Drying kinetics of pineapple agro-industrial residues: a new approach

Cinética de secagem de resíduos agro-industriais de abacaxi: uma nova abordagem

ABSTRACT
Drying kinetics of pineapple agro-industrial residues was studied using thin-layer of product at 40°C, 50°C, 60°C and 70°C, and airflow rate of 1.5 m/s. The diffusion model was modified and fitted to experimental data of moisture ratio of pineapple residue to estimate the diffusion coefficient as function of temperature, and a good fitting of Arrhenius equation was obtained, with a variance explained of 99.98%. Values of diffusion coefficients varied in the range from $4.82 \times 10^{-10}$ m²/s to $11.17 \times 10^{-10}$ m²/s, approximately. A modification was implemented in the Page’s equation to include the diffusion effects explicitly, leading to a less empirical and simpler model to describe drying kinetics of pineapple residue. The model presented in this work proved to be adequate to predict drying ratio of pineapple residue, if the material layer thickness is 1.0 cm, under the drying conditions used.

Keywords: Pineapple residue; drying kinetics; diffusion coefficient; drying modeling.

RESUMO
A cinética de secagem de resíduos agroindustriais de abacaxi foi estudada usando camada fina de produto a 40 ºC, 50 ºC, 60 ºC e 70 ºC e taxa de fluxo de ar de 1,5 m / s. O modelo de difusão foi modificado e ajustado aos dados experimentais da razão de umidade do resíduo de abacaxi para estimar o coeficiente de difusão em função da temperatura, e um bom ajuste da equação de Arrhenius foi obtido, com uma variação explicada de 99,98%. Os valores dos coeficientes de difusão variaram
de $4.82 \times 10^{-10}$ m$^2$/s to $11.17 \times 10^{-10}$ m$^2$/s, aproximadamente. Uma modificação foi implementada na equação de Page para incluir explicitamente os efeitos de difusão, levando a um modelo menos empírico e mais simples para descrever a cinética de secagem do resíduo de abacaxi. O modelo apresentado neste trabalho mostrou-se adequado para prever a taxa de secagem do resíduo de abacaxi, se a espessura da camada de material for de 1,0 cm, nas condições de secagem utilizadas.

**Palavras-chave:** Resíduo de abacaxi; cinética de secagem; coeficiente de difusão; modelagem de secagem.

**1 INTRODUCTION**

Brazil is the world's third largest fruit producer, followed only by China in first place and India in second, and fruit production stands out in Brazilian agribusiness, with production exceeding 40 million tons in recent years (ABRAFRUTAS, 2019; IBGE, 2019).

The area cultivated with fruits is about 3 million hectares and Brazilian production is mainly directed to the domestic market, with exportation of only 3% of this production. There is a wide variety in fruit production in Brazil, because crops are scattered throughout the country.

Pineapple (Ananas sp.) is one of the main fruits produced in Brazil, with a planted area of almost 71 thousand hectares and production of, approximately, 1.77 million tons (IBGE, 2019).

Fruits are generally consumed in natural or processed form. Fruit consumption in its natural form is very fast because quality is preserved only for a short period under storage or market exposure conditions. Fruits not consumed are discarded, causing great waste in the produce market. Some fruits are produced to be processed in the form of juice, pulps, concentrates, candies, jellies, among others, increasing the life of products, avoiding waste. However, processing inevitably generates about 30% to 40% of organic residues from the processed raw material. A part of these by-products is discarded irregularly, contrary to Brazilian environmental legislation (NASCIMENTO FILHO & FRANCO, 2015).

Fruit processing in Brazil such as pineapple, produces significant amounts of residues. However, the processing industries do not pay attention to the fact that these residues can be used to make new products, as they contain significant nutritional value. Fruit processing residues can be used, for example, in animal ration, including fish.

Products originating from these wastes contain proteins, fatty acids, vitamins and phosphorus, which, once discarded, decompose, resulting in environmental problems (GIORDANI JÚNIOR et al., 2014; SANTOS et al., 2014).

The utilization of these products depends on the processing used to allow the maintenance of their quality as much as possible during storage. One of the ways to meet this need is drying, as it is a method of preserving food known from ancient times by primitive societies, which used the drying of meat for consumption, using solar radiation. With this technique, human species found that dry
foods could be stored for long periods, because microorganisms such as fungi, yeast, and enzymes that degrade and alter their chemical composition cannot act in the absence of water (ARAÚJO, 2013; CARLOS & DELEZUCK, 2015).

