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Shelf Life Estimation of Taro Flour Packaged in Polypropylene (PP) and High-Density Polyethylene (HDPE) Using The Arrhenius Approach

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ABSTRACT

Taro flour stored for an extended period tends to experience a decline in quality. Therefore, determining the optimum storage period is essential. The Accelerated Shelf Life Testing (ASLT) method using the Arrhenius model was applied to estimate the shelf life of taro flour. The research on taro flour was carried out in three stages. The first stage involved the production of taro flour. The second stage included monitoring changes in quality during the storage period. The third stage focused on estimating the shelf life of taro flour packaged in polypropylene (PP) and high-density polyethylene (HDPE) materials. Drying and milling taro tubers produced taro flour with a final moisture content of 10%. During the storage period, observations were made on moisture content, whiteness degree, and protein content. Shelf life estimation was conducted using the Arrhenius model, with the selection based on a critical quality parameter protein content. The results indicated that the estimated shelf life of taro flour based on protein content in PP and HDPE packaging at 25 ℃ was 223 days and 285 days, respectively. Meanwhile, at storage temperature of 28 ℃, the shelf life of taro flour in PP and HDPE packaging was estimated to be 147 days and 183 days, respectively.

1. INTRODUCTION

Taro (*Colocasia esculenta* L.), locally called "*bentul*", is one of local food commodities with strong potential to be developed as an alternative carbohydrate source to support national food security in Indonesia. This plant can grow under extreme conditions, such as in flooded areas, shaded environments, and saline soils, and is widely consumed in traditional foods (Andarini & Risliawati, 2018). Total taro production in Bogor Regency in 2020 reached 11,165 tons, with a productivity of 161.24 quintals per hectare (BPS, 2021). Taro is also classified as a tuber crop that can serve as a staple food (Sulistyowati *et al*., 2014). It contains essential nutrients such as carbohydrates, protein, vitamins A, B1, C, and minerals. However, taro also contains calcium oxalate, an anti-nutritional and toxic compound (Saenphoom *et al*., 2016). Major taro production centers in Indonesia include Bogor and Malang, where the *bentul* taro variety is favored for its high yield and soft texture.

According to Putri *et al*. (2017), taro tubers are highly perishable after harvest. Therefore, processing them into products such as taro flour is necessary to extend their shelf life. Taro flour has a high starch content (70–80%) and can be used as a substitute for some of the functions of wheat flour. With its smooth texture and good digestibility, taro flour also holds promising economic potential. The flour is categorized as a food ingredient with low moisture content, allowing for a longer shelf life than other food products (Rostianti *et al*., 2018). Taro flour can maintain a long shelf life if its moisture content reaches equilibrium. According to SNI 3752-2018, standard maximum moisture content of flour is 14.5%.

Processing taro into flour requires proper drying, milling, and packaging techniques to preserve its nutritional value. The type of packaging plays a crucial role in preventing quality degradation during storage. Packaging protects the product from exposure to light, oxygen, and microbial contamination. Its purpose is to guard against potential physical damage and maintain the product's shelf life. Because taro flour is hygroscopic and easily absorbs water vapor from the environment, the choice of packaging is very important for preserving quality during storage. PP (polypropylene) and HDPE (High-Density Polyethylene) plastics are widely used for packaging in the food industry due to their wide availability, affordable cost, and ability to resist water vapor permeation and protect products from physical damage. The use of these two plastic types for packaging allows for a comparison of their effectiveness in protecting the quality of taro flour during storage and provides more applicable recommendations for the industry.

PP packaging is chosen for its high density, resistance to temperature and humidity variations, and low water absorption capacity, which together provide optimal protection for the product (Hafiza *et al*., 2023). The water vapor transmission rate (WVTR) of PP packaging is 3.30 $g \cdot m^{-2} \cdot day^{-1}$, with an oxygen permeability of 3.2 $ml \cdot \mu \cdot cm^{-2} \cdot day^{-1} \cdot atm^{-1}$ (Robertson, 2016). HDPE packaging is characterized by its greater strength, hardness, rough texture, and superior resistance to high temperatures. According to Sucipta *et al*. (2017), the advantages of HDPE packaging include higher strength compared to other plastic types, resistance to chemicals and water, and ease of processing and molding. The WVTR of HDPE packaging is 1.45 $g \cdot m^{-2} \cdot day^{-1}$, and its oxygen permeability is 0.1 $ml \cdot \mu \cdot cm^{-2} \cdot day^{-1} \cdot atm^{-1}$ (Robertson, 2016).

During storage, taro flour packaged in PP and HDPE may undergo quality changes that can lead to a decline in product quality. Therefore, it is essential to perform shelf life testing to ensure the quality and safety of taro flour throughout its shelf life. According to Harris & Fadli (2014), estimating the shelf life of food products is crucial as it provides consumers with information regarding product quality. One effective method used for this purpose is Accelerated Shelf Life Testing (ASLT) with the Arrhenius model approach, which simulates quality deterioration by increasing the storage temperature (Diniyah *et al*., 2015). This method is considered efficient, as it estimates shelf life quickly while maintaining accuracy (Nuraini & Widanti, 2020). Producers must determine shelf life to ensure product quality, nutritional value, and safety until the product reaches consumers and to prevent potential health risks associated with consuming expired products. Based on the explanation above, the objective of this study was to estimate the shelf life of taro flour stored in PP and HDPE plastic packaging. The shelf life of taro flour was analysed using the Arrhenius approach. Result of this study is expected to provide information to producers and consumers regarding the shelf life of taro flour stored in PP and HDPE packaging.

2. MATERIALS AND METHODS

The research was conducted at the Laboratory of Food and Agricultural Product Processing Engineering, Department of Mechanical and Biosystem Engineering, Faculty of Agricultural Technology, Integrated Laboratory, and Science Technopark IPB University, from May to November 2024.

