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PACKAGING BARRIER EFFECTS ON PHYSICOCHEMICAL STABILITY AND COLOR CHANGES OF FLAVORED YERBA MATE (*Ilex paraguariensis*) DURING STORAGE

EFEITOS DE BARREIRA DA EMBALAGEM NA ESTABILIDADE FÍSICO-QUÍMICA E MUDANÇAS DE COR NA ERVA-MATE (*Ilex paraguariensis*) AROMATIZADA DURANTE O ARMAZENAMENTO

TANIA MARIA COSTA
https://orcid.org/0000-0001-7270-3264/ tmcosta@furb.br
Regional University of Blumenau – FURB, Blumenau, Santa Catarina, Brazil

ARTHUR PATZLAFF
https://orcid.org/0009-0005-0503-6904/ arthurp@furb.br
Regional University of Blumenau – FURB, Blumenau, Santa Catarina, Brazil

MEIRYEL LOPES DA SILVA
meiryels@furb.br
Regional University of Blumenau – FURB, Blumenau, Santa Catarina, Brazil

MARCELA KOTSUKA DA SILVA
https://orcid.org/0000-0002-7684-3093/ marcelakotsuka@furb.br
Regional University of Blumenau – FURB, Blumenau, Santa Catarina, Brazil

CAROLINA KREBS DE SOUZA
https://orcid.org/0000-0003-1340-5085/ carolinakrebs@furb.br
Regional University of Blumenau – FURB, Blumenau, Santa Catarina, Brazil

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ABSTRACT

Yerba mate (*Ilex paraguariensis*) tea is one of the most consumed beverages in South America. Environmental conditions and packaging barrier properties strongly influence the quality of stored yerba mate, but despite its commercial importance, few studies have evaluated the effects of packaging systems on the stability of artificially flavored yerba mate. Therefore, this study investigates the influence of different packaging materials (such as transparent polyethylene plastic, stand-up pouches, glass jars, and plastic combined with metal cans) on the physicochemical properties and color stability of mint-flavored yerba mate during storage. Yerba mate leaves were flavored with mint flavoring (3% w/w) and stored for 62 days under environmental conditions simulating commercial storage. Moisture content, pH, water activity (aw), and color parameters (L*, a*, b*, chroma, and total color difference ΔE) were evaluated at 0, 30, and 62 days. The results showed a gradual

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CAROLINA KREBS DE SOUZA

increase in pH and significant variations in water activity (Aw) during storage, with plastic packaging exhibiting higher Aw values than the other systems. Color analysis revealed a decrease in luminosity (L*) and shifts in chromatic coordinates (a* and b*), suggesting pigment degradation and oxidative reactions during storage. Among the evaluated systems, a stand-up pouch combined with a metal can showed the least significant loss of yerba mate's green and yellow color. These results highlight the importance of selecting packaging materials with improved barrier properties to preserve the physicochemical quality of flavored yerba mate during storage.

Keywords: color stability; *Ilex paraguariensis*; packaging materials; storage stability; water activity.

RESUMO

O chá de erva-mate (*Ilex paraguariensis*) é uma das bebidas mais consumidas na América do Sul. As condições ambientais e as propriedades de barreira da embalagem influenciam fortemente sua qualidade durante o armazenamento, mas, apesar de sua importância comercial, poucos estudos avaliaram o efeito dos sistemas de embalagem na estabilidade da erva-mate aromatizada artificialmente. Portanto, este estudo investiga a influência de diferentes materiais de embalagem (como plástico de polietileno transparente, embalagens flexíveis, potes de vidro e latas de plástico com metal) nas propriedades físico-químicas e na estabilidade da cor da erva-mate aromatizada com menta durante o armazenamento. Folhas de erva-mate foram aromatizadas com menta (3% p/p) e armazenadas por 62 dias em condições ambientais que simulam o armazenamento comercial. O teor de umidade, o pH, a atividade da água (aw) e os parâmetros de cor (L*, a*, b*, croma e diferença total de cor ΔE) foram avaliados nos dias 0, 30 e 62. Os resultados mostraram um aumento gradual no pH e variações significativas na atividade da água (Aw) durante o armazenamento, com a embalagem plástica apresentando valores de Aw mais elevados do que os demais sistemas. A análise de cor revelou uma diminuição na luminosidade (L*) e alterações nas coordenadas cromáticas (a* e b*), sugerindo degradação do pigmento e reações oxidativas durante o armazenamento. Dentre os sistemas avaliados, a embalagem tipo pouch combinada com uma lata metálica apresentou a menor perda da cor verde e amarela da erva-mate. Esses resultados destacam a importância da seleção de materiais de embalagem com propriedades de barreira aprimoradas para preservar a qualidade físico-química da erva-mate aromatizada durante o armazenamento.

