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RESEARCH ARTICLE

DEVELOPMENT OF VALUE-ADDED TROPICAL ALMONDS (*Terminalia catappa* L.) AND EVALUATION OF PHYSICOCHEMICAL, SENSORY, NUTRITIONAL AND SHELF-LIFE PROPERTIES

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Abstract

Tropical almond (*Terminalia catappa* L.) kernels are a highly nutritious yet underutilized resource in Sri Lanka, despite their rich content of protein, healthy lipids, minerals, and bioactive compounds. Limited consumer awareness, processing difficulties, and a lack of value-added products have hindered their commercial potential. This study was conducted to develop two value-added snack products: sugar-coated and savory tropical almonds, and to evaluate their nutritional, physicochemical, functional, and shelf-life characteristics under different packaging conditions. Sugar-coated almonds were formulated using 30%, 40%, and 50% (w/w) sugar levels, while savory almonds were developed using 5%, 7.5%, and 10% (w/w) spice mixtures. Sensory evaluation indicated that the formulation containing 40% (w/w) sugar in the sugar-coated almonds and 7.5% (w/w) spice in the savory almonds received the highest overall acceptability scores. Proximate analysis revealed that savory almonds had the highest protein (39.60 ± 1.87%), fat (78.00 ± 4.21%), and fiber (7.15 ± 0.65%), which was attributed to the composition of the coating mixture. Sugar-coated almonds exhibited a lower peroxide value (5.70 ± 0.64 meq/kg), indicating better oxidative stability. Among functional properties, sugar-coated almonds showed higher antioxidant activity (30.04 ± 3.46 mM Trolox/g) while savory almonds demonstrated the highest flavonoid content (4.13 ± 1.06 mg QE/g). Shelf-life evaluations were conducted over 12 weeks using paper zip-lock pouches and zip-lock pouches with an inner aluminium foil layer, with or without silica gel, to assess changes in color, moisture content, pH, water activity, and microbial growth. Results indicated that packaging with an inner aluminium foil layer, combined with silica gel, provided the best protection, maintaining product quality and minimizing microbial growth throughout storage. Overall, the study demonstrates that value addition through sugar-coated and savory tropical almond snacks can significantly improve the usability and marketability of this underexploited nut, offering promising opportunities for commercial production and rural entrepreneurship.

Keywords: Nutritional composition, Packaging, Sensory evaluation, Shelf-life assessment, Sugar and savory snacks, Tropical almonds

INTRODUCTION

Tropical almond (*Terminalia catappa L.*), known as Indian almond, sea almond, or country almond, is a large tropical tree found in many regions, including Asia, Africa, Australia, and the Pacific Islands (Aniszewski *et al.,* 2019). Its kernels are highly valued for their nutritional benefits, containing 45–60% oil, 2030% protein, and vital minerals, vitamins, and bioactive compounds (Sahoo *et al.,* 2022; Kumar *et al.,* 2021). They are rich in unsaturated fatty acids, especially oleic (35 –45%) and linoleic acids (20–30%), along with tocopherols, phytosterols, and phenolic compounds, making them comparable or

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superior to nuts like almonds and cashews (Adewusi *et al.,* 2021).

Tropical almond kernels have great nutritional value but are not widely used in areas where the trees grow as ornamental or shade plants (Rathod *et al.,* 2023). They are usually eaten raw or roasted, or used in local sweets, but their commercial use is limited due to issues like rancidity, poor processing methods, and low consumer awareness (Pathak *et al.,* 2022). Developing coated kernel products could improve consumer acceptance and create market opportunities in the food industry (Mehyar *et al.,* 2012).

Coating technology has been successfully used on various nuts and seeds to enhance their taste, protect them from environmental damage, and extend their shelf-life (Fernandes *et al.,* 2018). Sugar coatings create sweet snacks for many consumers, while savory coatings cater to health-focused individuals seeking lower-sugar options and unique flavours (Rusu *et al*., 2019). The coating acts as a barrier against moisture and oxygen, preventing spoilage and maintaining texture (Kumar, 2022). Studies show that coated peanuts, cashews, almonds, and pistachios have greater crunchiness and longer shelf life than uncoated ones (Ghirardello *et al*., 2016; Gökmen & Şenyuva, 2006; Lima *et al.,* 2023).

The shelf life of tree nut products is primarily affected by lipid oxidation, leading to rancidity and the formation of harmful substances (Ciemniewska-Żytkiewicz *et al.,* 2021; Bottesini *et al.,* 2022). Tropical almond kernels, with their high levels of unsaturated fatty acids, are especially prone to oxidation during storage, particularly under unfavourable conditions of temperature, light, and oxygen (Ahmad *et al.,* 2023). Quality parameters such as peroxide value (PV), free fatty acid (FFA) content, p-anisidine value, thiobarbituric acid reactive substances (TBARS), and sensory attributes are critical indicators for assessing shelf-life stability and consumer acceptability of nut products (Nogueira *et al.,* 2021). Understanding how coated tropical almond kernels behave under different storage conditions is vital for ensuring safety and commercial viability (Hadidi *et al.,* 2022).

Recent advances in food coating technologies and shelf-life prediction models provide new opportunities to develop stable and commercially viable tropical almond kernel products (Duan *et al.,* 2023). The use of active and intelligent packaging systems, along with suitable coating formulations, can significantly improve oxidative stability and extend the shelf-life of high-fat food products (Ezati *et al.*, 2021). Despite the increasing interest in tropical almonds and the growth of the global tree nut market, there is a lack of scientific literature on the systematic development of value-added coated tropical almond kernel products, as well as a comprehensive evaluation of their physicochemical changes and shelf-life characteristics under controlled storage conditions (Kumar *et al.,* 2023). In particular, limited information is available on the development and comparative evaluation of sugar-coated and savory-coated tropical almond kernels as snack products. Moreover, the influence of different packaging materials and moisture-control systems on the storage stability of these coated tropical almond products remains insufficiently investigated. Therefore, this study was designed to determine the most acceptable formulation for sugar-coated and savory tropical almond snacks through sensory evaluation of different sugar and spice levels. The study also assessed the physicochemical, nutritional, functional properties, and shelf-life properties of the developed tropical almond nuts stored under different packaging materials and storage conditions to identify the most suitable packaging material and storage condition for maintaining the quality and safety of the developed sugar-coated and spice-coated tropical almond products. The findings of this research will contribute to the commercialization and value chain development of tropical almond kernels, provide scientific data for small-scale processors and entrepreneurs in tropical regions, and support the utilization of this nutritious yet underexploited tree nut resource.