2.1. Materials and Equipment

The primary material used was fresh taro tubers from farmers in Cijeruk District, Bogor Regency. Additional materials used for analysis included distilled water, alcohol, and sodium chloride (NaCl). The packaging materials used were PP plastic and HDPE plastic. The tools used in this study included desiccators, incubator eyela KCL 2000, oven, analytical balances, digital scales, sealers, whiteness meters, diskmills 80 mesh, tray dryer, and vibrating screens.

2.2. Research Procedure

The procedure in this study consisted of three stages. The first stage was the production of taro flour. The second stage involved observing quality changes during storage, in which the taro flour was packaged using PP and HDPE materials. The third stage was estimating the shelf life of taro flour in PP and HDPE packaging using the Accelerated Shelf Life Testing (ASLT) method with the Arrhenius approach. During storage, taro flour was stored at four temperatures, namely 35 °C, 40 °C, 45 °C, and 50 °C, using two types of packaging (PP and HDPE). Each combination of temperature and packaging was made in three replicates with 200 g of samples per replicate. The storage period at each temperature was different, namely 36 days at 35 °C, 28 days at 40 °C, 16 days at 45 °C, and 8 days at 50 °C. Taro quality was observed periodically according to the rate of quality change at each temperature.

2.3. Taro Flour Production

The production of taro flour began with the sorting of taro tubers. The tubers were cleaned to remove any adhering dirt. They were then peeled to separate the skin from the tuber flesh. The fresh taro flesh was washed under running water. Slicing was performed uniformly with a thickness of 3 mm. The sliced taro was then soaked in a 10% NaCl solution. After soaking, the taro slices were rinsed thoroughly and drained. Drying occured at 50 ℃ until the moisture content reaches 10%. The dried taro slices were subsequently ground into flour. Finally, the taro flour was sieved using an 80-mesh sieve to obtain particles of the desired size.

2.4. Measurement of Taro flour Quality Parameters

2.4.1. Moisture Content

The moisture content of the flour was analyzed using the oven-drying method (AOAC, 2012). The moisture content was calculated using Equation 1.

$$KA\ (\%wb) = \frac{B-C}{B-A} \times 100\% \tag{1}$$

where *KA* (%wb) is the moisture content on a wet basis (%), *A* is weight of the empty cup (g), *B* is weight of the cup with the sample before drying (g), and *C* is weight of the cup with the sample after drying (g).

2.4.2. Degree of Whiteness

The degree of whiteness was measured using a whiteness meter. Calibration was performed using a white standard of barium sulfate ($BaSO_4$), which has a whiteness value of 100%. A specified amount of the sample was placed into a special container, compacted, and then sealed. The container was subsequently placed in the device's measurement chamber. The whiteness value was displayed on the screen or read directly from the instrument. The whiteness degree of the flour was calculated from whiteness value displayed on the instrument using the following equation:

$$Degree\ of\ whiteness\ (\%) = \frac{A}{105} \times 100 \tag{2}$$

2.4.3. Protein Content

Protein content was analyzed using the Kjeldahl method. Samples were weighed at ±100 mg (A) and placed in a 100 ml Kjeldahl flask. Next, 1.9±0.1 g of K_2SO_4, 40±10 mg of HgO, and 3.8±0.1 ml of H_2SO_4 were added. A boiling stone was placed in the flask, then the sample was boiled for 1−1.5 h until the liquid became clear, then the flask and sample were cooled using cold water. The content of the flask and the rinsing water were transferred to a distillation apparatus. Five ml of H_3BO_4 solution and 4 drops of indicator was added to a 125 ml Erlenmeyer flask, then place it under the condenser with the tip of the condenser is well submerged in H_3BO_4. Add 8-10 ml of $NaOH\text{-}Na_2S_2O_3$ solution and place it in the distillation apparatus, then distil until ±15 ml of distillate is obtained in the Erlenmeyer flask. The distillate in the Erlenmeyer flask was then titrated with 0.02 N HCl solution until the color changes from green to blue. The amount of nitrogen was calculated after obtaining the blank volume (ml). The protein content was calculated using Equations (3) and (4).

$$N = \frac{a-b \times c \times 14.007 \times 100}{w} \tag{3}$$

$$P = \frac{N \times 6.25}{100-K_{a1}} \times 100\% \tag{4}$$

where *N* is the nitrogen content (%), *a* is the volume of HCl for sample titration (ml), *b* is the volume for blank titration (ml), *c* is the concentration of HCl (mol/1000 mol), and *w* is the sample weight (g).

2.5. Shelf Life Estimation

The observational data used as indicators of quality degradation during storage were tabulated and then subjected to a series of steps for estimating product shelf life using the Arrhenius equation (Hariyadi, 2019). The analytical data obtained at various storage temperatures were tabulated. These data were plotted to generate linear regression equations, as shown in Equation (3):

$$y = a + bx \quad (3)$$

where y is the product quality value, x is the storage duration (days), a is the initial quality value at the beginning of storage, and b is the rate of change in quality value. The slope (b) is obtained from this equation, which represents the reaction rate constant of the product's characteristic change or quality degradation (k). The reaction order with the highest coefficient of determination (R^2) is selected for further use in the Arrhenius equation. Data plotting is performed for zero- and first-order reactions to determine the appropriate reaction order. Zero-order refers to the relationship between k and storage time (t), while first-order refers to the relationship between ln k and storage time (t). The following equations for zero-order and first-order reactions express the quality degradation rate, respectively:

$$A_t = A_0 - kt \quad \text{(zeroth order)} \quad (4)$$

$$\ln A_t = \ln A_0 - kt \quad \text{(first order)} \quad (5)$$

where A_0 is the initial product quality value, A_t is the final product quality value, t is storage time (days), and k is the quality degradation rate constant.

