Numerical Simulation of the Drying Kinetics of Sweet Potato to Prevent the Growth of the Fungi *Rhizopus oryzae*

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**Abstract.** Sweet potatoes are prone to fungi *Rhizopus oryzae* that results in fast spoilage upon delivery due to its moisture content which can develop fungi that can give foul odor and color. The decrease in moisture content can prolong the shelf-life of the sweet potato. This problem can be addressed by a drying process where a hot tray air dryer was used. Sweet potatoes were cut to 5x5x30 mm uniformly and dried it at 40°C, 50°C, 60°C until the constant weight of the batch was obtained. Laplace Transform Model, Non-Linear Decomposition Model, and Page Model are the three mathematical model that were compared to determine what is the best fit for the drying of the sweet potato. Based on data gathered, Page Model is the best fit at 60°C. Page Model fitted best from the other two models with an average drying time of 115 minutes and 46 mins to obtain the desired moisture content of 10%.

**1. Introduction**

Exporting goods are beneficial for the development and growth of one’s economy. The Philippines export a lot of food crops such as coconut, mango, banana, sugarcane, sweet potato, cassava and pineapples [1]. In exporting goods, one factor to consider is shelf life expansion in order to maintain the quality of the product.

*Ipomoea batatas*, also known as sweet potato, is one of the most important food crops in tropical and subtropical countries like the Philippines. It is the most produced crop in the developing countries which covers the 80% world production because of its high productivity and easy growth [2], with an annual production of about 300 million tons [3]. According to the Philippine Statistics Authority, the production of sweet potato from October to December 2018 lowers by 1.1% compared to the production in October to December 2017. In 2018, the top producer of sweet potato is in the Central Visayas having a production of 17,310 Metric tons which is 13.4% of the total production of sweet potato followed by the Eastern Visayas and Zamboanga Peninsula which are 12.7% and 12.1% of the total production, respectively. The production of sweet potato from 130,000 Metric tons became 128,610 Metric tons which is a lot of losses in the production of sweet potato. Some of its losses is due to the post-harvest spoilage.

Sweet potato has many uses in the industry, it is used to manufacture flour, starch, and it is used as a raw material in the commercial production of animal feeds [4]. It is rich in starch, sugar, vitamin C, β-carotene, iron, and several other minerals. Sweet potato is an excellent source of energy having about 438 kJ/100 grams of edible portion [5]. Sweet potato decays rapidly due to the physiological changes and mechanical damage during harvesting, transportation, and handling. A considered limitation to the
cultivation of sweet potato is its short shelf life [6]. To extend its shelf life, the producers tend to turn it into chips and flours.

The largest post-harvest losses of a vegetable crop are due to the growth of fungi which leads to spoilage. The fungi *Rhizopus oryzae* is the large kind of fungi that causes the spoilage in the post-harvest storage of sweet potatoes. This fungus shows a physical evidence of spoilage. *Rhizopus* usually is present in the pre-harvest and post-harvest of many fruits and vegetables and a common cause of bread mold. It is mostly present in subtropical growing regions and common in the warmer tropics [7]. Through the process of drying the accumulation of fungi can be prevented.

Drying is the most common method used to improve the shelf life of an agricultural crop for it lessens the moisture content and the microorganisms which cause food spoilage and decay are unable to grow and multiply. There are many methods of drying that can be used such as sun drying, hot-air drying, solar drying, freeze drying, and heated-surface drying but, in this study, hot-air drying technique was used. In this study, three mathematical models were used to simulate the drying kinetics of sweet potato namely the Page, Laplace Transform, and Non-linear Decomposition models. Laplace Transform and Non-Linear Decomposition methods were mostly used for thin materials such as woods. Page model which is applied for food samples, was used as the basis for the comparison of the models experimentally. The main objective of the study is to prolong the shelf life of sweet potato after post-harvest through the process of hot air drying. Specific objectives include determination of best fit model that would describe the drying characteristics of pretreated sweet potato, determination of optimum drying temperature and shortest drying time to achieve the 10% moisture to inhibit the growth of *Rhizopus oryzae* on sweet potato strips, analyze the drying kinetics of treated and untreated sweet potatoes, and production of dried sweet potatoes without the growth of *Rhizopus oryzae*.

2. Materials and Methods

2.1 Sample Preparation

The sweet potatoes used in this study were obtained from a local market at Binangonan, Rizal. Firm, ripe, mature, undamaged crop and free from infection (visually detected) were selected.