MATERIALS & METHODS

Sample collection and preparation

Well- ripened and fallen fruits of tropical almond were collected under the tree located in Gampaha district (7.26570º N latitude and 79.85910º E longitude of 300 m above mean sea level) during the fruiting season of May to August 2024. The collected fruits were sorted to remove spoiled and damaged fruits, then dried under direct sunlight for 4 days to remove excess moisture. Then the sun-dried fruits were packed separately by month and stored in a cool, dry, and dark place until used for the study. The fruit was shelled manually by using a hammer to extract the seed kernel. The kernels were screened by the naked eye, and good-quality, undamaged kernels of the same size were selected. Other ingredients used to develop snacks, such as sugar, margarine, gram flour, rice flour, salt, and spices, were purchased from a supermarket in Matara.

Preparation of sugar-coated tropical almond

Pre-roasted tropical almond kernels were used to prepare sugar-coated tropical almonds. The kernels were dry roasted in a preheated stainless-steel pan over medium heat for approximately 8 -10 min until a light golden-brown color and characteristic nutty aroma developed. Sugar syrup was prepared by mixing granulated sugar and water (1:1, w/w) in a stainless-steel pan and heating until the sugar completely dissolved and the mixture reached a boiling stage (approximately 75 ºBrix). Butter was added to improve flavor and minimize crystallization, and heating was continued until the syrup reached the soft-ball stage (110–115 ºC). The pan-roasted tropical almond kernels were then added to the syrup and mixed thoroughly to ensure uniform coating. After heating was stopped, the mixture was continuously stirred during cooling to prevent clumping of the coated kernels. Once the coating solidified at room temperature, the sugar-coated tropical almonds were packed in double-layered high-density polyethylene (HDPE) packages at room temperature until further use in sensory analysis. Three different tropical almond nut samples were developed by varying the amounts of sugar content (Table 1).

Table 1: Formulations of tropical almonds with different sugar concentrations

Treatment	No of nuts	Butter (g)	Sugar (%)
S1	100	2.5	30
S2	100	2.5	40
S3	100	2.5	50

Preparation of savory tropical almond

Tropical almond kernels were dry-roasted in a preheated stainless-steel pan over medium heat for approximately 8–10 min, until a light golden-brown color and characteristic nutty aroma developed. The roasted kernels were then used to prepare savory-coated tropical almonds. A seasoning mixture consisting of a gram flour-rice flour mixture (1:1 w/w), salt, selected spice powders (chilli, turmeric, and cumin), and 5 mL of edible oil per 100 g of kernels was prepared. The warm roasted kernels were mixed with the seasoning mixture while still retaining residual heat to facilitate the spices' adhesion to the kernel surface. The coating was performed by manual mixing to ensure uniform distribution of the spices. Three different savory tropical almond nut samples were developed by varying proportions of the spice mixture (Table 2).

Table 2: Formulations of tropical almonds with different spice mixture levels

Treatment	No of nuts	Gram flour (g)	Rice flour (g)	Garlic paste (g)	Spice mixture (%)
T1	100	30	15	5	5
T2	100	30	15	5	7.5
T3	100	30	15	5	10

Sensory evaluation

Sensory evaluations were conducted to determine the consumer preference for the developed tropical almond snacks. A five-point hedonic scale was used to evaluate organoleptic properties, including texture, taste, aroma, color, appearance, and overall acceptability of the developed tropical almond snacks, using 30 semi-trained panelists.

Analysis of developed products

Determination of proximate composition

Proximate composition of developed products was tested according to the methods described by the Association of Official Analytical Chemists (AOAC), such as moisture (AOAC 934.01), Crude protein (AOAC 2001.11), Crude ash (AOAC 942.05), crude fiber (AOAC 978.10) and crude fat (AOAC 2003.05).

Analysis of physicochemical properties

Determination of color

Color parameters of the tropical almond samples (L*, a*, b*) were measured using a colorimeter (BIOBASE, BC-110/200, China).

Determination of pH value

pH was measured using a pH meter (AD132, Romania), and a homogenate was prepared from 5 g of each ground tropical almond sample with 20 mL of distilled water.

Determination of peroxide value (PV)

The PV was determined according to AOAC official methods (2002). Five grams of oil extracted from tropical almond samples using the Soxhlet extraction method were mixed with a 30 mL acetic: chloroform mixture (3:2 ratio) in a conical flask. After dissolution, 0.5 of saturated KI was added, and the mixture was kept in the dark with occasional shaking. Then, 30 mL of distilled water was added, and the mixture was titrated with 0.01 N sodium thiosulfate until the yellow color nearly disappeared. A further 0.5 mL of 1% starch was added, and titration continued until the blue color disappeared, and the final reading was recorded.

$$PV = \frac{\text{Titre x N}}{W} \times 1000$$

Eq.1

Where; Titre : mL of sodium thiosulphate used , N : Normality of sodium thiosulphate , and W : Weight of the sample

Analysis of functional properties

Preparation of extract

Extraction of bioactive compounds for total phenolic content, flavonoid content, and antioxidant activity analyses was carried out using a methanol–water extraction method. One gram of ground tropical almond sample was thoroughly mixed with 10.5 mL of methanol and 4.5 mL of distilled water. The mixture was vortexed and subsequently placed in a mechanical shaker for 1 hour at room temperature. After extraction, the samples were centrifuged at 5000 rpm for 15 minutes, and the supernatant was collected. The extraction procedure was repeated three times to ensure maximum recovery of bioactive compounds. Finally, the collected supernatants were pooled and used to determine total phenolic and flavonoid content and antioxidant activity.

Determination of total phenolic content

Total phenolic content was measured using the Folin-Ciocalteu method, as described by Ghasemzadeh *et al.* (2018). The Folin-Ciocalteu reagent was prepared by diluting 5 mL in 45 mL of distilled water. A 7.5% Na_2CO_3 solution was made by dissolving 7.5 g of Na_2CO_3 in 100 mL of distilled water. The acid stock solution (1000 µg/mL) was prepared by dissolving 1000 µg of gallic acid in 1 mL of ethanol. A sample or standard (200 µL) was mixed in a test tube with 1 mL of FCR and 1 mL of 7.5% Na_2CO_3 and diluted to 5 mL with distilled water. After incubating for 30 minutes in the dark, absorbance was measured at 765 nm using a UV-visible spectrophotometer (HACH DR3900, Hatch, Germany). The results were expressed as milligrams of gallic acid equivalents (GAE) per 1 g of the sample.

Determination of flavonoid content

Total flavonoid content was determined using the aluminium chloride colorimetric method, as reported by Chandra *et al*. (2014), with some modifications. A stock solution was prepared by dissolving 5 mg of Quercetin in 1 mL of ethanol to make a concentration of 5000 µg/mL. One milliliter sample or standard solution was measured into a ten milliliter volumetric flask, followed by the addition of 4 mL of distilled water and 0.3 mL of 5% $NaNO_2$ solution. After 5 minutes, 0.3 mL of 10% $AlCl_3$ was added, followed by 2 mL of 1 M NaOH, and the solution was diluted to the mark with distilled water and vortexed. Absorbance was measured at 510 nm using a UV-visible spectrophotometer (HACH DR3900, Hach, Germany) and flavonoid content was reported as mg of quercetin equivalent (QE) per 1 g.