The reaction order equation with the highest R^2 value was then used to plot ln k against $1/T$ (in Kelvin), allowing for the determination of the intercept and slope using the Arrhenius equation, as shown in Equation (6). This equation was further simplified to determine the temperature-dependent degradation rate constant (k) using Equation (7):

$$\ln k = ln\, k_o - \left(\frac{E_a}{R} \times \frac{1}{T}\right) \quad (6)$$

$$k = k_o \times e^{-\left(\frac{Ea}{R} \times \frac{1}{T}\right)} \quad (7)$$

where k is temperature-dependent degradation rate constant, k_o is the frequency factor (pre-exponential constant), Ea is the activation energy (J/mol), T is the storage temperature (K), and R is ideal gas constant (8,315 $J.mol^{-1}.K^{-1}$)

The shelf life of taro flour was determined by calculating the difference between the initial and final product quality values based on the degradation rate constant (k) at the storage temperature. According to Setiarto (2018), this can be calculated using the selected reaction kinetics equation, as shown in Equations (8) and (9):

$$t_s = \frac{(A_0 - A_t)}{k} \quad \text{(zeroth order)} \quad (8)$$

$$t_s = \frac{ln\, A_0 / ln\, A_t}{k} \quad \text{(first order)} \quad (9)$$

where t_s is the product shelf life (days), A_0 is the initial quality value, A_t is the final quality value (critical quality value), k is degradation rate constant as a function of storage temperature.

3. RESULTS AND DISCUSSION

The quality parameters observed during the shelf life of taro flour stored in PP and HDPE packaging included moisture content, whiteness, and protein content. The characteristics of the taro flour after approximately 8 hours of drying using a tray dryer indicated that the moisture content had reached 10%, the whiteness level was 80.40%, and the protein content was ±8.60.

The PP and HDPE packaging used in this study had different but relatively short shelf lives, both at low temperatures (25 °C) and high temperatures (≥ 35 °C). This was attributed to the low water vapor permeability of both packaging types, which helped protect the taro flour from excessive moisture uptake. HDPE, which generally has greater thickness and diffusion resistance, was slightly more effective in slowing changes in whiteness and protein content, although the difference was not substantial under the storage conditions applied.

3.1. Moisture Content

The trend of moisture content increase during storage, based on zero-order and first-order kinetics, is presented in Figure 1. Moisture content is one of the critical parameters in determining the quality, shelf life, and stability of taro flour products. Lower moisture content reduces the potential for microbial growth, thereby extending product shelf life. Conversely, higher moisture content shortens the shelf life of food products (Solihin *et al*., 2015). At the end of the storage period at temperatures of 35, 40, 45, and 50 °C with a relative humidity of approximately 70%, the moisture content of taro flour packed in PP packaging was 11.61%, 11.81%, 12.27%, and 13.07%, respectively. In HDPE packaging, the moisture content of taro flour at the same respective temperatures was 11.32%, 11.42%, 11.91%, and 12.71%. These results indicate that the moisture content of the taro flour had not yet reached the critical threshold. According to SNI 3752-2018 regarding wheat flour quality standards, taro flour is considered to have reached a critical point or undergone damage when its moisture content reaches 14.5%. This difference may be influenced by the type of packaging material used. The permeability of the packaging material to water vapor, the hygroscopic nature of the packaged food, and the humidity level of the surrounding air to the food product are considered factors that contribute to the increase in the water content of the packaged material during storage (Astuti *et al*., 2019).

The moisture content in food also determines the durability of the food; high water content makes it easy for bacteria, mold, and yeast to grow, so that changes in quality will occur (Warisin *et al*., 2024). The increase in the moisture content of taro flour is presumed to result from interactions between the material and the surrounding storage environment, in which water vapor from the atmosphere is absorbed into the PP and HDPE packaging. High humidity in the storage area facilitates water vapor absorption from the air into the material, increasing moisture content (Ariani *et al*., 2021).

