Numerical Simulation of the Drying Kinetics of Yellow Onions (*Allium cepa*) to Prevent the Growth of *Aspergillus niger*

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Abstract
Yellow onions are one of the commonly cultivated crops in the Philippines. Its high moisture content increases its vulnerability to fungus growth, *Aspergillus niger*, resulting in spoilage and agricultural losses. Drying is a widely-used method to extend the shelf-life of onions by reducing water activity and moisture content. The shelf-life of onions is prolonged when dried at 5% moisture content (MC). This study aimed to forecast the optimum temperature and shortest drying time required to attain the desired moisture content in yellow onions. Three mathematical models, the Laplace Transform Model, Page Model, and Nonlinear Decomposition Model, were simulated to describe the drying behavior of thinly-sliced yellow onions at temperatures of 50, 60, and 70 °C using a tray dryer. Among these models, the Nonlinear Decomposition Model yielded the best fit for yellow onions, exhibiting the lowest total error and highest coefficient of determination. The optimum drying temperature was found to be 70°C, proving efficient in producing quality yellow onions without any fungal growth at the shortest drying time of 89.82 minutes.

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

1. Introduction

Onions are important bulb agricultural species grown worldwide, such as in Europe, Asia, North America and Africa [1]. In the Philippines, onion varieties are widely grown in Central Luzon and the Ilocos Region [2]. Onion has a significant role in Filipino cuisine adding flavor in various dishes [3]. A substantial demand for onion with approximately 17,000 metric tons is consumed monthly [4]. Due to this, the domestic demand is attained through importation [5]. In the year 2022, the Philippines Statistics Authority (PSA), reported that 12.45% of the onion supply comes from importation [6]. Yellow onions are one of the most grown onion varieties in the country. They are known for their high amount of phenolic compounds [7]. Initially, yellow onions have a MC of 87.80% on a wet basis [8]. Its high moisture content makes it susceptible to black mold growth caused by *Aspergillus niger* [9].
Drying is an important process in the food preservation that uses thermal energy [10]. It is primarily known to be a mass transfer method of removing moisture from food products due to its simple operation [11]. Providing that moisture is reduced, microorganisms cannot grow [12].

A reduced moisture content of 4-5% in onions prevents spoilage and microorganism reproduction [13]. The main objective of this study is to prolong the shelf-life of yellow onion through drying.
Specific objectives are:

- to determine the suitable mathematical model that describes the drying kinetics of yellow 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*.

2. Methodology

2.1 Sample Preparation

Medium-sized yellow onions, devoid of any mold, were bought from a wet marketplace in Balintawak, Quezon City. Onions were thoroughly cleaned before slicing it 4 to 5 millimeters (mm) thick using a sharp kitchen knife [14] as depicted in Figure 1. A vernier caliper was used to ensure the uniform thickness of onions.

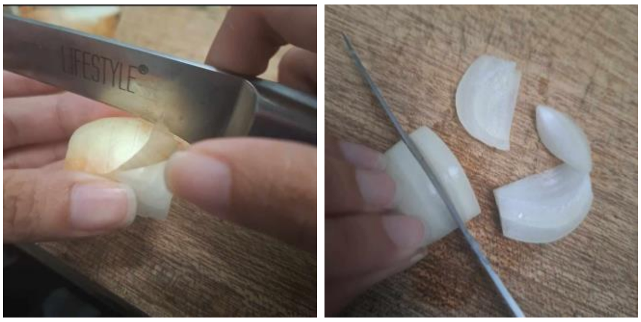

Figure 1. Peeling and Slicing of Onions

2.2 Drying experiment

A tray dryer was used in a batch drying experiment of yellow onions. To attain a stable condition for the experiment, the dryer was preheated at constant temperature and air velocity. Thinly sliced yellow onions were arranged in a static tray with uniform distance in between and dried at 50°C. Weight of onions was measured at a 5 minute interval until constant weight was attained. This process was done in triplicate with varying temperatures of 60°C and 70°C [15].

Figure 2. Yellow Onion Samples Before Drying

2.3 Determination of moisture ratio

Equation 1 was used to determine the moisture ratio (MR) of yellow onions during drying process:

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

2.4 Numerical simulation of drying curves

Numerous drying kinetic models are utilized in the drying processes involved in food engineering. In the drying kinetics of yellow onions, three mathematical models: the Page, Laplace Transform, and Nonlinear Decomposition models, were simulated. The experimental values of moisture ratio (MR) for yellow onions were fitted into the three mathematical models. The models were evaluated for its capability to best-fit the drying curves of yellow onions based on the highest coefficient of determination, R^2, and the least total error

Page Model. This model was derived from Newton's Law of Cooling. It states that the drying rate is affected by the variations in moisture content between the material being dried and the equilibrium moisture content for the given drying condition. The equation of the Page model is shown in Equation 2.

