Vol. 25, No. 2(2026) Cat26748

Revista Mexicana de Ingeniería Química

Shelf-life prediction and degradation kinetics of bioactive compounds in biscuits fortified with *Ehretia asperula* leaf powder under different packaging materials

Predicción de la vida útil y cinética de degradación de los compuestos bioactivos en galletas fortificadas con polvo de hojas de *Ehretia asperula* bajo diferentes materiales de envasado

U.N. Le[1], M. V. Kieu[1], T. D. Luu[2], N. M. P. Nguyen[1], T. T. Chau[1], T. T. N. Do[3], C. N. Tran[1]*

[1]Institute of Food and Biotechnology, Can Tho University, Can Tho City, Viet Nam.

[2]College of Agriculture, Can Tho University, Can Tho City, Viet Nam.

[3]Can Tho University of Technology, Can Tho City, Viet Nam.

Received: December 31, 2025; Accepted: March 16, 2026

Abstract

Biscuits were developed by supplementing *E. asperula* leaf powder and were packaged in three different materials: paper laminate (PAPER/PET/PE), aluminum laminate (Al/PET/PE), and polypropylene (PP). The study was conducted to investigate changes in biscuit quality during storage through various parameters, which were moisture content, water activity (a_w), hardness, color values (L* and a*), total polyphenol content (TPC), total flavonoid content (TFC), and total counts of aerobic microorganisms (AMBC) and yeasts/molds (YMC). Results showed that the texture of the biscuits deteriorated rapidly after 8 weeks of storage in all packaging types. In particular, it was indicated that moisture increased (1.66-2.81 times) and hardness decreased (1.67-2.18 times). However, although a_w varied notably (0.4852-0.6328), the reached levels permissive for microbial growth (>0.60), the product consistently maintained low microbial counts (<10 CFU/g) throughout storage. It was suggested that other inhibitory factors played a dominant role in microbial control. Meanwhile, the degradation of TPC and L* in the biscuits followed a biphasic kinetic model, while TFC and a* followed a first-order kinetic model (R^2>0.95). The estimated shelf-life indicated that biscuits packed in Al/PET/PE maintained better quality than those packed in PAPER/PET/PE and PP. Therefore, Al/PET/PE packaging appears to be the most effective material for maintaining the quality of biscuits supplemented with *E. asperula* leaf powder during storage.

Keywords: Biscuits, degradation kinetics, *Ehretia asperula*, packaging and storage.

Resumen

Se desarrollaron galletas suplementadas con polvo de hojas de *E. asperula* y se envasaron en tres materiales diferentes: laminado de papel (PAPER/PET/PE), laminado de aluminio (Al/PET/PE) y polipropileno (PP). El estudio monitoreó los cambios en la calidad de las galletas durante el almacenamiento mediante varios parámetros, incluyendo el contenido de humedad, la actividad de agua (aw), la dureza, los valores de color (L* b^* a*), el contenido total de polifenoles (TPC), el contenido total de flavonoides (TFC) y los recuentos totales de microorganismos aeróbicos mesófilos (AMBC) y de levaduras/hongos (YMC). Los resultados mostraron que la textura de las galletas se deterioró rápidamente después de 8 semanas de almacenamiento en todos los tipos de envase. En particular, se indicó que la humedad aumentó (1.66-2.81 veces) y la dureza disminuyó (1.67-2.18 veces). Sin embargo, aunque el aw varió notablemente (0.4852-0.6328) y alcanzó niveles permisivos para el crecimiento microbiano (>0.60), el producto mantuvo consistentemente bajos recuentos microbianos (<10 UFC/g) durante todo el almacenamiento. Se sugirió que otros factores inhibitorios desempeñaron un papel dominante en el control microbiano. Mientras tanto, la degradación del TPC y de L* en las galletas siguió un modelo cinético bifásico, mientras que el TFC y a* siguieron un modelo cinético de primer orden (R^2>0,95). La vida útil estimada indicó que las galletas envasadas en Al/PET/PE mantuvieron una mejor calidad que las envasadas en PAPER/PET/PE y PP. Por lo tanto, el envase Al/PET/PE parece ser el material más eficaz para mantener la calidad de las galletas suplementadas con polvo de hojas de *E. asperula* durante el almacenamiento.

Palabras clave: galletas, cinética de degradación, *Ehretia asperula*, empaque y almacenamiento.

*Corresponding author. E-mail: tcnhan@ctu.edu.vn ;

https://doi.org/10.24275/rmiq/Cat26748

ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Biscuits are among the most widely consumed snack foods, produced in almost all countries worldwide, with the United Kingdom recognized as a pioneer in the industrialization of the biscuit manufacturing sector (Manley, 2011). Biscuits are high in calories and are favored by consumers for their pleasant flavor and convenience. The quality attributes of biscuits are sensitive to moisture, oxygen, and microorganisms in the environment; therefore, they are prone to changes during storage, which significantly affect their sensory properties and usability (Manley, 2011). Accordingly, Pasqualone *et al*. (2014) reported a significant reduction in phenolic content during storage of grape-pomace-enriched biscuits. The hardness of biscuits made from germinated Chenopodium album flour also decreased significantly over storage time in both packaging types, namely low-density polyethylene (LDPE) and metalized polypropylene (MET-PPE) (Jan & Singh, 2017). Previously, Tran *et al*. (2025) investigated the formulation and baking conditions to develop biscuits supplemented with powder from *E. asperula* leaves, which are rich in TPC=2.65±0.07 mg GAE/g and TFC=1.72±0.12 mg QE/g. The study indicated that the product has high commercial potential; however, changes in biscuit quality during storage were not evaluated. Meanwhile, *E. asperula* leaves are traditionally used in Vietnam as a medicinal herb to treat the following related deseases as gastritis, hepatitis, cirrhosis, and cancer. In addition, the leaves can serve as a substitute for synthetic antioxidants, helping to prevent lipid oxidation and enhance the storage stability of biscuits (Tran *et al*., 2023).

In the market, it is also necessary to investigate appropriate packaging materials and estimate the product's shelf life to maintain quality attributes and minimize external impacts besides the finding the optimal conditions of processing (Robertson, 2017; Singh *et al*., 2025). Up to now, various new packaging materials have been developed, including plastic films, aluminum foil, biodegradable polymers, and nanocomposites (Deshwal & Panjagari, 2019). Although these packaging types differ, they are all based on specific base materials possessing characteristic properties for preserving different products. For example, packaging made from metal-based materials can prevent moisture absorption and oxidation; therefore, the shelf life of biscuits can be extended (Deshwal & Panjagari, 2019). At the same time, estimating the storage duration and quality deterioration of biscuits under different packaging materials and environmental conditions is highly important. In fact, there are many factors affecting the storage duration of biscuits, which are temperature, equilibrium relative humidity, oxygen partial pressure, light exposure, packaging permeability, and packaging configuration (Singh *et al*., 2025).

