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Development and Evaluation of A Sustainable Processed Goat's Cheese Analogue Fortified With Millet-Zein Cheese Base: Optimizing Nutritional, Functional, and Sensory Properties for Arid Regions

El-sayed M. Abdeen*
Animal and Poultry Breeding Department, Desert Research Center, Almatariya, Cairo, 1753, Egypt

THE growing demand for sustainable and functional plant-based dairy alternatives has driven innovation in cheese analogue production. This study developed a processed goat cheese analogue fortified with a plant-based base derived from millet, zein protein, and tapioca starch, evaluating its nutritional, functional, and sensory properties. Millet was processed (soaking, germination, fermentation) to enhance its protein bioavailability and reduce antinutrients. Substitution levels of 25, 50, 75, and 100% of the millet cheese base were tested against a traditional goat processed cheese control (100% dairy). Results indicated that (50% substitution (T2) achieved optimal sensory acceptance, closely resembling, meltability, and flavor of conventional cheese. Higher substitutions (75–100 %) reduced fat content (≤ 3.72%) and improved antioxidant activity (e.g., 52.8% DPPH retention in T4 after 3 months) but compromised texture and flavor complexity. Meltability increased during storage (69.5–76.7 mm in control), while millet cheese base (100%) formulations exhibited superior emulsion stability (21.7% oil separation in T4 vs. 33.8% in control). Microbiological analysis confirmed enhanced safety, with millet cheese-based showing lower microbial growth (3.7 log CFU/g vs. 5.3 log CFU/g in control) and no detectable pathogens. The study highlights the viability of 50–75% plant substitution for producing nutritionally enriched, sustainable cheese analogues, addressing health and environmental trends. Challenges remain in optimizing 100 % plant-based formulations for texture and flavor. This work contributes to food security in arid regions like the Halayeb-Shalateen-Abu Ramad triangle by leveraging locally available crops, offering a model for resource-efficient dairy alternatives.

Keywords: Goat processed cheese – millet cheese base- zein protein – tapioca starch.

Introduction

The growing demand for functional foods, driven by health benefits, environmental sustainability, and dietary preferences, has led to the increased popularity of processed cheese and its plant-based alternatives. Cheese analogs, which serve as substitutes for traditional dairy cheese, have emerged as a viable option for consumers seeking non-dairy or vegan products (Durak et al., 2025). The majority of plant cheese recipes include additional ingredients like coconut oil and starch to help the end product attain its function and shape but reduces the nutritional value (Grasso et al., 2021; Grasso et al., 2022). For example, the majority of ordinary cheeses have a protein value of around 18–25%, while commercial vegan cheeses have much lower protein values ranging from 0.6–3%. It is not easy to create plant-based foods that have high protein levels and the same look, feel, and functionality as the regular cheeses. This is mainly because of the special structures and properties of the proteins (Zhang et al., 2024). The use of plant proteins as the main structural component of plant-based cheese has been studied in the past. Pea-based cheeses or soy

*Corresponding Author: E-mail: Saidabdeen7@gmail.com, ORCID ID https://orcid.org/0000-0003-0912-2269
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milk for cream cheese substitutes (Li et al., 2020) have been the focus of most of these studies. Due to its melt-stretch and viscoelastic properties, which are similar to those of Cheddar cheese, zein has been studied and used in plant-based cheeses alone or in conjunction with other plant proteins like pea or chickpea (Grasso et al., 2024; Mattice & Marangoni, 2020; Salgado et al., 2023; Dobson & Marangoni, 2023). Zein, a protein derived from corn, is valued for its ability to stabilize emulsions and mimic the texture of dairy cheese (Mattice & Marangoni, 2020). Similarly, millets are gaining recognition for their nutritional profile, affordability, and functional properties, making them an ideal base for plant-based dairy products (Kumar et al., 2018). Prepared cheese and impersonation cheese items are encased in steady oil-in-water emulsions to create a smooth, uniform texture, while additional dairy and non-dairy additive ingredients such as eggs, milk, normal cheeses, and consumable oils or fats are blended with them for their rheological properties, softness, moisture level, etc, during the warm treatment. Processed cheese items also have an important function as garnish on prepared dishes like pizzas. Pizza stands. The softening properties of zein, when combined with flour, water, and oil, make it a suitable protein substitute for plant-based cheese in dissolving applications. It can also be softened to similar levels as cheese when added to corn starches and gums (Mattice and Marangoni, 2020). In addition, zein's properties make it popular for stabilizing emulsions and sequestering vitamins. The synthesis of zein and other plant-based proteins into nourishment items like cheeses can produce similar surfaces and flavors, while advertising health benefits such as increased protein availability and assimilation by LAB (Shunmugapriya et al., 2020) Millets are an excellent choice for plant-based drain sources due to their health benefits and affordability. Millet drain fulfilled the physical criteria for a plant-based drain, with the protein substance ranging from. Moreover, millets are generally low in fat and rich in unsaturated fats and rich source of bioactive and antioxidant properties that help predict non-communicable diseases such as weight gain, cardiovascular disease, infertility, and diabetes mellitus. (Kumar et al, 2018). This trend has fueled the rise of plant-based products, veganism, and vegetarianism. Understanding the varying functions of plant-based proteins is crucial for developing new plant-based goods (Dekkers et al., 2018). Millets are a great source of essential amino acids, especially those that include sulfur, such cysteine and methionine, which have been shown to have therapeutic advantages (Meena et al., 2024). Despite these innovations, there is a need for further research to optimize the formulation of plant-based cheeses and ensure they meet consumer expectations. This study investigates the effects of substituting traditional goat processed cheese with plant-cheese based alternatives derived from zein proteins, millet flour, and oil (coconut + corn) at varying levels (25, 50, 75, and 100%). By evaluating the rheological, textural, and sensory properties of these formulations, the research aims to contribute to the development of high-quality plant-based cheese products that align with modern dietary trends and consumer preferences.

Materials and Methods

Materials

Millet Shandaweel 1 was obtained from Filed Crops Institute, Agricultural Research Center Ministry of Agriculture, Giza, Egypt. Zein protein, butter oil, coconut oil, corn oil, Ras cheese and tapioca starch, cheddar cheese flavor and Table salt were purchased from the local market, Giza, Egypt, Commercial JOHA emulsifying salts S9 (E452 sodium polyphosphate, E339sodium orthophosphate) were obtained from BK-Ladenburgcorp., Gmbh, Germany, lecithin and YF-L812® starter cultures containing: *Lactobacillus delbrueckii ssp bulgaricus* and *Streptococcus thermophilus* were purchased from Chr. Hansen's Lab., Copenhagen, Denmark.