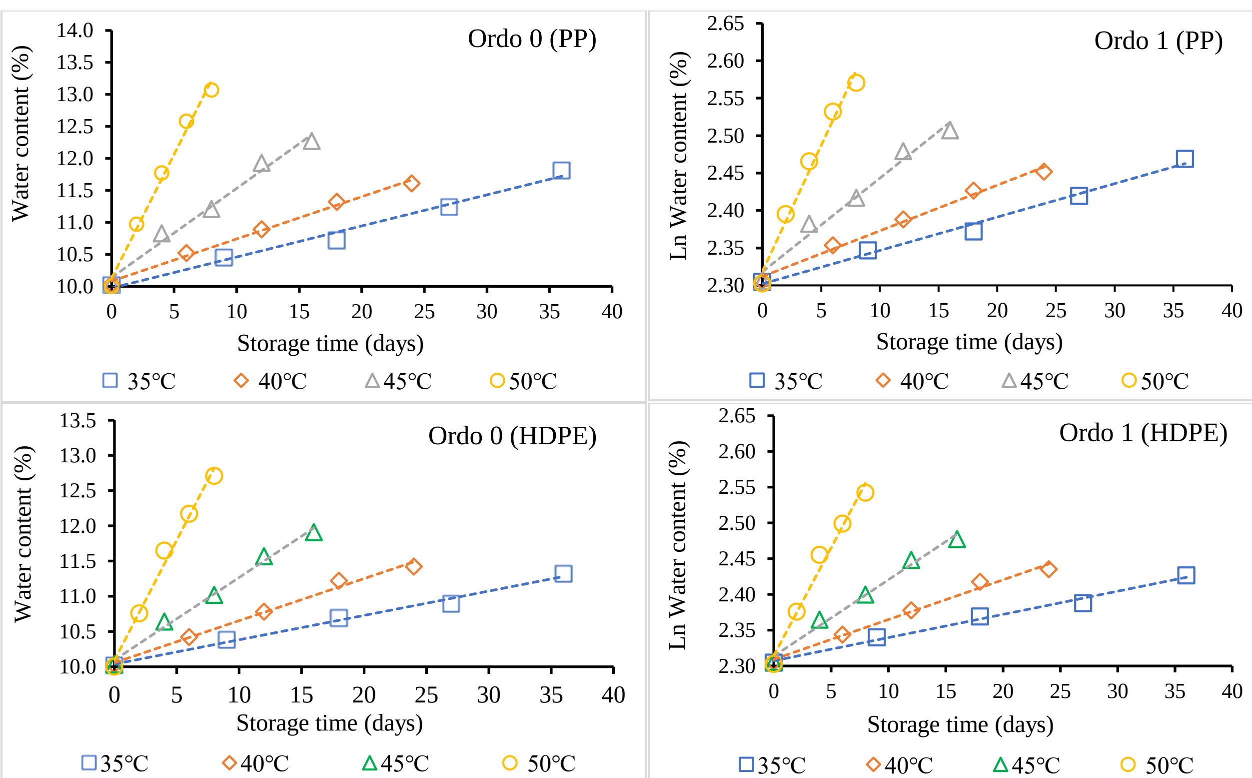

Figure 1. Moisture content increment of taro flour during storage using PP and HDPE packaging

Tabel 1. Equation for water content of taro flour based on zeroth order for four different temperatures

Packaging and Temperature	Equations	R^2	*k*	ln(*k*)
PP 35 °C	$KA_{t1} = 9.974 + 0.0486t$	0.9846	0.0486	-3.02413
PP 40 °C	$KA_{t1} = 10.082 + 0.066t$	0.9934	0.0660	-2.71810
PP 45 °C	$KA_{t1} = 10.138 + 0.1395t$	0.9825	0.1395	-1.96969
PP 50 °C	$KA_{t1} = 10.128 + 0.3875t$	0.9884	0.3875	-0.94804
HDPE 35 °C	$KA_{t1} = 10.038 + 0.0346t$	0.9896	0.0346	-3.36390
HDPE 40 °C	$KA_{t1} = 10.058 + 0.0597t$	0.9896	0.0597	-2.81842
HDPE 45 °C	$KA_{t1} = 10.096 + 0.1173t$	0.9917	0.1173	-2.14302
HDPE 50 °C	$KA_{t1} = 10.092 + 0.3415t$	0.9874	0.3415	-1.07441

Note : KA_{t1} = water content of taro flour as a function of storage time *t* (day)

Table 2. Equation for water content of taro flour based on first order for four different temperatures

Packaging and Temperature	Equations	R^2	*k*	ln(*k*)
PP 35 °C	$ln\ KA_{t1} = 2.302 + 0.0045t$	0.9890	0.0045	-5.40368
PP 40 °C	$ln\ KA_{t1} = 2.3119 + 0.0061t$	0.9900	0.0061	-5.09947
PP 45 °C	$ln\ KA_{t1} = 2.3182 + 0.0125t$	0.9765	0.0125	-4.38203
PP 50 °C	$ln\ KA_{t1} = 2.3187 + 0.0336t$	0.9797	0.0336	-3.39323
HDPE 35 °C	$ln\ KA_{t1} = 2.3072 + 0.0032t$	0.9898	0.0032	-5.74460
HDPE 40 °C	$ln\ KA_{t1} = 2.3093 + 0.0056t$	0.9875	0.0056	-5.18499
HDPE 45 °C	$ln\ KA_{t1} = 2.3137 + 0.0107t$	0.9877	0.0107	-4.53751
HDPE 50 °C	$ln\ KA_{t1} = 2.3245 + 0.0301t$	0.9800	0.0301	-3.50323

Note : KA_{t1} = water content of taro flour as a function of storage time *t* (day)

High humidity in the storage environment promotes the absorption of water vapor from the air into the product. However, the permeability properties of the packaging differ noticeably: PP has higher water vapor permeability than HDPE, making taro flour in PP packaging more susceptible to moisture increase during storage. In contrast, HDPE, with its superior moisture-barrier properties, can suppress the rate of water absorption, resulting in more stable flour quality. These findings indicate that a packaging material's resistance to moisture is a critical factor influencing product shelf life.

The kinetic model or reaction order is selected based on the regression equation with the highest coefficient of determination (R^2). According to (Arif, 2016), a higher R^2 value indicates a better fit and greater model accuracy to the observed data. The zero-order moisture content increase exhibited a higher R^2 value than the first-order model, indicating that the zero-order kinetic equation provides a better representation for determining the rate of change in taro flour as a function of storage temperature. The plotting of *k* values at various storage temperatures based on the zero-order model for both packaging types is presented in Figure 2.

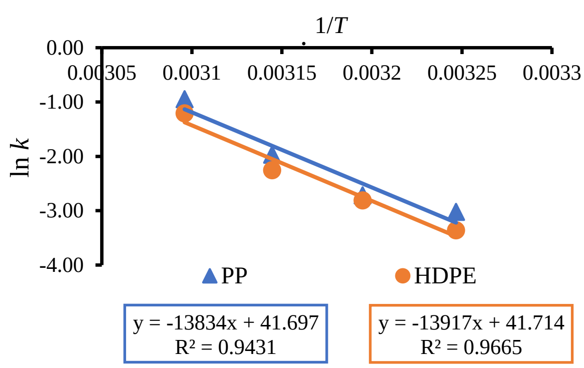

Figure 2. Arrhenius equation plot based on zero order function for water content of taro flour

The reaction order indicates the slope value (k), which represents the rate constant for the increase in moisture content of taro flour in various packaging types during storage. Equations describing the quality degradation at each storage temperature were obtained from the zero-order and first-order plots. The average coefficient of determination (R^2) for zero-order kinetics in PP and HDPE packaging was 0.9910 and 0.9895, respectively. Meanwhile, the average R^2 values for first-order kinetics in PP and HDPE packaging were 0.9912 and 0.9862, respectively. Based on the R^2 values, which are close to 1.0 under all conditions, it can be concluded that the kinetic models employed are highly effective in describing changes in moisture content during storage.