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

The linearized drying rate equation of the Page Model is shown in Equation 3.

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

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

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

Equation 4 is transformed into a Laplace transform model, integrated, and simplified to create Equation 5. This equation is used to simulate the characteristics of the drying rate of yellow onion slices.

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

Nonlinear Decomposition Model. The Nonlinear Decomposition Model is derived from the differential equation of batch decomposition given in Equation 6, where the value of n is not equal to one.

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

The linearized Nonlinear Decomposition Model is shown in Equation 7.

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

The modified Equation 7 is expressed in the form of moisture ratio, as shown in the Equation 8:

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

2.5 Determination of the suitable model

The graphs of experimental and predicted drying data (Moisture Ratio (MR) vs. t) at different experimental temperatures (50, 60, and 70°C) were analyzed using three mathematical models: Page Model, Laplace Transform Model, and Non-linear Decomposition Model. The coefficient of determination, R^2 values for both the Page Model and the Nonlinear Decomposition Model were determined, and the residence time, τ, for the Laplace Transform Model. The total error for all three models was computed. These models were compared for the best fit drying curves of yellow onions based on the highest value of the coefficient of determination, R^2 and the least total error. Visual inspection of the graphs confirmed the selected best-fit model.

2.6 Quality of dried yellow onion slices

Yellow onion slices were heated at the predicted optimum drying temperature and shortest drying time to attain 5% MC from the drying from both the drying experiment and numerical simulations. The dried samples were stored in polyethylene bags for four weeks at room temperature with weekly monitoring for visual observation of possible growth of black mold fungus. Same procedure was done to fresh, undried yellow onions.

2.7 Determination of the drying time to attain 5% moisture content

The drying time to attain the required 5% MC in yellow onions was calculated using Lagrange interpolation. This approach, described by the general Equation 9, constructs nth-order polynomials that transverse (n+1) points. These polynomials presume a curved relationship of data, enabling more accurate interpolation of values. The specific equations were represented by Equations 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:

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

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

3. Results and Discussion

3.1 Analysis of drying behavior

The drying behavior of yellow onions was greatly affected by temperature. As shown in Figure 3, the shortest drying time of 100 minutes was achieved by using the highest drying temperature of 70°C to achieve equilibrium moisture content in yellow onions. Drying temperatures at 60°C and 50°C required a drying time of 150 and 285 minutes, respectively.

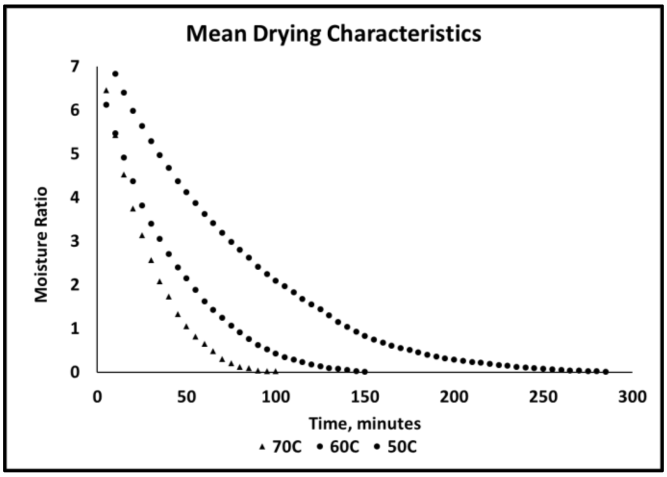

Figure 3. Mean Drying Characteristics of Dried Yellow Onion Slices at Different Temperatures

3.2 Determination of best fit model and optimum drying temperature

The values of the coefficient of determination, R^2, for both the Page and Non-linear Decomposition Models and residence time, τ, for the Laplace Transform Model with the total error for all three models, were organized and displayed in Table 1. At 70°C drying temperature, the Non-linear Decomposition Model gave a high coefficient of determination and least total error and across three trials compared to the other models, exhibited significant accuracy in modeling of yellow onion slices data, providing accurate predictions of its future behavior. Through visual examination, the Non-linear Decomposition Model provided the best fit to the experimental data at 70°C, as depicted in Figure 6 in contrast to the fit of the experimental and corrected drying data of the Page Model and Laplace Transform Model, as depicted in Figure 4 and Figure 5, respectively. Hence, the Non-linear Decomposition Model is the most appropriate model for predicting the thin-layer drying characteristics of yellow onion slices at optimum drying temperature of 70°C. Additionally, the Non-linear Decomposition Model is typically used for thin-layer drying like wood, passion fruit seeds, cocoa beans, and green beans [16, 17].