Methods

Preparation of plant cheese base

1. Preparation of millet milk and yoghurt cheese

According to Nair et al. (2020) and Mugocha et al. (2000) methods with some modifications, millet Shandaweel 1 grains were soaked for 12 hr, drained, and pulverized with water to extract milk. The extracted milk was filtered using muslin cloth, pasteurized at 63°C for 30 minutes, and cooled to room temperature. The pasteurized milk was inoculated with a 1:1 ratio of *Lactobacillus bulgaricus* and *Streptococcus thermophilus* and incubated at 42°C for 6 hours to form yoghurt. The yoghurt was refrigerated, and the resulting curd was drained overnight in cloth bags, packed in PVC containers, and stored at 5-7°C until use.

2. Preparation of zein protein emulsion

According to Rutkevičius et al. (2018) and

De Folter et al. (2021) methods with some modifications, zein protein (2-3% by weight) was dissolved in mixed alcohol (ethanol) +water (after that evaporated alcohol) and adjusted to a pH 6.5 using citric acid and adding 0.05% lecithin. After that corn oil (9%) and coconut oil (9%) were blended with the zein solution and stirring continuously with high speed. Tapioca starch (2%) was mixed with cold water to form slurry, added to the zein-oil emulsion, and heated to 70-80°C to achieve a smooth, thickened consistency.

3. Preparation of plant processed cheese base

Millet yoghurt cheese was blended with the zein protein emulsion at 70-80°C. Salt (1% by weight) and cheddar cheese flavor were added, and the mixture was packed into containers for storage.

4. Manufacture of processed cheese analogue

Goat processed cheese analogues (Control) were prepared by blending matured Ras cheese, goat soft cheese curd, butter oil, emulsifying salts, and water in a laboratory processing kettle. The blends were adjusted to contain 42% total solid, 21% fat, and 2.5% emulsifying salts. Millet processed cheese base was substituted for cheese at ratios of 25, 50, 75, and 100%. The mixture was cooked at 85-90°C for 10 min, hot-filled into glass jars, and stored 1,2 and 3-month at 5±2°C for analysis, shown in Fig1.

Methods of analysis

Physicochemical properties

Meltability and oil separation were evaluated for all processed cheese analogues. Meltability was measured as the spread diameter after heating, while oil separation was determined as the percentage of free oil released during storage, evaluated using a method Fernandez & Kosikowski, (1986). The percentage of Meltability was calculated from the following equation: Meltability (%) = Area of melted discs-Area of original discs.

Color analysis

Cheese color was measured using a Mini Scan portable colorimeter (Hunter Associates Laboratory Inc., Reston, VA, USA). Color standardization was done using black and white standard plates placed in a 3.5 mL plastic bag normally used for cheese packaging. The measurements for cheese color were done by using commission International del 'Eclairage (1978) L*, a* and b* values with illuminant D65. The a* value is an indicator of red (+) and green (−). The b*value is an indicator of yellow (+) and blue (−). The L*value is an indicator of luminosity (the degree of lightness from black to white). Because combining a* value and b*value gives a better color indication than their individual values, hue angle was calculated as the inverse tangent of the ratio b*/a* according to the manufacturer's instructions. The petri dish was placed directly on the colorimeter sensor. The color intensity (C*) "Eq. 1", the hue angle (h_{ab}°) "Eq. 2" and total color difference (ΔE) "Eq. 3" in comparison to the untreated control, was calculated as, whereas h_{ab}° = 90° for a yellow hue and h_{ab}° = 0° for a red hue, the values were expressed as follow:

$$\text{Color intensity } (C^*) = (a^{*2}+b^{*2})^{0.5} \longrightarrow \quad (1)$$

$$\text{Hue angle } (h_{ab}\,°) = \text{Arctan } (b^*/a^*) \longrightarrow \quad (2)$$

$$\text{Total color difference } (\Delta E) = [(L-L0)^2+(a-a0)^2+(b-b0)2]^{0.5} \longrightarrow \quad (3)$$

The color was expressed as a whiteness index (WI*) Eq. 4 based on the following formula (Al-Hooti et al., 2000):

$$WI^* = 100-[(100-L^*)^2+a^{*2}+b^{*2}]^{0.5} \longrightarrow \quad (4)$$

The Browning Index (BI*) Eq. 5 was calculated as described by (Palou et al.,1999) using the following formula:

$$\text{Browning index } (BI^*) = [100(x-0.31)]/0.172 \longrightarrow \quad (5)$$

Where: $x = [(a + 1.75L)/ (5.645L + (a - 3.012b))]$

Texture profile analysis (TPA)

Texture measurements of samples were performed according to Bourne (2002) with the universal testing machine (Cometech, B type, Taiwan) provided with the software. Back extrusion cell with a 35 mm diameter compression disc

Chemical composition and analysis

The chemical composition of raw materials and processed goat's Cheese analogue were analyses as shown in Table 1 and Table 3. Proximate analysis included moisture, fat, protein, ash, and carbohydrate content following the methods AOAC, (2007). Polyphenols, total flavonoids, phytic acid, and tannins were also measured by James, (1995). Antioxidant activity was determined as a described by Re et al. (1999). The pH values of the cheese samples were measured using a digital pH meter (HANNA) equipped with a glass electrode (Electric Instruments Limited).