3.2. Degree of Whiteness

Whiteness is a crucial parameter in evaluating the quality of taro flour, as it directly influences visual appearance and consumer acceptance. A bright white color reflects hygienic and high-quality processing and significantly enhances the final product's visual appeal. Changes in the whiteness of taro flour during storage under four temperature conditions (35–50 °C) and two packaging types (PP and HDPE) are presented in Figure 3. The decrease in whiteness occurs more rapidly at higher storage temperatures. At 35 °C, the decline in whiteness is relatively gradual compared to other temperatures. At 40 °C, the declining rate increases further. More drastic reductions in whiteness are observed at 45 °C and 50 °C, with the most rapid decrease occurring at 50 °C, where a sharp decline is observed in < 10 days.

The kinetics of whiteness degradation, based on zero- and first-order models, are illustrated in Figure 3. Storage at elevated temperatures can accelerate the decline in whiteness due to oxidation reactions and the degradation of color pigments in taro flour. In PP packaging, the whiteness of taro flour decreases more rapidly than in HDPE packaging across all temperature treatments. HDPE packaging is better able to preserve whiteness, particularly at lower temperatures. At higher temperatures (45 °C and 50 °C), the reduction in whiteness is more pronounced and occurs more quickly in PP packaging compared to HDPE, indicating that HDPE offers superior protection against color degradation. The results suggest that as storage temperature increases, the rate of whiteness reduction also accelerates. This can be attributed to more rapid oxidation reactions at elevated temperatures, causing discoloration in taro flour.

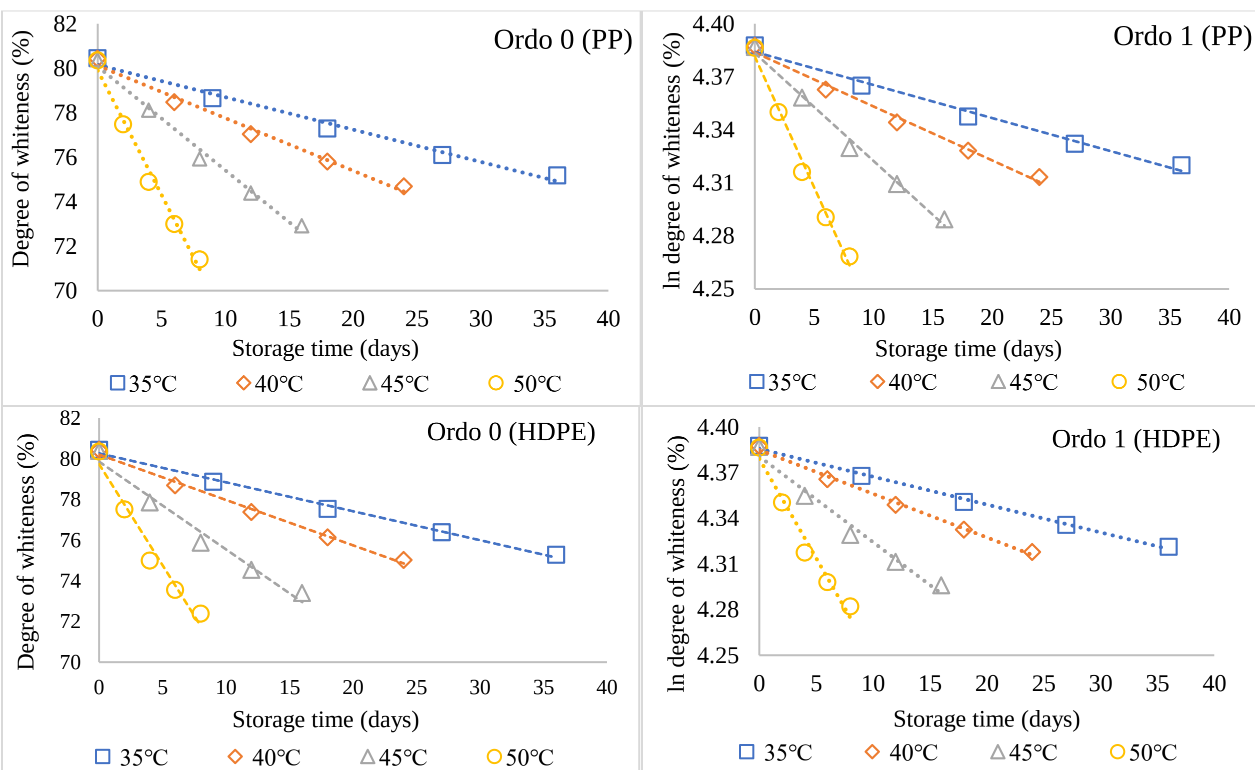

Figure 3. Declining of degree of whiteness of taro flour during storage using PP and HDPE packaging

Table 3. Equation for degree of whiteness of taro flour based on zeroth order for four different temperatures

Packaging and Temperature	Equations	R^2	k	ln(k)
PP 35 °C	$KA_{t2} = 80.074 - 0.1381t$	0.9756	0.1381	-1.97978
PP 40 °C	$KA_{t2} = 80.076 - 0.2307t$	0.9794	0.2307	-1.46664
PP 45 °C	$KA_{t2} = 79.746 - 0.4305t$	0.9666	0.4305	-0.84281
PP 50 °C	$KA_{t2} = 79.716 - 0.9725t$	0.9691	0.9725	-0.02789
HDPE 35 °C	$KA_{t2} = 80.114 - 0.1134t$	0.9698	0.1134	-2.17683
HDPE 40 °C	$KA_{t2} = 80.182 - 0.2172t$	0.9898	0.2172	-1.52693
HDPE 45 °C	$KA_{t2} = 79.838 - 0.3877t$	0.9688	0.3877	-0.94752
HDPE 50 °C	$KA_{t2} = 79.828 - 0.8720t$	0.9730	0.8720	-0.13696

Note : KA_{t2} = degree of whiteness of taro flour as a function of storage time t (day)

Table 4. Equation for degree of whiteness of taro flour based on first order for four different temperatures