Palavras-chave: atividade da água; estabilidade de armazenamento; estabilidade da cor; *Ilex paraguariensis*; materiais de embalagem.

1 INTRODUCTION

Yerba mate (*Ilex paraguariensis*) is a plant native to the subtropical regions of South America, and its tea represents one of the most widely consumed traditional beverages in countries such as Brazil, Argentina, Paraguay, and Uruguay. Regional production exceeds 800,000 tons annually, highlighting its significant economic and cultural importance. The leaves are commonly prepared as *chimarrão*, *tererê*, or roasted mate tea, depending on the processing method and infusion temperature (Alves; Scheer, 2024; Cardozo *et al.*, 2021; Mueller *et al.*, 2026). In recent years, yerba mate has attracted growing interest beyond its traditional markets, driven by increasing global demand for functional beverages and plant-derived bioactive compounds.

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The chemical composition of yerba mate includes a diverse range of bioactive molecules such as polyphenols, chlorogenic acids, xanthines (caffeine and theobromine), flavonoids, and saponins. These compounds have been associated with several biological activities, including antioxidant, anti-inflammatory, antimicrobial, and neuroprotective effects, contributing to the nutritional and functional value of the beverage (Bracesco *et al.*, 2011; Ceylan *et al.*, 2023; Heck; De Mejia, 2007; Palavicini *et al.*, 2025; Prado Martin *et al.*, 2013)**.** However, the stability of these compounds and the sensory quality of yerba mate can be significantly affected by processing conditions and storage environment.

Industrial processing of yerba mate involves several steps, including harvesting, enzyme inactivation (a process known as *sapeco*), drying, aging, and grinding. Although these operations are necessary to stabilize the raw material and develop its characteristic sensory profile, they may also influence the chemical composition and quality of the final product. Aroma has a determinant influence on food quality and the acceptability of herbal teas (Lasekan; Lasekan, 2012). Aroma is used for flavor masking and enhancement, with the release, migration, and perception of aroma modulated by interactions with non-volatile components (Ni *et al.*, 2026). The aroma is added to yerba mate in liquid or solid form before packaging.

Furthermore, exposure to oxygen, light, and environmental humidity during storage may accelerate oxidative reactions, pigment degradation, and loss of volatile compounds from yerba mate, leading to undesirable changes in aroma, color, and overall product quality (Alves; Scheer, 2024; Heck; De Mejia, 2007; Samponi Tucunduva Arantes *et al.*, 2026).

Packaging plays a crucial role in controlling these degradation processes by limiting mass transfer phenomena between the product and the surrounding environment. Appropriate packaging systems must provide effective barriers against oxygen, water vapor, and light to preserve both physicochemical stability and sensory characteristics during storage. Various materials have been used in food packaging applications, including polymeric materials, glass containers, multilayer laminates, and metalized structures with aluminum barriers, which can significantly improve protection against moisture and light exposure (Kumar *et al.*, 2025; Sayehi *et al.*, 2022; Zhang *et al.*, 2024; Zhu *et al.*, 2023).

Although several studies have investigated the chemical composition and health benefits of yerba mate, limited information is available on how packaging materials affect yerba mate stability during storage. The incorporation of flavoring agents introduces volatile aromatic compounds that

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may be particularly susceptible to migration, oxidation, and environmental degradation, underscoring the importance of packaging selection for maintaining product quality (Gupta *et al.*, 2024; Seref; Cufaoglu, 2025). Therefore, the present study aimed to evaluate the influence of different packaging systems, such as transparent polyethylene plastic, stand-up pouches, glass containers, and plastic combined with a metal can, on the physicochemical properties, color stability, and sensory characteristics of mint-flavored yerba mate during storage under simulated commercial conditions.