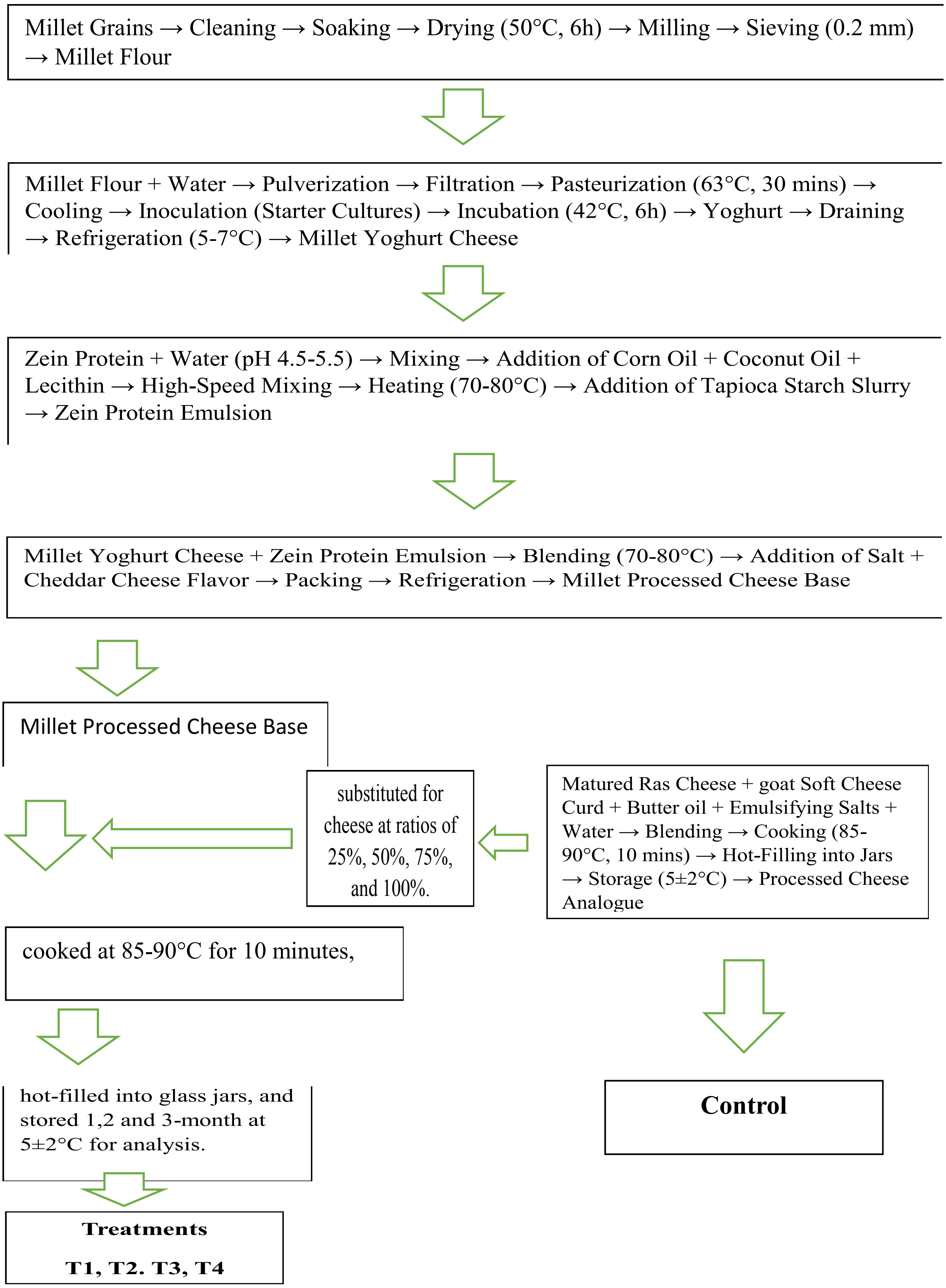

Fig. 1. Diagram of Preparation of processed goat's Cheese analogue fortified with plant-cheese base.

TABLE 1. Composition of raw materials used in the manufacture of processed cheese spread.

Parameters	Ras cheese	goat soft cheese	millet cheese	zein protein	Tapioca starch
TS	62.41±0.23	37.13±0.36	24.13±0.51	80.00±0.62	87.00±0.46
Fat %	32.18±0.15	16.23±0.16	3.72±0.24	0.00	0.00
Protein %	19.05±0.37*	11.75±0.32*	6.46±0.43**	80.00±0.55**	0.00
Ash %	4.18±0.62	2.15±0.46	1.14±0.33		0.20±0.29
Fiber %	0	0	0.66±0.83		0.00
Carbohydrate	1.43±0.35	3.09±0.19	3.56±0.27		85.00±0.39
pH	5.64±0.36	4.61±0.19	4.53±0.28		6.60±0.14

*Protein% – N × 6.38. **Protein % – N × 4.38

TABLE 2. Formulations of processed cheese spread analogue with millet cheese base.

Ingredients	Formula				
	Treatments (%)				
	Control	T1	T2	T3	T4
Ras cheese	30	26.25	22.5	7.5	0
goat soft cheese	45	23.25	19.93	10.63	0
millet cheese base	0	11.68	23.35	35.03	51
zein protein	0	4.39	4.83	10.08	12.13
oil	4	7.34	8.02	14.56	18.1
emulsifying saltsS9	2.5	2	2	2	2
Tapioca starch	0	0.75	1	1.5	2
lecithin	0	0.05	0.05	0.05	0.05
water	18.5	24.29	18.32	18.66	14.72
Total (%)	100	100	100	100	100

Treatments T1, T2, T3, T4 with 25, 50, 75 and 100 % millet cheese base substitution of cheese base respectively.

Amino acid profile of processed goat cheese analogue

Amino acid profile analysis was conducted using Eppendorf-Biotronic LC 3000 amino acid analyzer (Eppendorf-Biotronic, Hamburg, Germany) according to AOAC, (2007).

Sensory properties

Samples were sensory scored by 12 panelists according to the scheme of Meyer (1973) for external appearance (20 points). Body and texture were counted for 40 points and aroma and flavor (40 points). The course of scoring for each sample was repeated three times

Statistical analysis

The data were analyzed by the one-way ANOVA test according to the appropriate experimental designs, and reported as (means ± standard deviations), which were separated by Duncan's New Multiple Range Test at $p<0.05$ (Kirk, 2007) using SPSS computer program, version 16.0 (SPSS Inc., Chicago, IL, USA

Results and Discussion

Nutritional content of millet cheese base

The result obtained from the analysis of the proximate composition of the samples is as shown in Table 3. The content of crude protein, fat, fiber, ash and carbohydrates vary depending on the processing methods of millet (millet flour processing and millet milk processing). Millet flour processing affected significantly (p<0.05) on macro composition moisture increases with treatment soaking, germination and roosted. This indicates that the moisture content increased significantly (p<0.05) during germination. This may be the whole grain absorbs moisture from the soaking medium during germination and starts to metabolize, which in turn affects the grain structure, with longer soaking time, more cells in the seed are hydrated (Enwere, 1998; Giami, 1993; Guemra, et al., 2024; Harbone 1973). Protein content remains relatively stable across treatments (heat treatment and fermentation, with increase in the millet cheese base (5.46%). This suggests that the processing methods significantly (p<0.05) affect protein levels, while the cheese-making process might concentrate it, (Johnson et al. 1986; Kinsella, 1976). Fat content is highest in soaked millet (6.89%) and generally significantly (p<0.05) decreases with further processing. The millet cheese base has the lowest fat content (2.72%). Fiber content decreases substantially with processing. Raw millet has the highest fiber (2.47%), while the millet cheese base has the lowest (0.66%). This decrease is particularly notable after germination and further processing. Similar to fiber, ash content (representing minerals) decreases with processing, with raw millet having the highest value (1.83%) and the millet cheese base the lowest (1.14%). Carbohydrates are the major component, showing a decreasing trend with increased processing. Raw millet has the highest carbohydrate content (72.84%), significantly (p<0.05) reducing in the millet cheese base (15.16%). This decrease could be due to the removal of some carbohydrate components during processing, particularly in cheese making. Processing such as soaking, germination, roasting, and heat treatment and fermentation are widely used for improving the properties, palatability and reduce the levels of polyphenols, total flavonoids, phytic acid, and tannins. The millet cheese base has the lowest levels of these antinutrients. This reduction is crucial as these compounds can interfere with nutrient absorption, that results agree with (Duenas et al., 2009; Gallegos-Infante et al., 2010; Pradeep & Guha, 2011; Chandrasekara & Shaidi 2011a; Guemra et al., 2024; Shahidi & Chandrasekara, 2015).

