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Accelerated shelf life estimation of pumpkin bar using arrhenius-based aslt with aluminum foil packaging

Perkiraan umur simpan untuk bar labu menggunakan ASLT berbasis arrhenius dengan kemasan aluminium foil

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Abstract

Pumpkin bars are practical functional food products; however, their distribution is often hampered by a lack of data on quality degradation kinetics in the tripos environment. This study aimed to estimate the shelf life of pumpkin bars using the Accelerated Shelf Life Test (ASLT) method with the Arrhenius approach and to evaluate the effectiveness of aluminum foil packaging in maintaining product quality. This study used an experimental design conducted at the Food Laboratory of the Riau Ministry of Health Polytechnic and SIG Laboratory from January to October 2025. Samples were stored at 35, 40, and 45°C, and a control temperature of 18°C for 30 days, with observations every 7 days. The parameters observed included moisture content, water activity (Aw), and the presence of mold and yeast. Data analysis used the Arrhenius kinetic model to calculate the reaction rate constant and estimate the shelf life. The results showed that the product was stable in terms of mold and yeast <10 colonies/g. Increased moisture content (8.5–14%) and Aw (0.52–0.67) were the main limiting factors for the growth of these Based on Arrhenius calculations, the shelf life of the product was estimated to be 23–35 days at 35–45°C. Moisture content and sensory degradation were the main determinants of the shelf life of pumpkin bars in aluminum foil packaging.

Keywords: Pumpkin bar, Preservation, ASLT, Aluminum foil.

Abstrak

Pumpkin bar merupakan produk pangan fungsional praktis,namun distribusinya sering terkendala oleh minimnya data kinetika degradasi mutu di lingkungan tripos. Penelitian ini bertujuan memperkirakan umur simpan pumpkin bar menggunakan metode *Accelerated Shelf Life Test* (ASLT) dengan pendekatan Arrhenius serta mengevaluasi efektivitas kemasan aluminium foil dalam mempertahankan kualitas produk. Penelitian menggunakan desain eksperimental yang dilaksanakan di Laboratorium Pangan Poltekkes Kemenkes Riau dan SIG Laboratorium pada Januari–Oktober 2025. Sampel disimpan pada suhu 35°C, 40°C, 45°C, dan suhu kontrol 18°C selama 30 hari dengan pengamatan setiap 7 hari. Parameter yang diamati meliputi kadar air, aktivitas air (Aw), dan kapang dan khamir. Analisis data menggunakan model kinetika Arrhenius untuk menghitung konstanta laju reaksi dan estimasi umur simpan. Hasil menunjukkan produk stabil secara kapang dan khamir <10 koloni/g. Peningkatan kadar air (8,5–14%) dan Aw (0,52–0,67) menjadi faktor pembatas utama. Berdasarkan perhitungan Arrhenius, umur simpan produk diperkirakan 23–35 hari pada suhu 35–45°C. Kadar air dan degradasi sensori merupakan faktor penentu utama umur simpan pumpkin bar dalam kemasan aluminium foil.

Kata Kunci: Pumpkin bar, Pengawetan, ASLT, Aluminium foil.

Introduction

Determining the shelf life is an important aspect of food product quality and safety control. Shelf life is defined as the period during which a product is fit for consumption and has acceptable sensory, chemical, physical, and microbiological quality when stored under appropriate conditions (Haouet et al., 2018). Recent studies have indicated that errors in shelf-life estimation can lead to increased food waste and food safety risks, particularly for high-carbohydrate and high-fat products (Atencio et al., 2022). This issue is increasingly urgent amid the rising global food waste (Thi et al., 2015). Therefore, an evidence-based scientific approach is required to accurately and efficiently estimate the shelf life.

Although research on the shelf life of dry foods is growing, specific studies on pumpkin bars remain limited. Previous studies have only assessed changes in bioactive content and lipid oxidation resistance in pumpkin-based bars without simultaneously evaluating their physicochemical and sensory degradation (Manzocco et al., 2020). The characteristics of pumpkin bars as complex intermediate-moisture products, containing fat, carbohydrates, and bound moisture, require a multi-parameter approach to understand their deterioration kinetics (Choosuk et al., 2022). Furthermore, most snack bar studies use shelf life estimates based on conventional long-term testing; therefore, the effectiveness of the Arrhenius-based Accelerated Shelf Life Test (ASLT) method on pumpkin bars has not been widely evaluated (Pratiwi et al., 2019; Hariono et al., 2023). Empirical data on the quality deterioration patterns of pumpkin bars under tropical storage conditions are also limited, particularly regarding the dynamics of moisture content, water activity, and sensory parameters as determinants of shelf life-limiting factors (Giannakourou et al., 2023). The role of water activity (Aw) is crucial because even slight changes can trigger significant texture and sensory degradation (Madhumathy, 2021). This research gap highlights the need for scientific studies that integrate physicochemical and sensory evaluations to calculate the shelf life of pumpkin bars using the Arrhenius kinetic model through the ASLT method.

