Analysis of red chilli drying kinetics affected by low-temperature long time blanching

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Abstract. The drying kinetics of red chillies in the effect of low-temperature long time blanching were investigated. The blanching process was carried out at 70 °C for 10, 15, and 20 minutes. The drying process lasts for 32 to 35 hours to reduce the moisture content from 82.24% (wb) to 8.84% (wb). The experimental data were fitted to three mathematical models of thin-layer drying, namely the Henderson and Pabis, Lewis, and Page models. The result shows that the Page model is the most suitable model for predicting moisture ratio in chilli drying with low-temperature long time blanching treatment. This suitability is evidenced by the highest R² value, which ranges from 0.9709 to 0.9786, and also the lowest RMSE and MBE values range from 0.0503 to 0.0579 and 0.0025 to 0.0034, respectively. Meanwhile, the effective moisture diffusivity varies from $5.6300 \times 10^{-9}$ m²/s to $6.5662 \times 10^{-9}$ m²/s for the treatments studied.

1. Introduction
Chilli is an agricultural commodity that is considered essential and has a high economic value in Indonesia. However, this fresh chilli product is very easily damaged after being harvested, not stored for a long time. By processing chillies into dried chillies, the selling price will be increased, the shelf life is relatively longer, the coverage of the marketing area is more expansive, and its availability is guaranteed at all times.

To produce good quality dried chillies, a pretreatment process is needed before drying. One of the pretreatment processes that can be done is by blanching. Blanching is a relatively fast heating process to inactivate enzymes. Blanching is generally carried out at temperatures up to 100 °C, water, water vapour, or microwave energy [1]. The blanching process before drying can prevent browning reactions in chillies, both enzymatic and non-enzymatic browning reactions. This browning reaction is avoided in the chilli drying process because it is detrimental to colour aesthetics. The quality of dried chillies is determined by the brightness of the colour [2].

Research on the effects of blanching as a pretreatment before drying chillies has been widely conducted. However, the blanching process is generally carried out in a high-temperature range and a relatively short time, namely 90-110°C, with blanching times ranging from 0.5-9 minutes [3-6]. Meanwhile, research on the effect of blanching treatment on chillies at low temperature and relatively long time, commonly known as the low-temperature long time (LTLT) blanching method, is still relatively rare. The LTLT blanching method also affects physical and sensory qualities, as reported by [7-9].
On the other hand, several studies have also reported that the high-temperature short time (HTST) blanching method also positively affects drying kinetics. Still, not many have reported the effect of LTLT blanching on the drying kinetics of red chillies, especially for specific temperature ranges and blanching times. Existing studies have limitations and are only suitable for certain drying conditions, as conducted by [2], which involves the LTLT blanching process for chillies at different blanching temperatures, durations, and a discussion of research directed at dryer performance. A study by [10] also involved the LTLT blanching method in drying chillies with varying temperature ranges and blanching times but has not discussed the mathematical model of drying and effective moisture diffusivity. Meanwhile, [11] used different types of chilli, temperature ranges, and duration of LTLT blanching and a research discussion that was more focused on the structural and physical properties of chillies.

Based on these problems, research was carried out to study the drying kinetics of red chillies, which was affected by the LTLT blanching method. The results of this study are expected to complement the information regarding the drying kinetics of chillies using specific drying methods and the LTLT blanching pretreatment process to optimize the drying process and improve the quality of the dried chillies produced to match the expected rate. With complete information, it is hoped that the technique and performance of chillies drying will be further improved.

2. Materials and methods

2.1. Experimental procedures
Red chillies that had been pretreated with LTLT blanching at a temperature of 70 °C for 10, 15 and 20 minutes were then dried using a thin layer method with a greenhouse effect type solar dryer (figure 1). This dryer had dimensions of 14 m x 8.5 m x 3.5 m with a shelf size of 1.2 m x 0.8 m x 0.05 m. The blanching process was carried out using water at a predetermined temperature and time. The amount of chilli used for each treatment was 500 grams. Each treatment was repeated three times. The drying process was carried out every day from 9.00 am to 4.00 pm, until there was no longer a decrease in chillies mass (constant mass). Observations made during the drying process were to measure the change in chillies mass, moisture content, drying rate, drying temperature, relative humidity, and solar radiation, which were carried out every 1 hour.