Determination of total antioxidant activity by DPPH radical scavenging method

The DPPH assay as a TEAC was evaluated following the modified method of Gulcin and Alwasel (2023). A 0.1 mM DPPH radical solution was prepared by dissolving 0.0039 g DPPH in 100 mL of methanol, and a 60% (v/v) ethanol solution was prepared by mixing 60 mL of ethanol with 40 mL of water. A 1 mM Trolox stock solution was prepared by dissolving 25 mg Trolox in 100 mL of a volumetric flask. For the assay, 1 mL of 0.1 mmol DPPH solution was mixed with 0.1 mL of methanolic extract from standard solutions. Then the solution was vortexed and left in the dark for 30 minutes. Optical density readings were taken at 517 nm using a UV-visible spectrophotometer (HACH DR3900, Hatch, Germany), and antioxidant activity was expressed as mmol Trolox equivalents (TE) per gram.

Shelf-life analysis of the developed products

After the initial product analysis, the developed sugar-coated, savory tropical almond snacks were subjected to a shelf-life study under various packaging and moisture-control conditions. Four packaging treatments were used, i.e., (1) paper zip-lock pouch without silica gel, (2) paper zip-lock pouch with silica gel, (3) aluminium foil-lined zip-lock pouch without silica gel, and (4) aluminium foil-lined zip-lock pouch with silica gel (Figure 1). The packaged samples were stored at room temperature (27 ± 2 °C) under ambient relative humidity (70–75% RH) for 12 weeks. Samples were analyzed at two-week intervals (0, 2, 4, 6, 8, and 12 weeks) to evaluate changes in physicochemical and microbiological properties.

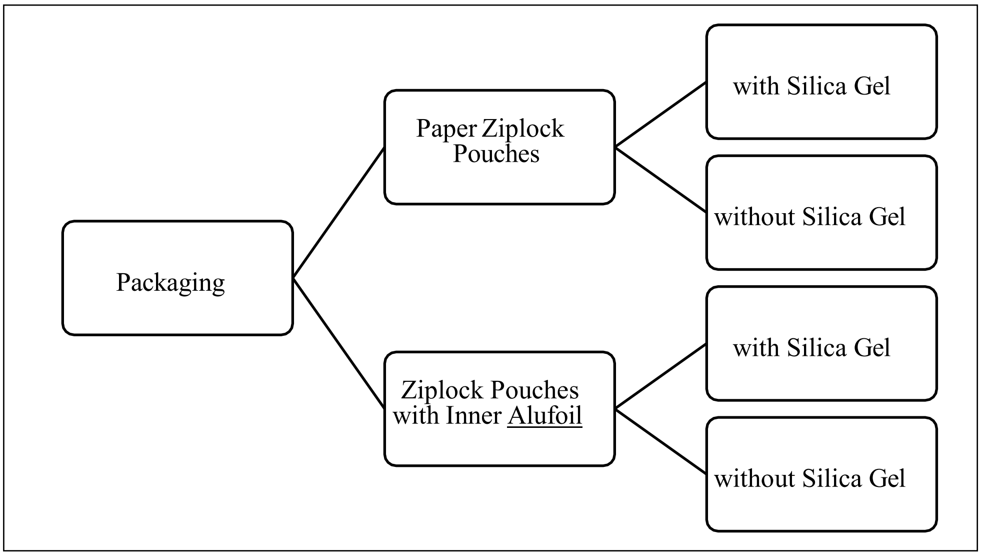

Figure 1: Packaging types of developed tropical almond products

The shelf-life assessment included measurements of moisture content, pH, color, water activity, total plate count (TPC), and yeast and mould counts to determine the most suitable packaging system to maintain product quality and safety during storage. Microbiological analyses, including total plate count (TPC) and yeast and mold count, were conducted according to Igbabul *et al.* (2014). TPC was determined using Plate Count Agar (PCA), while yeast and mold counts were determined using Rose Bengal Agar. Results were expressed as colony-forming units per gram (CFU/g).

Statistical analysis

The study was conducted using a Completely Randomized Design (CRD), in which treatments were randomly assigned to experimental units. All physicochemical, functional, and shelf-life analyses were performed in triplicate, and the results are presented as mean ± standard deviation. Data obtained from these analyses were subjected to one-way analysis of variance (ANOVA), followed by Tukey's post-hoc test for mean separation at a significance level of $p < 0.05$ using MINITAB version 17.0 (Minitab Inc., State College, PA, USA). Sensory evaluation data obtained using a five-point hedonic scale were analyzed using the non-parametric Kruskal-Wallis test in Statistix version 10.0 (Analytical Software, Tallahassee, FL, USA), as hedonic scale responses are ordinal in nature and may not satisfy the assumptions of normality required for parametric tests. Statistical significance was determined at $p < 0.05$.

RESULTS AND DISCUSSION

Sensory properties of sugar-coated tropical almond

Sensory evaluation of sugar-coated tropical almonds prepared with different sugar concentrations (30%, 40%, and 50% w/w) showed that sugar concentration significantly influenced crunchiness, sweetness, and overall acceptability (Table 3).

Table 3: Mean rank values of sensory attributes of sugar-coated tropical almonds prepared with different sugar concentrations

Attributes	Sugar % (w/w)		
	30%	40%	50%
Appearance	53.35^{a}	44.00^{b}	39.15^{c}
Color	54.40^{a}	44.52^{ab}	37.58^{b}
Sweetness	54.05^{a}	41.65^{b}	40.80^{b}
Crunchiness	32.75^{c}	55.40^{ab}	48.35^{b}
Mouth feel	38.88^{c}	53.58^{a}	44.03^{b}
Overall acceptability	42.37^{b}	53.20^{a}	40.93^{b}

Values are presented as mean ranks obtained from the Kruskal–Wallis test. Different superscript letters within the same row indicate significant differences among treatments at $p < 0.05$.

Among the formulations tested, the 40% sugar-coated sample received the highest scores for crunchiness and overall acceptability, indicating that this sugar level provided an optimal balance between sweetness and textural quality. The lower acceptability of the 30% sugar-coated sample may be attributed to insufficient coating formation. In contrast, the 50% sugar-coated sample may have been less preferred due to excessive sweetness and a thicker coating that could mask the natural flavor of the almond kernels.

