leaving them for four days at room temperature. The dark color of the dried onion slices is due to the enzymatic browning, an oxidation reaction that causes foods to turn brown [24].

Fig. 7. Dried red onions.

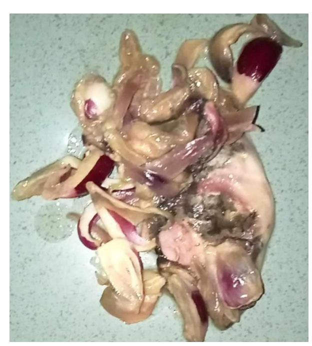

Fig. 8. Black mold in fresh red onion.

E. Tray dryer and solar panel specifications

The 70°C optimum drying temperature and shortest drying time of 67.27 minutes to achieve 5% MC in red onions determined from the drying experiment were utilized in the design of the tray dryer. Table 3 shows the tray dryer specification sheet for the design of a solar-powered tray dryer with a capacity of 100 kg red onion slices with a thickness of 4 to 5 mm. The drying chamber, made of 6 mm non-corrosive food-grade material stainless steel 304, measures 1.3 x 0.7 x 1.6 m [25]. A 32 mm wool fiber was used for insulation [14]. A 1 HP vane-axial fan was utilized for constant airflow [26]. Forty aluminum trays with 0.5 x 0.5 x 0.01 m dimensions were selected due to their heat-retaining properties [27]. The efficiency of the tray dryer, η_D, was calculated to be 91.47%, exceeding the minimum drying efficiency of 75%.

Table 3: Tray Dryer Specifications

Design Parameters	Specifications
Capacity (kg)	100
Temperature Range (°C)	60 – 70
Quantity of Heat Required to Remove the Moisture (MJ)	206.59
Overall Dimension (m)	1.7 x 1.4 x 0.8
Size of Drying Chamber	1.3 x 0.7 x 1.6
Internal and External Material of Construction	Stainless Steel 304
Type of Insulation of Chamber	Wool Fiber
Type of Fan	Vane Axial
Motor Capacity (HP)	1
Power of Fan (W)	942.28
Fan Material of Construction	Aluminum
Heating Element	Heating Coils
Power of Heater (KW)	51.19
Heating Element Material of Construction	Stainless Steel 304
Number of Trays	40
Tray Size (m)	0.5 x 0.5 x 0.01
Tray Material of Construction	Aluminum
Number of Doors	2
Door Material of Construction	Stainless Steel 304
Type of Insulation of Door	Wool Fiber
Number of Legs	4
Location of Support	4 Columns 90° apart, Triangular cross-section
Drying Efficiency (η_D)	91.47%

Table 4: Heuristics for Tray Dryer

Parameters	Specification
Onion Thickness (mm)	4 - 5
Minimum Drying Chamber Air Velocity (m/s)	0.2
Minimum Drying Efficiency	75%
Moisture Content without Fungal Growth	4 - 5%
Drying Temperature (°C)	60 - 70

Table 5: Solar Panel Specifications

Design Parameters	Specifications
Mode of Operation	Solar Power
Power Requirement (kW)	13.77
Tilt Direction	23.10°
Material of Construction	Polycrystalline Silicon
Mode of Storage	Lithium-ion Batteries
Capacity	12V, 400Ah
Number of Batteries	122

Tray dryer Innovation. The use of solar panels was incorporated into the design of the tray dryer as an innovation to maximize solar energy during the harvest season and facilitate green energy without compromising the system's efficiency. As shown in Table 5, the calculated power was 13.77 kW, utilizing 122 batteries with 12V and 400Ah capacity. Fig. 9 illustrates the diagram of 33 designed solar panels that provide 415W each.

Fig. 9. Rendered diagram of solar panels

Material of construction and dimensions are shown in the 2D and 3D models of the tray dryer in Figs. 10 and 11, respectively. Another innovation: an air recirculation vent with a diameter of 0.2 m was included in the design. The mechanism of air recirculation operates by partially recycling the air through a collection in the discharge duct to be introduced again into the drying chamber, increasing the system's heating efficiency [27].

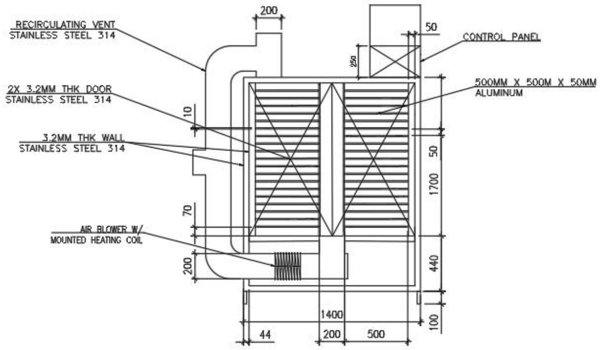

Fig. 10. 2D sketch of tray dryer

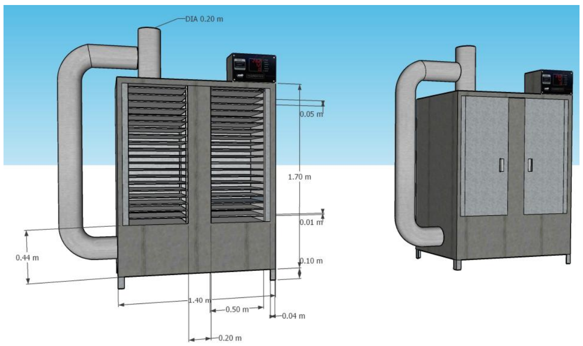

Fig. 11. 3D sketch of tray dryer

IV. CONCLUSION

The Page Model best fits the drying behavior of red onion with the least total error, the highest coefficient of determination, and good visual inspection. The optimum drying temperature was 70°C with the shortest drying time of 67.27 mins. to attain 5% moisture content in red onion. Quality dried red onion was produced without the growth of *Aspergillus niger*. A tray dryer was designed to dry 100 kg of red onions for a small-scale setting with dimensions 1.4 x 0.8 x 1.7 m using 40 trays and a heating requirement of 13.77 kW. Solar panels and a recirculating mechanism of air were innovations.

V. FUTURE SCOPE

It is recommended that future researchers pre-treat their onions with 0.2% potassium metabisulfite solution to retain their original color after drying.

NOMENCLATURES

M - mass of red onions and water, g, at any time, t
M_e - equilibrium mass of red onions and water, g
MR - moisture ratio at any time, t
n - order of the reaction, positive integer
a, k - drying constant
M_i - initial mass of sample, kg
$x_{1,2,3}$ - corrected MR
$f(x_{0,1,2,3})$ - corresponding time of corrected MR
- space time
MR_o - initial moisture ratio
M_w - amount of moisture removed, kg
M_P - mass of red onion, kg
x_0 - initial moisture content
x_f - final moisture content
E_a - quantity of heat required to remove the moisture, J
C_p - heat capacity of red onion, kJ/kg °C
T_f - final temperature, °C
T_i - initial temperature, °C
L_v - latent heat of vaporization, kJ/kg
P_h - power of heater, W
t_D - drying time, s
ρ_p - density of red onion, kg/m^3
V_t - volume of tray, m^3
bhp - blower horsepower, hP
V_a - volumetric flow rate, cfm
η_D - efficiency of dryer, %
η_B - efficiency of battery
P_f - power of fan, W
β - solar angle tilt
m_a - mass flow rate of air, kg/s
PV - power requirement of solar photovoltaic system
PGF - panel generation factor
DoD - depth of discharge

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