Therefore, the application of kinetic models as computational tools to predict the quality deterioration of biscuits during storage has become a crucial research line and has demonstrated high reliability (Kumar & Mishra, 2004; Van Boekel, 2008; Dak *et al.,* 2014). Most studies indicate that the product quality degradation during storage follows first-order kinetics (Kumar & Mishra, 2004; Van Boekel, 2008; Dak *et al.,* 2014). However, the product quality deterioration may also follow different kinetic models such as Biphasic kinetics or Weibull kinetics, depending on the types of product, storage conditions, and the specific quality attributes being monitored (Verbeyst *et al.,* 2013; Kumar *et al.,* 2015). So, selecting an appropriate kinetic model can be the crucial to predict shelf life accurately and ensure product stability, as different quality parameters may deteriorate at different rates under the same storage conditions. In order to inherit and further develop the values of previous research, as well as to support the commercialization of biscuits supplemented with powder from *E. asperula* leaves, this study focuses on analyzing changes in moisture content, water activity, hardness, color, and bioactive compound content of the biscuits. In addition, kinetic analysis was applied to evaluate the changes in selected quality parameters of the biscuits under different packaging materials.

2 Materials and methods

2.1 Raw materials

E. asperula leaves were procured from March to July from Cao Thang, Luong Son, Hoa Binh, transported to the laboratory under ambient conditions on the same day, and stored in a cold room at 2-4ºC. The raw materials were required to be free of impurities, intact, undamaged, and free from pest infestation. In addition, *E. asperula* leaf powder was prepared according to the method described by Tran *et al*. (2023) and stored in Al/PET/PE packaging until use.

2.2 Sample preparation

The biscuits supplemented with *E. asperula* leaf powder formulation were 44% wheat flour, 22% sugar, 15% butter, 18% egg yolk, 0.5% salt, and 0.5% sodium bicarbonate, with 12% *E. asperula* leaf powder substituted (based on the initial weight of wheat flour) (Tran *et al.,* 2024). Firstly, sugar, butter, and egg yolk was mixed vigorously beaten to form a smooth and homogeneous emulsion. Subsequently, the flour mixture and other dry ingredients were gradually added to the emulsion and mixed until an elastic and cohesive dough was obtained. The dough was then sheeted and shaped to a fixed dimension (5 mm thickness and 5 cm diameter). The biscuits were baked at 170ºC in an oven (ATO-CRL8076, Aqua, China) for 15 minutes, and cooled to room temperature before storage.

2.3 Storage conditions

Five biscuits/bag in Al/PET/PE, PAPER/PET/PE, and PP sealed by vacuum (Boxer 42, Henkelman, Netherlands) sealer, approximately 0.5-2% residual air. Then, samples were stored at room temperature (30±2ºC and relative humidity of approximately 90%, which was measured using a digital hygrometer – LR5001, HIOKI, Japan) for 8 weeks. The samples were arranged upright on racks to ensure the same conditions. For each type of packaging, samples were randomly collected for analysis of quality parameters.

2.4 Quality evaluation

Moisture content was determined using a convection drying oven (UNB200, Memmert, Germany) by drying the samples at 105ºC to constant weight according to the AOAC method 950.46 (AOAC, 2000). Meanwhile, water activity was determined at 25 ºC using a water activity meter (TDL, Aqualab, USA).

The hardness of the biscuits, defined as the maximum penetration force, was determined using a texture analyzer (TA.XTplus, Stable Micro Systems, UK). The biscuits were placed horizontally on a flat platform and centered under a P/5S probe. The measurement conditions were set as follows: pre-test, test, and post-test speeds of 1, 2, and 10 mm/s, respectively, and a penetration distance of 5 mm (Tran *et al.*, 2024).

The color of biscuits supplemented with *E. asperula* leaf powder was determined using a handheld colorimeter (CR-410, Konica Minolta Measuring Instruments, Japan). Color was expressed in the CIELab coordinate system with the following parameters: lightness (L*: 100=white, 0=black), redness (a*: ± red–green), and yellowness (b*: ± yellow–blue). Each sample was measured in triplicate at different positions on the biscuit surface.

Extraction of bioactive compounds from *E. asperula* biscuits was conducted following Nguyet *et al.* (2019) with slight modifications. Briefly, 0.5 g of ground biscuit was homogenized in 15 mL of methanol using an Ultra-Turrax homogenizer (T 18 digital ULTRA-TURRAX®, IKA, Germany) for 45 s at 1000 rpm. The extracts were centrifuged at 3000 rpm for 15 min (DM0412, DLAB, USA). Throughout extraction, samples were kept cold (0-5ºC) on ice until analysis.

The TPC in the extracts was measured using the Folin-Ciocalteu technique described by Nguyen *et al.* (2019) with some modifications. Specifically, 1 mL of the extract was thoroughly mixed with 1 mL of water, then 0.5 mL of 10% (v/v) Folin-Ciocalteu reagent was added, and the mixture was left at room temperature for 6 minutes. Subsequently, 1.5 mL of 20% (w/v) sodium carbonate solution was added to the mixture, which was then incubated for 2 hours. The absorbance of the mixture was measured using a spectrophotometer (UV-1800, Shimadzu, Japan) at 765 nm. The result was calculated and expressed in gallic acid equivalent per gram of dry weight of sample (mg GAE/g) according to eq(1).

The TFC in extracts was measured using an aluminum chloride colorimetric method of Pham *et al.* (2020) with some modifications. 500 μL of extract or standard solution of various concentrations was mixed with 1.5 mL of methanol, 100 μL of 10% $AlCl_3$, 100 μL of 1 M CH_3COOK, and 2.8 mL of distilled water. This mixture was incubated at room temperature in the dark for 45 min before absorbance was measured against the blank at 415 nm using a spectrophotometer (UV-1800, Shimadzu, Japan). The result was calculated and expressed in quercetin equivalent per gram of dry weight of sample (mg QE/g) according to eq(1).

$$P = C \times \frac{V \times k}{M'} \tag{1}$$

Where, P is the TPC (GAE mg/g of sample) or TFC (QE mg/g of sample), C is the concentration of sample established from the calibration curve (mg/mL), V is the volume of extract (mL), M' is the weight of extract (g), and k is dilution coefficient (if any).

Microbiological analysis was performed by determining the total aerobic mesophilic count and total yeast/mold count using the plate count method on Plate Count Agar (PCA, Himedia, India) and Yeast Glucose Chloramphenicol (YGC, Merck, Germany) media, respectively. The procedures followed the Vietnamese standard TCVN 4884-1:2015 (Directorate for Standards, Metrology and Quality [DSMQ], 2015).

2.5 Modelling of quality changes

Kinetic models can be used to describe the reaction rate as a function of storage time and to predict quality changes in food products during processing and storage (Van Boekel, 2008; Kumar & Mishra, 2004). The degradation of quality attributes (such as polyphenols, vitamins, and antioxidants) is commonly described by a first-order kinetic model (Ramaswamy & Marcotte, 2006) or a Weibull model (Peleg, 2006), depending on the nonlinear behavior of the experimental data. Some studies have reported that food quality may involve two simultaneous degradation mechanisms, which can be appropriately represented by a Biphasic model (Ling & Lund, 1978; Verbeyst et al., 2013). Accordingly, this study examined the suitability of several common kinetic models (Table 1) in describing the degradation behavior of biscuits supplemented with *E. asperula* leaf powder during storage.

Table 1. Predictive kinetic modeling of food quality during storage.