These findings are consistent with previous studies demonstrating that consumer acceptance of coated nut products is strongly influenced by flavor and texture attributes. Grosso and Resurreccion (2002) reported that the acceptability of coated and roasted peanuts was closely associated with desirable flavor characteristics and texture. Similarly, Larrauri *et al*. (2016) showed that edible coatings can influence the sensory quality of almond products, while Lipan *et al*. (2019) identified sweetness as an important factor affecting consumer preference. Based on the sensory results, the formulation containing 40% sugar was selected as the most suitable sugar-coated tropical almond product.

Sensory properties of savory tropical almonds

Sensory evaluation data for savory tropical almonds were analyzed using the Kruskal–Wallis test and are presented as mean rank values (Table 4). Spice concentration significantly influenced appearance, crunchiness, mouthfeel, and overall acceptability. Among the formulations tested, the 7.5% (w/w) spice formulation achieved the highest overall acceptability, indicating greater consumer preference compared with the 5% and 10% (w/w) spice levels. The lower acceptability of the 5% spice formulation may be attributed to insufficient flavor intensity, whereas the 10% spice formulation may have produced an excessively strong spice flavor that reduced palatability. The superior performance of the 7.5% spice formulation suggests that it provided a desirable balance between seasoning intensity and the characteristic nutty flavor of tropical almond kernels. Similar findings have been reported for seasoned snack products, in which seasoning level and coating characteristics significantly influenced flavors perception, texture, and consumer acceptability (Navya *et al.*, 2021; Christman *et al.*, 2018). Based on these results, the 7.5% spice formulation was selected as the most suitable savory tropical almond product for further analyses.

Table 4: Mean rank values of sensory attributes of savory tropical almonds prepared with different spice levels

Attributes	Spice % (w/w)		
	5%	7.5%	10%
Appearance	40.17^{b}	55.33^{a}	41.00^{b}
Color	41.60^{b}	53.78^{a}	41.12^{b}
Spiciness	40.23^{b}	46.53^{b}	49.73^{a}
Crunchiness	29.38^{b}	54.48^{a}	52.63^{a}
Mouth feel	35.52^{b}	52.62^{a}	48.37^{b}
Overall acceptability	33.40^{c}	57.08^{a}	46.02^{b}

Values are presented as mean ranks obtained from the Kruskal–Wallis test. Different superscript letters within the same row indicate significant differences among treatments at $p < 0.05$.

Nutritional, physicochemical, and functional properties of developed products

The proximate composition of untreated, sugar-coated, and savory tropical almond samples showed significant differences ($p < 0.05$) among treatments, indicating that processing and formulation had a notable impact on the nutritional and physicochemical properties of the final products (Table 5).

Table 5: Proximate composition of tropical almond samples

Property (%)	Untreated tropical almonds	Sugar-coated tropical almonds	Savory tropical almonds
Moisture Content	3.98 ± 0.13^{a}	3.03 ± 0.19^{b}	3.52 ± 0.15^{c}
Crude Protein	25.89 ± 2.82^{a}	29.43 ± 1.99^{a}	39.60 ± 1.87^{b}
Crude Fat	53.14 ± 5.64^{a}	48.01 ± 3.41^{a}	78.00 ± 4.21^{b}
Crude Fiber	5.64 ± 0.66^{a}	4.98 ± 0.36^{a}	7.15 ± 0.65^{b}
Ash Content	4.31 ± 0.13^{a}	2.40 ± 0.29^{b}	4.07 ± 0.03^{a}

Values are presented in mean ± standard deviation (n=3), while different letters for values in each row indicate significant differences ($p < 0.05$)

The moisture content of untreated tropical almond nuts (3.98 ± 0.13%) was within the typical range reported for almonds (3-6%), confirming their classification as low-moisture foods (Yada *et al.,* 2011). Processing treatments resulted in slight but significant reductions in moisture content, particularly in sugar-coated samples (3.03 ± 0.19%), which may be attributed to the hygroscopic nature of sugar and moisture redistribution during coating. The relatively low moisture content observed across all samples is advantageous for shelf stability, as reduced water availability is associated with decreased microbial growth and extended shelf life (Pleasance *et al.,* 2018).

Significant differences in protein content were observed among treatments, with savory tropical almonds exhibiting the highest value (39.60 ± 1.87%). This value exceeds previously reported protein contents for tropical almonds, which range from approximately 17.66% to 32% (Olatidoye *et al.*, 2011; Yada *et al.*, 2011). The higher protein content of the savory product is likely attributable to the incorporation of gram flour into the coating, as gram flour is a protein-rich ingredient (Jukanti *et al.*, 2012). In contrast, the addition of sugar to sugar-coated almonds may have resulted in a dilution effect because sugar primarily contributes carbohydrates. Variations in protein content reported in the literature may also be influenced by differences in cultivar, growing conditions, analytical methods, and the basis of expression (wet or dry weight).

Similarly, fat content was significantly higher in the savory sample (78.00 ± 4.21%) than in the untreated and sugar-coated samples. This increase may be attributed to the incorporation of coconut oil during processing and to the product's lower moisture content, which can increase the relative proportion of fat when expressed on a wet-weight basis. Previous studies have reported fat contents of approximately 50–55% in tropical almonds (Salawu *et al.*, 2018), suggesting that processing conditions can substantially influence the final lipid content. Natural variation in fat content may also arise from differences in genotype, soil characteristics, and climatic conditions (Salawu *et al.*, 2018).

Crude fiber content differed significantly ($p < 0.05$) among treatments, with savory tropical almonds recording the highest value (7.15 ± 0.65%). This increase may be attributed to the incorporation of gram flour, rice flour, and spices during coating. In contrast, the lower fiber content of sugar-coated almonds may be due to the dilution effect of added sugar, which does not contribute dietary fiber. The untreated sample contained 5.64 ± 0.66% crude fiber, which was lower than the 15.54% reported by Salawu *et al*. (2018). Such variations may be attributed to differences in cultivar, processing conditions, and analytical methods.

Ash content, an indicator of total mineral content, showed similar values in untreated (4.31 ± 0.13%) and savory tropical almonds (4.07 ± 0.03%), whereas sugar-coated almonds exhibited a significantly lower ash content (2.40 ± 0.29%). These values are generally comparable with previously reported ash contents ranging from 3.76% to 4.84% for tropical almonds (Udotong *et al*., 2015; Salawu *et al*., 2018). The reduced ash content in sugar-coated almonds is likely due to the dilution effect of added sugar, which contributes negligible mineral content.

Overall, the results demonstrate that processing methods significantly influence the nutritional composition of tropical almond products. While sugar coating primarily reduced the relative proportions of fiber and minerals, savory coating enhanced protein, fat, and fiber contents, thereby modifying the nutritional profile of the final product.