Fresh from the market, the sweet potatoes were washed, peeled and sliced uniformly into 30mm x 5mm x 5mm dimension by using a kitchen knife. A vernier caliper was used for accurate measurements. The sweet potato strips were soaked in 2%(w/v) Potassium Metabisulfite (KMS) solution at 50°C for 15 minutes to preserve the freshness of the sample and to help prevent active growth of microorganisms. The treated sweet potato strips were drained under standard condition.

2.2 Drying Experiment

A hot-air dryer was used for the drying process of the sweet potato samples. The equipment consists of three drying trays constructed by stainless steel sheets which are arranged perpendicularly to the flow of hot air as shown in Figure 1. The hot-air dryer was pre-heated until a constant temperature of 40°C was reached.
The sliced potato samples were placed evenly in a weighed static tray which covered the whole drying area as shown in Figure 2. The treated sweet potato strips were then placed inside the hot-air dryer.

![Figure 2. Arrangement of sweet potatoes in a tray](image)

Weighing of air-dried treated sweet potato samples was monitored every 5-minute interval until a constant weight is reached. The weighing of the sample was done not more than 2 minutes to avoid significant amount of moisture that may be absorbed by the sample. Also, three trials were conducted for the drying experimentation. The procedure was repeated at 50°C and then at 60°C.

2.3. Determination of Moisture Ratio

Moisture ratio (MR) of sweet potato slices during air drying experiments was calculated on a dry basis using the following equation:

\[
MR = \frac{M - Me}{Me}
\]  

where \(M\) is the weight of the sample at any time \(t\) and \(Me\) is the final and equilibrium weight of the sample.

2.4. 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 sweet potato namely the Page, Laplace Transform, and Non-linear Decomposition models were evaluated. These models were tested for the best fitting of the drying curves of sweet potato based on the highest coefficient of determination, \(R^2\) and lowest total error.

2.4.1. Page Model

Page model was derived from Newton’s Law of Cooling, the drying rate is proportional to the difference of moisture content between the material being dried and the equilibrium moisture content for the respective drying condition.

\[
MR = ae^{-kt^n}
\]  

By linearizing the drying rate equation, the resulting equation was shown in equation 3.

\[
lnMR = lna - kt^n
\]  

Where \(n\) is the manipulated variable, \(MR\) is the moisture ratio at any time \(t\), the values of the drying constants, \(k\) and \(a\) are determined by linear regression as the slope and intercept respectively. The
The coefficient $k$, is related to effective diffusivity when the drying process takes place only in the falling rate period and liquid diffusion controls the process.

2.4.2. Laplace Transform Model
Laplace Transform model was derived from the overall material balance obtained from the drying system (see equation 4). It is carried out by subtracting the input with the output in the system and equating it with the rate of accumulation.

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

By converting the above equation into Laplace transform, the resulting simplified equation was shown below:

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

Where $M$ is the weight at any time $t$, $M_e$ represents the equilibrium weight and $M_i$ is the initial weight of the sweet potato strips and $\tau$ represents the space time and manipulated variable in this model. Tau ($\tau$) is manipulated to give the least total error. This is defined as necessary time needed to treat one reactor volume of feed based on entrance condition [8].

2.4.3. Non-Linear Decomposition Model
The Non-Linear Decomposition model is carried out through batch decomposition at any $n$, where $n$ is not equal to one (see equation 6).

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

Equation 6 is then linearized as shown in equation 7.

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

The equation can be adjusted and expressed in the form of moisture ratio as follows:

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

Where $MR$ is the moisture ratio at any time $t$, the values of $k$ and $MR_0$ are determined through linear regression as the slope and intercept, respectively, using the linearized equation shown in equation 7. $MR_0$ is the initial moisture ratio and $n$ is the order of reaction and the manipulated variable in this model. Whereas, $k$ is the drying rate constant.

2.5. Selection of the Best Kinetic Model
The model that gave the highest coefficient of determination, $R^2$ and the least total error was selected as the best-fit model. The selection of the best-fit model was further confirmed by visual inspection among the graphs. Experimental and corrected $MR$ that are treated using the 3 Models were plotted vs the drying time for each drying temperature for the three trials. The model that gave the best-fit with the experimental data was selected to be the kinetic model that best describes the drying characteristics of sweet potato strips.