Yellow squash (Cucurbita moschata) is a local commodity with high levels of beta-carotene, dietary fiber, and antioxidants, and has great potential as a functional food ingredient (Karadenİz et al., 2024). According to (2023),, there has been an increase in national horticultural production, including yellow squash, particularly in the Sumatra and Riau regions. However, this increase in production has not been accompanied by the optimization of value-added product diversification. The development of pumpkin bars from this local commodity is highly relevant as an effort to diversify functional foods with guaranteed quality and stability (Durry et al., 2024). One potential diversification strategy is the development of pumpkin bars. However, the quality stability and shelf life of pumpkin-based products for distribution and retail markets have not yet been thoroughly investigated. Consequently, the increase in yellow pumpkin production has created an urgent need for research on the formulation and durability of processed products, such as food bars, to enable the more widespread and sustainable utilization of this commodity.

Snack bar products generally experience a decline in quality owing to fat oxidation reactions, non-enzymatic browning, and moisture migration during storage (Manzocco et al., 2020). Fluctuations in temperature and moisture accelerate chemical reactions and shorten shelf life (Surahman et al., 2020). Therefore, a fast and accurate method for determining shelf life is needed, one of which is the Accelerated Shelf Life Test (ASLT) using the Arrhenius kinetic model approach (Nirwana et al., 2022). However, the ASLT method has limitations, namely, it assumes a consistent damage pattern across temperatures and does not consider potential changes in reaction mechanisms at extreme temperature ranges (Ebrahim et al., 2021). Despite these limitations, the use of the Arrhenius ASLT remains the most common and accurate approach if the test conditions are optimized (Rachtanapun & Tantala, 2025). Alternative methods, such as the predictive *Shelf Stability Index* model or the probabilistic Monte Carlo approach, have begun to be used for some dry foods but have not been widely applied to pumpkin-based bars (Parente & Ricciardi, 2025). Therefore, the application of ASLT remains relevant for estimating the shelf life of pumpkin bars; however, interpretation based on critical quality parameters is required to ensure accurate and representative results.

Packaging is an important factor in maintaining product quality and stability. Aluminum foil packaging has been proven to be effective in inhibiting oxidation and moisture migration in low-moisture food products (Giannakourou et al., 2023). However, most studies on aluminum foil packaging have only been conducted on cereal bars and granola, while empirical evidence on snack bars with different moisture and fat contents is still very limited. Therefore, the performance of multi-layer packaging, such as aluminum foil, needs to be validated against products with specific matrices, such as pumpkin bars (Alias et al., 2022). Furthermore, no studies have simultaneously linked the effectiveness of aluminum foil packaging with the Arrhenius-based quality decline model to produce measurable shelf life estimates (Turan & Schifferstein, 2024). Given these limitations, this study aimed to estimate the shelf life of pumpkin bars using the ASLT method with an Arrhenius kinetic model approach, and evaluate the effectiveness of aluminum foil packaging in maintaining the physicochemical quality during storage.

Methods

Research Design

This study used an experimental design with the Arrhenius approach ASLT method. The selection of storage temperatures was based on the distribution and storage conditions of tropical foods, namely 35 °C, 40 °C, and 45 °C as accelerated deterioration temperatures, and 18 °C as the control temperature to simulate cold storage. These temperatures were chosen because they are within a range that can accelerate the deterioration reaction without causing extreme damage to the physical structure of the product, thus allowing for stable degradation patterns for the application of the Arrhenius model (Ebrahim et al., 2021). Sampling observations were conducted on days 0, 7, 14, 21, 28, and 30 to record quality changes in the early, middle, and late stages of quality degradation.

Research Location and Time

The research was conducted at the Food Chemistry and Microbiology Laboratory of the Riau Ministry of Health Polytechnic and the SIG Laboratory in Pekanbaru from January to October 2025, covering the stages of sample preparation, storage, quality testing and data analysis. Both laboratories were ISO/IEC 17025 certified for food testing, ensuring the validity and traceability of the instrument measurement results. Instrument calibration was performed regularly by the internal laboratory prior to testing to ensure data reliability.