Physicochemical properties of developed products

The physicochemical properties of untreated, sugar-coated, and savory tropical almonds) showed a significant difference ($p < 0.05$), indicating that processing and formulation had a considerable influence on product characteristics (Table 6).

Table 6: Physicochemical properties of tropical almond samples

Sample		Untreated tropical almond	Sugar-coated tropical almond	Savory tropical almond
Color	L*	23.60 ± 0.48^{a}	24.05 ± 0.52^{a}	20.0 ± 0.69^{b}
	a*	11.06 ± 0.23^{a}	8.02 ± 0.52^{b}	13.60 ± 1.16^{c}
	b*	5.65 ± 0.56^{a}	3.73 ± 0.64^{b}	0.54 ± 0.35^{c}
pH value		6.89 ± 0.005^{a}	6.87 ± 0.010^{a}	6.31 ± 0.005^{b}
Water activity		0.57 ± 0.004^{a}	0.56 ± 0.001^{b}	0.23 ± 0.002^{c}
Peroxide Value (meq/kg)		5.75 ± 1.20^{a}	5.70 ± 0.64^{a}	7.25 ± 0.49^{b}

Values are mean ± standard deviation (n=3), while different letters for values in each row indicate significant differences ($P < 0.05$)

Color parameters differed among treatments, indicating that coating and seasoning affected the visual properties of tropical almonds. The sugar-coated sample showed the highest L* value (24.05 ± 0.52), possibly due to the reflective effect of the sugar coating. In contrast, the savory sample showed the lowest L* value (20.00 ± 0.69), indicating a darker appearance. This may be associated with thermal processing and non-enzymatic browning reactions, including Maillard reactions and caramelization, which contribute to color development in heated foods (Gökmen & Şenyuva 2006). The higher a* value of savory almonds (13.60 ± 1.16) may be attributed to pigments from seasoning ingredients such as chilli and turmeric, which impart red-orange and yellow tones (Chittaragli and Menon 2023).

The pH values of the untreated (6.89 ± 0.005) and sugar-coated (6.87 ± 0.010) samples were similar and near neutral, indicating that sugar coating had a minimal effect on acidity. In contrast, savory almonds showed a significantly lower pH (6.31 ± 0.005), possibly due to the incorporation of seasoning ingredients, such as garlic paste. This slight reduction in pH may influence sensory properties and microbial stability (Gram *et al*., 2002).

Water activity was lowest in savory almonds (0.23 ± 0.002), probably due to moisture loss during processing and water binding by coating ingredients such as flour, salt, and spices. The lower water activity of sugar-coated almonds may be related to the hygroscopic nature of sugar, which reduces the availability of free water. Since most pathogenic bacteria cannot grow below a water activity of approximately 0.85, the low water activity values observed in this study suggest good potential storage stability (Tapia *et al*., 2020; Liu *et al*., 2022).

Peroxide value (PV), an indicator of primary lipid oxidation, was higher in savory almonds (7.25 ± 0.49 meq/kg) than in untreated and sugar-coated samples. This increase may be associated with oil incorporation, heat exposure, and seasoning components that could promote oxidative reactions. However, the PV values remained below the Codex limit of 10 meq active oxygen/kg oil for virgin and cold-pressed fats and oils, indicating that severe lipid oxidation had not occurred (Barku *et al*., 2012; Iyekowa *et al*., 2023).

Overall, the results indicate that coating and seasoning influenced the physicochemical properties of tropical almonds, particularly color, pH, water activity, and oxidative stability, all of which are important determinants of product quality and shelf life.

Functional properties of developed products

The functional properties of untreated sugar-coated and savory tropical almond samples showed significant differences ($p < 0.05$), indicating that processing and formulation influenced the bioactive profiles of the products (Table 7).

Table 7: Functional properties of tropical almond samples

Sample	Untreated tropical almond	Sugar-coated tropical almond	Savory tropical almond
Antioxidant activity (mM TE/g)	25.71 ± 0.31^{b}	30.04 ± 3.460^{a}	27.04 ± 1.10^{b}
Total phenol content (mg GAE/g)	5.90 ± 0.16^{a}	5.60 ± 0.016^{a}	2.80 ± 0.35^{b}
Flavonoid content (mg QE/g)	2.16 ± 0.14^{a}	2.81 ± 0.350^{a}	4.13 ± 1.06^{a}

Values are mean ± standard deviation (n=3), while different letters for values in each row indicate significant differences ($P < 0.05$)

Antioxidant activity, which reflects the ability of bioactive compounds to neutralize free radicals (Gulcin, 2012), was highest in sugar-coated tropical almonds (30.04 ± 3.46 mM TE/g), followed by savory and untreated samples. The higher antioxidant activity observed in sugar-coated almonds may be associated with the formation of Maillard reaction products during thermal processing. Previous studies have reported that Maillard reaction products can exhibit antioxidant properties through radical scavenging, metal-chelating, and reducing activities (Yilmaz & Toledo, 2005; Nooshkam *et al*., 2019). Therefore, the increased antioxidant activity may be attributed to both the native bioactive compounds present in tropical almond kernels and antioxidant compounds formed during the sugar-coating process.

Total phenolic content was highest in untreated tropical almonds (5.90 ± 0.16 mg GAE/g), whereas savory samples showed a significantly lower value (2.80 ± 0.35 mg GAE/g). Polyphenols are important bioactive compounds associated with antioxidant and anti-inflammatory activities (Hussain *et al*., 2016). The reduction in total phenolic content may be attributed to thermal degradation during processing and dilution effects resulting from the incorporation of coating ingredients. A similar but less pronounced reduction was observed in sugar-coated almonds.

Flavonoid content did not differ significantly among treatments ($p > 0.05$), although savory tropical almonds exhibited the highest numerical value (4.13 ± 0.06 mg QE/g). This trend may be related to the presence of flavonoid-containing spices used in the savory coating (Yashin *et al*., 2017). Overall, the results suggest that processing methods can differentially affect the functional properties of tropical almonds, with sugar coating enhancing antioxidant activity, while thermal processing may reduce phenolic content.

Shelf–life analysis of sugar-coated and savory tropical almonds in different packaging materials

The shelf-life stability of sugar-coated and savory tropical almonds was significantly influenced by packaging material and moisture control (Figures 1 and 2). Among the tested systems, paper pouches, aluminium foil pouches, and their combinations with silica gel showed clear differences in their ability to preserve product quality.