The production of fish and shrimp in rural areas by small farmers favors social inclusion and food security (SANTOS, SIEBER & FALCON, 2014). For these small producers, the price of commercial rations is a limiting factor for their production, so the option of using alternative feed in rations formulation can make the cost of this activity viable and even increase their income (SANTOS-FILHO et al., 2016).

According to the scenario presented here, agro-industrial residues, if properly processed and chemically analyzed, can be an alternative food source for humans and animals. This contributes to the reduction of the environmental impact caused by their disposal. According to the foregoing context, this work aims to present a modeling of drying kinetics of agro-industrial residues resulting from the production of pineapple (Ananas sp.) pulps, aiming their use to produce flour as alternative ingredient in the composition of animal feed.

2 LITERATURE REVIEW

2.1 BACKGROUND

The literature contain data on the chemical composition of various agro-industrial residues from the fruit processing industry, highlighting their nutritional importance and suggestions for use (NASCIMENTO FILHO & FRANCO, 2015).

The chemical composition of agro-industrial byproducts has been evaluated for their addition to animal feed. Several authors have concluded that these by-products can be safely used in animal feed. The main chemical composition of pineapple used in this study, found in the literature, is summarized in Table 1 (SILVA et al., 2014).

| Table 1 – Main chemical composition of pineapple (Ananas sp.). |
|-----------------------------|----------------|
| Component       | Composition (%) |
| Protein         | 7.74            |
| Lipid           | 8.24            |
| Fiber           | 51.22           |

2.2 PINEAPPLE (ANANAS SP.)

Pineapple is a tropical fruit originating from South America widely cultivated throughout Brazil, with a production of 1.8 million tons, approximately, in 2018 (IBGE, 2019), and contains the
bromelain enzyme that has digestive function, also found in other plants of the Bromeliaceae family (FRANÇA-SANTOS et al., 2009). Research has shown that this enzyme can reduce muscle inflammation and aid digestion (FILETI et al., 2009).

Pineapple fruit has excellent nutritional composition with the presence of macro and micronutrients, such as vitamins A, B1, B2, C, and niacin, complemented by the profile of mineral salts such as calcium, copper, phosphorus, magnesium, potassium and sodium (FRANCO, 1989; LUKMANJI et al., 2008). Therefore, according to results found in the literature, as shown in Table 1, the by-product of pineapple can be safely used in animal feed.

2.3 RESIDUES AND ENVIRONMENT

The most diverse industrial production systems have been developed over time generating, simultaneously, technological and economic development, but produce waste that is returned to the environment, which is not always of practical use (NASCIMENTO FILHO & FRANCO, 2015).

This problem is due to humanity's relentless search for food to meet its needs, generating organic leftovers that are discarded due to lack of utility. With the increase in the world population, its effects began to be noticed, becoming worrying when they reached levels of irreparable degradation in some aspects (SANTOS et al., 2014).

The disposal of solid waste is a common practice, determined by cultural values, beliefs and habits, improperly using urban environments as a deposit of these materials (MUCELIN & BELLINE, 2008). However, when considering organic products thrown in inappropriate places in open areas, they decompose, polluting water and soil (GIORDANI JUNIOR et al., 2014).

Pollution generated by the disposal of the food industry has been treated as an inevitable consequence of economic development, although recent studies suggest that, according to current models, the effects caused by this technological advance may not offset the damage caused to nature (SANTOS et al., 2014).

2.4 IMPORTANCE OF FOOD RESIDUES

The production models used to meet population demand contribute to the production of large amounts of residues by agroindustry. These residues have not been rationally used and, in most cases, are discarded without any action (NASCIMENTO FILHO & FRANCO, 2015).

Residues produced by agroindustry are rich in nutrients and can be redirected to some form of use, minimizing waste (GIORDANI JUNIOR et al., 2014; SANTOS et al., 2017).