Samples

The samples were pumpkin bars formulated in the laboratory and packaged in aluminum foil packaging. The basic formula consisted of yellow pumpkin flour (50%), taro flour (50%), palm sugar, egg, margarine, and pumpkin seeds. A total of 16 samples were analyzed (4 temperatures × 4 products). Storage was carried out at 18 °C (control), 35 °C, 40 °C, and 45 °C to observe the dynamics of quality decline in the tropical temperature range. Although the number of samples per temperature was relatively small, technical replicates were performed to ensure data consistency.

Work Procedure

The samples were stored for 30 days, and observations were made every 7 days. The parameters observed included moisture content, water activity (Aw), and microbiology (molds and yeasts). Moisture content was analyzed based on the SNI 01-2891-1992 method, while Aw was measured using a Rotronic Hygrolab (USA). Texture (hardness and crispness) was analyzed using a Texture Analyzer TA-XT2 with a Three-Point Bend Rig (HDP/3PB) probe. Microbiological analysis was performed using the plate count method and expressed as colonies/g.

Data Processing Techniques

The test results were compiled in a table for each quality parameter and storage temperature. The quality change rate constant (k) was obtained by determining the slope of the linear regression between ln(quality parameter) and time. Next, the relationship between ln k and 1/T (K^{-1}) was analyzed using linear regression to obtain the slope (m) and intercept (b), and the activation energy (Ea) was calculated using the following equation:

$$In\ k\ = -\frac{E_a}{R}.\frac{1}{T} + InK_0$$
$$E_a\ = -m \times\ R$$

With R=8.314 $J/mol^{-1}K^{-1}$. The estimated shelf life at room temperature was obtained from the quality degradation equation, based on the rate constant (k) at the target temperature. This data processing approach refers to the Arrhenius model for low-moisture foods (Nirwana et al., 2022).

Ethical Clearance

This study was approved by the Health Research Ethics Committee (KEPK) of the Riau Ministry of Health Polytechnic (registration number LB.02.03/EA/KEPK-PKR/167/2025). All testing procedures, including sensory tests, were conducted in accordance with the principles of safety, confidentiality, and voluntary consent from all the respondents.

Result and Discussion

The results of the observation showed that an increase in storage temperature had a significant effect on the rate of change in the quality of the pumpkin bars. At a control temperature of 18 °C, the water content increased from 9.78% to 13.65% on the 30th day, whereas at 45 °C, the increase was more pronounced, from 8.72% to 14.03%. This indicates that moisture migration occurs more rapidly at higher temperatures. A similar pattern was observed for water activity (Aw), where Aw at 18 °C increased gradually from 0.580 to 0.667, whereas at 45 °C, it increased more dramatically from 0.537 to 0.662 over the same period. The difference in the Aw increase gradient between temperatures proves that high temperatures accelerate the transition of food systems towards conditions that support physical and sensory instability.

Although microbiological parameters (mold and yeast) remained below the detection limit until day 30 for all temperatures, the increase in water content and Aw at high temperatures has the potential to accelerate microbial growth after the testing limit, so that physicochemical parameters can be considered as factors limiting the shelf life. Monitoring the consistency of change patterns between temperatures also showed that 40 °C and 45 °C produced the fastest quality changes, followed by 35 °C, while 18 °C showed the slowest changes. Thus, the data support the application of the Arrhenius model, as the acceleration of deterioration increases systematically with increasing temperature, rather than randomly. (Table 1).

Table 1. Results of microbiological testing, moisture content, and water activity (AW) of pumpkin bars

Storage Temperature	Parameter	Day 0	Day 7	Day 14	Day 21	Day 28	Day 30
Temperature 18°C	Mold (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Yeast (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Moisture Content (%)	9.78	10.38	10.94	11.40	13.52	13.65
	Water Activity (WA)	0.580	0.616	0.633	0.636	0.664	0.667
Temperature 35 (°C)	Mold (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Yeast (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Moisture Content (%)	9.01	10.47	10.67	10.89	11.61	11.95
	Water Activity (WA)	0.521	0.622	0.623	0.623	0.637	0.659
Temperature 40 (°C)	Mold (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Yeast (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Moisture Content (%)	8.50	9.67	10.72	10.79	11.97	13.08
	Water Activity (WA)	0.583	0.635	0.635	0638	0.650	0.661
Temperature 45 (°C)	Mold (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Yeast (colony/g)	< 10	< 10	< 10	< 10	< 10	< 10
	Moisture Content (%)	8.72	9.12	9.46	11.50	12.65	14.03
	Water Activity (WA)	0.537	0.570	0.614	0.619	0.649	0.662

Shelf Life Calculation

The results of the Accelerated Shelf-Life Test (ASLT) using the Arrhenius approach on pumpkin bars packaged in aluminum foil showed different chemical quality changes at each storage temperature (35 °C, 40 °C, and 45

°C) during 30 d of observation. A temperature of 18 °C was used as a control and was therefore not included in the shelf-life calculation.