Chemical composition of processed cheese analogue

The effect of the addition of millet cheese base on the chemical composition of the goat processed cheese treatment analogues supplemented with millet cheese base with different ratio are shown in Table 4. The obtain results showed that both the control cheese and goat processed cheese analogue containing millet cheese base were found to be within the commotional range of processed cheese The addition of 25, 50, 75, and 100% millet chees base significantly increased the total solids, protein, ash, and carbohydrate contents of the treatment goat processed cheese compared with the control. This was expected as the recipes were adjusted before the cooking process in all experiments, due to good standardization of cheese blends before processing. Overall, Carbohydrate contents were the highest in treatments with millet cheese base (T1, T2, T3 and T4) and the lowest in control. These results may be due to the decrease in the percentage of millet cheese base with increasing the percentage of millet cheese base. These results agree with those of Alwohaibi et al. (2023) and khalifa et al. (2020).

Physical properties

Meltability

Meltability represents an essential practical attribute of processed cheese merchandise, characterized by using the ability of cheese to liquefy and disperse when subjected to warmth, that's regularly followed by means of a noticeable degradation within the structural integrity of character cheese shreds (Guinee, 2011). Results from Table 5 show the impact of supplementation of millet cheese base by different ratios on meltability . The meltability of goat processed cheese significantly decreased (p<0.05) with the increased ratio of millet cheese base. Meltability of goat proceeded cheese analogue increased in all samples during storage, this is agreed with Abd Elmontaleb (2023) and Hamdy et al. (2021). This gradual increase during storage might be due to the interactions between proteins and emulsifying salts as well as the higher dissociation of casein (Hamdy et al., 2021; Tamime,et al.,1999 and Dharaiya, et al., 2019), and this may be attributed to the stabilization of protein networks and fat globules during storage (Dharaiya et al., 2019; Hafiz, et al.,2024).

TABLE 3. Effect of processing methods on nutritional content of millet cheese base.

Parameters	U	Millet Flour processing			Millet milk processing			
		S	SG	SGR	MM	H	F	C
Moisture	7.72±0.16^{e}	8.87±0.18^{d}	14.39±0.42^{c}	18.92±0.28^{b}	88.15±0.11^{a}	88.58±0.18^{a}	88.60±0.13^{a}	7373.87±0.27^{f}
Protein %	10.25±0.87^{ab}	10.19±1.35^{ab}	10.72±1.45^{a}	10.15±1.12^{ab}	2.56±1.54^{c}	2.54±0.^{21c}	2.69±1.4^{c}	66.46±0.99^{b}
Fat%	4.89±0.07^{c}	6.89±0.06^{a}	5.48±0.08^{b}	5.19±0.05^{bc}	1.18±0.26^{e}	1.10±0.52^{e}	1.09±0.14^{e}	2.72±0.46^{d}
Fiber%	2.47±0.23^{a}	1.72±1.23^{b}	1.14±0.50^{c}	1.08±0.16^{cd}	0.92±0.44^{cd}	0.53±0.26^{d}	0.53±0.61^{d}	0.66±0.56^{d}
Ash%	1.83±1.63^{a}	1.77±0.92^{a}	1.68±0.88^{a}	1.59±0.39^{ab}	0.55±0.11^{c}	0.51±0.22^{c}	0.51±0.32^{c}	1.14±0.44^{b}
Carbohydrate%	72.84±0.4^{a}	70.56±0.06^{a}	66.59±0.07^{b}	63.07±0.09^{ab}	6.64±0.13^{c}	6.73±0.24^{c}	6.59±0.31^{c}	15.16±0.24^{b}
Polyphenol mg/100g	275.60±0.01^{a}	258.24±0.21^{b}	98.13±0.63^{c}	89.46±0.21^{c}	78.18±0.16^{d}	39.09±1.22^{e}	19.30±0.12^{f}	9.45±0.32^{g}
Total Flavonoids	158.00±0.44^{a}	148.05±0.32^{b}	56.26±0.17^{c}	51.28±0.19^{c}	44.82±0.24^{d}	22.41±0.39^{e}	11.06±0.46^{f}	7.63±0.42^{f}
Phytic acid mg/100g	564.00±0.53^{a}	302.87±0.14^{b}	145.38±0.40^{c}	83.10±0.14^{d}	72.63±0.51^{e}	36.31±0.40^{f}	17.92±0.16^{g}	13.44±0.34^{g}
Tannins mg/100g	235.00±0.13^{a}	173.20±0.17^{b}	65.81±0.11^{c}	40.25±0.37^{d}	35.18±0.37^{e}	17.59±0.19^{f}	8.68±0.29^{g}	5.64±0.13^{g}

$^{a-g}$Means (n=3) within a row with different superscripts differ (p<0.05). U = Untreated, S= Soaking, R=Roasted, G=Germination, MM= Millet milk, H=Heat treatment, F=Fermentation, C= millet cheese base.

TABLE 4. Chemical composition (%) of fresh processed cheese analogues as affected by different substitution levels of millet cheese base.