The nutritional value of food is not constant, as it depends on its composition and on the processing performed in the industry, which can differentiate between the amount of peel, bagasse and seeds, causing differences in the quality of the resulting byproducts (GARCIA, ROMERO &
The scientific literature contains information on the chemical composition of some agro-industrial residues, coming from the fruit processing industry, revealing their nutritional importance and suggestions of ways of use indicated by several authors.

One way to take advantage of food residues is to perform its proper processing and chemical evaluation for use in animal feed formulation (NASCIMENTO FILHO & FRANCO, 2015).

2.5 UTILIZATION OF AGROINDUSTRY RESIDUES FOR ANIMAL FEEDING

Agroindustry processes fruits to produce pulp, juices and other products, and from this processing, there are materials that are rich in nutrients, normally discarded, because companies have no way to use them. However, these leftover foods, when properly processed and evaluated for their chemical composition, could enter the composition of animal feeding (TEIXEIRA et al., 2014).

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One of the biggest barriers to livestock production is the cost of food, because feed that forms the basis of ratios is not always available in the region where they are manufactured or consumed. These components include soybean, corn, and wheat’s brans, and rice chira (usually any flour residue), among others (MICHELATO et al., 2013).

The cost of feed production can increase significantly due to the transportation cost, increasing the cost of animal production, which represents around 70% of the total production costs (NOGUEIRA, FARIA FILHO & CAMARGO, 2016). In the farming of sea fish and shrimp, commercial rations can reach approximately 80% of the production cost, depending on age and species farmed (SANCHES, SILVA & RAMOS, 2014).

The identification of nutritional levels of agro-industrial residues, such as those from brewery, sunflower, soursop (*Annona muricata*), grape, cassava, peanut, acerola, passion fruit, and pineapple, among others, if used properly, can help to balance diets intended for animal feeding (SILVA et al., 2014).

The agro-industrial leftovers from brewery, cashew, cupuassu (*Theobroma grandiflorum*), guava, mango, passion fruit, and pineapple have great potential for animal feeding, favoring the reduction of environmental impacts caused by the improper disposal of these residues (GIORDANI JÚNIOR et al., 2014).

Studies related to the nutritional composition and storage conditions of agro-industrial waste contribute to enable its more appropriate use in the raising of animals, including ruminants. Thus,
these wastes start to acquire economic and social importance, generating employment and income (NASCIMENTO FILHO & FRANCO, 2015; CRUZ et al., 2013).

Several alternative diets, elaborated with different types of agro-industrial residues to feed different fish species were tested by several authors, with significant results (TORELLI et al., 2010; PEREIRA JUNIOR et al., 2013; MARINHO et al., 2016; LAZZARI et al., 2015; BEZERRA et al., 2014; SOUZA et al., 2013; LIMA et al., 2011; MELO et al., 2012).

Proper use of food from agro-industrial waste requires some form of processing (SILVA et al., 2014). A process used to prevent or retard the deterioration of a product is drying, which must be performed properly, to reduce the product moisture content, but preserving its nutritional qualities (PEREIRA et al., 2013).

This paper discusses the drying process of residues from pineapple pulp produced by agro-industry as a way of preserving their nutritional quality for use in the formulation of fish rations.

2.6 DRYING PROCESS

Drying is one of the oldest methods used to preserve food, because, according to historical records, primitive societies already practiced dehydrating meat using solar energy, and today in industry there are several similar methods for processing food by dehydration, which is the essential method of preserving food products (ARAÚJO, 2013).

Drying is a process of simultaneous heat and mass transfer. Heat is required to evaporate the water flowing from the surface of the product to an external medium, usually air, due to the vapor pressure difference between the surface and the external medium (BROOKER, BAKKER-ARKEMA & HALL, 1992; PARK et al., 2014).

Drying is very important in industrial transformation processes to add value to products manufactured in various production segments, requiring specialized labor (MACHADO et al., 2013; ALMEIDA, TOMASELLI & KLITZKE, 2017).

In agricultural and food products, in particular, the drying process occurs practically at a decreasing rate, involving complex phenomena described by mathematical models to predict the drying rate. Due to the complexity of the drying process, empirical models have been used to predict the drying rate more accurately, although most of these models are based on diffusional and capillary theories (PARK et al., 2014).