Table 1: Summary of Results

Temperature (°C)	Page Model			Laplace Transform Model		Nonlinear Decomposition Model		
	n	R^2	Total Error	τ	Total Error	n	R^2	Total Error
50	1.52	0.9966	0.090	65.98	0.582	0.76	0.9991	0.183
60	1.70	0.9889	0.133	42.00	0.413	0.77	0.9993	0.090
70	1.83	0.9932	0.094	25.69	0.477	0.70	0.9928	0.050

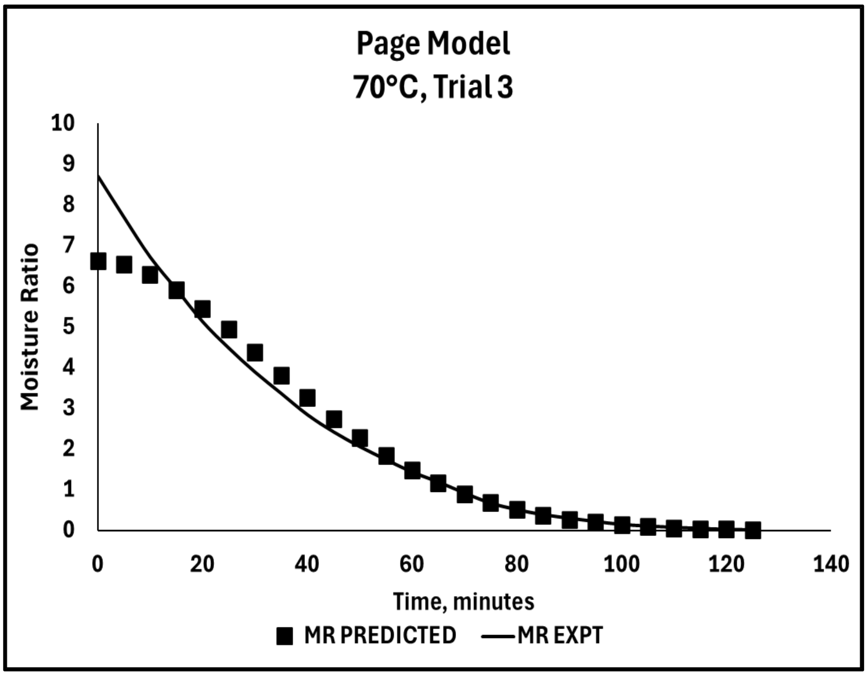

Figure 4. Comparison of Predicted and Experimental Moisture Ratio Values of Yellow Onions Using Page Model (70°C, Trial 3)

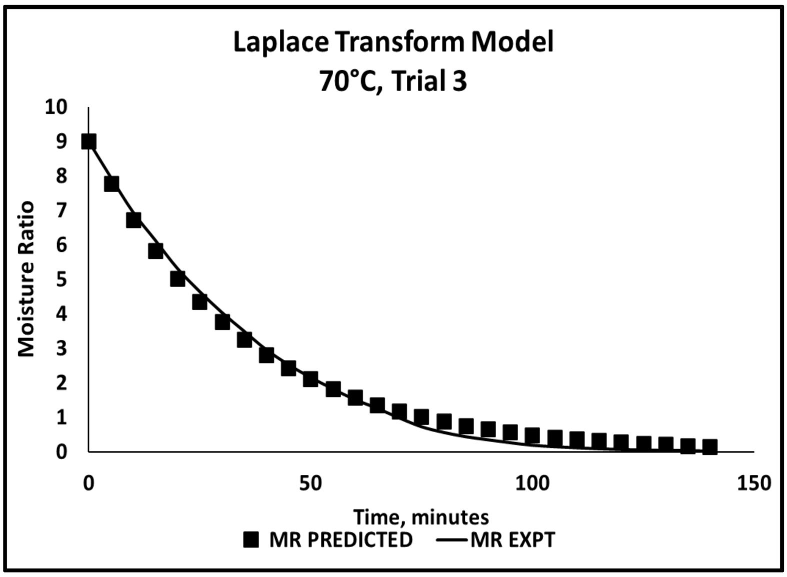

Figure 5. Comparison of Predicted and Experimental Moisture Ratio Values of Yellow Onions Using Laplace Transform Model (70°C, Trial 3)