2.6. Determination of Drying Time, $t$
The drying time to attain 10% moisture was determined by using the third order version of Lagrange method of interpolation shown in equation 9 by substituting values obtained from previous working equations.
\[ f(x) = \frac{(x - x_1)(x - x_2)(x - x_3)}{(x_0 - x_1)(x_0 - x_2)(x_0 - x_3)}f(x_0) + \frac{(x - x_0)(x - x_2)(x - x_3)}{(x_1 - x_0)(x_1 - x_2)(x_1 - x_3)}f(x_1) \]

\[ + \frac{(x - x_0)(x - x_1)(x - x_3)}{(x_2 - x_0)(x_2 - x_1)(x_2 - x_3)}f(x_2) + \frac{(x - x_0)(x - x_1)(x - x_2)}{(x_3 - x_0)(x_3 - x_1)(x_3 - x_2)}f(x_3) \]

(9)

Where \( x \) is the desired moisture content of sweet potato strips, \( f(x) \) is the time at which the desired moisture content is achieved, \( x_0, x_1, x_2, \) and \( x_3 \) are the corresponding percent moisture at time \( f(x_0), f(x_1), f(x_2) \) and \( f(x_3) \) given that desired moisture is in between the values of \( x_0, x_1, x_2, \) and \( x_3 \).

2.7. Drying Experimentation and Analyses of Untreated Sweet Potato Strips

The untreated sweet potato strips were dried and weighing of air-dried untreated samples was monitored every 5-minute interval until a constant weight is reached. The drying experimentation of untreated samples were done in three trials. Numerical simulation of the drying curves using the 3 models, selection of the best kinetic model and determination of the optimum temperature and shortest drying time to achieve 10% moisture content were done.

For the untreated and treated sweet potato strips, the sample were dried under the determined shortest drying time and optimum drying temperature. Both the air-dried untreated and treated sweet potato strips were put into polythene re-sealable bag and examined for rot at room temperature for 14 days. Color, texture, and odor were also observed at the end of the incubation period.

3. Results and Discussion

3.1. Interpretation of Drying Curves

3.1.1. Page Model Interpretation

Figure 3 shows the best fit data of the experimental and corrected moisture ratio versus drying time for the Page Model at 60°C. The graphs show that the corrected value overlaps the experimental value. Through visual inspection, 60°C trial 2 shows the best fit drying curve compared to all other graphs. For the application of the analytical values, the best fit was determined through the highest coefficient of determination \((R^2)\). Figure 4 has the highest coefficient of determination and least total error with a value of 0.9976 and 6.13169x10^{-6} respectively.

![Figure 3. Comparison of Experimental and Corrected Values, Moisture Ratio Versus Drying Time at 60°C, trial 2 (Page Model)](image)

3.1.2. Laplace Transform Interpretation

Figure 4 shows that the experimental values almost completely overlapped the corrected values. Residence time \((\tau)\), was determined using trial and error that gives a least total error. The total error was obtained through the summation of the squared difference of \( M \) experimental and \( M \) corrected. Values for total error were 1.049x10^{-4}, 2.734x10^{-5}, and 2.643x10^{-5} for 40°C, 50°C and 60°C, respectively. Lowest residence time was obtained at 60°C, trial 3 with a value of 22.3.
3.1.3. Non-Linear Decomposition Model Interpretation

Figure 5 shows that the experimental and corrected values were overlapped at some point, this signifies the state of being fit of the data to the model. Also, it showed that even though the drying temperature and order of reaction changes, the trend of the graph did not change. The total error obtained were $2.023 \times 10^{-5}$, $2.289 \times 10^{-5}$, and $2.931 \times 10^{-5}$ for 40°C, 50°C and 60°C, respectively. The drying temperature 60°C has the lowest total error and its graph is almost overlapped all throughout the curve and its coefficient of determination is 0.9973 while in 40°C and 50°C it is 0.9857 and 0.9777, respectively, that makes graph of 60°C, trial 2 using Non-Linear Decomposition Method best fits the experimental values.

3.2. Effect of Drying Temperature

Figure 6 shows the trend of the change in the moisture ratio with respect to the drying time needed to have a constant weight of the different drying temperatures that was assigned during the experiment. The drying temperature is indirectly proportional to drying time. The lowest drying temperature has the longest drying time needed to achieve constant weight, while the highest drying temperature has the shortest drying time to achieve constant weight at 40°C. In the experiment, the longest drying time of 415 minutes happened in trial 3 at 40°C. On the other hand, the drying time of 115 minutes happened in trial 2 at 60°C.
3.3. Determination of the Best-fit Model
Among the 3 models, the Page Model gave the highest coefficient of determination of 0.9976 and lowest total error of 6.13169E-06. With these results, it is safe to say that Page Model is the best-fit model in the drying of sweet potato strips. The selection of the Page Model at 60°C trial 2 as the best kinetic model was confirmed by visual inspection of the graphs.