The drying process of biological products, described by diffusional theory, involves mechanisms of molecular diffusion, capillary diffusion, surface diffusion, hydrodynamic flow, vapor diffusion and thermal diffusion (PARK et al., 2014). The diffusion coefficient is the effective diffusivity that includes the effects of all these phenomena, which may influence water migration, and its value is always obtained experimentally (CAMICIA et al., 2015).
Several authors have used several models that describe the drying kinetics of agricultural and biological products. Generally, the models that best fit experimental data are either completely empirical or partially theoretical (BROOKER, BAKKER-ARKEMA & HALL, 1992). One of these models was presented by Page in 1949, and is derived from Newton's law of cooling by including an empirical parameter that corrects any distortions in the exponential solution of the original model. This model has shown excellent results in describing drying kinetics of biological products, represented by the moisture ratio defined in Equation (1):

$$M_r = \frac{M(t) - M_e}{M_0 - M_e} = \exp(-k \cdot t^\beta)$$

were

- $M_r$ = Moisture ratio, [ ];
- $M(t)$ = Instantaneous moisture content, dry basis, [$kg/kg$];
- $M_0$ = Initial moisture content, dry basis, [$kg/kg$];
- $M_e$ = Equilibrium moisture content, dry basis, [$kg/kg$];
- $t$ = Time, [min].
- $k$ = Material and temperature dependent drying constant, [1/min];
- $\beta$ = Material and temperature dependent coefficient, [ ].

A variety of partially theoretical models are derived from the solution of the diffusion equation for several known geometric shapes, mainly flat-plate, cylindrical and spherical. Two examples are the Midilli (MIDILLI, KUKUK & YAPAR, 2002) and Cavalcanti Mata (GOUVEIA et al., 2011) models, which have provided excellent results in predicting drying kinetics of food materials. However, Midilli's model needs four empirical parameters, while Cavalcanti Mata's needs five parameters, which requires more experimental data to obtain a good model fit.

Because of thin-layer drying characteristic for determining the drying kinetics curves, the solution of diffusion equation can also be used, with restrictions, to describe the process. In this case, the solution for a flat-plate (CRANK, 1975) was used:

$$M_r = \sum_{n=0}^{\infty} \left(\frac{8}{\pi^2}\right) \left(\frac{1}{(2n+1)^2}\right) \cdot \exp\left\{-\left(\frac{\pi^2}{L^2}\right) \left(\frac{(2n+1)^2}{4}\right) \cdot D \cdot t\right\}$$
were

\[ L = \text{Characteristic dimension (half thickness) of the flat plate, } [m]; \]

\[ D = \text{Diffusion coefficient, } [m^{2}\cdot s]; \]

\[ n = \text{Number of terms, } []; \]

Diffusion coefficient, \( D \), can be determined from fitting diffusion equation to the experimental data of drying kinetics, and a prediction model can be obtained by fitting Arrhenius equation to the diffusion coefficient data (MIRZAEE et al., 2009):

\[
D = D_0 \cdot \exp \left( -\frac{E_a}{R \cdot T} \right)
\]

were

\[ D = \text{Diffusion coefficient, } [m^{2}\cdot s]; \]

\[ D_0 = \text{Pre-exponential factor, } [m^{2}\cdot s]; \]

\[ E_a = \text{Activation energy, } [J/mol]; \]

\[ R = \text{Gases universal constant, } [J/mol \cdot K]; \]

\[ T = \text{Absolute temperature, } [K]. \]

3 METODOLOGY

Agro-industrial residues samples of pineapple (Ananas sp.), resulting from the production of pulps and juices, were submitted to thin layer drying at temperatures 40°C, 50°C, 60°C and 70°C. Prior to drying, the samples were prepared and properly packaged in plastic bags and kept under appropriate storage conditions. Subsequently, the initial moisture content of each sample was determined by the standard oven method (AOAC, 1995) to begin the drying process. Figure 1 shows a tray with pineapple residues ready for drying.
During drying, the mass of each sample was determined by weighing the trays at the beginning of the process and at regular but not equally spaced intervals. In the first 30 minutes the samples were weighed every 5 minutes; between 30 and 60 minutes the weighing was performed every 10 minutes; between 60 and 105 minutes the weighing was every 15 minutes; from 105 minutes onwards the samples were weighed every 60 minutes until they reached constant weight. Samples were kept in the oven chamber for an additional 24 hours to ensure stability of equilibrium moisture content.