No.	Model name	Equation	
1	First-order	$\frac{Q_t}{Q_o} = exp(-kt)$	(2)
2	Biphasic	$\frac{Q_t}{Q_o} = \alpha exp(-k_1 t) + (1 - \alpha) exp(-k_2 t)$	(3)
3	Weibull	$\frac{Q_t}{Q_o} = \exp\left(-\frac{t}{k}\right)^n$	(4)

Where Q_o and Q_t denote the quality parameters (L*, a*, TPC, and TFC) measured at the initial time and at different storage periods (t, weeks). The term k represents the reaction rate constant ($week^{-1}$), while k_1 and k_2 correspond to the rate constants of the first and second stages, respectively. The parameter α indicates the fraction of the fast phase, and n describes the shape of the degradation curve.

In the first-order model, the half-life ($t_{1/2}$) is the time required to degrade the initial quality by 50% at a specified temperature (eq 5). While, the decimal reduction time (D) is the time required to degrade the initial quality by 90% at a specified temperature (eq 6):

$$t_{1/2} = \frac{\ln(2)}{k} \tag{5}$$

$$D = \frac{\ln(10)}{k} \tag{6}$$

2.6 *Statistical analysis*

Nonlinear regression analysis was performed using Statgraphics Centurion software (version 19.1, Statgraphics Technologies, Inc., Virginia) to estimate the model coefficients. In the regression analysis, the best-fitting model describing storage behavior across different packaging conditions was identified using statistical indicators such as the correlation coefficient (R^2), chi-square (χ^2), and root mean square error (RMSE). A higher R^2 combined with lower χ^2 and RMSE values indicates a better agreement between the experimental observations and the predicted data of the mathematical model. Statgraphics Centurion software was also used to test the differences between treatments using analysis of variance (ANOVA) and the least significant difference (LSD) test at a 5% significance level.

3 Results and discussion

3.1 *Changes in moisture content, water activity, and hardness of E. asperula leaf powder-supplemented biscuits during storage*

The results in Figure 1a show that the moisture content of the biscuits increased linearly over 8 weeks of storage. Specifically, the biscuit moisture content gradually increased from 6.44% to 10.89% after 8 weeks, compared with the initial value of 3.70%. Similarly, Silav-Tuzlu and Tacer-Caba (2021) reported an increase in the moisture content of buckwheat-chia biscuits from 5.4% to 9.1% after 45 days of storage. Biscuits are characterized by low moisture and low water activity, which makes them highly hygroscopic; thus, they readily absorb moisture from the surrounding environment during storage (Silav-Tuzlu & Tacer-Caba, 2021). The present study also indicated that aluminum-laminated packaging (Al/PET/PE) most effectively preserved the quality of *E. asperula* leaf powder-supplemented biscuits, followed by polypropylene (PP) and paper-laminated (PAPER/PET/PE) packaging. After eight weeks, the moisture content of biscuits stored in Al/PET/PE packaging increased 1.66-fold compared with the initial value, which was lower than that stored in PP (2.46-fold) and paper-laminated (2.81-fold) packaging. In a related study, Jan and Singh (2017) found that the moisture content of millet-based biscuits increased from approximately 3.4% to 4.8% when stored in LDPE, while it remained almost unchanged over 120 days in MET-PPE packaging. These findings suggest that the rate of moisture uptake in biscuits strongly depends on the type of packaging material and its barrier properties (Robertson, 2017; Singh *et al.*, 2025). Similarly, a_w increased during storage (Figure 1b). However, the fluctuation was not consistent: during the first two weeks, a_w slightly decreased, then gradually increased and became unstable from week 3 onward. A comparable trend was observed by Jan and Singh (2017), who reported that the water activity of biscuits increased from 0.58 to 0.60 after 120 days of storage.

Moisture content and a_w are two physical parameters that are directly proportional to each other; however, they are inversely related to product hardness. The results showed that the hardness of the biscuits significantly decreased after 8 weeks of storage; hardness declined from 43.36±0.07 N to 19.87±1.16 N for paper-based packaging, 22.11±1.03 N for PP, and 26.02±0.43 N (Figure 1c). The most pronounced reduction was observed in paper-based packaging (53.35%), followed by PP packaging (47.96%), while aluminum-based packaging exhibited

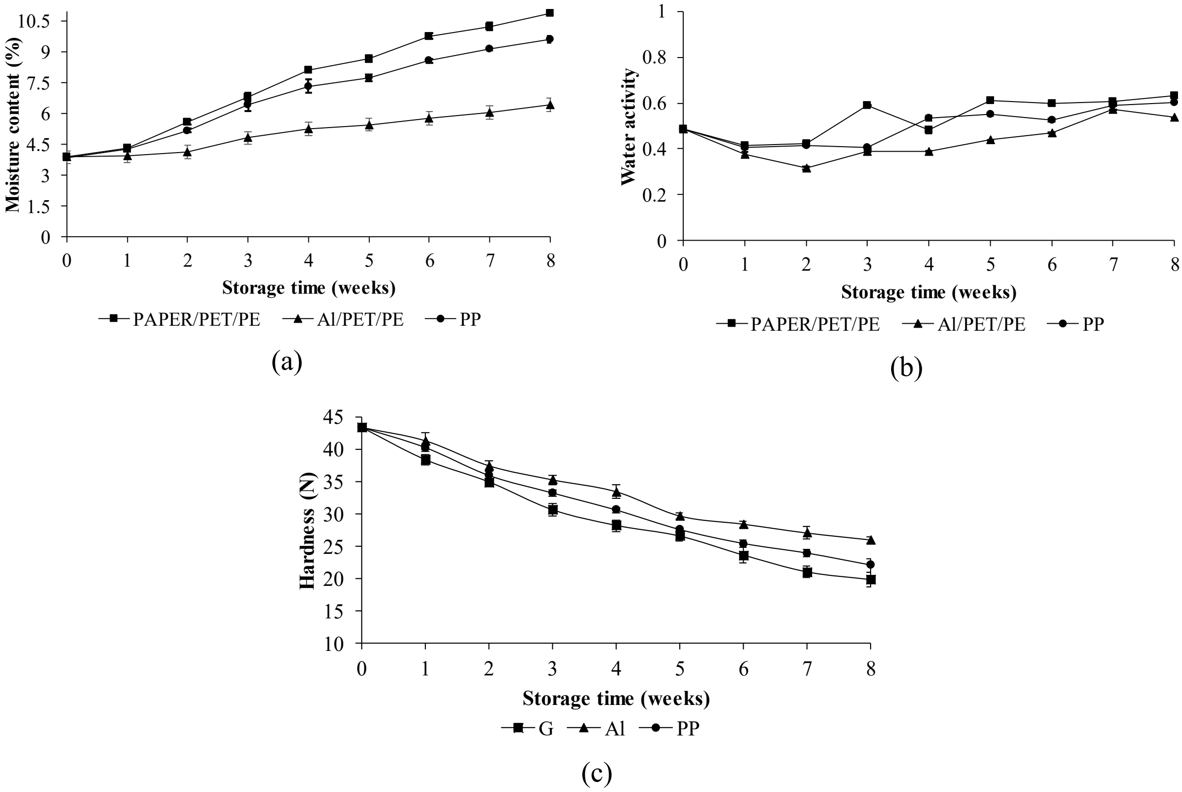

Figure 1. Changes in moisture content (a), water activity (b), and hardness (c) of *E. asperula* leaf powder-supplemented biscuits during storage in different types of packaging. *Data are presented as mean ± standard deviation, n = 3.*

Table 2. Changes in L* and a* values of *E. asperula* leaf powder-supplemented biscuits stored in different types of packaging over time.