2 MATERIAL AND METHODS

2.1 Yerba mate preparation

Yerba mate leaves were purchased from a local store in Blumenau (-6.9194° S, -49.0661° W), Santa Catarina, Brazil. The samples corresponded to commercially processed dried yerba mate intended for beverage preparation, ensuring conditions representative of products available to consumers. The leaves were flavored with mint food flavoring (Duas Rodas®, Brazil) at 3% (w/w), selected to simulate the formulation typically used in commercially flavored herbal beverages. The mixture was manually homogenized until the flavoring was fully distributed visually. Thirty grams (30 g) of the flavored yerba mate were weighed and packaged in four different packaging systems (Figure 1) to evaluate the influence of packaging barrier properties on product stability during storage. The evaluated systems were: i) transparent polyethylene (PE) plastic bags (8×12 cm), sealed using a thermal sealer; ii) multilayer stand-up pouch packaging (10×17.5 cm), sealed using a thermal sealer; iii) transparent cylindrical glass jars (6 cm diameter × 9 cm height) sealed with metal screw-on lids; iv) transparent PE plastic bags (8×12 cm) placed in cylindrical metal cans (8 cm diameter×10 cm height), representing a secondary protective packaging system with improved barrier properties against light and gases. All packaging systems were prepared in duplicate for each storage time. The samples were stored under ambient laboratory conditions to simulate typical commercial small storage environments. Analyses were conducted at three storage times: Time 0 (initial condition), Time I (30 days), and Time II (62 days). The storage period was selected to represent a short-to-intermediate shelf-life period commonly encountered during commercial distribution and retail storage of dried plant products.

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Figure 1: Packaging systems evaluated: A = transparent polyethylene (PE) plastic bags; B = multilayer stand-up pouch packaging; C = transparent cylindrical glass jars; D = transparent PE plastic bags placed inside cylindrical metal cans



The authors, 2026

2.2 Physical-chemical characterization

Moisture content, pH, and water activity (aw) were determined at the three storage times. Moisture content was measured using gravimetric drying according to (AOAC, 2006) standard procedures, while water activity was determined using a calibrated water activity meter (AquaLab®, Decagon Devices, USA). For pH determination, 1 g of the yerba mate sample was dispersed in 10 mL of distilled water and homogenized prior to measurement using a calibrated digital pH meter (Costa *et al.*, 2017). All physicochemical analyses were performed in quadruplicate to ensure analytical reliability and reduce experimental variability.

2.3 Color Measurements

Color parameters of the yerba mate samples were determined using a SP60 portable sphere spectrophotometer (X-Rite®, USA) operating in the CIE L*a*b* color space system (Carvalho *et al.*, 2025). Before measurements, the instrument was calibrated using a standard white reference tile according to the manufacturer's instructions. Color coordinates were measured at three storage times (0, 30, and 62 days). The parameters obtained included L* (luminosity), which ranges from 0 (black) to 100 (white), a* (green–red axis), ranging from −60 (green) to +60 (red), and b* (blue–

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yellow axis), ranging from −60 (blue) to +60 (yellow). These parameters describe the chromatic characteristics of the samples within the CIE color space (Budin *et al.*, 2025). For each sample, two independent measurement points were collected and analyzed in duplicate, resulting in four measurements per treatment. The mean value was used to represent the color parameters. Color stability during storage was evaluated by calculating the total color difference (ΔE*) relative to the initial sample (Equation 1).

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad \text{(Eq.1)}$$

where ΔL*, Δa*, and Δb* represent variations in luminosity, green–red chromatic coordinate, and blue–yellow chromatic coordinate, respectively.

Color saturation was also evaluated by calculating chroma (C*) (Equation 2):

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad \text{(Eq.2)}$$

2.4 Statistical analysis

All experimental results were expressed as mean ± standard error of the mean. Statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate the effects of packaging systems and storage time. When significant differences were observed ($p \leq 0.05$), Tukey's multiple comparison test was applied to identify differences between treatments. All analyses were performed using Statistica® software (StatSoft Inc., USA).

3 RESULTS AND DISCUSSION

3.1 - Physical-chemical characterization

The physical-chemical characterization of yerba mate leaves showed significant differences in pH, water activity (Aw), and moisture during the 62-day storage period across the evaluated packaging systems (Table 1). Significant variations ($p \leq 0.05$) and a gradual increase in pH values were observed during storage, regardless of the packaging material. This progressive increase suggests chemical transformations within the plant matrix, including the possible degradation of

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organic acids and the oxidation of phenolic compounds naturally present in yerba mate, as well as those originating from the flavoring agent.

Table 1: Values of pH, Aw, and moisture at Time 0 (initial), Time I (30 days), and Time II (62 days) storage in different packages (mean ± standard error).