After drying, three samples were taken from dried product to determine the final moisture content by the standard oven method (AOAC, 1995), which is equal to the dynamic equilibrium moisture content in this case.

Moisture ratio values were determined using the masses of samples obtained by the weighing during drying using Equation (4):

\[ M = \left( \frac{W_i - W_f}{W_i} \right) \times 100 \]  

were

- \( M \) = Moisture content, wet basis [%];
- \( W_i \) = Initial sample mass, [kg];
- \( W_f \) = Final sample mass, [kg].

Since the solution of Equation (2) has an infinite number of terms, for it to be applied it must be truncated to a finite number of terms but, to satisfy the initial condition, \( M_r(0) = 1 \), a great number of terms is still needed. However, assuming one term solution and performing some adjustments, the resulting equation can be used to determine the drying kinetics and the diffusion coefficient with reasonable accuracy for food materials. Then, Equation (2) can be rewritten as:
\[ M_r = \left( \frac{8}{\pi^2} \right) \cdot \exp \left\{ -\left( \frac{\pi}{2L} \right)^2 \cdot D \cdot t \right\} \] (3)

It is obvious that Equation (3) does not satisfy the initial condition, because the term \( \frac{8}{\pi^2} \) is not equal to the unity. To resolve this problem, this term was set equal to the unity leading to a single exponential:

\[ M_r = \exp \left\{ -\varphi(L, D) \cdot t \right\} \] (4)

The relationship of function \( \varphi(L, D) \) with the characteristic dimension of the material thin-layer, \( L \), and the diffusion coefficient, \( D \), is defined in Equation (5), assuming the thin-layer as a flat-plate:

\[ \varphi(L, D) = \left( \frac{\pi}{2L} \right)^2 \cdot D \] (5)

The software Statistica 7.0 was used to fit Equation (4) to experimental thin-layer drying data of pineapple residue to obtain estimates of locally constant function, \( \varphi(L, D) \). From this estimates, the diffusion coefficients were determined directly using Equation (5).

Since the major objective in this paper was to find a model that gives good fitting to experimental data and, at same time, keeps the diffusion coefficient implicitly, the locally constant function was redefined to include parameter \( k \):

\[ \varphi(L, D) = \left( \frac{\pi}{2L} \right)^2 \cdot D \cdot k \] (6)

Now, a more general model is defined by a modification in Page’s model:

\[ M_r = \exp \left\{ -\varphi(L, D) \cdot t^\beta \right\} \] (7)

It should be highlighted that Equation (7) is equivalent to Equation (2), when both \( k \) and \( \beta \) equals to the unity. Combining Equation (6) and (7), the final model was written for the drying kinetics of a flat thin-layer of food material:

\[ M_r = \exp \left\{ -\left( \frac{\pi}{2L} \right)^2 \cdot D \cdot k \cdot t \right\}^\beta \] (8)
Using Microsoft Excel, Arrhenius equation was fitted to the values of diffusion coefficient by a linearization procedure to estimate the parameters of the model. The maximum diffusion coefficient, $D_0$, and the energy of activation, $E_a$, were estimated by inverse transformation. Parameter $k$ also follows Arrhenius type equation and was estimated in this same way.

4 RESULTS AND DISCUSSION

The results of drying residues of pineapple in thin-layer of 1.0 cm thick at temperatures of 40°C, 50°C, 60°C, and 70°C are presented in Table 1.

These results were expected because, in agricultural product drying processes, water viscosity decreases with increasing temperature, directly influencing the internal fluid flow resistance, which facilitates the diffusion of water molecules on the material capillaries.

Diffusion is the process by which mass is transported from one part of a system to another part as a result of a concentration gradient. The process leads to an equilibrium of concentration within the system.

In the case of drying, liquid water diffuses from the interior of porous material to its surface, then evaporates to surrounding air due to a difference in concentration between water vapor at the surface and the air.