Packaging and Temperature	Equations	R^2	k	ln(k)
PP 35 °C	$ln\, KA_{t2} = 4.3831 - 0.0018t$	0.9785	0.0018	-6.31997
PP 40 °C	$ln\, KA_{t2} = 4.3832 - 0.003t$	0.9822	0.003	-5.80914
PP 45 °C	$ln\, KA_{t2} = 4.3791 - 0.0056t$	0.9714	0.0056	-5.18499
PP 50 °C	$ln\, KA_{t2} = 4.3788 - 0.0128t$	0.9741	0.0128	-4.35831
HDPE 35 °C	$ln\, KA_{t2} = 4.3835 - 0.0014t$	0.9724	0.0014	-6.57128
HDPE 40 °C	$ln\, KA_{t2} = 4.3845 - 0.0028t$	0.9917	0.0028	-5.87814
HDPE 45 °C	$ln\, KA_{t2} = 4.3802 - 0.005t$	0.9730	0.0050	-5.29832
HDPE 50 °C	$ln\, KA_{t2} = 4.3802 - 0.0114t$	0.9772	0.0114	-4.47414

Note : KA_{t2} = degree of whiteness of taro flour as a function of storage time t (day)

The regression graph shows a negative slope, which corresponds to the decrease in the whiteness degree of taro flour during storage. According to the principles of reaction kinetics, however, the reaction rate constant (k) must always be positive. Therefore, k is determined from the absolute value of the slope using the equation $k = -$ (slope). This approach is consistent with both zero-order and first-order kinetic models, where the regression slope is negative, but the rate constant is still defined as positive (Labuza & Riboh, 1982).

The reaction order reflects the slope value (k), which represents the rate constant. From the zero-order and first-order plots, equations describing the decrease in the degree of whiteness at each storage temperature were obtained. The increase in the k value with rising storage temperature indicates that higher temperatures accelerate color degradation in the packaging. This finding is consistent with reaction kinetics theory, which states that the reaction rate increases with temperature. Previous studies also demonstrated that color degradation in packaging materials may result from oxidation and photodegradation reactions triggered by exposure to elevated temperatures (Robertson, 2016).

The average coefficient of determination (R^2) for the zero-order kinetic model in PP and HDPE packaging was 0.9809 and 0.9862, respectively. For the first-order model, the average R^2 values were slightly higher at 0.9839 for PP and 0.9890 for HDPE packaging. These results indicate that the decrease in whiteness in PP and HDPE packaging is better described by the first-order kinetic model, as reflected by the higher R^2 values.

The relationship between the reaction rate constant (k), expressed as the natural logarithm (ln k), and the inverse of the absolute temperature ($1/T$) for the decrease in whiteness according to the first-order reaction model in both PP and HDPE packaging is presented in Figure 4. Based on the linear regression equations obtained, the slope of each line reflects the activation energy (Ea) of the whiteness degradation process. The regression lines exhibit a negative slope, indicating that as temperature increases (i.e., as $1/T$ decreases), the rate constant k increases, meaning whiteness degrades more rapidly. The regression equation for PP packaging is y = 37.887 – 13636x, with a coefficient of determination (R^2) of 0.9766, while the equation for HDPE packaging is y = 36.213 – 13131x, with an R^2 of 0.9806.

The coefficient of determination (R^2) values for both types of packaging indicate that the linear regression models effectively describe the relationship between ln k and $1/T$. The decrease in the whiteness of taro flour is influenced by both storage temperature and the type of packaging material, with HDPE packaging generally offering better protection against whiteness degradation compared to PP packaging. In addition to these factors, other variables that may affect

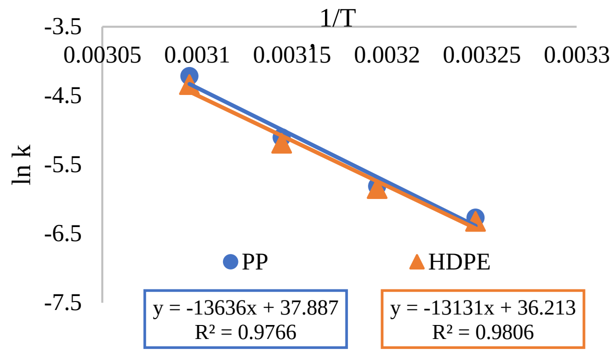

Figure 4. Arrhenius equation plot based on first order function for degree of whiteness of taro flour

the color of flour include the original color of the tuber, surface area, drying duration, heating temperature, and any fermentation processes involved (Ode *et al*., 2020). Furthermore, the use of NaCl solution during the soaking stage can also influence the brightness of the resulting flour (Saudarah *et al*., 2023).

3.3. Protein Content

The relationship between protein content reduction and storage time in different packaging types is presented in Figure 5. Protein plays an important role in providing structure and texture to the final product, as well as influencing the functional properties of flour, such as water absorption. According to Solihin *et al*. (2015), protein degradation in dry food ingredients may occur due to Maillard reactions, protein oxidation, and interactions with water during storage. Elevated storage temperatures can accelerate changes in protein structure and chemical reactivity, ultimately reducing nutritional quality.