![Figure 1. Greenhouse effect type solar dryer [2].](image)

Measurement of moisture content was carried out using the AOAC method [12]. Moisture content is calculated by the following equations [13-14]:

\[
M = \frac{w(t) - d}{w(t)} \times 100\% \tag{1}
\]

\[
X = \frac{w(t) - d}{d} \tag{2}
\]

Where M is the moisture content of the wet basis (%), X is the moisture content of the dry ground (g water/g dry matter), d is the mass of the dry matter/DM (g), and w(t) is the mass of the material at time t (g).
The drying rate is described as decreasing moisture content and evaporation of water from the material during the drying process. The drying rate is calculated by the following equation [15]:

\[ DR = \frac{M_t - M_{t+dt}}{dt} \]  

(3)

DR is the drying rate (g\textsubscript{water}/g\textsubscript{dry matter}. h), Mt and Mt + dt are the moisture content of the dry basis at t and t + dt, respectively, and t is the drying time (h).

2.2. Mathematical modelling

The drying kinetics of chillies were studied with several mathematical models of thin-layer drying in table 1. The mathematical model is calculated based on the moisture ratio (MR) graph of experimental results to the drying time. The results obtained are drying constants k, a, and n, which are then used to find the value of the MR model [16]. The MR is calculated by the following equation [17]:

\[ MR = \frac{M_t - M_e}{M_0 - M_e} \]  

(4)

MR is the moisture ratio, Mt is the moisture content at the specified time, Mo is the initial moisture content, and Me is the equilibrium water content.

Table 1. Mathematical model used to describe thin layer drying.

| Model              | Equation                                                                 | Reference |
|--------------------|--------------------------------------------------------------------------|-----------|
| Page               | MR = exp (-kt\textsuperscript{n}) ln (-ln (MR)) = ln (k) + n ln (t)       | [16,18]   |
| Lewis              | MR = exp (-kt) ln (MR) = -kt                                             | [15,17]   |
| Henderson and Pabis| MR = a exp (-kt) ln (MR) = -kt + ln (a)                                   | [19,20]   |

The finest model reliability indicators used are the coefficient of determination (R\textsuperscript{2}), mean bias error (MBE), and root mean square error (RMSE), which are calculated by the following equations [13,21]:

\[ R^2 = \frac{\sum_{i=1}^{N} [MR_{i} - MR_{exp,i}]^2}{\sum_{i=1}^{N} [MR_{i} - \bar{MR}_{exp}]^2} \]  

(5)

\[ MBE = \frac{1}{N} \sum_{i=1}^{N} [MR_{pre,i} - MR_{exp,i}]^2 \]  

(6)

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{N} [MR_{pre,i} - MR_{exp,i}]^2}{N}} \]  

(7)

Where MR\textsubscript{exp,i} is the experimental MR, MR\textsubscript{pre,i} is the predicted MR, N is the number of observations, and n is the number of constants.

2.3. Effective moisture diffusivity

The movement of water in the material towards the surface is known as effective diffusivity [22]. Based on Fick's Second Law of Diffusion, effective diffusivity refers to the rate at which water diffuses during the drying process [28]. For prolonged drying, the Ficks Law equation can be simplified as follows [19]:
\[ MR = \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_{\text{eff}} t}{4L^2} \right) \]  

(8)

Where \( D_{\text{eff}} \) is the effective moisture diffusivity \((\text{m}^2/\text{s})\), \( t \) is the drying time \((\text{s})\), and \( L \) is the thickness of the material \((\text{m})\).