	Time (weeks)	PAPER/PET/PE	Al/PET/PE	PP
L*	0			46.68±0.38^{a}
	1	45.76±0.21^{b}	46.36±0.31^{ab}	46.19±0.16^{b}
	2	45.38±0.12^{c}	46.16±0.34^{b}	45.84±0.37^{b}
	3	44.46±0.03^{d}	45.53±0.16^{c}	44.64±0.10^{c}
	4	43.88±0.07^{e}	44.48±0.24^{d}	44.14±0.42^{d}
	5	43.53±0.05^{f}	44.18±0.21^{d}	43.85±0.13^{d}
	6	43.01±0.04^{g}	43.80±0.17^{e}	43.23±0.19^{e}
	7	42.82±0.03^{g}	43.60±0.16^{ef}	42.93±0.09^{ef}
	8	42.50±0.14^{h}	43.33±0.13^{g}	42.79±0.17^{f}
a*	0			-6.22±0.19^{i}
	1	-5.41±0.02^{h}	-6.05±0.10^{f}	-5.63±0.09^{h}
	2	-4.68±0.07^{g}	-5.66±0.14^{f}	-4.82±0.09^{g}
	3	-3.77±0.04^{f}	-5.05±0.24^{e}	-4.18±0.09^{f}
	4	-3.19±0.07^{e}	-4.46±0.10^{d}	-3.38±0.28^{e}
	5	-2.81±0.13^{d}	-3.91±0.13^{c}	-2.88±0.15^{d}
	6	-2.27±0.08^{c}	-3.6±0.19^{b}	-2.42±0.16^{c}
	7	-1.93±0.11^{b}	-3.50±0.11^{a}	-2.12±0.21^{b}
	8	-1.48±0.12^{a}	-3.38±0.07^{a}	-1.81±0.11^{a}

Data are presented as mean ± standard deviation, n = 3; different letters within the same column (a, b, c, ...) indicate statistically significant differences among treatments at $p < 0.05$.

the best retention, with a decrease of 38.76% compared to the initial week (43.36±0.07 N). Similar results were reported according to Jan and Singh (2017), which were a significant decrease in biscuit hardness during storage in both packaging types (LDPE and MET-PPE), with a greater reduction in LDPE due to its higher moisture absorption capacity.

3.2 *Changes in color (L* and a*) of E. asperula leaf powder-supplemented biscuits during storage*

L* and a* values are crucial parameters determining the lightness and greenish hue of *E. asperula* leaf powder-supplemented biscuits. Table 1 shows that the lightness (L*) of the biscuits decreased across all three packaging types. Similarly, the brightness of the biscuits decreased from 36.60±2.60 to 24.50±0.30 when stored in LDPE and to 34.78±0.50 in MET-PPE (Jan & Singh, 2017). In this study, the L* value of *E. asperula* biscuits was 46.68±0.38. After 8 weeks, the L* of biscuits stored in Al/PET/PE (43.33±0.13) maintained the brightness better than the PAPER/PET/PE and PP packaging (42.50±0.14 and 42.79±0.17, respectively). In addition, the a* value representing the characteristic blue pigment of the biscuits showed an increase, indicating a decrease in blue color intensity (Table 1). PAPER/PET/PE and PP packaging showed a significant decrease in a* values during the first few weeks of storage, and after 8 weeks, the a* values were -1.48±0.12 and -1.81±0.11, respectively, compared to -6.22±0.19 at week 0. This change is attributed to biochemical reactions occurring within the product during storage, primarily oxidative browning and storage-induced non-enzymatic reactions, which decrease brightness and alter the color. As a result, the biscuits gradually turned brown due to the formation of reaction products (Rai & Chauhan, 2008), thereby reducing L* and increasing a* values.

3.3 *Changes in TPC and TFC of E. asperula leaf powder-supplemented biscuits during storage*

The results in Table 3 show that both TPC and TFC decreased significantly over the storage period. Specifically, TPC and TFC decreased by 2.46-3.47 times and 4.56-7.22 times, respectively - a trend also reported in several previous studies. TPC of burger meat decreased significantly after 14 days of storage (from 45.34-75.03 mg gallic acid/100 g meat to 24.37-49.47 mg gallic acid/100 g meat) (Akcan *et al*., 2023). Pasqualone *et al*. (2014) observed a similar loss of phenolic compounds in grape pomace-enriched biscuits during storage. Furthermore, different packaging materials exhibited varying effects on the stability of bioactive compounds in the biscuits.

Table 3. Changes in TPC and TFC of *E. asperula* leaf powder-supplemented biscuits stored in different types of packaging over time.

	Time (weeks)	PAPER/PET/PE	Al/PET/PE	PP
TPC (mg GAE/g)	0			2.88 ± 0.27^{a}
	1	2.51 ± 0.04^{a}	2.40 ± 0.01^{b}	2.31 ± 0.01^{b}
	2	2.01 ± 0.01^{b}	2.17 ± 0.05^{bc}	2.13 ± 0.15^{bc}
	3	1.54 ± 0.07^{c}	2.04 ± 0.06^{c}	1.98 ± 0.12^{c}
	4	1.42 ± 0.06^{cd}	1.65 ± 0.07^{d}	1.57 ± 0.04^{d}
	5	1.25 ± 0.01^{cd}	1.56 ± 0.02^{de}	1.55 ± 0.06^{d}
	6	1.13 ± 0.01^{de}	1.44 ± 0.05^{def}	1.42 ± 0.02^{de}
	7	0.95 ± 0.03^{ef}	1.29 ± 0.05^{ef}	1.23 ± 0.04^{ef}
	8	0.83 ± 0.03^{f}	1.17 ± 0.02^{f}	1.08 ± 0.01^{f}
TFC (mg QE/g)	0			2.6 ± 0.10^{a}
	1	2.04 ± 0.04^{b}	2.12 ± 0.15^{b}	2.06 ± 0.06^{b}
	2	1.60 ± 0.06^{c}	1.88 ± 0.06^{c}	1.79 ± 0.01^{c}
	3	1.45 ± 0.04^{c}	1.67 ± 0.03^{d}	1.34 ± 0.08^{d}
	4	0.87 ± 0.07^{d}	0.88 ± 0.05^{e}	0.89 ± 0.03^{e}
	5	0.63 ± 0.08^{e}	0.75 ± 0.03^{ef}	0.78 ± 0.04^{ef}
	6	0.53 ± 0.06^{ef}	0.68 ± 0.03^{ef}	0.68 ± 0.02^{fg}
	7	0.49 ± 0.10^{ef}	0.63 ± 0.14^{f}	0.58 ± 0.04^{gh}
	8	0.36 ± 0.09^{f}	0.57 ± 0.04^{f}	0.45 ± 0.03^{h}

Data are presented as mean ± standard deviation, n = 3; different letters within the same column (a, b, c, ...) indicate statistically significant differences among treatments at $p<0.05$.

Table 4. Total aerobic mesophilic bacterial count (AMBC) and total yeast and mold count (YMC) of biscuits stored in different types of packaging over time.

Packaging	Parameter	Time (weeks)								
		0	1	2	3	4	5	6	7	8
PAPER/PET/PE	AMBC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10
	YMC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10
Al/PET/PE	AMBC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10
	YMC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10
PP	AMBC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10
	YMC (CFU/g)	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10	X<10

Data are presented as mean ± standard deviation, n = 3.