Table 2. Shelf life calculation of moisture content, water activity, mold, and yeast

Parameter	Temperature (T) (⁰°C)	(1/T) K	k	In K	Ea	K_0	Daily Quality Decline Rate (K)	Shelf Life (days)
Moisture Content	35	0.003245	0.098	-2.32	48.4	1.6 x 10^7	0.098	35.6
	40	0.000319	0.152	-1.88			0.152	26.3
	45	0.003332	0.177	-1.73			0.177	23.0
Water Activities	35	0.003245	0.00460	-5.382	-8.51	1.40 x$^{10^{-4}}$	0.00460	28.04
	40	0.003193	0.00260	-5.952			0.00260	25.77
	45	0.003332	0.00417	-5.481			0.00417	27.12
Total yeast mold	35	0.003245	0	-	-	-	0	Stable (> 30 days)
	40	0.003193	0	-			0	Stable (> 30 days)
	45	0.003332	0	-			0	Stable (> 30 days)

Description:
T = Storage temperature (°C)
1/T = Reciprocal of absolute temperature (Kelvin^{-1})
k = Reaction rate constant
ln k = Natural logarithm of the reaction rate constant
Ea = Activation energy (kJ/mol)
K_0 = Pre-exponential factor (Arrhenius constant)
K = Rate of deterioration per day

Table 2 shows that the reaction rate constant (k) increased consistently with increasing temperature, which is consistent with the first-order kinetics characteristic of the Arrhenius model. Although the number of test points was limited to three acceleration temperatures, the R^2 value of the ln k versus 1/T graph was 0.93, indicating a high level of model fit. This reinforces the validity of using the Arrhenius model to predict the rate of quality deterioration in pumpkin bars.

Although inferential statistical analysis was not performed, prediction uncertainty was minimized through technical replication, standardized testing, and the consistency of the linear increase pattern between temperatures. Therefore, the modeling results are considered scientifically robust enough for shelf-life estimation purposes, although observations over a wider temperature range could further improve the accuracy of the results.

The Arrhenius graph generated from the decay rate data (k) shows a linear relationship between the ln k value and 1/T (K^{-1}) for the two main quality parameters, namely, moisture content and water activity. The linearity of the Arrhenius curve indicates that changes in pumpkin bar quality follow first-order reaction kinetics, and thus, the Arrhenius model is valid for estimating shelf life.

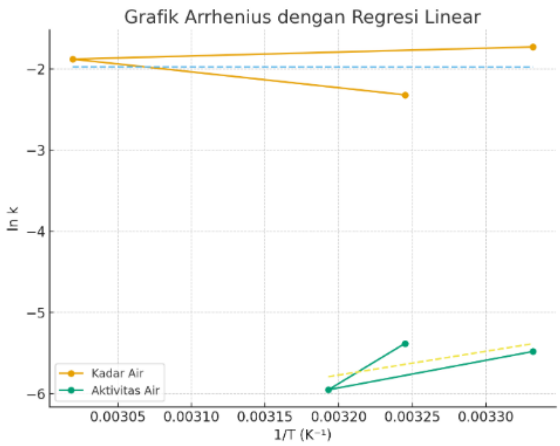

Figure 1. Arrhenius graph

Overall, the Arrhenius graph shows that pumpkin bars are more susceptible to accelerated quality deterioration at higher storage temperatures and that the Arrhenius model can accurately represent these quality changes. Therefore, storage at low temperatures is highly recommended to maintain the physical stability and extend the shelf life of pumpkin bars.

Moisture Content

Changes in *moisture content* are a dominant factor in determining the shelf life of dry food products such as Pumpkin Bars. Based on the results of Arrhenius kinetics calculations, the moisture content increased with increasing storage temperature, resulting in the highest reaction rate constant (k) at 45 °C. This indicates that high temperatures accelerate moisture absorption from the environment owing to differences in water vapor pressure between the product and the surrounding air.