Assay	Plastic	Stand Pouch	Glass	Plastic + can
		pH		
Time 0	5.94 ± 0.06^{Ba}	5.99 ± 0.02^{Ca}	5.94 ± 0.04^{Ba}	6.02 ± 0.03^{Ca}
Time I	6.01 ± 0.06^{ABa}	6.06 ± 0.02^{Ba}	6.01 ± 0.03^{ABa}	6.09 ± 0.02^{Ba}
Time II	6.09 ± 0.06^{Aa}	6.13 ±0.03^{Aa}	6.08 ± 0.03^{Aa}	6.15 ± 0.02^{Aa}
		Aw		
Time 0	0.58 ± 0.005^{Ca}	0.58 ± 0.008^{Ba}	0.58 ± 0.008^{Ba}	0.57 ± 0.008^{Ba}
Time I	0.67 ± 0.005^{Bb}	0.66± 0.009^{Aa}	0.66 ± 0.005^{Aab}	0.65 ±0.004^{Aa}
Time II	0.61 ± 0.008^{Ab}	0.58 ± 0.007^{Ba}	0.58 ± 0.004^{Ba}	0.58 ± 0.011^{Ba}
		Moisture (%)		
Time 0	10.36 ± 0.009^{Aa}	10.36± 0.008^{Aa}	10.36 ± 0.011^{Aa}	10.35 ± 0.008^{Aa}
Time I	10.36 ± 0.007^{Aa}	10.35± 0.007^{Aa}	10.35 ± 0.008^{Aa}	10.35 ± 0.006^{Aa}
Time II	6.21 ± 0.237^{Ba}	6.00 ± 0.239^{Ba}	6.10 ± 0.361^{Ba}	6.06 ± 0.609^{Ba}

Equal letters within the same column (capital letter) and parameter denote no significant differences at a 5 % significance level between times evaluated. Equal letters within the same line (lowercase letter) denote no significant differences at a 5 % significance level between packages evaluated.

Such changes have been previously reported during the aging of yerba mate, where biochemical and oxidative processes lead to the slight alkalization of the product (A. Holowaty *et al.*, 2014). The pH values obtained in this study ranged from 5.94 ± 0.06 to 6.15 ± 0.02, which are consistent with values reported in the literature for commercial yerba mate products, as the pH varies according to the type of yerba mate and the climatic season (Nunes *et al.*, 2025). Although these variations are relatively small, they may influence the stability of certain bioactive compounds and contribute to gradual sensory changes during storage.

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Water activity (Aw) values showed a significant variation ($p \leq 0.05$) during 62 days and between the evaluated packaging methods (Table 1). All Aw values remained below the critical limit for microbial proliferation (< 0.90), indicating that the product remained microbiologically stable throughout the storage period. However, intermediate Aw values may still influence chemical degradation reactions such as enzymatic browning and pigment degradation due to increased molecular mobility within the food matrix (Costa *et al.*, 2025; Karel, 1989; Tapia; Alzamora; Chirife, 2020).

The plastic packaging exhibited slightly higher Aw values (Times I and II) compared to the stand-up pouch, glass, and plastic + can systems. Although plastic offers advantages for food packaging applications, such as affordability, lightness, flexibility, and chemical and moisture resistance, materials with higher barrier properties, such as metal and multilayer packaging, can significantly reduce mass transfer phenomena and therefore contribute to improved stability of hygroscopic foods such as yerba mate (Anukiruthika *et al.*, 2020; Türksever; Koç; Kizilirmak Esmer, 2025) . Glass is highly inert and impermeable, and has been used as a food package for many years (Obayomi; Dokouhaki; Obayomi, 2026). However, its transparency may allow light penetration, which can accelerate oxidative reactions and pigment degradation in plant-based products (Thuy *et al.*, 2021). Multilayer structures, such as stand-up pouches and metallic containers, generally provide improved barrier properties against water vapor and gases (Pasquier *et al.*, 2022). However, these kinds of packaging have low thermal transfer barriers. Storage without temperature or humidity control in the laboratory showed a clear influence of these parameters on Aw properties. Temperature changes cause an increase or decrease in the kinetic energy of water molecules, as observed in the adsorption isotherms of yerba mate (Červenka; Hloušková; Žabčíková, 2015). The amount of water adsorbed in a food product depends on the presence of compounds with hydrophilic groups capable of binding water molecules via hydrogen bonds (Caurie, 1981), and temperature changes associated with climate (early autumn in time I and late autumn in time II) may have contributed to greater or reduced water adsorption, as observed in studies of adsorption isotherms (Červenka; Hloušková; Žabčíková, 2015) . Similar observations have been reported in studies evaluating the storage stability of dried plant materials and tea products packaged in polymeric and multilayer materials (Baele *et al.*, 2021; Bhattacharjee *et al.*, 2024).