The aluminum-laminated packaging most effectively maintained the bioactive components, with final values of 1.17±0.02 mg GAE/g (TPC) and 0.57±0.04 mg QE/g (TFC). This was followed by PP packaging (1.08±0.01 mg GAE/g and 0.45±0.03 mg QE/g), while paper-laminated packaging showed the fastest degradation (0.83±0.03 mg GAE/g and 0.36±0.09 mg QE/g) after 8 weeks. Paper and PP films have lower gas-barrier properties, whereas aluminum film provides a high barrier to gas transmission. Consequently, gas permeation-particularly oxygen-occurs more readily through paper and PP packaging than through aluminum (Deshwal & Panjagari, 2019). The varying gas permeability and diffusion rates among packaging materials directly influence the internal quality of stored products, as oxygen exposure accelerates the degradation of phenolic compounds present in the flour (Pasqualone *et al*., 2014).

3.4 *Total aerobic mesophilic bacterial count and total yeast and mold count of biscuits supplemented with E. asperula leaf powder over time*

The results of the effect of different packaging types on the microbiological quality of *E. asperula* leaf powder-supplemented biscuits are presented in Table 4. The findings indicate that the total yeast and mold count, as well as the total aerobic mesophilic bacteria in the biscuits, monitored over 8 weeks under the same storage conditions in three types of packaging, were below the detection limit (<10 CFU/g) (Table 4). Throughout the storage period, no microbial growth was detected in the biscuit samples. These results are consistent with the Vietnamese Standard TCVN 12940:2020 for *E. asperula* leaf powder-supplemented biscuits, which specifies that the total aerobic plate count should be in the range of $5x10^5$-$5x10^6$ CFU/g, and the total yeast and mold count should be less than 150 spores/g (DSMQ, 2020). The results showed that after 8 weeks of storage, the biscuits maintained good quality at a safe level, without being contaminated by microorganisms. Overall, the microbiological quality indicators of biscuits in all three packaging types showed insignificant differences (p>0.05). Accordingly, after 8 weeks of storage, the microbial growth in the biscuits was observed to be very low (X<10 at PAPER/PET/PE, Al/PET/PE, and PP) (Table 4). However, some studies have noted an increase in the number of microorganisms during the storage of nutrient-rich products such as mango soy yogurt powder, extruded products from sprouted soybeans, and biscuits (Kumar & Mishra, 2004; Jan *et al*., 2017). Jan *et al*. (2017) showed microbial counts in extruded products and biscuits significantly increase from $1.7x10^3$ to $7.8x10^4$ CFU/g and from $2.0x10^3$ to $9.8x10^4$ CFU/g, respectively, when stored in LDPE after 120 days. Besides, Kumar and Mishra (2004) noted that multi-layered aluminum packaging inhibited the growth of microorganisms in nutrient-rich products such as mango-soy yogurt powder. Similarly, biscuits preserved in PE/AL/PP multilayer film showed slower microbial growth after 120 days, in which the total colony count increased from $1.7x10^3$ to $4.5x10^4$ CFU/g for extruded products and from $2.0x10^3$ to $6.84x10^4$ CFU/g for biscuits (Jan *et al*., 2017). This shows that packaging materials play a crucial role in maintaining the stability of microbial growth during storage, mainly due to differences in gas and water vapor permeability. Specifically, PE packaging has higher oxygen and moisture permeability than aluminum, thus accelerating the absorption of moisture and gases necessary for microbial growth (Robertson, 2017).

3.5 *Kinetics of quality changes in biscuits supplemented with E. asperula leaf powder during storage*

The suitability of the kinetic models and the kinetic parameters describing the degradation of TPC, TFC, L*, and a* was evaluated in this study (Table 5). Accordingly, all three selected models (First-order, Biphasic, and Weibull) demonstrated a high degree of goodness-of-fit, with high average correlation coefficients (R^2) and low chi-square and RMSE values (R^2>0.95, χ^2<$4.10x10^{-3}$, and RMSE<0.05). The results indicated that the Biphasic model provided the best fit for describing the degradation of TPC and L* (R^2=98.87; χ^2=1.00x10^{-3}; RMSE=0.0262 and R^2=97.80; χ^2=5.18x10^{-5}; RMSE=0.0063, respectively). Meanwhile, TPC in germinated rice during drying followed a zero-order model (R^2 ranged from 0.9833-0.9925) (Loan *et al.*, 2025). In contrast, the First-order model showed better suitability for characterizing the degradation of TFC and a* (R^2=97.65; χ^2=2.30x10^{-3}; RMSE=0.0433 and R^2=98.24; χ^2=8.30x10^{-4}; RMSE=0.0263, respectively). The Biphasic model is known to be commonly used to describe two-stage degradation behavior of compounds (or enzymes) that exhibit different decomposition rates, in which the more labile fraction is rapidly degraded while the remaining, more stable fraction breaks down more slowly (Ling & Lund, 1978; Verbeyst *et al.*, 2013). In contrast, the First-order model describes linear degradation as a function of time at a given temperature (Van Boekel, 2008). This indicates a similarity in the theoretical basis of the two models. TPC is known as the total content of phenolic compounds in *E. asperula* leaves, including flavonoids, phenolic acids, and tannins (Tran *et al.*, 2023). Different compounds in terms of structure and thermal stability present in a product lead to heterogeneous degradation via various mechanisms and rates (Vamos-Vigyázó, 1981). This results in a non-linear degradation curve of TPC, with a rapid initial decline followed by a slower decline later on (Figure 2a). In contrast, TFCs have relatively homogeneous chemical characteristics, mainly consisting of flavone or flavonol glycosides or aglycones, so they degrade linearly and follow first-order kinetics (Ramaswamy & Marcotte, 2006). Regarding color, brightness (L*) is simultaneously affected by many factors, among which the oxidation of polyphenols, chlorophyll, or other easily degradable pigments occurs abruptly in the early stages, causing the formation of brown compounds, which is the main reason for the gradual decrease in the L* value of biscuits during storage (Verbeyst *et al.*, 2013). In contrast, changes in the a* value are largely governed by the degradation of dominant red pigments, a process that generally follows first-order kinetics (Rathinasabapathi *et al.*, 2024).

Table 5. Kinetic parameters of the degradation of TPC, TFC, L*, and a* in biscuits supplemented with *E. asperula* leaf powder stored in different types of packaging.