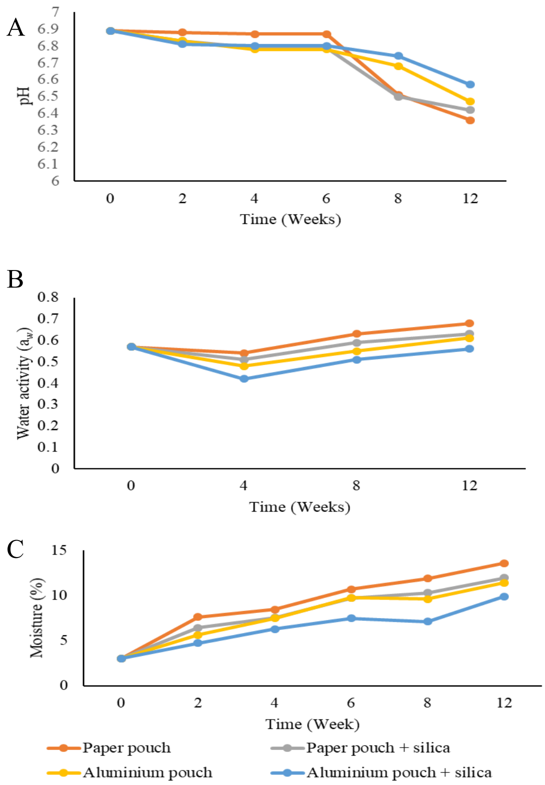

Figure 2: Variation of pH (A), water activity (B), and moisture content (C) of sugar-coated tropical almonds during the storage period

Storage stability of sugar-coated and savory tropical almonds was significantly influenced by packaging material and the presence of silica gel. Detailed changes in color parameters, pH, moisture content, water activity, total plate count, and yeast and mold counts during storage are presented in *Supplementary Tables S1* and *S2*. Overall, aluminium foil pouches combined with silica gel provided better preservation of product quality than paper pouches, as evidenced by improved color stability, lower moisture uptake, lower water activity, reduced microbial growth, and better pH stability throughout the 12-week storage period.

Color parameters changed progressively during storage in all packaging treatments, indicating the occurrence of storage-related physicochemical changes. However, samples packaged in aluminium foil pouches with silica gel generally exhibited smaller changes in L*, a*, and b* values than those stored in paper pouches, suggesting improved color retention. This may be attributed to the superior barrier properties of aluminium foil against oxygen, moisture, and light, while silica gel reduced moisture accumulation within the package. Similar observations have been reported in low-moisture food products, where improved packaging barriers contributed to enhanced color stability during storage (Pathare *et al*., 2013).

Moisture content and water activity increased in all treatments during storage, but to a lesser extent in samples packaged in aluminium foil pouches with silica gel (*Supplementary Table S1*). The greater increases observed in paper pouch treatments indicate greater moisture transfer from the surrounding environment due to their lower moisture-barrier properties. Since water activity is a critical factor governing deterioration reactions and microbial growth, controlling moisture uptake is essential for maintaining the quality of low-moisture foods (Tapia *et al*., 2020).

Microbial counts remained low throughout storage but increased gradually toward the end of the storage period, particularly in paper pouch treatments. This increase was accompanied by corresponding increases in moisture content and water activity, suggesting that moisture uptake created more favorable conditions for microbial survival and growth. In contrast, aluminium foil pouches with silica gel maintained lower moisture content and water activity and consequently showed lower total plate counts and yeast and mold counts. These findings highlight the close relationship between packaging performance, moisture control, and microbial stability during storage (Lima *et al*., 2023).

Changes in pH were comparatively small; however, samples stored in aluminium foil pouches with silica gel generally exhibited greater pH stability than those stored in paper pouches. This may be related to reduced moisture migration and slower chemical deterioration reactions under improved storage conditions (Figure 3).

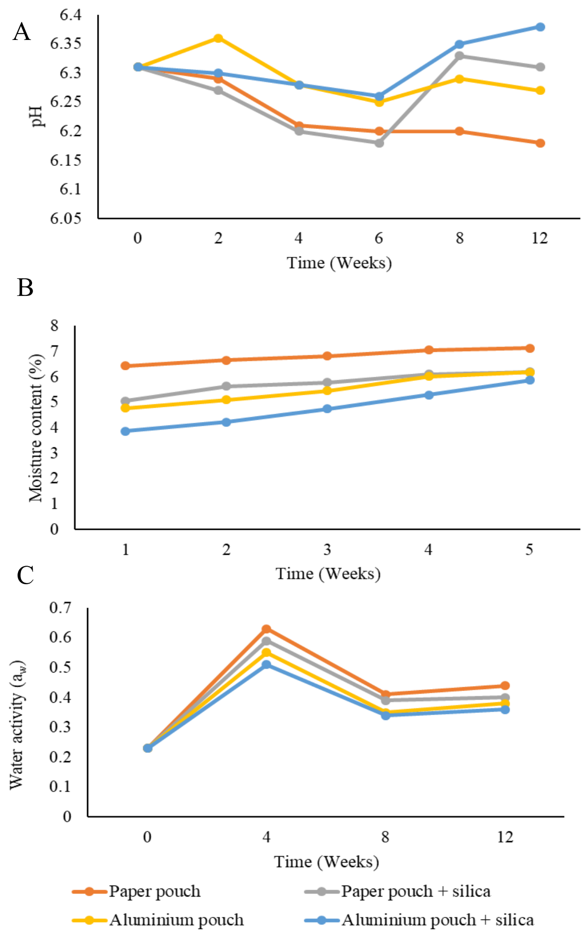

Figure 3: Variation of pH (A), water activity (B), and moisture content (C) of savory tropical almonds during the storage period

Overall, the results demonstrate that aluminium foil pouches combined with silica gel provided the most effective packaging system for preserving the physicochemical and microbiological quality of both sugar-coated and savory tropical almonds during storage. Although the products remained relatively stable during the 12-week storage period, this duration may be insufficient for predicting commercial shelf life. Therefore, further studies involving longer storage periods and accelerated shelf-life testing are recommended to establish shelf-life more accurately under commercial conditions.

CONCLUSIONS

This study demonstrated the potential of tropical almond (*Terminalia catappa* L.) kernels as an underutilized raw material for the development of value-added snack products. Both sugar-coated and savory-coated formulations exhibited acceptable sensory, nutritional, and functional characteristics, highlighting the effectiveness of coating-based processing in enhancing consumer appeal and promoting the utilization of tropical almond kernels. The results further showed that formulation and packaging significantly influenced product quality and storage stability. Under the conditions evaluated in this study, aluminium foil pouches combined with silica gel provided better preservation of product quality than paper pouches, indicating the importance of moisture and oxygen barrier properties in maintaining the stability of low-moisture snack products. However, this finding is limited to the 12-week ambient storage conditions investigated. Overall, the study provides scientific evidence supporting the value addition and potential commercialization of tropical almond-based snack products. Nevertheless, the findings should be interpreted in light of certain limitations, including the limited sensory panel size, the relatively short storage period, and the absence of accelerated shelf-life and consumer-scale acceptability studies. Future research should focus on extended storage evaluations, accelerated shelf-life testing, larger consumer studies, and pilot-scale production to further establish product stability, consumer acceptance, and commercial feasibility.