Equation (8) is then simplified into equation (9) as follows [18,25]:

\[
\ln \ln (MR) = \ln \ln \left( \frac{8}{\pi^2} \right) - \left( \frac{\pi^2 D_{\text{eff}}}{4L^2} t \right)
\]

(9)

Effective moisture diffusivity is measured by plotting experimental drying data in the form of \( \ln MR \) compared to drying time. The slope \((k)\) attained from the curve is then used to determine the effective moisture diffusivity through the equation (10) as follows [20]:

\[
k = \frac{\pi^2 D_{\text{eff}}}{4L^2}
\]

(10)

3. Results and discussion

3.1. Drying atmospheric conditions

Drying atmospheric conditions such as temperature, relative humidity, and solar radiation significantly affect the drying characteristics [26]. Drying chillies using a greenhouse effect type solar dryer provides less uniform drying conditions. The intensity of daily solar radiation influences it as a source of heat energy in the dryer. This affects the drying process. The power of solar radiation significantly affects the temperature in the drying chamber, affecting the speed in reducing the moisture content of chillies that are being dried [27,28].

When the weather is hot, the intensity of solar radiation is very high, and the temperature received by the dryer will also be increased. Similarly, if the weather is cloudy, the intensity of solar radiation will be low so that the temperature obtained by the drying room will be lower [2,29]. Therefore, the drying process with this dryer will run more effectively if it is done in favourable weather conditions.

The highest drying temperature and solar radiation intensity achieved during this drying process are 63.43 °C and 1059.35 W/m² which occurs at the peak of solar radiation between 12.00 am to 1.00 pm. The lowest temperature and solar radiation intensity is 29.54 °C and 283.51 W/m² which appears when the weather is cloudy, while the drying temperature and solar radiation intensity averages 50 °C and 687.74 W/m².

In contrast to the intensity of solar radiation, drying temperature and relative humidity (RH) have an inverse relationship, where the higher the weather, the lower the relative humidity. This relative humidity affects the water vapour removal process. If the relative humidity is high, the difference in vapour pressure inside and outside the material is slight, thus inhibiting water vapour transfer from inside to outside the material. The ability of the material to release water from the surface will be more extraordinary with increasing air temperature in the drying chamber [24,30]. The relative humidity is usually higher in the morning than during the day. The average relative humidity during the drying process is 27.12%. The atmospheric conditions for chillies drying during the drying process are shown in figure 2 as follows.
3.2. Drying kinetics of red chilli

Fresh chillies have an initial moisture content of up to 82.24% (wb), indicating a high moisture content in chillies after harvest. For dried chilli products, the expected moisture content is a maximum of 11% (wb) based on SNI 01-3389-1994 standards. Moisture content is one of the determining indicators for the quality of dried chillies. The low moisture content makes dried chillies last longer in storage. To meet these standards, a drying process of 32-35 hours is required to reduce the moisture content of chillies to ± 8.84% (wb), depending on each treatment. The decrease in the moisture content of chillies during the drying process is shown in figure 3.

![Figure 3. Drying kinetics of red chilli.](image)

Figure 2. Atmospheric conditions in chillies drying using a greenhouse effect type solar dryer

Figure 3 also shows that a significant decrease in moisture content occurred, especially in the first 8 hours. However, after 25 hours of drying, there is a relatively small decrease in moisture content until an equilibrium moisture content is reached. In this study, treatment B20 was the fastest to achieve equilibrium moisture content, namely for 32 hours of drying, treatment B15 for 34 hours, and treatment B10 was the longest with a drying process of 35 hours. This shows that the B20 treatment impacts the amount of water evaporation from the material compared to other treatments.

The rate at which moisture content decreased is closely related to the LTLT blanching pretreatment that was carried out. Chilli with a longer blanching duration will dry faster, which means a blanching duration of 20 minutes is the best treatment in this study. This is presumably because there is more cell damage in the longer blanching duration so that it affects the cell permeability of the material. As a result, the chillies become more porous with softer tissue. In this condition, water from the inside of the material escapes and evaporates faster, resulting in lower moisture content after drying. This result is also in line with the study results of [10,31,32].
The change in moisture content during the drying process is also related to the drying rate [14]. Both of these are significantly influenced by the drying temperature, as explained in the drying atmospheric conditions section, where the drying temperature is highly dependent on the intensity of the solar radiation. The drying temperature, which tends to fluctuate during the drying process, also causes fluctuations in the drying rate. The amount of moisture released per unit time varies greatly depending on the temperature received by the material. When the drying temperature is high due to the high intensity of solar radiation, more water will evaporate from the material.