	Models	Packaging	Model constants	R^2		χ^2		RMSE	
		PAPER/PET/PE	k=0.1679	98.3418		0.00113		0.0317	
	First-order	Al/PET/PE	k=0.1212	97.6865	97.40	0.00100	1.29 x10^{-3}	0.0299	0.0336
		PP	k=0.1288	96.1596		0.00173		0.0392	
		PAPER/PET/PE	α=0.7828; k_1=0.2418; k_2=0.0225	99.0265		0.00118		0.0281	
TPC	Biphasic	Al/PET/PE	α=0.6544; k_1=0.0659; k_2=0.3180	98.9515	98.87	0.00081	1.00 x10^{-3}	0.0233	0.0262
		PP	α=0.8784; k_1=0.1011; k_2=1.6011	98.6306		0.00101		0.0271	
		PAPER/PET/PE	k=0.6423; n=0.1078	98.3419		0.00148		0.0339	
	Weibull	Al/PET/PE	k=1.7575; n=0.2128	97.6866	97.40	0.00132	1.69 x10^{-3}	0.0319	0.0359
		PP	k=1.7033; n=0.2192	96.1596		0.00226		0.0419	
		PAPER/PET/PE	k=0.2484	98.5023		0.00155		0.0371	
	First-order	Al/PET/PE	k=0.2084	95.5838	97.65	0.00429	2.30 x10^{-3}	0.0618	0.0433
		PP	k=0.2274	98.8639		0.00107		0.0309	
		PAPER/PET/PE	α=0.6431; k_1=0.2491; k_2=0.2474	98.5023		0.00276		0.0429	
TFC	Biphasic	Al/PET/PE	α=0.5628; k_1=0.2093; k_2=0.2074	95.5838	97.65	0.00764	4.10 x10^{-3}	0.0714	0.0500
		PP	α=0.7784; k_1=0.2284; k_2=0.2236	98.8639		0.00190		0.0357	
		PAPER/PET/PE	k=0.2127; n=0.0529	98.5023		0.00202		0.0397	
	Weibull	Al/PET/PE	k=1.0785; n=0.2248	95.5838	97.65	0.00561	3.01 x10^{-3}	0.0661	0.0463
		PP	k=1.7547; n=0.3989	98.8639		0.00140		0.0330	
		PAPER/PET/PE	k= 0.0131	95.3440		5.05x10^{-5}		0.0067	
	First-order	Al/PET/PE	k= 0.0099	96.1680	96.09	3.30x10^{-5}	3.97 x10^{-5}	0.0054	0.0059
		PP	k= 0.0121	96.7553		3.55x10^{-5}		0.0056	
		PAPER/PET/PE	α=1.1002; k_1=0.0142; k_2=0.0251	95.2800		9.10x10^{-5}		0.0078	
L*	Biphasic	Al/PET/PE	α=0.0242; k_1=0.0082; k_2=0.0099	96.1680	96.43	5.87x10^{-5}	6.39 x10^{-5}	0.0063	0.0065
		PP	α=0.0845; k_1=0.1276; k_2=0.0046	97.8469		4.19x10^{-5}		0.0053	
		PAPER/PET/PE	k=4.8278; n=0.0634	95.3439		6.59x10^{-5}		0.0072	
	Weibull	Al/PET/PE	k=1.1451; n=0.0114	96.1679	96.09	4.31x10^{-5}	5.18 x10^{-5}	0.0058	0.0063
		PP	k= 3.3360; n=0.0403	96.7553		4.64x10^{-5}		0.0060	
		PAPER/PET/PE	k= 0.1651	99.5004		0.00038		0.0185	
	First-order	Al/PET/PE	k= 0.0809	96.1731	98.24	0.00142	8.30 x10^{-4}	0.0356	0.0263
		PP	k= 0.1489	99.0530		0.00069		0.0248	
		PAPER/PET/PE	α=0.6775; k_1=0.1653; k_2=0.1649	99.5004		0.00068		0.0213	
a*	Biphasic	Al/PET/PE	α=0.0078; k_1=0.0795; k_2=0.0810	96.1732	98.24	0.00253	1.48 x10^{-3}	0.0411	0.0303
		PP	α=0.6139; k_1=0.1492; k_2=0.1489	99.0534		0.00123		0.0286	
		PAPER/PET/PE	k=0.0807; n=0.0133	99.5004		0.00050		0.0197	
	Weibull	Al/PET/PE	k=0.2878; n=0.0233	96.1732	98.24	0.00186	1.09 x10^{-3}	0.0380	0.0281
		PP	k=0.1467; n=0.0219	99.0534		0.00090		0.0265	

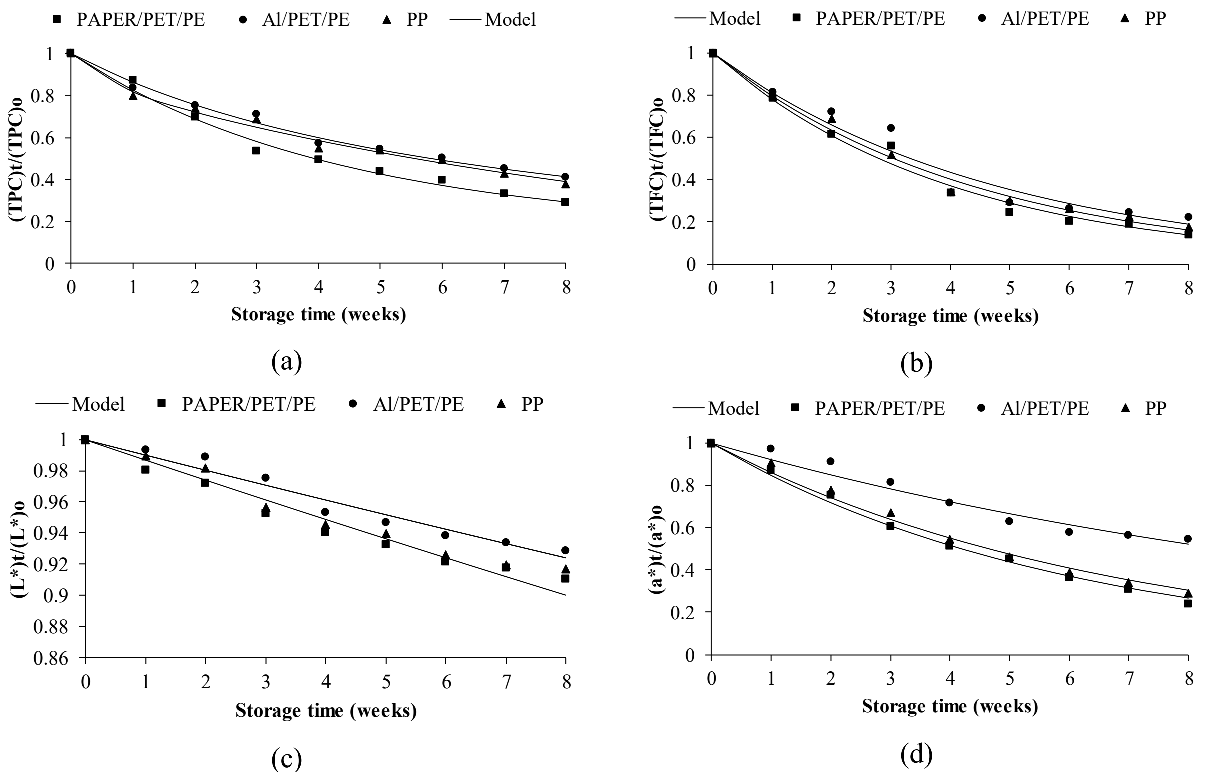

Figure 2. The degradation kinetics of TPC (a), TFC (b), L* (c), and a* (d) in biscuits supplemented with *E. asperula* leaf powder during storage in different types of packaging.