Table 1. Initial and final moisture content of pineapple residues, and drying time, on the temperature range of 40-70°C.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Moisture Content</th>
<th>Drying Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial (% w. b.)</td>
<td>Final (Equilibrium) (% w. b.)</td>
</tr>
<tr>
<td>40</td>
<td>87.91</td>
<td>7.18</td>
</tr>
<tr>
<td>50</td>
<td>88.75</td>
<td>5.07</td>
</tr>
<tr>
<td>60</td>
<td>87.25</td>
<td>4.40</td>
</tr>
<tr>
<td>70</td>
<td>86.77</td>
<td>2.92</td>
</tr>
</tbody>
</table>

The parameters estimates for drying kinetics of pineapple residue were obtained by fitting Equation (4) to experimental data, especially to obtain the diffusion coefficients at prescribed drying conditions, then, using these results, Equation (7) was also fitted. The results for both models are presented in Tables 2 to 5.

The results in Tables 2 to 5 show that the parameters change in the direction of obtaining a better model fitting. This is corroborated by an increase in the coefficient of determination, with variance explained in the range 99.75 % to 99.89 %, and a decrease in the quadratic error, in all cases, ranging from $6.55 \times 10^{-2}$ to $7.77 \times 10^{-3}$, on the average.
Table 2. Parameters estimates for a 1.0 cm thick thin-layer of pineapple residue dried at 40°C, with an airflow of 1.5 m/s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>Fitted Models</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Modified Diffusion</td>
<td>Modified Page</td>
<td></td>
</tr>
<tr>
<td>Locally constant function, [1/min]</td>
<td>$\varphi(L, D)$</td>
<td>2.853 x 10$^{-3}$</td>
<td>3.174 x 10$^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Diffusion coefficient, [m$^2$/min]</td>
<td>$D$</td>
<td>2.891 x 10$^{-8}$</td>
<td>2.891 x 10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>Empirical power coefficient, [ ]</td>
<td>$\beta$</td>
<td>1.000</td>
<td>1.372</td>
<td></td>
</tr>
<tr>
<td>Empirical drying parameter, [ ]</td>
<td>$k$</td>
<td>1.000</td>
<td>8.989</td>
<td></td>
</tr>
<tr>
<td>Variance explained, [%]</td>
<td>$R^2$</td>
<td>97.86</td>
<td>99.83</td>
<td></td>
</tr>
<tr>
<td>Squared error, [ ]</td>
<td>$SE$</td>
<td>10.50 x 10$^{-2}$</td>
<td>8.54 x 10$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Characteristic dimension, [m]</td>
<td>$L$</td>
<td>5.00 x 10$^{-3}$</td>
<td>5.00 x 10$^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Parameters estimates for a 1.0 cm thick thin-layer of pineapple residue dried at 50°C, with an airflow of 1.5 m/s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>Fitted Models</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Modified Diffusion</td>
<td>Modified Page</td>
<td></td>
</tr>
<tr>
<td>Locally constant function, [1/min]</td>
<td>$\varphi(L, D)$</td>
<td>3.817 x 10$^{-3}$</td>
<td>5.899 x 10$^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Diffusion coefficient, [m$^2$/min]</td>
<td>$D$</td>
<td>3.867 x 10$^{-8}$</td>
<td>3.867 x 10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>Empirical power coefficient, [ ]</td>
<td>$\beta$</td>
<td>1.000</td>
<td>1.340</td>
<td></td>
</tr>
<tr>
<td>Empirical drying parameter, [ ]</td>
<td>$k$</td>
<td>1.000</td>
<td>6.471</td>
<td></td>
</tr>
<tr>
<td>Variance explained, [%]</td>
<td>$R^2$</td>
<td>99.07</td>
<td>99.75</td>
<td></td>
</tr>
<tr>
<td>Squared error, [ ]</td>
<td>$SE$</td>
<td>4.10 x 10$^{-2}$</td>
<td>11.15 x 10$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Characteristic dimension, [m]</td>
<td>$L$</td>
<td>5.00 x 10$^{-3}$</td>
<td>5.00 x 10$^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Parameters estimates for a 1.0 cm thick thin-layer of pineapple residue dried at 60°C, with an airflow of 1.5 m/s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>Fitted Models</th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Modified Diffusion</td>
<td>Modified Page</td>
<td></td>
</tr>
<tr>
<td>Locally constant function, [1/min]</td>
<td>$\varphi(L, D)$</td>
<td>5.016 x 10$^{-3}$</td>
<td>9.937 x 10$^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Diffusion coefficient, [m$^2$/min]</td>
<td>$D$</td>
<td>5.099 x 10$^{-8}$</td>
<td>5.099 x 10$^{-8}$</td>
<td></td>
</tr>
<tr>
<td>Empirical power coefficient, [ ]</td>
<td>$\beta$</td>
<td>1.000</td>
<td>1.315</td>
<td></td>
</tr>
<tr>
<td>Empirical drying parameter, [ ]</td>
<td>$k$</td>
<td>1.000</td>
<td>5.064</td>
<td></td>
</tr>
<tr>
<td>Variance explained, [%]</td>
<td>$R^2$</td>
<td>98.34</td>
<td>99.89</td>
<td></td>
</tr>
<tr>
<td>Squared error, [ ]</td>
<td>$SE$</td>
<td>6.74 x 10$^{-2}$</td>
<td>4.30 x 10$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Characteristic dimension, [m]</td>
<td>$L$</td>
<td>5.00 x 10$^{-3}$</td>
<td>5.00 x 10$^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Parameters estimates for a 1.0 cm thick thin-layer of pineapple residue dried at 70°C, with an airflow of 1.5 m/s.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter</th>
<th>Fitted Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locally constant function, [1/min]</td>
<td>φ(L,D)</td>
<td>6.613 × 10⁻³</td>
</tr>
<tr>
<td>Diffusion coefficient, [m²/min]</td>
<td>D</td>
<td>6.700 × 10⁻⁸</td>
</tr>
<tr>
<td>Empirical power coefficient, [ ]</td>
<td>β</td>
<td>1.000</td>
</tr>
<tr>
<td>Empirical drying parameter, [ ]</td>
<td>k</td>
<td>1.000</td>
</tr>
<tr>
<td>Variance explained, [%]</td>
<td>R²</td>
<td>98.72</td>
</tr>
<tr>
<td>Squared error, [ ]</td>
<td>MSE</td>
<td>4.86 × 10⁻²</td>
</tr>
<tr>
<td>Characteristic dimension, [m]</td>
<td>L</td>
<td>5.00 × 10⁻³</td>
</tr>
</tbody>
</table>