Parameters	Treatments				
	Control	T1	T2	T3	T4
Total solids	41.88±0.21^{c}	41.35±0.15^{d}	41.84±0.19^{c}	43.01±0.09^{b}	43.86±0.20^{a}
Fat	20.96±0.16^{a}	20.00±0.36^{b}	19.36±0.24^{c}	20.00±0.13^{b}	20.00±0.27^{b}
Protein	11.00±0.23^{c}	12.00±0.14^{b}	12.00±0.16^{b}	13.00±0.19^{a}	13.00±0.13^{a}
Ash	2.22±0.17^{a}	1.73±0.29^{b}	1.64±0.34^{bc}	0.94±0.37^{c}	0.58±0.25^{d}
Carbohydrate	7.42±0.15^{d}	7.62±.31^{d}	8.84±0.28^{c}	9.07±0.22^{b}	10.28±0.19^{a}

$^{a-d}$ Means (n=3) within a row with different superscripts differ (p <0.05). C=100 % C, T1=75% C, T2=50% C+50 % P, T3=75 % P +25 % C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

TABLE 5. Meltability and oil separation (%) of fresh processed cheese analogues as affected by different substitution levels of millet cheese base.

Storage period (month)	Treatments				
	Control	T1	T2	T3	T4
	Meltability (mm)				
Fresh	69.53±0.04^{a}	65.86±0.07^{b}	66.09±0.05^{b}	65.57±0.11^{b}	65.75±0.02^{b}
1	72.36±0.12^{ab}	71.32±0.18^{b}	72.88±0013^{a}	70.00±0.09^{c}	69.50±0.11^{d}
2	74.25±0.08^{bc}	74.77±0.09^{b}	75.88±0.02^{a}	74.34±0.03^{bc}	71.25±0.07^{c}
3	76.67±0.20^{bc}	77.25±0.26^{b}	78.25±0.32^{a}	76.00±0.29^{c}	73.00±0.20^{d}
	Oil separation (%)				
Fresh	33.85±0.32^{a}	30.55±0.29^{b}	28.71±0.41^{c}	25.28±0.35^{d}	21.70±0.28^{e}
1	37.02±0.17^{a}	36.52±0.42^{ab}	35.42±0.34^{ab}	30.37±0.21^{b}	28.78±0.17^{c}
2	44.53±0.38^{a}	43.41±0.26^{ab}	40.98±0.08^{b}	35.78±0.18^{c}	32.21±0.09^{d}
3	48.33±0.25^{a}	46.37±0.51^{ab}	41.27±0.23^{b}	39.80±0.29^{bc}	37.60±0.36^{c}

$^{a-e}$Means (n=3) within a row with different superscripts differ (p <0.05). C=100 % C, T1=75% C, T2=50% C+50 % P, T3=75 % P +25 % C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

Oil separation

Oil separation in goat processed cheese analogue samples decreased significantly (p<0.05) with increase millet cheese base. Result from Table 5 show the lowest oil separation in T4 (21.70%), likely due to its high starch content (tapioca starch) can be stabilize emulsions in processed cheese analogues. Oil separation of goat processed cheese analogue increased in all samples during storage, higher oil separation in control (48.33% at three months) and T1 (46.37% at three months) might be due to partial substitution, where the interplay between milk fats and millet components created a less stable emulsion over time. Similar findings were reported by Masotti et al. (2018), where partial substitution affected emulsion stability in cheese analogues.

Textural profile analysis (TPA)

Cheese's texture is a crucial aspect of its quality. It is a mixture of various characteristics, including hardness, cohesive ness, gumminess, springiness, and chewiness. Gumminess is the product of both hardness and cohesiveness. Chewiness is the sum of both gumminess and springiness, which is the degree of flexibility at which cheese can be stretched before returning to its original length. The textural features of the goat processed cheese analogues with varying substitution ratios of with millet cheese base during storage at 5±2°C for 3 months were presented in Table 6. It is noticed that the hardness decreased (p<0.05) significantly with the increase of the millet cheese base ratio. The hardness recorded the highest values in control, T1, T2 and T3, respectively. Also, the hardness values of all treatments increased (p<0.05) significantly during the storage period for 3 months. Other texture parameters, such as adhesiveness, cohesiveness, gumminess, springiness and chewiness, were determined. All treatments showed significantly (p<0.05) low values with the increase of millet cheese base ratio supplementation compared with the control. The adhesiveness, cohesiveness and springiness values were recorded in Table 6. Gumminess values decreased with the increase of millet cheese base ratio and low levels in control treatments. Chewiness value was the highest in control, T1and T2 treatments. During the storage period, the chewiness increased, with the control experiencing the highest chewiness, possibly due to the combined effects of hardness, cohesiveness, and springiness. The lower chewiness values in the control with millet cheese base suggest that these ingredients due to a less chewy texture. Millet cheese base ingredients suggest that these ingredients may help maintain the elasticity of the cheese analogues during storage, which could be beneficial for the sensory quality of the product. These results are agreement with (Trivedi, et al., 2008; Awad, et al., 2014; Khalifa, et al., 2020). Therefore, millet cheese base can enhancement cheese quality, especially in its physical characteristics. Hence, the higher level of zein protein and tapioca starch in millet cheese base would improve the cheese's texture. It is expected to produce better-quality cheese as an innovative cheese product.

Total phenol, total flavonoid and antioxidant activity (DPPH)

Total phenol compounds, total flavonoid compounds and antioxidant activity (DPPH) radical scavenging activity %of goat processed cheese analogue supplemented with millet cheese base presented in Fig. 2 during storage at 5°C for 3-month. The results showed that the total phenol and total flavonoid compound significantly (p<0.05) higher in (T1, T2, T3 and T4) treatments than control. This could be attributed to the increase of millet cheese base addition. The percentage of inhibition of DPPH radicals in goat processed cheese analogue samples increased with increasing millet cheese base concentration, due to, it has high levels of total phenol, and total flavonoid compounds. On the other hand, the Total phenol, total flavonoid and antioxidant activity (DPPH) of all treatments decreased significantly (p<0.05) during storage period. These results agree with those of (Alwohaibi et al., 2023; khalifa et al., 2020).

Color Profile

Table (7) presents the Color changes of processed cheese analogues with supplemented with millet cheese base (T1–T4) during storage period of 3 months at 5±2°C. Lightness (L*) values of fresh processed cheese analogues with supplemented with millet cheese base recorded slightly significant (p<0.05) decrease values with increase millet cheese base ratio. However, the lightness (L* value) of all cheese samples was low values during storage time. This could be attributed to the increase in acidity and proteolysis that occurs during the storage period and the transformation of casein into a more soluble state, which may lead to a decrease in white ness. The a* values (redness) of cheese samples were significantly increased (P < 0.05) when higher levels of millet cheese base were added, these results agree with (Alwohaibi et al., 2023). Additionally, the average redness (a*) of all cheeses increased with an increased storage period (Table 7). These results may be due to the a* values of cheese being affected by microbiological, biochemical, chemical, and physical changes that happen during processing and storage. The b* (yellow components) value showed a significant ($p<0.05$) decreased when the proportion of millet cheese base was increased. The hue angle (h*), chroma (C*), white index (WI), total Color Difference (ΔE), and browning index (BI) were found to be improved in all fortified cheeses compared to the control group. Additionally, the improvement in color of the goat processed cheese analogue increased with higher percentages of added millet cheese base, indicating a positive correlation between millet cheese base concentration and quality improvements. These results highlight millet's potential to enhance color retention and reduce browning in plant-based analogues, supported by its antioxidant-rich profile and compatibility with emulsifying salts.