3.4. Determination of the Shortest Drying Time
Table 1 shows that trial 2 at 60°C drying temperature gave the highest coefficient of determination and least total error. With these results, the drying time at 10% moisture content was computed through the values in 60°C trial 2 using the 3rd order Lagrange Method. The drying time at 10% moisture content is 46.01 minutes.

| Temperature | Trial | n | R²  | Total Error          | Drying Time, mins. |
|-------------|-------|---|-----|----------------------|--------------------|
| 60°C        | 1     | 1.2 | 0.9760 | 1.75x10⁻⁵       | 58.51              |
| Treated     | 2     | 1.2 | 0.9976 | 6.13x10⁻⁶       | 46.01              |
|             | 3     | 0.8 | 0.9901 | 1.58x10⁻⁵       | 87.01              |

3.5. Rhizopus oryzae Analysis
After 14 days of storage, by visual observation, Figure 7 (a) shows that there is no sign of Rhizopus oryzae on the air-dried sweet potato containing 10% moisture content. In Figure 7 (b) the fungi, most likely Rhizopus oryzae which is a cottony white colored mycelium [9] showed up after 3 days. According to Hagenimana, V. (2010), there would be no fungal growth at 10% moisture content of the sweet potato [10].
3.6. Comparison of Treated and Untreated Sweet Potato

Table 2 shows the comparison of the treated and untreated values of sweet potato at 60°C. The untreated sweet potato has a lower coefficient of determination and higher total error than the treated sweet potato for the 3 models. This shows that the treated sweet potato is best-fit than the untreated sweet potato.

### Table 2. Comparison of Treated and Untreated Sweet Potato Values

| Temperature | Trial | Page Model | Laplace Transform Model | Non-Linear Decomposition Model |
|-------------|-------|------------|-------------------------|--------------------------------|
|             |       | $k$ | $R^2$ | Total Error | $r$ | Total Error | $k$ | $R^2$ | Total Error |
| 60°C Treated | 1     | 0.0190 | 0.9760 | $1.75 \times 10^{-5}$ | 24.2 | 2.24x10-4 | 0.0392 | 0.9955 | $3.84 \times 10^{-5}$ |
|             | 2     | 0.0265 | 0.9976 | $6.13 \times 10^{-6}$ | 29.47 | 7.32x10-5 | 0.0492 | 0.9973 | $2.93 \times 10^{-5}$ |
|             | 3     | 0.0889 | 0.9901 | $1.58 \times 10^{-5}$ | 24.7 | 2.64x10-5 | 0.0399 | 0.9822 | $1.00 \times 10^{-5}$ |
| 60°C Untreated | 1     | 0.0121 | 0.9743 | $5.83 \times 10^{-5}$ | 31.2 | 2.71x10-5 | 0.0280 | 0.9861 | $6.65 \times 10^{-5}$ |
|             | 2     | 0.0774 | 0.9972 | $5.09 \times 10^{-6}$ | 31.9 | 1.20x10-5 | 0.0280 | 0.9936 | $1.87 \times 10^{-5}$ |
|             | 3     | 0.0834 | 0.9958 | $1.54 \times 10^{-5}$ | 29.2 | 4.10x10-5 | 0.0369 | 0.9949 | $2.01 \times 10^{-5}$ |

The comparison of air-dried untreated sweet potato strips and treated sweet potato strips in a polythene re-sealable bag was shown in Figure 8(a) and Figure 8(b), respectively. The air-dried treated samples showed a good sensory quality parameter such as color and texture compared to air-dried untreated sample. It can be observed that the dried treated samples showed a greater appearance acceptability since the natural color of sweet potatoes was preserved. Also, the texture of the air-dried treated samples were light and less tough compared to untreated samples.

![Figure 8. Dried (a) untreated and (b) treated sweet potato strips](image)

4. Conclusion

The Page model was found to be the most suitable to describe the drying characteristics of treated and untreated sweet potato strips with the least total error and highest coefficient of determination. The optimum drying temperature was 60°C with a drying time of 46.01 minutes to achieve 10% moisture that inhibit the growth of *Rhizopus oryzae*. The pre-treated sweet potato strips avoided the undesirable changes such as the natural color, texture and odor of sweet potatoes after air-drying. It has been found that through the process of hot-air drying, the growth of the fungi *Rhizopus oryzae* was inhibited.

This study can be further improved by using other mathematical models to compare if the suitable model determined in this study is indeed the best model in describing the drying kinetics of sweet potato strips. Also, it is recommended to design a hot-air dryer that will fit the drying characteristics of sweet potato strips obtained in this study for development of cost effective and energy efficient hot-air dryer. For the hot-air dryer, it is recommended to use kanthal wire instead of using nichrome wire due to its higher operating temperature and higher melting temperature. Also, it is advisable to fix the built-in digital timer in the dryer for improved monitoring of time. For the improvement of data gathering, a desiccator will help to avoid moisture absorption of the sample while weighing.
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