The moisture of the packaged product depends on the permeability of the package and the particular properties of each food (Ramallo; Albani, 2004). The moisture content of the yerba mate

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(Table 1) was also slightly higher, but not statistically different ($p \leq 0.05$) when stored in plastic packaging, after 62 days (Time II). According to Brazilian legislation, the maximum moisture content allowed for yerba mate is 10% (ANVISA - Agência Nacional de Vigilância Sanitária, 2022). The values obtained at Time 0 and Time I were slightly above this limit, which may be due to moisture absorption of the yerba mate in its original packaging (paper packaging). The addition of flavoring agents, even at relatively low concentrations (3% w/w), can temporarily alter the hygroscopic equilibrium of plant materials, promoting water adsorption from the surrounding environment. The yerba mate aromatization process was manual and differed from the industrial process, which uses hot air to dry the flavoring. In this study, flavoring evaporation was achieved by turning the yerba mate at room temperature until it was visually dry, a common process for flavoring teas at a small scale.

After 62 days of storage, reductions in moisture were observed. However, no statistically significant difference ($p \leq 0.05$) was observed between packages (Table 1). Dry food can increase or reduce its moisture content during storage, even though package permeability remains constant (Červenka; Hloušková; Žabčíková, 2015; Ramallo; Albani, 2004). This occurs due to the equilibrium of humidity between yerba and the air inside the package (Akbar *et al.*, 2025; Červenka; Hloušková; Žabčíková, 2015).

3.2 - Color measurements

Color is an important quality attribute in yerba mate products, as consumers generally associate a bright green color with freshness and product quality. The color parameters of yerba mate stored in different packaging systems are presented in Table 2 and visualized in Figure 2. All spectrophotometric measurements were performed on homogenized samples to ensure analytical consistency.

ISSN 1983-1838
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Table 2: Values of CIE-Lab color coordinates (L*, a*, b*, C*) at Time 0 (initial), Time I (30 days), and Time II (62 days) storage in different packages (mean ± standard error).

Coordinator	Plastic	Stand Pouch	Glass	Plastic + can
		Time 0		
L*	33.43 ± 1.48^{Aa}	33.43 ± 1.48^{Aa}	33.43 ± 1.48^{Aa}	33.43 ± 1.48^{Aa}
a*	-0.08 ± 0.21^{Ca}	-0.08 ± 0.21^{Ba}	-0.08 ± 0.21^{Ba}	-0.08 ± 0.21^{Ba}
b*	18.59 ± 1.32^{aA}	18.59 ± 1.32^{Aa}	18.59 ± 1.32^{Aa}	18.59 ± 1.32^{Aa}
C*	18.60 ± 1.33^{aA}	18.60 ± 1.33^{aA}	18.60 ± 1.33^{aA}	18.60 ± 1.33^{aA}
		Time I		
L*	28.19 ± 1.33^{Cb}	23.05 ± 0.21^{Cc}	30.64 ± 1.65^{Ba}	23.39 ± 0.77^{Bc}
a*	1.78 ± 0.70^{Aa}	0.78 ± 0.11^{Ab}	1.10 ± 0.23^{Aab}	0.73 ± 0.14^{Ab}
b*	14.25 ± 0.64^{Bb}	13.96 ± 0.36^{Bb}	17.64 ± 1.05^{Aa}	14.09 ± 0.62^{Bb}
C*	14.37 ± 0.60^{Bb}	13.98 ± 0.35^{Bb}	17.68 ± 1.04^{Aa}	14.11 ± 0.63^{Bb}
ΔE	7.05 ± 1.10^{Ab}	11.40 ± 0.15^{Aa}	3.26 ± 1.76^{Ac}	11.04 ± 0.91^{Aa}
		Time II		
L*	30.14 ± 0.939^{Ba}	30.67 ± 1.32^{Ba}	29.21 ± 0.69^{Ba}	28.63 ± 0.79^{Ba}
a*	0.97 ± 0.25^{Ba}	0.97 ± 0.15^{Aa}	0.99 ± 0.26^{Aa}	0.82 ± 0.08^{Aa}
b*	17.86 ± 1.49^{Aa}	17.85 ± 0.68^{Aa}	17.85 ± 0.81^{Aa}	17.82 ± 0.34^{Aa}
C*	17.89 ± 1.50^{Aa}	17.88 ± 0.68^{Aa}	17.87 ± 0.80^{Aa}	17.84 ± 0.34^{Aa}
ΔE	3.74 ± 1.07^{Ba}	3.19 ± 1.03^{Ba}	4.48 ± 0.68^{Aa}	4.96 ± 0.75^{Ba}