Amino acid profile

Results presented in the table S1 show the total amino acid contents of (in mg/g sample) of processed cheese analogues made from varying proportions of goat processed cheese (C) with millet cheese base (P) at different levels. The results revealed significant ($p<0.05$) changes in both essential and non-essential amino acids over a 3-month storage period. The 50:50 blends (TF3 and TS3) consistently showed higher essential amino acids (Methionine, Leucine and Phenylalanine) concentrations in comparison to other amino acids during storage period (Abd Elmontaleb et al., 2023). The results suggesting that a balanced proportion of goat and millet cheese provides a stable protein matrix. Storage of 3 months at 5°C led to changes in amino acid profiles, with some amino acids significant ($p<0.05$) increasing, and good blended cheese formulations can enhance amino acid stability during storage (Kemter et al., 2018). The decrease in lysin (LYS) content in millet cheese formulations is consistent with reports of (LYS) being susceptible to degradation in plant-based dairy analogues (Zhang et al., 2024).

Microbiological examination

Results presented in Table 8 indicated that the millet cheese base addition at different levels show significant ($p<0.05$) on total viable count (TVC).These results indicated that addition millet cheese base decreased significant ($p<0.05$) the contents of these bacterial count. For example, T4 had 3.7 Log10 CFU/g after 3 months, compared to 5.3 Log10 CFU/g in control. The decrease was associated with level of addition of millet cheese base. These results could be due to millet's derived phenolic compounds (e.g., ferulic acid) and flavonoids (e.g., quercetin) disrupt microbial cell membranes and inhibit enzyme activity, reducing microbial growth. So millet cheese base (T2–T5) demonstrated improved microbial stability during storage, with lower TVC and yeast/mold counts compared to the control. These results are in agreement with reported by Takó et al. (2020) and Dagalia (2012). Results also indicated that the total viable count gradually increased with advance of storage period. On the other hand molds and yeast detected in all samples, but as light gradual decrease was observed with millet cheese base treatments. However, coliform bacteria were not detected in either fresh sample until 2 months for all treatments and appear after 1month in control treatments while T3 and T4 keeping good quality. These results validate millet's potential as a natural preservative in plant-based dairy alternatives, supporting extended shelf-life and food safety.

Sensory characteristics

Sensory evaluation of processed cheese analogues as affected by different substitution levels of millet cheese base is shown in Table 9. Appearance was significantly ($P<0.05$) affected by the addition of millet cheese base and the lowest score were recorded in control. While during storage, all treatments samples were decreased, which may be due to changes in the color and surface condition of the cheese analogue during storage. This indicates that the addition of a certain proportion of millet processed cheese base (P) can improve the appearance of the cheese analogue. This is consistent with the findings of Abd El-Wahed & Hassanien (2019), who reported that the addition of peanut cream fat improved the appearance of processed cheese spread analogues. Body and texture score were improved with the increase of millet cheese base ratio. The highest value was presented in T1 and T2 (31.62) and (31.33) respectively. Statistical analysis exhibited a significant difference ($p<0.05$) among all treatments compared to the control. Properties of millet cheese base are used to enhance body and texture in the goat processed cheese as an emulsion, water-retention agents, stabilizers and thickeners (Khalifa et al., 2020; Amara, et al., 2022). The flavor scores of all treatments were significantly ($p<0.05$) compared to the control, it improved with the addition of millet cheese base. The flavor score for the different treatments were significant ($p<0.05$) compared to the control. T1 and T2 had higher flavor scores from start and end storage time, indicating that the addition of millet cheese base can enhance the flavor of the cheese analogue. However, the flavor scores of all treatments decreased significantly during storage. The sensory analysis showed that the treatments with millet cheese base T1 and T2 at 25 and 50% (w/v) respectively had the highest overall acceptability because millet cheese base facilitates to produce a smooth texture and a good appearance. Total scores of all treatments decreased with the storage period. T1 had the highest total scores throughout the storage period, followed by T2, while the control group had the lowest scores. These results agree with those obtained by (Awad et al., 2014; El-dardiry et al., 2017; Mohamed et al., 2016; Khalifa et al., 2020). The results suggest that a suitable combination of control (goat processed cheese) and (millet cheese base) can produce a cheese analogue with better sensory properties.

TABLE 6. Texture Profile Analysis of Processed Cheese Analogues during Storage.