Similarly, the degradation kinetics of L* in tomato puree or the browning index in garlic have been shown to follow biphasic model model (Barreiro *et al*., 1997; Fante & Noreña, 2012). Goñi and Salvadori (2011) also demonstrated that changes in the redness of beef during roasting were well described by a biphasic model. Similarly, Verbeyst *et al*. (2013) noted that the degradation of vitamin C in strawberries and raspberries upon high heat and pressure treatment followed biphasic model. In contrast, the degradation of anthocyanins in blackcurrant juice followed a first-order model (Harbourne *et al*., 2008). Kumar and Mishra (2004) reported that color degradation of mango-soy yogurt powder during storage followed first-order kinetics. Similarly, Rathinasabapathi *et al.* (2024) demonstrated that color changes in herb-coated pear slices during storage were well described by first-order kinetic models.

The kinetic results describing TPC degradation in biscuits fortified with *E. asperula* leaf powder were best fitted by the Biphasic model, indicating that the fast phase was dominant across all three packaging types (α>0.65) (Table 5). Among them, PP packaging exhibited the highest proportion of the fast phase (α = 0.8784), reflecting that most polyphenols underwent rapid degradation during the initial stage. In contrast, Al/PET/PE showed a lower α value (0.6544), suggesting a smaller extent of initial degradation and greater stability in the early storage period. At the same time, the fast-phase reaction rate constant (k_1) of PAPER/PET/PE reached the highest value (0.2418) among the others, indicating a pronounced initial degradation rate of TPC. In contrast, Al/PET/PE obtained the lowest k_1 value (0.0659), thereby better maintaining TPC. In the slow phase, TPC degradation in Al/PET/PE (k_2=0.3180) occurred at a more considerable rate compared to PAPER/PET/PE (0.0225). Meanwhile, PP recorded a rapid slow-phase degradation process, reducing the long-term stability of polyphenols (k_2=1.6011). These trends are consistent with the experimental curves showing two distinct stages of TPC degradation (Figure 2a). The significant decrease in the initial phase may be related to the oxidation of free polyphenols. In constract, gradual degradation of bound forms or secondary oxidative reactions was mainly performed in the slow phase (Vamos-Vigyázó, 1981; Ling *et al.,* 2015). Paper-based and PP packaging possess lower barrier properties than aluminum-based packaging, particularly in terms of gas permeability (Deshwal & Panjagari, 2019). However, gases (especially oxygen) are significant factors influencing the transformation of phenolic compounds or chlorophyll present in the product (Pasqualone *et al.,* 2014). Al/PET/PE package performed the best TPC preservation capacity due to its lower initial degradation rate and greater stability throughout storage, whereas PP showed a stronger degradation trend in both the fast and slow phases

Table 6. Estimated degradation parameters of biscuits enriched with *E. asperula* leaves stored in different packaging materials.

	Packaging	TPC (mg GAE/g)	TFC (mg QE/g)	L*	a*
$t_{1/2}$ (weeks)	PAPER/PET/PE	-	2.79	-	4.2
	Al/PET/PE	-	3.33	-	8.57
	PP	-	3.05	-	4.66
D (weeks)	PAPER/PET/PE	-	9.27	-	13.95
	Al/PET/PE	-	11.05	-	28.46
	PP	-	10.13	-	15.46

(-): Not determined

The degradation kinetics of L* based on a two-phase model showed that the L* of biscuits in PAPER/PET/PE degraded rapidly in the early stages of storage (α=0.9032 and k_1=0.1833). In contrast, Al/PET/PE showed a slow and stable decrease in L* (α=0.0242, k_1=0.0082 and k_2=0.0099). Furthermore, the k_2 value of Al/PET/PE is approximately equal to k_1, confirming that the degradation process is slow and stable. Meanwhile, the L* of biscuits in PP also showed a more stable decline compared to PAPER/PET/PE, however, it was less stable than Al/PET/PE (α=0.0845, k_1=0.1276) (Table 5). The study results showed that the brightness (L*) of biscuits supplemented with *E. asperula* leaf powder was most stable when stored in Al/PET/PE packaging, followed by PP, while PAPER/PET/PE packaging yielded the least stable results. Packaging materials significantly influence the oxidation of polyphenols, chlorophyll, and other biodegradable pigments, leading to the formation of darkening compounds. Therefore, the L* value of biscuits over storage time was decreased (Verbeyst *et al.*, 2013; Pasqualone *et al.*, 2014). In addition, the degradation of TFC and a* in *E. asperula* biscuits stored in Al/PET/PE packaging was slower than in PAPER/PET/PE and PP packaging. TFC and a* recorded the lowest k values when stored in aluminum (Al/PET/PE) packaging (0.2084 and 0.0809, respectively) (Table 4). Al/PET/PE packaging had superior barrier properties, effectively limiting oxidation and flavonoid degradation, while stabilizing chlorophyll and polyphenol pigments. These changes were mainly observed in the a* value (Ramaswamy & Marcotte, 2006; Patras *et al.*, 2010; Deshwal & Panjagari, 2019). Conversely, PAPER/PET/PE and PP both showed poor barrier properties, accelerated oxidation, and led to faster degradation of TFC and a* (Deshwal & Panjagari, 2019). In addition, the first-order model allowed estimation of the 50% ($t_{1/2}$) and 90% (D) quality degradation of biscuits in the three types of packaging. The kinetic results showed that biscuits supplemented with *E. asperula* leaf powder packaged in Al/PET/PE packaging maintained the TFC and a* values effectively ($t_{1/2}$=3.33; D=11.05 weeks and $t_{1/2}$=8.58; D=28.46 weeks, respectively) (Table 6). Similarly, Dak *et al.* (2014) found that the shelf life of dried pomegranate seeds stored in aluminum (ALP) packaging reached 187 days, almost double that of HDPP packaging (96 days). In general, Al/PET/PE packaging is suitable for preserving biscuits supplemented with *E. asperula* leaf powder to maintain the biological activity and sensory characteristics of the biscuits, thereby extending their shelf life.

Conclusions

Changes in the quality parameters of biscuits supplemented with *E. asperula* leaf powder were significantly influenced by the type of storage packaging. Parameters such as moisture content, aw, hardness, color, TPC, TFC, total microbial count, and total yeast and mold count showed significant changes during storage. Accordingly, the results indicated that moisture content and a_w increased significantly, while the other parameters tended to decrease. Meanwhile, total aerobic microorganisms and total yeast and mold counts remained below the detection limit throughout storage. Kinetic results indicated that the degradation of TPC and L* followed the Biphasic model, whereas TFC and a* followed first-order kinetics. In addition, the estimated times for 50% and 90% reduction of TFC and a* in biscuits packaged in Al/PET/PE were better maintained compared to the other two packaging types. Thus, Al/PET/PE demonstrated superior protective effectiveness, maintaining biscuit quality more effectively throughout storage compared to PAPER/PET/PE and PP. However, the study was limited in evaluating quality changes of *E. asperula* biscuits under different storage temperatures to predict a more specific shelf life of biscuits supplemented with *E. asperula* leaf powder.

Acknowledgements

This study was funded by Can Tho University under the project code T2024-129.

References

Akcan, T., Özünlü, O., Ergezer, H., & Gökçe, R. (2023). Exploring the impact of acorn extract on the quality and taste of beef meat burgers. *Revista Mexicana de Ingeniería Química, 23*(1), Alim2311. https://rmiq.org/iqfvp/Numbers/V22/No2/Alim2311.pdf

AOAC. (2000). *Official methods of analysis of AOAC International (17th ed.)*. Gaithersburg, MD, USA: AOAC International.