This condition generally occurs at the beginning of drying, where the free water content in the material is still very high. An increase in temperature causes an increase in the amount of water evaporation. This indicates the high drying rate of the chillies at the beginning of the drying process. However, the drying rate will still decrease over time, even though the drying temperature is increased, which means that the longer the drying process runs, the water release from the material will be relatively small or be in a falling rate period. In the falling rate period, the diffusion process is the dominant physical mechanism in water movement in the material [33]. The diffusion of water displacement from the material to the surface causes the decrease in water mass to be slighter. After the water in the material drops, the water vapour pressure in the material will decrease until there is a balance with the surrounding air and there is no more water displacement [34]. The relationship between the drying rate of chillies against time and moisture content of the dry basis is shown in figure 4.

The LTLT blanching pretreatment also played a significant role in accelerating the drying rate, especially for the B20 treatment. This occurs because the LTLT blanching pretreatment can reduce resistance to water vapour movement, increasing the drying rate [35,36]. This process occurs due to
structural changes in the material during the blanching process, which causes the opening of the material's pores to become larger so that it increases the rate of water evaporation [31]. Thus, LT LT blanching pretreatment is reasonable to be applied to shorten the drying time of chillies. This result is also in line with the results of research by [2,10,31].

3.3. Mathematical model of chilli drying

The drying characteristics of red chillies are defined by the relationship between the moisture ratio value and the drying time, as shown in figure 5. The resulting drying curve interprets the factors that affect increasing and decreasing the drying rate. Changes in temperature, moisture ratio, and moisture content of chillies affect the constant drying value. The combination of drying factors that can increase the moisture diffusivity leads to an upsurge in the drying constant [16].

![Figure 5. The relationship between moisture ratio and drying time](image)

The results of the experimental data analysis describing the drying characteristics of chillies, which are shown by the correlation curve between moisture ratio and time in figure 5, are then evaluated by three mathematical models of thin-layer drying. The moisture ratio value was applied to several mathematical models of thin-layer drying, and a non-linear regression analysis was performed. The analysis process produces the constant values of each drying model, which are shown in table 2.

Based on the analysis results presented in table 2, the Page model has the highest $R^2$ value and the lowest RMSE and MBE values compared to the other two treatments. It is known that the higher the $R^2$ value approaches one and the lower the RMSE and MBE values come 0, the higher the level of suitability of the model [16]. This indicates that the Page model is the most accurate model in describing the drying characteristics of chillies based on the resulting constant value. In several other studies, the Page model is also known to the best model to describe the drying characteristics of different materials, as found in the results of studies by [18] for parsley leaves, [13] for seaweed, and [21] for green beans.

| Model | Treatment | Constant | Equations | $R^2$ | RMSE | MBE |
|-------|-----------|----------|-----------|-------|-------|-----|
| Page  | B10       | 0.03     | 1.41      | 0.97  | 0.050 | 0.002 |
|       |           | 7        | 5         |       |       |     |
|       | B15       | 0.03     | 1.43      | 0.97  | 0.052 | 0.002 |
|       |           | 6        | 8         |       |       |     |
|       | B20       | 0.03     | 1.45      | 0.97  | 0.057 | 0.003 |
|       |           | 8        | 5         |       |       |     |
| Lewis | B10       | 0.16     |           | 0.87  | 0.152 | 0.023 |
|       |           | 9        |           |       |       |     |
Furthermore, to determine the suitability of the moisture ratio predicted by the Page model with the moisture ratio from experimental data on chilli drying, the expected moisture ratio was then compared with the observed moisture ratio in a curve. A good comparison result will form a curve angle close to 45 degrees, which indicates the suitability of the predicted moisture ratio with the experimental moisture ratio [37]. The level of conformity between the expected results of the mathematical model and the actual results of the drying process is very suitable for each treatment, with $R^2$ values ranging from 0.971-0.978. Thus, this drying model can predict the moisture content of chillies at various drying times to control the drying process according to the desired results. The comparison between the expected moisture ratio of the Page model and the experimental moisture ratio for each treatment is shown in figure 6.