Characters	Storage Period (Month)	Control	T1	T2	T3	T4
Hardness (N)	Fresh	2.8 ± 0.21^{a}	2.5 ± 0.35^{ab}	2.3 ± 0.29^{b}	2.1 ± 0.13^{bc}	1.9 ± 0.1^{c}
	1	3.0 ± 0.3^{a}	2.7 ± 0.2^{ab}	2.5 ± 0.1^{b}	2.3 ± 0.2^{bc}	2.1 ± 0.1^{c}
	2	3.2 ± 0.4^{a}	2.9 ± 0.3^{ab}	2.7 ± 0.2^{b}	2.5 ± 0.1^{bc}	2.3 ± 0.2^{c}
	3	3.5 ± 0.5^{a}	3.1 ± 0.4^{ab}	2.9 ± 0.3^{b}	2.7 ± 0.2^{bc}	2.5 ± 0.1^{c}
Gumminess (N)	Fresh	1.7 ± 0.1^{a}	1.6 ± 0.2^{ab}	1.5 ± 0.1^{ab}	1.4 ± 0.1^{b}	1.3 ± 0.1^{b}
	1	1.8 ± 0.2^{a}	1.6 ± 0.1^{ab}	1.5 ± 0.2^{b}	1.4 ± 0.1^{b}	1.3 ± 0.1^{b}
	2	1.9 ± 0.3^{a}	1.7 ± 0.2^{ab}	1.6 ± 0.1^{ab}	1.5 ± 0.2^{b}	1.4 ± 0.1^{b}
	3	2.0 ± 0.4^{a}	1.8 ± 0.3^{ab}	1.7 ± 0.2^{ab}	1.6 ± 0.1^{ab}	1.5 ± 0.2^{b}
Chewiness (N)	Fresh	1.2 ± 0.1^{a}	1.1 ± 0.2^{ab}	1.0 ± 0.1^{ab}	0.9 ± 0.1^{ab}	0.8 ± 0.1^{b}
	1	1.3 ± 0.2^{a}	1.1 ± 0.1^{ab}	1.0 ± 0.2^{ab}	0.9 ± 0.1^{ab}	0.8 ± 0.1^{b}
	2	1.4 ± 0.3^{ab}	1.2 ± 0.2^{ab}	1.1 ± 0.1^{ab}	1.0 ± 0.2^{ab}	0.9 ± 0.1^{b}
	3	1.5 ± 0.4^{a}	1.3 ± 0.3^{ab}	1.2 ± 0.2^{ab}	1.1 ± 0.1^{ab}	1.0 ± 0.2^{b}
Springiness(m)	Fresh	0.75 ± 0.03^{c}	0.78 ± 0.04^{bc}	0.80 ± 0.02^{ab}	0.82 ± 0.03^{ab}	0.85 ± 0.01^{a}
	1	0.70 ± 0.02^{c}	0.75 ± 0.03^{bc}	0.78 ± 0.04^{ab}	0.80 ± 0.02^{ab}	0.82 ± 0.03^{a}
	2	0.68 ± 0.03^{c}	0.72 ± 0.04^{bc}	0.75 ± 0.02^{ab}	0.78 ± 0.03^{ab}	0.80 ± 0.02^{a}
	3	0.65 ± 0.04^{ab}	0.68 ± 0.03^{ab}	0.70 ± 0.02^{ab}	0.72 ± 0.04^{ab}	0.75 ± 0.03^{a}
Cohesiveness (ratio)	Fresh	0.60 ± 0.02^{ab}	0.62 ± 0.03^{ab}	0.65 ± 0.04^{ab}	0.68 ± 0.02^{ab}	0.70 ± 0.03^{a}
	1	0.58 ± 0.01^{ab}	0.60 ± 0.02^{ab}	0.62 ± 0.03^{ab}	0.65 ± 0.04^{ab}	0.68 ± 0.02^{ab}
	2	0.55 ± 0.02^{c}	0.58 ± 0.03^{ab}	0.60 ± 0.02^{ab}	0.62 ± 0.03^{ab}	0.65 ± 0.04^{a}
	3	0.50 ± 0.03^{c}	0.55 ± 0.02^{bc}	0.58 ± 0.03^{ab}	0.60 ± 0.02^{ab}	0.62 ± 0.03^{a}

$^{a-c}$ Means (n=3) within a row with different superscripts differ ($p<0.05$). C=100 % C, T1=75% C, T2=50% C+50 % P, T3=75 % P +25 % C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

N: Newton m: metre

TABLE 7. Color profile analysis of processed cheese analogues during storage.

Color values	Storage Period (Month)	Treatment				
		Control	T1	T2	T3	T4
L*	Fresh	65.2 ± 1.2[a]	64.8 ± 1.0[ab]	64.5 ± 0.9[ab]	64.2 ± 0.8[ab]	63.9 ± 0.7[b]
	1	64.5 ± 1.1[a]	64.2 ± 1.0[ab]	63.9 ± 0.9[ab]	63.6 ± 0.8[ab]	63.3 ± 0.7[b]
	2	63.8 ± 1.0[a]	63.5 ± 0.9[ab]	63.2 ± 0.8[ab]	62.9 ± 0.7[b]	62.6 ± 0.6[b]
	3	63.0 ± 0.9[a]	62.7 ± 0.8[ab]	62.4 ± 0.7[ab]	62.1 ± 0.6[ab]	61.8 ± 0.5[b]
a*	Fresh	-12.4 ± 0.5[a]	-12.1 ± 0.4[ab]	-11.8 ± 0.3[ab]	-11.1 ± 0.2[b]	-11.2 ± 0.1[b]
	1	-12.0 ± 0.6[a]	-11.7 ± 0.5[ab]	-11.5 ± 0.4[ab]	-10.9 ± 0.3[b]	-10.3 ± 0.2[c]
	2	-11.6 ± 0.7[a]	-11.3 ± 0.6[ab]	-11.0 ± 0.5[ab]	-10.7 ± 0.4[b]	-10.4 ± 0.3[b]
	3	-11.2 ± 0.8[a]	-10.9 ± 0.7[ab]	-10.6 ± 0.6[ab]	-10.3 ± 0.5[ab]	-10.0 ± 0.4[b]
b*	Fresh	20.1 ± 0.8[a]	19.8 ± 0.7[ab]	19.5 ± 0.6[ab]	19.2 ± 0.5[ab]	18.9 ± 0.4[ab]
	1	19.6 ± 0.9[a]	19.3 ± 0.8[ab]	19.0 ± 0.7[ab]	18.7 ± 0.6[b]	18.4 ± 0.5[b]
	2	19.1 ± 1.0[a]	18.8 ± 0.9[ab]	18.5 ± 0.8[ab]	18.2 ± 0.7[ab]	17.9 ± 0.6[b]
	3	18.6 ± 1.1[a]	18.3 ± 1.0[ab]	18.0 ± 0.9[ab]	17.7 ± 0.8[b]	17.4 ± 0.7[ab]
(WI)	Fresh	82.3 ± 0.5[a]	81.8 ± 0.4[ab]	81.3 ± 0.3[ab]	80.8 ± 0.2[b]	80.3 ± 0.1[b]
	1	81.5 ± 0.6[a]	81.0 ± 0.5[ab]	80.5 ± 0.4[b]	80.0 ± 0.3[bc]	79.5 ± 0.2[c]
	2	80.8 ± 0.7[a]	80.3 ± 0.6[ab]	79.8 ± 0.5[bc]	79.3 ± 0.4[bc]	78.8 ± 0.3[c]
	3	80.0 ± 0.8[a]	79.5 ± 0.7[ab]	79.0 ± 0.6[ab]	78.5 ± 0.5[bc]	78.0 ± 0.4[c]
(h°)	Fresh	55.6 ± 0.3[a]	55.2 ± 0.4[ab]	54.8 ± 0.5[b]	54.4 ± 0.6[bc]	53.9 ± 0.7[c]
	1	54.9 ± 0.4[a]	54.5 ± 0.5[ab]	54.1 ± 0.6[ab]	53.6 ± 0.7[bc]	53.1 ± 0.8[c]
	2	54.3 ± 0.6[a]	53.9 ± 0.7[b]	53.5 ± 0.8[bc]	53.0 ± 0.9[bc]	52.5 ± 1.0[c]
	3	53.7 ± 0.9[a]	53.3 ± 1.0[ab]	52.9 ± 1.1[bc]	52.4 ± 1.2[bc]	51.9 ± 1.3[c]
(C)	Fresh	22.9 ± 0.4[a]	22.5 ± 0.3[ab]	22.1 ± 0.2[ab]	21.7 ± 0.1[bc]	21.3 ± 0.1[c]
	1	22.3 ± 0.5[a]	22.0 ± 0.4[ab]	21.6 ± 0.3[b]	21.2 ± 0.2[bc]	20.8 ± 0.1[c]
	2	21.9 ± 0.6[a]	21.5 ± 0.5[ab]	21.1 ± 0.4[ab]	20.7 ± 0.3[bc]	20.3 ± 0.2[c]
	3	21.4 ± 0.7[a]	21.0 ± 0.6[ab]	20.6 ± 0.5[b]	20.2 ± 0.4[bc]	19.8 ± 0.3[c]
(BI*)	Fresh	12.1 ± 0.2[a]	11.9 ± 0.1[ab]	11.7 ± 0.1[ab]	11.5 ± 0.1[ab]	11.3 ± 0.1[b]
	1	11.8 ± 0.2[a]	11.6 ± 0.1[ab]	11.4 ± 0.1[ab]	11.2 ± 0.1[ab]	11.0 ± 0.1[ab]
	2	11.5 ± 0.2[a]	11.3 ± 0.1[ab]	11.1 ± 0.1[ab]	10.9 ± 0.1[ab]	10.7 ± 0.1[ab]
	3	11.2 ± 0.2[a]	11.0 ± 0.1[ab]	10.8 ± 0.1[ab]	10.6 ± 0.1[ab]	10.4 ± 0.1[ab]
(ΔE)	Fresh	0.0 ± 0.0[c]	0.5 ± 0.1[bc]	1.0 ± 0.2[bc]	1.5 ± 0.3[ab]	2.10 ± 0.4[a]
	1	2.5 ± 0.5[c]	3.0 ± 0.6[bc]	3.5 ± 0.7[bc]	4.0 ± 0.8[ab]	4.5 ± 1.0[a]
	2	5.0 ± 1.0[c]	5.5 ± 1.2[bc]	6.0 ± 1.4[bc]	6.5 ± 1.6[ab]	7.0 ± 1.8[a]
	3	7.5 ± 1.5[c]	8.0 ± 1.7[bc]	8.5 ± 1.9[bc]	9.0 ± 2.0[ab]	9.5 ± 2.2[a]