Barreiro, J. A., Milano, M., & Sandoval, A. J. (1997). Kinetics of colour change of double concentrated tomato paste during thermal treatment. *Journal of Food Engineering, 33*(3–4), 359–371.

Dak, M., Sagar, V. R., & Jha, S. K. (2014). Shelf-life and kinetics of quality change of dried pomegranate arils in flexible packaging. *Food Packaging and Shelf Life*, 2(1), 1-6. https://doi.org/10.1016/j.fpsl.2014.04.005

Deshwal, G. K., & Panjagari, N. R. (2019). Review on metal packaging: materials, forms, food applications, safety and recyclability. *Journal of Food Science and Technology, 57*(7), 2377-2392. https://doi.org/10.1007/s13197-019-04172-z

Directorate for Standards, Metrology and Quality. (2015). TCVN 4884-1:2015. *Microbiology of food and animal feeding stuffs - Horizontal method for the enumeration of microorganisms - Part 1: Colony count at 30°C by the pour plate technique*. Hanoi, Vietnam: Science and Technics Publishing House. *(In Vietnamese)*.

Directorate for Standards, Metrology and Quality. (2020). TCVN 12940:2020. *Baked mooncake*. Hanoi, Vietnam: Ministry of Science and Technology. *(In Vietnamese)*.

Fante, L., & Noreña, C. P. Z. (2012). Enzyme inactivation kinetics and colour changes in Garlic (*Allium sativum* L.) blanched under different conditions. *Journal of Food Engineering,108*(3), 436-443.

Goñi, S. M., & Salvadori, V. O. (2011). Kinetic modelling of colour changes during beef roasting. *Procedia Food Science,* 1, 1039-1044.

Harbourne, N., Jacquier, J. C., Morgan, D. J., & Lyng, J. G. (2008). Determination of the degradation kinetics of anthocyanins in a model juice system using isothermal and non-isothermal methods. *Food Chemistry, 111*(1), 204-208.

Jan, R., Saxena, D. C., & Singh, S. (2017). Effect of storage conditions and packaging materials on the quality attributes of gluten-free extrudates and cookies made from germinated chenopodium (*Chenopodium album*) flour. *Journal of Food Measurement and Characterization, 11*(3), 1071-1080. https://doi.org/10.1007/s11694-017-9484-7

Kumar, P., & Mishra, H. N. (2004). Storage stability of mango soy fortified yoghurt powder in two different packaging materials: HDPP and ALP. *Journal of Food Engineering, 65*(4), 569-576. https://doi.org/10.1016/j.jfoodeng.2004.02.022

Ling, A. C., & Lund, D. B. (1978). Determining kinetic parameters for thermal inactivation of heat-resistant and heat-labile isozymes from thermal destruction curves. *Journal of Food Science, 43*(4), 1307–1310. https://doi.org/10.1111/j.1365-2621.1978.tb15295.x

Loan, L. T. K., Tat, T. Q., Minh, P. D. T., Thao, V. T. T., Hoang, P. T. M., Nhi, T. T. Y., & Tai, N. V. (2025). Modeling of dehydration, polyphenol thermal degradation, and rehydration of instant germinated VD20 rice: Mathematical and artificial intelligence model. *Revista Mexicana de Ingeniería Química, 24*(1), Alim24400. https://doi.org/10.24275/rmiq/Alim24400

Manley, D. J. R. (2011). *Manley's technology of biscuits, crackers and cookies (4th ed.)*. Cambridge, UK: Woodhead Publishing. https://doi.org/10.1533/9780857093646

Nguyen, N. M. P., Le, T. T., Vissenaekens, H., Gonzales, G. B., Van Camp, J., Smagghe, G., & Raes, K. (2019). In vitro antioxidant activity and phenolic profiles of tropical fruit by-products. *International Journal of Food Science and Technology, 54*(4), 1169-1178 https://doi.org/10.1111/ijfs.14093

Pasqualone, A., Bianco, A. M., Paradiso, V. M., Summo, C., Gambacorta, G., & Caponio, F. (2014). Physico-chemical, sensory and volatile profiles of biscuits enriched with grape marc extract. *Food Research International, 65*, 385-393. https://doi.org/10.1016/j.foodres.2014.07.014

Pham, D. C., Nguyen, H. C., Le, N. T. H., Ho, H. L., Trinh, T. K., Riyaphan, J.,

& Weng, C. F. (2020). Optimization of ultrasound-assisted extraction of flavonoids from *Celastrus hindsii* leaves using response surface methodology and evaluation of their antioxidant and antitumor activities. *BioMed Research International*, 2020, 1-9. https://doi.org/10.1155/2020/3497107

Rai, S., & Chauhan, A. S. (2008). Quality attributes of drum-dried papaya-cereal flakes developed from ripe papaya (*Carica papaya* L.). *Electronic Journal of Environmental, Agricultural and Food Chemistry*, 7(5), 2914-2931.

Rathinasabapathi, S., Rasane, P., Singh, A., Singh, J., Kaur, S., Nanda, V., Kaur, J., Gunjal, M., Bhadariya, V., Ercisli, S., Ullah, R., & Ali, E. A. (2024). Image analysis-based discoloration rate quantification and kinetic modeling for shelf-life prediction in herb-coated pear slices. *Scientific Reports*, 14, 1647. https://doi.org/10.1038/s41598-024-51840-y

Robertson, G. L. (2017). *Food packaging: Principles and practice (3rd ed.).* CRC Press.

Silav-Tuzlu, G., & Tacer-Caba, Z. (2021). Influence of chia seed, buckwheat and chestnut flour addition on the overall quality and shelf life of the gluten-free biscuits. *Food Technology and Biotechnology, 59*(4), 463-474. https://doi.org/10.17113/ftb.59.04.21.7204

Singh, V. K., Verma, S., Chaudhary, V., & Shahi, N. C. (2025). Impact of packaging materials and storage conditions on the shelf life and quality of biscuits. *International Journal of Food Science and Nutrition*, 10(2), 9-11.

Tran Chi Nhan, Le Ngoc Tuyen, Tran Thi Cam Hong, Tran Trong Nguyen Luu Thai Danh, Do Thi Tuyet Nhung, Nguyen Nhat Minh Phuong (2023). Surveying the effect of drying methods on the quality of *Ehretia asperula* Zoll. & Mor. leaf powder. *Journal of Agriculture and Environment*, 2(6), 273-280.

Tran Chi Nhan, Le Uyen Nhi, Kieu Minh Vuong, Nguyen Tuan Anh, Luu Thai Danh, Nguyen Nhat Minh Phuong, Chau Thanh Tuan (2024). Research on the development of biscuits supplemented with *Ehretia asperula* Zoll. & Mor. leaf powder. *Journal of Agriculture and Environment, 2*(12), 120-128.

Van Boekel, M. A. (2008). Kinetic modeling of food quality: A critical review. *Comprehensive Reviews in Food Science and Food Safety, 7*(1), 144-158. https://doi.org/10.1111/j.1541-4337.2007.00036.x

Verbeyst, L., Bogaerts, R., Van der Plancken, I., Hendrickx, M., & Van Loey, A. (2013). Modelling of vitamin C degradation during thermal and high-pressure treatments of red fruit. *Food and Bioprocess Technology, 6*(4), 1015-1023