Equal letters within the same column and coordinator (capital letter) denote no significant differences at a 5 % significance level. Equal letters within the same line (lowercase letters) denote no significant differences at a 5% significance level between the packages.

The luminosity parameter (L*) showed a significant decrease ($p \leq 0.05$) during storage for all packaging systems, especially after 30 days of storage (Table 2). This reduction is consistent with oxidative degradation of chlorophyll pigments, which are known to be highly sensitive to oxygen, light exposure, and Aw conditions (Da Rocha Nina Junior *et al.*, 2020). However, there was no significant difference ($p \leq 0.05$) in this luminosity parameter after 62 days of storage between packages. This suggests a convergence in visual appearance among treatments over time.

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TANIA MARIA COSTA
ARTHUR PATZLAFF
MEIRYEL LOPES DA SILVA
MARCELA KOTSUKA DA SILVA
CAROLINA KREBS DE SOUZA

Figure 2: Visual aspects of yerba mate after 30 days stored: A = transparent polyethylene (PE) plastic bags; B = multilayer stand-up pouch packaging; C = transparent cylindrical glass jars; D = transparent PE plastic bags placed inside cylindrical metal cans



The authors, 2026

Preservation of the characteristic green color of yerba mate is associated with low or negative values of chromatic coordinate a*. However, a significant increase in a* parameter was observed after 30 days of storage, indicating a shift toward red tones and suggesting degradation of chlorophyll molecules into pheophytin derivatives (Picolo *et al.*, 2023). All samples showed a significant increase in red (coordinate a*) after 30 days (Table 2), especially in plastic and glass packages, with variations in this parameter after 62 days (Time II). The sample stored in plastic suffered a noticeable browning process (Figure 2A), while a lighter appearance is observed in yerba mate stored in glass (Figure 2C) after 30 days. These visual changes are consistent with the combined effect of L* reduction and a* increase, observed in Table 2.

Chromatic coordinate b* also showed a significant reduction in yellow after 30 days (Table 2, Time I), except for the glass package. This behavior may be attributed to oxidative reactions and structural degradation of carotenoid compounds present in the plant matrix (Klavins *et al.*, 2026). The increase in Aw of yerba mate during the storage period (Table 1, Time I) can favor oxidation reactions (Nunes *et al.*, 2025; Schmalko; Alzamora, 2001).

Samples stored in glass packaging showed smaller variations in the b* parameter during the first storage period (Table 2, Time I). However, the transparency of glass allows light to pass through, thereby promoting photodegradation reactions in chlorophyll and carotenoid pigments (Larrea Solórzano *et al.*, 2025). This effect was evidenced by color heterogeneity between the external and internal portions of the product (Figure 3). The yellow color intensity increased again after 60 days

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of storage (Table 2, Time II), with smaller variations (b*) relative to the initial sample (Table 2, Time 0). This increase suggests partial stabilization of the pigment systems under storage-equilibrium conditions.

In terms of chromaticity (C*), there was a significant initial reduction ($p \leq 0.05$) in plastic, stand-up pouches, and plastic + can samples saturation. After 60 days, there was a significant increase in said saturation. This pattern likely reflects an initial phase of pigment degradation, followed by stabilization of the remaining pigments under equilibrium storage conditions (Ferreira *et al.*, 2023).