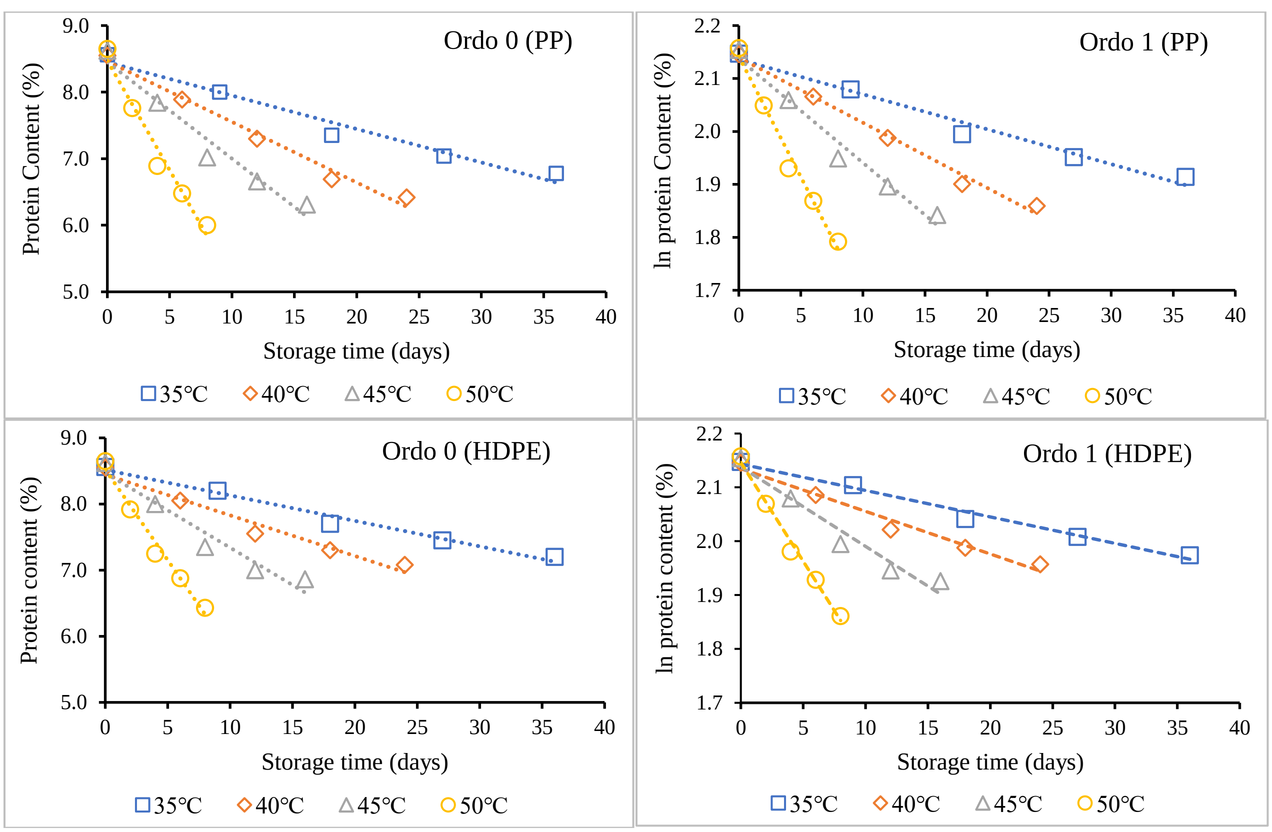

Figure 5. Declining of protein content of taro flour during storage using PP and HDPE packaging

The protein content in taro flour at the beginning of storage was approximately 8.40% and tended to decrease over time. This decrease was caused by protein damage, including denaturation and coagulation. At 50 °C, the protein content decreased in both types of packaging, with HDPE showing slightly better performance in slowing protein degradation compared to PP. Storage at 35 °C resulted in the slowest rate of protein decline in both types of packaging. Rostianti *et al.* (2018) reported that the protein content of beneng taro flour was 3.4%, while the protein content of kimpul taro flour was 8.54% (Paramita & Ambarsari, 2017). Overall, the protein content of taro flour in this study was higher than that reported in previous studies.

Tabel 5. Equation for protein content of taro flour based on zeroth order for four different temperatures

Packaging and Temperature	Equations	R^2	k	ln(k)
PP 35 °C	$KA_{t3} = 8.45 - 0.0502t$	0.9657	0.0502	-2.99174
PP 40 °C	$KA_{t3} = 8.462 - 0.091t$	0.9830	0.0910	-2.39690
PP 45 °C	$KA_{t3} = 8.45 - 0.145t$	0.9607	0.1450	-1.93102
PP 50 °C	$KA_{t3} = 8.472 - 0.329t$	0.9706	0.3290	-1.11170
HDPE 35 °C	$KA_{t3} = 8.516 - 0.0386t$	0.9808	0.0386	-3.25450
HDPE 40 °C	$KA_{t3} = 8.444 - 0.0615t$	0.9645	0.0615	-2.78872
HDPE 45 °C	$KA_{t3} = 8.47 - 0.113t$	0.9438	0.113	-2.18037
HDPE 50 °C	$KA_{t3} = 8.522 - 0.274t$	0.9803	0.274	-1.29463

Note : KA_{t3} = protein content of taro flour as a function of storage time *t* (day)

Tabel 6. Equation for protein content of taro flour based on first order for four different temperatures

Packaging and Temperature	Equations	R^2	k	ln(k)
PP 35 °C	$ln\ KA_{t3} = 2.1362 - 0.0066t$	0.9746	0.0066	-5.02069
PP 40 °C	$ln\ KA_{t3} = 2.1395 - 0.0123t$	0.9892	0.0123	-4.39816
PP 45 °C	$ln\ KA_{t3} = 2.1375 - 0.0197t$	0.9739	0.0197	-3.92714
PP 50 °C	$ln\ KA_{t3} = 2.1418 - 0.0456t$	0.9843	0.0456	-3.08785
HDPE 35 °C	$ln\ KA_{t3} = 2.1433 - 0.0049t$	0.0049	0.9853	-5.31852
HDPE 40 °C	$ln\ KA_{t3} = 2.1347 - 0.0079t$	0.0079	0.9726	-4.84089
HDPE 45 °C	$ln\ KA_{t3} = 2.1380 - 0.0148t$	0.0148	0.9538	-4.21313
HDPE 50 °C	$ln\ KA_{t3} = 2.1463 - 0.0367t$	0.0367	0.9898	-3.30498

Note : A_{t3} = protein content of taro flour as a function of storage time *t* (day)