AUTHOR CONTRIBUTION

KRRG conducted the research, summarizing the initial draft; KMCF conceptualization, supervision, and editing the manuscript; GSNF supervision and editing the manuscript; PKT summarizing the draft manuscript.

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***Supplementary Table S1*: Shelf-life properties of sugar-coated tropical almond samples**

Time Period	Packaging Type	Color			pH	Water activity	Moisture content (%)	Total plate count	Total plate count	Yeast and mould count
		L*	a*	b*						
After two weeks	Paper pouch	25.45 ± 0.55^{a}	18.85 ± 0.24^{a}	5.41 ± 0.41^{a}	6.88 ± 0.011^{a}	ND	7.63 ± 0.53^{a}	7.63 ± 0.53^{a}	ND	ND
	Paper pouch with silica	26.06 ± 0.34^{a}	17.85 ± 1.17^{a}	6.79 ± 0.81^{a}	6.83 ± 0.010^{b}	ND	6.43 ± 0.48^{b}	6.43 ± 0.48^{b}	ND	ND
	Aluminiumpouch	17.08 ± 0.90^{b}	27.04 ± 1.31^{b}	2.97 ± 0.18^{b}	6.83 ± 0.005^{b}	ND	5.63 ± 0.31^{b}	5.63 ± 0.31^{b}	ND	ND
	Aluminiumpouch with silica	24.14 ± 1.04^{a}	18.05 ± 0.59^{a}	9.19 ± 0.81^{c}	6.81 ± 0.005^{b}	ND	4.72 ± 0.40^{c}	4.72 ± 0.40^{c}	ND	ND
After four weeks	Paper pouch	11.47 ± 1.28^{a}	13.88 ± 0.65^{ac}	31.39 ± 1.03^{a}	6.87 ± 0.010^{a}	0.54 ± 0.002^{a}	8.46 ± 0.41^{a}	8.46 ± 0.41^{a}	ND	ND
	Paper pouch with silica	12.82 ± 0.73^{a}	16.83 ± 0.62^{b}	29.12 ± 1.03^{b}	6.79 ± 0.005^{b}	0.51 ± 0.001^{b}	7.54 ± 0.44^{a}	7.54 ± 0.44^{a}	ND	ND
	Aluminiumpouch	11.02 ± 0.38^{a}	15.01 ± 0.64^{a}	28.04 ± 0.87^{b}	6.78 ± 0.005^{b}	0.48 ± 0.001^{c}	7.48 ± 0.46^{a}	7.48 ± 0.46^{a}	ND	ND
	Aluminiumpouch with silica	11.16 ± 0.69^{a}	12.76 ± 0.50^{c}	24.21 ± 0.72^{c}	6.80 ± 0.005^{b}	0.42 ± 0.002^{d}	6.28 ± 0.25^{b}	6.28 ± 0.25^{b}	ND	ND
After six weeks	Paper pouch	31.39 ± 1.03^{a}	10.96 ± 0.52^{a}	15.19 ± 0.75^{a}	6.87 ± 0.010^{a}	ND	10.70 ± 0.41^{a}	10.70 ± 0.41^{a}	ND	ND
	Paper pouch with silica	29.12 ± 1.03^{b}	13.71 ± 0.09^{b}	10.85 ± 0.80^{b}	6.79 ± 0.005^{b}	ND	9.73 ± 0.29^{a}	9.73 ± 0.29^{a}	ND	ND
	Aluminiumpouch	28.04 ± 0.87^{b}	11.32 ± 0.22^{a}	10.12 ± 0.64^{b}	6.78 ± 0.005^{b}	ND	9.76 ± 0.63^{a}	9.76 ± 0.63^{a}	ND	ND
	Aluminiumpouch with silica	24.21 ± 0.72^{c}	13.56 ± 0.39^{b}	7.59 ± 0.85^{c}	6.80 ± 0.005^{b}	ND	7.46 ± 0.81^{b}	7.46 ± 0.81^{b}	ND	ND
After eight weeks	Paper pouch	27.18 ± 0.29^{a}	5.26 ± 0.08^{a}	10.91 ± 0.81^{a}	6.51 ± 0.010^{a}	0.63 ± 0.022^{a}	11.89 ± 0.39^{a}	11.89 ± 0.39^{a}	ND	ND
	Paper pouch with silica	27.37 ± 0.99^{a}	4.89 ± 0.81^{a}	9.43 ± 0.27^{b}	6.50 ± 0.010^{a}	0.59 ± 0.002^{b}	10.29 ± 0.30^{b}	10.29 ± 0.30^{b}	ND	ND
	Aluminiumpouch	30.90 ± 1.08^{b}	6.66 ± 0.80^{ab}	8.32 ± 0.24^{bc}	6.68 ± 0.005^{b}	0.55 ± 0.002^{c}	9.62 ± 0.21^{b}	9.62 ± 0.21^{b}	ND	ND
	Aluminiumpouch with silica	32.90 ± 1.77^{b}	7.62 ± 0.76^{b}	7.88 ± 0.289^{c}	6.74 ± 0.005^{c}	0.51 ± 0.010^{d}	7.10 ± 0.25^{c}	7.10 ± 0.25^{c}	ND	ND
After twelve weeks	Paper pouch	25.44 ± 1.20^{a}	7.71 ± 0.10^{a}	2.26 ± 0.01^{a}	6.36 ± 0.005^{c}	0.68 ± 0.020^{a}	13.57 ± 0.87^{a}	13.57 ± 0.87^{a}	60.00 ± 14.10^{a}	35.00 ± 7.07^{a}
	Paper pouch with silica	24.25 ± 0.67^{a}	7.55 ± 0.04^{a}	4.32 ± 0.57^{a}	6.42 ± 0.010^{b}	0.63 ± 0.013^{b}	11.94 ± 0.51^{ab}	11.94 ± 0.51^{ab}	40.00 ± 14.10^{b}	20.00 ± 7.07^{ab}
	Aluminiumpouch	21.41 ± 1.13^{b}	7.64 ± 0.40^{a}	3.43 ± 0.26^{b}	6.47 ± 0.005^{b}	0.61 ± 0.010^{b}	11.42 ± 0.40^{bc}	11.42 ± 0.40^{bc}	25.00 ± 7.07^{c}	15.00 ± 7.07^{ab}
	Aluminiumpouch with silica	24.25 ± 0.67^{a}	7.55 ± 0.04^{a}	4.02 ± 0.33^{a}	6.57 ± 0.005^{a}	0.56 ± 0.003^{c}	9.91 ± 0.62^{c}	9.91 ± 0.62^{c}	15.00 ± 21.20^{c}	5.00 ± 7.07^{b}