Models parameters estimates and fitted equations are summarized in Table 6, and graphical representations are shown thereafter.

The variation of diffusion coefficient, with temperature is shown in Figure 2, along with the fitted model and coefficient of determination. The slope of the linearized model was used to estimate the energy of activation that was equal to 25.00 kJ/mol.

Table 6. Diffusion coefficients D, parameters β and k, and fitted models for a 1.0 cm thick thin-layer of pineapple residue.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Parameters</th>
<th>Diffusion Coefficient¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>β</td>
<td>k</td>
</tr>
<tr>
<td>40</td>
<td>1.372</td>
<td>8.989</td>
</tr>
<tr>
<td>50</td>
<td>1.340</td>
<td>6.471</td>
</tr>
<tr>
<td>60</td>
<td>1.315</td>
<td>5.064</td>
</tr>
<tr>
<td>70</td>
<td>1.286</td>
<td>4.000</td>
</tr>
</tbody>
</table>

Activation energy | Arrhenius coefficient | Universal gas constant
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Eₐ = 25.00 kJ/mol</td>
<td>D₀ = 7.096 × 10⁻⁶ m²/s</td>
<td>R = 8.3145 J/mol · K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fitted Models</th>
<th>Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>ln(D) = -3006.5 [1/(T + 273.15)] - 11.856</td>
<td>99.98 %</td>
</tr>
<tr>
<td>β = -0.0028T + 1.4839</td>
<td>99.79 %</td>
</tr>
<tr>
<td>ln (k) = 74.344 (1/T) + 0.3563</td>
<td>99.25 %</td>
</tr>
</tbody>
</table>

¹Units in diffusion model are m²/s.

It is observed either in Table 6 or Figure 2 the excellent fitting of Arrhenius equation to diffusion coefficient data, allowing for determination of the activation energy with accuracy. The values of diffusion coefficients ranged from 4.818 × 10⁻¹⁰ m²/s to 11.167 × 10⁻¹⁰ m²/s, with a
variance explained of 99.98 %. Although values of diffusion coefficients were not found in the literature searched for pineapple residues, these values are comparable to those found for pineapple in general (RAVULA et al., 2017; BAPTESTINI et al., 2016; FURTADO et al., 2014; MINAEI et al., 2011; BORSATO et al., 2009; MIRZAEEE et al., 2009).