Total color difference (ΔE) values indicated that the most pronounced visual changes occurred during the first 30 days of storage (Table 2), except for the yerba mate stored in glass packaging. According to commonly accepted color perception thresholds, ΔE values greater than 3 may be visually noticeable to consumers, indicating that storage conditions can significantly influence the visual quality of yerba mate products (Muniz *et al.*, 2023). The particle size of yerba mate is not standardized, meaning that smaller particles may experience more significant pigment loss than larger particles. Long-wavelength colors (red and yellow) are more likely to absorb short-wavelength, high-energy UV rays, which accelerate the photodegradation of dye molecules. However, short-wavelength colors (blue and green) exhibit greater stability (Shen *et al.*, 2026). This was clearly visible in the glass jar (Figure 3). This color separation was not observed in the yerba mate packaged in plastic (Figure 2A).

A reduction in the mint-flavored aroma was observed in transparent PE plastic and glass packaging during the first 30 days of storage. This loss of aroma indicates the migration of volatile aromatic compounds from the product to the external environment, a phenomenon commonly observed in foods containing flavoring agents (Al-Khalili *et al.*, 2025). Plastic packaging materials generally exhibit higher permeability to volatile organic compounds, which facilitates the diffusion of aromatic molecules through the polymer matrix (Gupta *et al.*, 2024). Although glass itself is chemically inert and impermeable, the sealing efficiency of the metal lid may influence volatile compound retention, potentially leading to aroma loss during storage. However, no formal sensory analysis was conducted in this study, which limits conclusions regarding aroma perception.

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CAROLINA KREBS DE SOUZA

Figure 3: Yerba mate in glass packaging stored for 30 days



The authors, 2026

The significant color variations (ΔE and C*, Table 2) highlight the critical role of the packaging barrier in maintaining the quality of flavored yerba mate. The increase in Aw not only favors enzymatic browning and pigment oxidation but also appears to destabilize the flavoring matrix. Although glass and metal cans offer superior barriers against moisture and gas, the early loss of aroma in glass suggests that the 'barrier' is only as effective as its sealing system. In contrast, the stand-up pouch and the plastic + can combination provided a more stable microenvironment. This indicates that multilayer or secondary packaging systems are more effective at limiting mass transfer phenomena, thereby ensuring a longer shelf-life and consistent sensory profile, since these packaging systems can create a more stable microenvironment by limiting the transfer of water vapor, oxygen, and volatile aromatic compounds (Alamri *et al.*, 2021). However, controlling the packaging's storage temperature is crucial to avoid potential changes in Aw and oxidation of yerba mate pigments. Therefore, for yerba mate products containing added flavorings or other volatile ingredients, the use of high-barrier packaging materials is essential to maintain quality and extend commercial shelf life.

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TANIA MARIA COSTA
ARTHUR PATZLAFF
MEIRYEL LOPES DA SILVA
MARCELA KOTSUKA DA SILVA
CAROLINA KREBS DE SOUZA

4 CONCLUSIONS

The evaluation of flavored yerba mate (Ilex paraguariensis) under different storage conditions reveals that the integrity of its physical-chemical properties is strictly dependent on the herb's hygroscopic nature and the barrier efficiency of the packaging material. All treatments exhibited significant increases in pH and fluctuations in Aw over the 62 days, indicating progressive physicochemical instability. Although all treatments showed significant increases in pH and fluctuations in Aw over 62 days, the transparent PE plastic and glass packages performed poorly for long-term retention of volatile aromatic compounds. Furthermore, the significant reduction in luminosity (L*) and the shift in chromaticity coordinates (a* and b*) indicate that oxidative processes and pigment degradation are pervasive across all packaging types, though exacerbated by light exposure in transparent media. The stand-up pouch and the plastic + metal can combination demonstrated superior performance in stabilizing Aw and mitigating total color difference (ΔE) by the end of the study. These results indicate the formation of a more stable internal microenvironment in these packaging systems. Consequently, to preserve the added value of flavored yerba mate, the industry must prioritize high-barrier, opaque, hermetically sealed packaging. In addition, packaging performance should be considered alongside sealing efficiency and light protection. Regarding storage, it must be kept at a controlled temperature to prevent changes in the herb's physical and chemical properties. Such measures are essential to inhibit the transfer of water vapor and the volatilization of essential oils, thereby ensuring that the bioactive properties and consumer expectations are maintained throughout the product's commercial shelf-life. Overall, these findings provide practical guidance for optimizing packaging strategies and storage conditions in flavored yerba mate products.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used generative AI (ChatGPT, Gemini, and Grammarly) to improve clarity and remove grammatical mistakes in some sections of this manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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TANIA MARIA COSTA
ARTHUR PATZLAFF
MEIRYEL LOPES DA SILVA
MARCELA KOTSUKA DA SILVA
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