Values are mean ± standard deviation (n=3), while difference letters for values in each column indicate significant differences ($P < 0.05$)

***Supplementary Table S2*: Shelf-life properties of savory tropical almond samples**

Time Period	Packaging Type	Color			pH	Water activity	Moisture content (%)	Total plate count	Total plate count	Yeast and mould count
		L*	a*	b*						
After two weeks	Paper pouch	25.45 ± 0.55^{a}	18.85 ± 0.24^{a}	5.41 ± 0.41^{a}	6.88 ± 0.011^{a}	ND	7.63 ± 0.53^{a}	7.63 ± 0.53^{a}	ND	ND
	Paper pouch with silica	26.06 ± 0.34^{a}	17.85 ± 1.17^{a}	6.79 ± 0.81^{a}	6.83 ± 0.010^{b}	ND	6.43 ± 0.48^{b}	6.43 ± 0.48^{b}	ND	ND
	Aluminiumpouch	17.08 ± 0.90^{b}	27.04 ± 1.31^{b}	2.97 ± 0.18^{b}	6.83 ± 0.005^{b}	ND	5.63 ± 0.31^{b}	5.63 ± 0.31^{b}	ND	ND
	Aluminiumpouch with silica	24.14 ± 1.04^{a}	18.05 ± 0.59^{a}	9.19 ± 0.81^{c}	6.81 ± 0.005^{b}	ND	4.72 ± 0.40^{c}	4.72 ± 0.40^{c}	ND	ND
After four weeks	Paper pouch	11.47 ± 1.28^{a}	13.88 ± 0.65^{ac}	31.39 ± 1.03^{a}	6.87 ± 0.010^{a}	0.54 ± 0.002^{a}	8.46 ± 0.41^{a}	8.46 ± 0.41^{a}	ND	ND
	Paper pouch with silica	12.82 ± 0.73^{a}	16.83 ± 0.62^{b}	29.12 ± 1.03^{b}	6.79 ± 0.005^{b}	0.51 ± 0.001^{b}	7.54 ± 0.44^{a}	7.54 ± 0.44^{a}	ND	ND
	Aluminiumpouch	11.02 ± 0.38^{a}	15.01 ± 0.64^{a}	28.04 ± 0.87^{b}	6.78 ± 0.005^{b}	0.48 ± 0.001^{c}	7.48 ± 0.46^{a}	7.48 ± 0.46^{a}	ND	ND
	Aluminiumpouch with silica	11.16 ± 0.69^{a}	12.76 ± 0.50^{c}	24.21 ± 0.72^{c}	6.80 ± 0.005^{b}	0.42 ± 0.002^{d}	6.28 ± 0.25^{b}	6.28 ± 0.25^{b}	ND	ND
After six weeks	Paper pouch	31.39 ± 1.03^{a}	10.96 ± 0.52^{a}	15.19 ± 0.75^{a}	6.87 ± 0.010^{a}	ND	10.70 ± 0.41^{a}	10.70 ± 0.41^{a}	ND	ND
	Paper pouch with silica	29.12 ± 1.03^{b}	13.71 ± 0.09^{b}	10.85 ± 0.80^{b}	6.79 ± 0.005^{b}	ND	9.73 ± 0.29^{a}	9.73 ± 0.29^{a}	ND	ND
	Aluminiumpouch	28.04 ± 0.87^{b}	11.32 ± 0.22^{a}	10.12 ± 0.64^{b}	6.78 ± 0.005^{b}	ND	9.76 ± 0.63^{a}	9.76 ± 0.63^{a}	ND	ND
	Aluminiumpouch with silica	24.21 ± 0.72^{c}	13.56 ± 0.39^{b}	7.59 ± 0.85^{c}	6.80 ± 0.005^{b}	ND	7.46 ± 0.81^{b}	7.46 ± 0.81^{b}	ND	ND
After eight weeks	Paper pouch	27.18 ± 0.29^{a}	5.26 ± 0.08^{a}	10.91 ± 0.81^{a}	6.51 ± 0.010^{a}	0.63 ± 0.022^{a}	11.89 ± 0.39^{a}	11.89 ± 0.39^{a}	ND	ND
	Paper pouch with silica	27.37 ± 0.99^{a}	4.89 ± 0.81^{a}	9.43 ± 0.27^{b}	6.50 ± 0.010^{a}	0.59 ± 0.002^{b}	10.29 ± 0.30^{b}	10.29 ± 0.30^{b}	ND	ND
	Aluminiumpouch	30.90 ± 1.08^{b}	6.66 ± 0.80^{ab}	8.32 ± 0.24^{bc}	6.68 ± 0.005^{b}	0.55 ± 0.002^{c}	9.62 ± 0.21^{b}	9.62 ± 0.21^{b}	ND	ND
	Aluminiumpouch with silica	32.90 ± 1.77^{b}	7.62 ± 0.76^{b}	7.88 ± 0.289^{c}	6.74 ± 0.005^{c}	0.51 ± 0.010^{d}	7.10 ± 0.25^{c}	7.10 ± 0.25^{c}	ND	ND
After twelve weeks	Paper pouch	25.44 ± 1.20^{a}	7.71 ± 0.10^{a}	2.26 ± 0.01^{a}	6.36 ± 0.005^{c}	0.68 ± 0.020^{a}	13.57 ± 0.87^{a}	13.57 ± 0.87^{a}	60.00 ± 14.10^{a}	35.00 ± 7.07^{a}
	Paper pouch with silica	24.25 ± 0.67^{a}	7.55 ± 0.04^{a}	4.32 ± 0.57^{a}	6.42 ± 0.010^{b}	0.63 ± 0.013^{b}	11.94 ± 0.51^{ab}	11.94 ± 0.51^{ab}	40.00 ± 14.10^{b}	20.00 ± 7.07^{ab}
	Aluminiumpouch	21.41 ± 1.13^{b}	7.64 ± 0.40^{a}	3.43 ± 0.26^{b}	6.47 ± 0.005^{b}	0.61 ± 0.010^{b}	11.42 ± 0.40^{bc}	11.42 ± 0.40^{bc}	25.00 ± 7.07^{c}	15.00 ± 7.07^{ab}
	Aluminiumpouch with silica	24.25 ± 0.67^{a}	7.55 ± 0.04^{a}	4.02 ± 0.33^{a}	6.57 ± 0.005^{a}	0.56 ± 0.003^{c}	9.91 ± 0.62^{c}	9.91 ± 0.62^{c}	15.00 ± 21.20^{c}	5.00 ± 7.07^{b}

Values are mean ± standard deviation (n=3), while difference letters for values in each column indicate significant differences ($P < 0.05$)