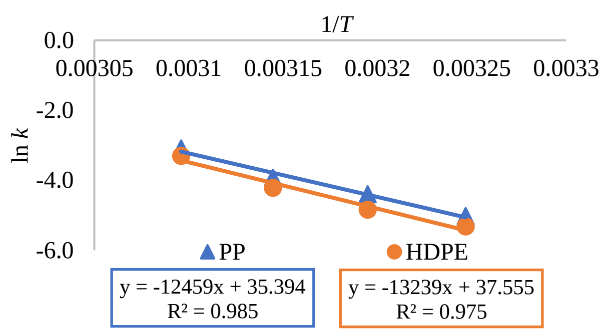

Figure 6. Arrhenius equation plot based on first order function for protein content of taro flour

After obtaining the linear regression curves, the R^2 value was calculated for each regression equation. The reaction order was then determined, with the order showing a higher average R^2 value being used to estimate the shelf life of taro flour. The average R^2 of the first-order model was greater than that of the zero-order model, indicating that the first-order model provides a better fit for describing changes in protein content. Therefore, the first-order model was used to estimate the shelf life of taro flour. The relationship between ln k and *1/T* of first-order reactions can be seen in Figure 6. The intercept value of the above equation is the value of ln k. In this case, the values of ln k and k are obtained from plotting the relationship between ln k and 1/*T* in PP and HDPE packaging. The Arrhenius equation can be constructed based on the values of -Ea/R and k obtained. A regression of the relationship between the values of ln k and 1/*T* of taro flour in PP and HDPE packaging is created. Then, using the rate of change in the quality of taro flour, the value of k is obtained based on storage time, temperature, and type of packaging.

From the Arrhenius plots describing decrasing protein content, two regression equations were obtained for each type of packaging, representing the relationship between the rate constant of quality deterioration and storage temperature. For PP packaging, the regression equation is y = 35.394 − 12459x, with a coefficient of determination R^2 of 0,985. For HDPE packaging, the equation is y = 37.555 − 13239x, with an R^2 of 0.975. The relatively high R^2 values, both approaching 1, indicate that the regression models reliably describe the influence of storage temperature on decrasing protein. These findings suggest that higher storage temperatures accelerate protein, which in turn shortens the shelf life of taro flour.

3.4. Shelf Life of Taro Flour

Shelf life estimation is conducted to determine the maximum duration for which a product remains suitable for consumption. Shelf life is one of the key factors influencing product quality. Over time, deterioration can occur, leading to a decline in the final product's quality and potentially rendering it unfit for consumption (Ariani *et al*., 2021). According to Kusnandar *et al*. (2010), determining the critical quality attribute in shelf life estimation involves identifying essential components within the product that are likely to interact with other substances or degrade during storage. Shelf life estimation using the Arrhenius approach is performed by examining the constant dependence of the reaction rate on temperature.

According to Arif (2016), the reaction order can be determined by plotting the decrease in quality parameters, which may follow either zero-order or first-order kinetics. The reaction order with the higher coefficient of determination (R^2) is then selected. In taro flour, the critical value is determined based on the protein content parameter. The selection of the reaction order is carried out by fitting the quality degradation data to a first-order model and deriving the corresponding linear regression equation. The Arrhenius equation for each quality parameter of taro flour is presented in Table 7.

Table 7. Arrhenius equation for each parameter of taro flour in PP and HDPE packaging

Packaging		**Quality Parameters**		
		Water content	**Degree of whiteness**	**Protein content**
PP	Equation	y = -13834x + 41.697	y = -12929x + 35.575	y = -12459x + 35.394
	-Ea/*R*	-13834	-12929	-12459
	ln *k*	41.697	35.575	35.394
HDPE	Equation	y = -13917x + 41.714	y = -13661x + 37.759	y = -13239x + 37.555
	-Ea/*R*	-13917	-13661	-13239
	ln *k*	41.714	37.759	37.555

Table 8. Estimation of the shelf life of taro flour in PP and HDPE packaging at various storage temperatures.

Temperature (°C)	**Taro Flour Shelf Life (days)**	
	PP	**HDPE**
25	223	285
28	147	183
35	57	67
40	30	34

Of the three quality parameters observed—moisture content, whiteness, and protein content—the analysis indicates that protein content provides the best fit with both the zero-order and first-order kinetic models, as evidenced by a high coefficient of determination (R^2), a consistent linear relationship between ln k and *1/T*, and a logical Ea value. The critical value of taro flour is determined based on the protein content parameter. The appropriate reaction order is selected by plotting the quality degradation data according to zero-order and first-order kinetics, followed by the development of linear regression equations. Once the protein content is identified as the critical quality parameter, the temperature-dependent rate constant (*k*) is determined for each type of packaging. The estimated shelf life of taro flour stored in PP and HDPE packaging at various storage temperatures, determined using the Accelerated Shelf Life Testing (ASLT) method with the Arrhenius equation, is presented in Table 8.

4. CONCLUSION

The results of shelf-life estimation for taro flour packaged in PP and HDPE show that lower storage temperatures lead to longer shelf life. Conversely, higher storage temperatures accelerate the deterioration of taro flour quality, indicating that for each increase in temperature, the reaction rate approximately doubles compared to lower temperatures. During storage, the quality of taro flour in both PP and HDPE packaging changes, as reflected by increased moisture content, reduced whiteness, and decreased protein levels. HDPE is generally more effective in slowing the rate of quality degradation, particularly in terms of whiteness and protein, although the difference compared to PP is not substantial. Based on shelf-life calculations using protein content as the critical quality parameter, taro flour stored at 25 °C can last up to 223 days in PP packaging and 285 days in HDPE packaging. At 28 °C, the estimated shelf life is 147 days in PP packaging and 183 days in HDPE packaging.

For the next stage of research, it is necessary to estimate the shelf life by adding carbohydrate (starch) parameters and conducting organoleptic quality tests. In addition, other types of packaging, such as aluminum foil or multilayer packaging, can be added to the packaging used.

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