**Figure 6.** Comparison between predicted MR using the Page model with experimental MR

An example of using a mathematical model to form a chilli drying curve is shown in figure 7. An example curve is made based on the actual moisture ratio and the predicted moisture ratio results of the Page model with the equation $MR = \exp (-0.038) (t^{1.455})$ as shown in table 2. Examples of application curves given are for treatment B20. From Figure 7, it can be seen that the predicted moisture ratio curve is very close to the actual moisture ratio curve, so it can be said that this Page model is suitable as a mathematical model of chilli drying.
Figure 7. Comparison of the mathematical model drying curve for treatment B20

3.4. Effective moisture diffusivity ($D_{\text{eff}}$)

In the drying process, effective diffusivity ($D_{\text{eff}}$) shows the movement of water in the material to carry out the diffusion process to the surface due to differences in water vapor pressure. According to [38], the speed of water movement from the inside of the material towards the surface is essential because, in volumetric drying, the knowledge of the material experiences an increase in temperature due to heating. During a decreasing drying rate, the diffusivity will be slower due to the molecular bonding of water in the material, inhibiting the diffusivity process.

The $D_{\text{eff}}$ value obtained from the analysis of the slope method is shown in Table 3. The value of the analysis results is following the broad range for foodstuffs, which is $10^{-11}$ - $10^{-9}$ m$^2$/s [39]. This result is also in line with several other foodstuff studies, such as in [20] and [40]. The difference in the $D_{\text{eff}}$ value is influenced by factors such as temperature, dimensions, the type of material, and the thickness of the material [41].

The lowest $D_{\text{eff}}$ value in this study is B10 because the drying time at B10 is longer than other treatments. The shorter the drying time, the $D_{\text{eff}}$ value will also increase because the faster drying time means that the dried material has a higher drying rate. The drying rate in this study is also greatly influenced by the blanching time and other factors, where the more extended the chillies go through the blanching process, the higher the drying rate, as in treatment B20. This is supported by [18], which states that $D_{\text{eff}}$ depends on the drying temperature and the composition and variation of the material.

Table 3. The effective moisture diffusivity value of red chili for each treatment

| Treatment | Effective moisture diffusivity, $D_{\text{eff}}$ (m$^2$/s) |
|-----------|----------------------------------------------------------|
| B10       | $5.630 \times 10^{-9}$                                   |
| B15       | $5.980 \times 10^{-9}$                                   |
| B20       | $6.566 \times 10^{-9}$                                   |

4. Conclusions

Based on the results of chillies drying with different LTLT blanching duration, it is concluded that the blanching process duration gives different drying kinetics effects. The longer the LTLT blanching process is carried out, the faster the drying rate will be. The evaluation results of the three selected mathematical models show that the Page model is the model that most accurately describes the drying characteristics of red chillies for the three treatments based on the resulting constant values. The mathematical equation of the Page model for B10 is $MR = \exp (-0.037) \times t^{1.415}$ with $R^2$ value of 0.978, RMSE of 0.050, and MBE of 0.002, B15 is $MR = \exp (-0.036) \times t^{1.438}$ with $R^2$ value of 0.976, RMSE of 0.052, and MBE of 0.002, and B20 is $MR = \exp (-0.038) \times t^{1.455}$ with $R^2$ of 0.970, RMSE of 0.057, and MBE of 0.003. Meanwhile, the effective moisture diffusivity for B10 is $5.630 \times 10^{-9}$ m$^2$/s, B15 is $5.980 \times 10^{-9}$ m$^2$/s, and B20 is $6.566 \times 10^{-9}$ m$^2$/s.
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