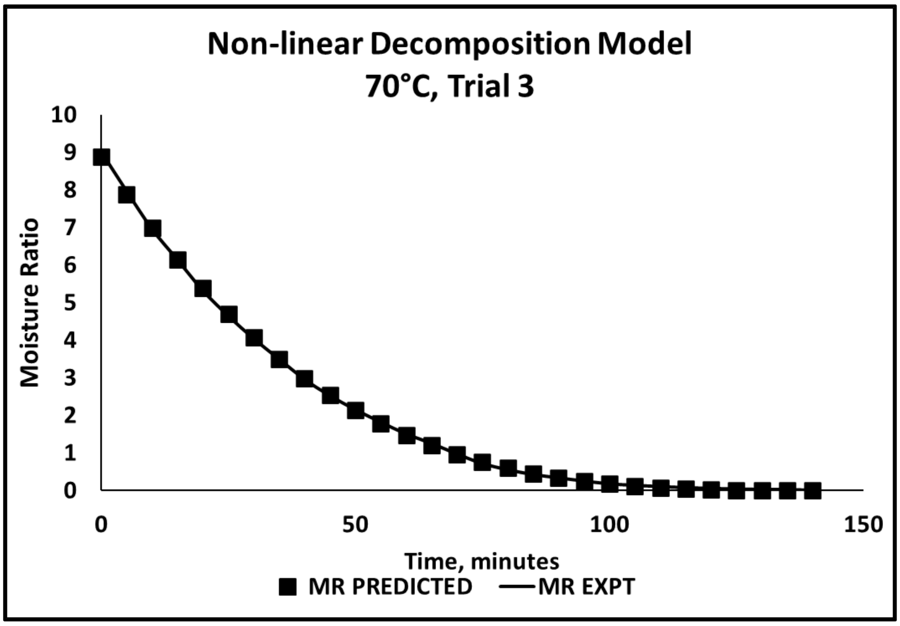

Figure 6. Comparison of Predicted and Experimental Moisture Ratio Values of Yellow onions Using Non-linear Decomposition Model (70°C, Trial 3)

3.3 Analysis of dying time

As predicted by the Non-linear Decomposition Model, the shortest drying time was exhibited at 70°C (Trial 1) drying temperature. Hence, as shown in Table 2, the shortest drying time to attain a 5% MC at which the proliferation of microorganisms in yellow onion slices is unlikely to occur is 89.82 minutes, where 70°C is the optimum drying temperature.

Table 2: Calculated Drying Time For Yellow Onion Slices at 70°C to Attain 5% Moisture Content as Predicted by Non-linear Decomposition Model using Lagrange Interpolation

Trial No.	Drying Time, mins
1	89.82
2	95.14
3	113.85

3.4 *Aspergillus niger* analysis

Yellow onion slices were heated at 70°C for 89.82 minutes, the predicted optimum drying temperature and shortest drying time to attain 5% MC from both the drying experiment and numerical simulations. By visual inspection, there was no trace of *Aspergillus niger* or black mold fungus on the fourth week of storage as shown in Figure 7. On the other hand, fresh, undried yellow onions after 4 weeks of storage at room temperature exhibited black mold growth on its surface as shown in Figure 8.

Figure 7. Dried Yellow Onions

Figure 8. Black Mold in Yellow Onions

4. Conclusion and Recommendations

4.1 Conclusion

The Non-linear Decomposition Model that exhibited the least total error, the highest coefficient of determination, and a satisfactory visual inspection, is the most appropriate model to describe the drying behavior of yellow onions. With the shortest drying time of 89.82 minutes, 70°C was the optimum drying temperature to achieve a 5% MC in yellow onions. Quality dried yellow onion showed no growth of *Aspergillus niger*.

4.2 Recommendations

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 yellow onions and water, g, at any time, t

M_e - equilibrium mass of yellow 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

τ - space time

MR_o - initial moisture ratio

m_i - initial moisture content, %

m_f - final moisture content, %

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