Figure 2. Diffusion coefficient, $D \ (m^2/s)$, of pineapple residue as a function of temperature, $T \ (K)$, fitted to Arrhenius equation.

\[
\ln D = -3006.5 \frac{1}{T} - 11.856 \\
R^2 = 0.9998
\]

Parameter $\beta$ varies linearly with temperature, as shown in Figure 3, along with the fitted model and coefficient of determination. A simple linear model fits very well on the observed data, with a variance explained of 99.79 % in the temperature range from 40°C to 70°C.

Figure 3. Parameter $\beta$ of modified Page model for pineapple residue as a function of drying temperature.

\[
\beta = -0.0028T + 1.4839 \\
R^2 = 0.9979
\]

On the other hand, parameter $k$ varies with temperature but also follows Arrhenius equation. A fitted linearized model is represented in Figure 4, along with the coefficient of determination, showing a variance explained of 99.25 %. This parameter is a kind of drying constant in the original
Page’s model, but their values are different because does not include the diffusion coefficient neither the other effects, which are treated separately.

Figure 4. Parameter $k$ of modified Page model for pineapple residue as a function of drying temperature.

Now, the thin-layer drying model for pineapple residue can be presented including the parameters obtained so far, for temperature range from 40°C to 70°C, airflow rate of 1.5 m/s and layer thickness 1.0 cm:

\[
M_r = \exp \left[ - \left( \frac{\pi}{2L} \right)^2 \cdot D \cdot k \cdot t \right] \tag{9}
\]

\[
D = \exp \left[ - \frac{3006.5}{(T + 273.15)} \right] \tag{10}
\]

\[
k = \exp \left( - \frac{74.344}{T} \right) \tag{11}
\]

\[
\beta = -0.0028 T + 1.4839 \tag{12}
\]

Drying kinetics simulated using Equations (9) to (12) for the specified drying conditions in this work, and graphical representations of observed and predicted results are shown in Figure 5.
The quality of fittings are shown in Figures 6 to 9 using correspondence correlation analysis between predicted and observed moisture ratio. It is observed that, for all specified drying conditions, the model described by Equation (9) fitted very well to the drying kinetics of pineapple residue, corroborated by the high correlation between predicted and observed data (greater than 0.999), and variance explained above 99.8% (Tables 2 to 5).

Therefore, the new simple model gives very good fitting to the experimental data and can be used to predict the drying kinetics of pineapple residue with accuracy, under conditions used in this work.
Figure 7. Comparison of predicted and observed moisture ratio of pineapple residue dried in thin layer at 50°C and airflow rate of 1.5 m/s.

Figure 8. Comparison of predicted and observed moisture ratio of pineapple residue dried in thin layer at 60°C and airflow rate of 1.5 m/s.

Figure 9. Comparison of predicted and observed moisture ratio of pineapple residue dried in thin layer at 70°C and airflow rate of 1.5 m/s.
5 CONCLUSIONS

The drying kinetics of pineapple residue was studied by drying a 1.0 cm thick layer of product at 40°C, 50°C, 60°C and 70°C, and airflow rate of 1.5 m/s.

The diffusion model was modified and fitted to experimental data of moisture ratio of pineapple residue to estimate the diffusion coefficient as function of temperature. The Arrhenius equation fitted very well to the diffusion coefficients, with a variance explained of 99.98 %.

Diffusion coefficients varied in the range from $4.8178 \times 10^{-10}$ m$^2$/s to $11.1673 \times 10^{-10}$ m$^2$/s. Although data of diffusion coefficient for pineapple residue were not found in the searched literature, these values are according to data found for pineapple in general.

A modification was implemented in the Page’s equation, and a less empirical simple model was obtained to describe drying kinetics of pineapple residue with good accuracy, comparable to other more complex models found in the literature. This model maintained the original characteristics but included the diffusion effects explicitly.

The model developed in this work can be used to predict drying ratio of pineapple residues, if the material layer thickness is 1.0 cm, although this effect can be easily modeled by repeating the experiments using different layer thickness.

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REFERENCES