Increased moisture content accelerates chemical reactions, such as non-enzymatic browning and color degradation, and can reduce the crispness of the bar. These results are consistent with those of Pertiwi et al. (2020), who reported a significant increase in the moisture content of pumpkin-glutinous rice snack bars during storage at 35–45 °C, with a decline in sensory quality when the moisture content exceeded 10%.

The increase in water content at high temperatures is caused not only by the difference in water vapor pressure between the product and the environment but also by the characteristics of the pumpkin bar formulation. The pumpkin puree content, which is rich in soluble fiber and simple sugars, is hygroscopic and facilitates the absorption of water vapor from the surrounding air (Kaur, 2023). Additionally, lipid components can reduce local water activity but do not completely inhibit moisture diffusion into the carbohydrate matrix (Manzocco et al., 2020). Environmental factors, such as relative storage humidity, also accelerate moisture migration, especially in tropical climates with high humidity (Surahman et al., 2020).

Water content exceeding the critical limit (~10%) reduces the physical durability of the product and accelerates non-enzymatic browning reactions and color degradation (Pertiwi et al., 2020). The mechanism of this texture reduction involves the glass transition of the carbohydrate matrix at high moisture content, causing the product to become soft and brittle (Seth et al., 2015). Therefore, the estimated shelf life of 23–35 days shows the high influence of storage humidity control on the quality stability of Pumpkin Bars.

Water Activity

Water activity (Aw) describes the amount of free water that can be used by microbes and in biochemical reactions. Based on the acceleration test results, the aw value increased with the storage temperature, and the reaction rate constant (k) increased with the temperature, in accordance with the Arrhenius model. The obtained activation energy (Ea) is low, indicating that changes in aw are relatively slow and stable with respect to temperature changes (Ebrahim et al., 2021).

The aw value increased during storage but remained below the microbial growth threshold (< 0.70). The increase in aw is mainly due to internal water redistribution and the humectant properties of carbohydrates and sugars in the product (Parente & Ricciardi, 2025). However, on a real storage scale, fluctuations in the relative humidity of warehouses or during transportation can trigger moisture cycling, which accelerates the increase in aw, even in sealed packaging (Giannakourou et al., 2023). This moisture cycling phenomenon can cause a local increase in Aw sufficient to initiate chemical and physical degradation reactions, even though the total average (Aw) remains low (Wang et al., 2025).

Based on the maximum limit of aw 0.65 to prevent microbial growth in low-moisture foods, an estimated shelf life of 26–28 days applies to dry and stable storage. Moisture control during retail distribution is an important factor in maintaining the physical, chemical, and sensory qualities of products (Zakaria et al., 2025).

Molds and Yeasts

Microbiological testing results showed that the number of molds and yeasts remained constant (10 CFU/g) from day 0 to day 30 at all temperatures (35, 40, and 45 °C), indicating that the combination of low moisture content and aw < 0.70 is effective in suppressing microbial activity (Nirwana et al., 2022). This stability indicates that the microbiological safety of the product is highly dependent on the internal moisture conditions and packaging integrity.

However, during storage, the potential for cross-contamination may arise due to mechanical damage to the packaging, water vapor condensation, or consumer handling after opening the product (Atencio et al., 2022). Therefore, the application of *hurdle technology* through humidity, temperature, and packaging type control is recommended as a strategy to extend the shelf life without adding synthetic preservatives (Haouet et al., 2018; Hadi et al., 2022).

Based on microbiological safety, pumpkin bars are safe to store for more than 30 days, as long as there is no increase in aw due to packaging damage or humid conditions. However, the application of hurdle technology combining humidity control, low temperature, and active packaging is recommended to extend the shelf life without synthetic preservatives.

Conclusion

The study concluded by estimating the shelf life of pumpkin bars using the Accelerated Shelf Life Test (ASLT) method with the Arrhenius approach and aluminum foil packaging, showing that product quality can be maintained well during storage, and that changes in quality are mainly influenced by moisture content and sensory characteristics. Thus, controlling the humidity and storage temperature are key factors in maintaining the shelf life of pumpkin bars.

In practice, storage at a stable room temperature and low humidity is recommended to minimize the rate of water vapor absorption. The use of aluminum foil packaging with a high water vapor barrier has proven effective and should be maintained. For further research, it is recommended to explore active packaging technologies, such as the use of oxygen scavengers and moisture absorbers in packaging. The effectiveness of this method should be evaluated using more specific and measurable quality parameters, such as peroxide value measurement for fat oxidation, texture analysis (hardness) using a Texture Analyzer, and monitoring of microbiological growth to validate a more comprehensive shelf life extension strategy.

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