[a-c]Means (n=3) within a row with different superscripts differ ($p<0.05$). C=100 % C, T1=75% C, T2=50% C+50 % P, T3=75 % P +25 % C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

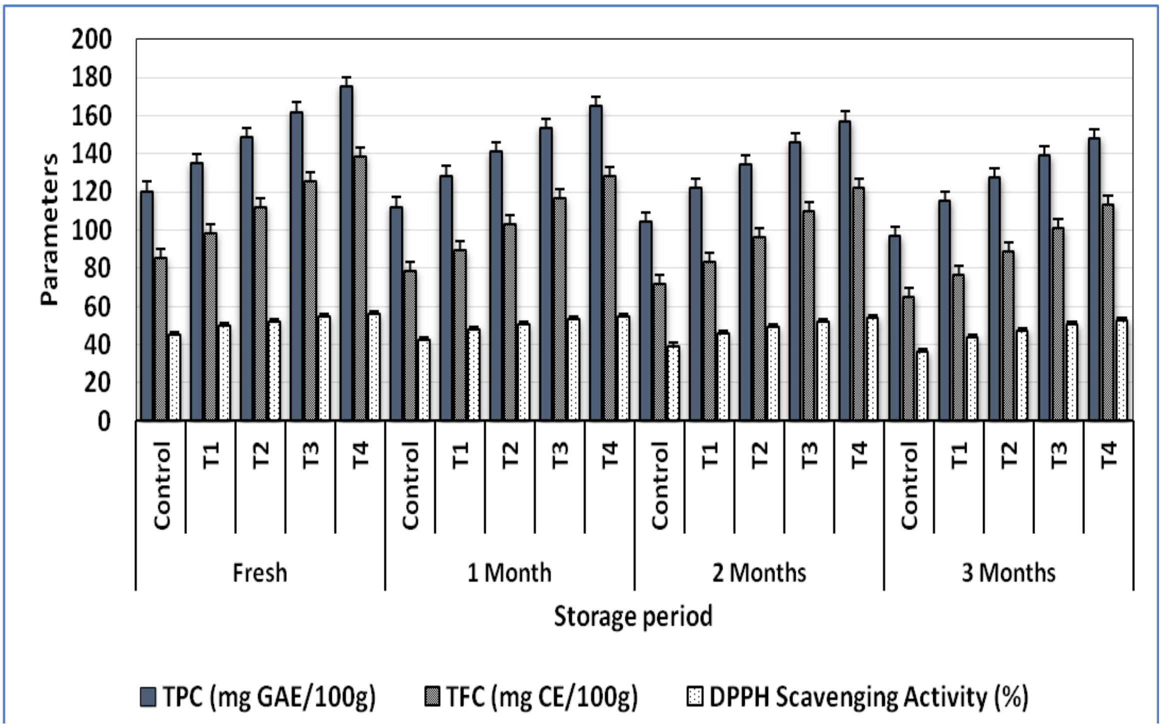

Fig. 2. Total phenolic content (TPC), total flavonoid content (TFC) and antioxidant activity (DPPH) of goat cheese analogues during storage.

TABLE 8. Microbiological properties of processed cheese analogues during storage.

Microbiology analysis	Storage Period (Months)	Control	T1	T2	T3	T4
Total Viable Count (TVC, log CFU/g)	Fresh	3.5 ± 0.2^{a}	3.2 ± 0.1^{ab}	3.0 ± 0.2^{ab}	2.8 ± 0.1^{b}	2.5 ± 0.2^{c}
	1	4.3 ± 0.3^{a}	3.8 ± 0.2^{b}	3.6 ± 0.3^{bc}	3.1 ± 0.2^{c}	3.0 ± 0.2^{c}
	2	4.9 ± 0.4^{a}	4.2 ± 0.3^{b}	3.9 ± 0.3^{bc}	3.5 ± 0.2^{c}	3.3 ± 0.2^{c}
	3	5.3 ± 0.5^{a}	4.7 ± 0.4^{b}	4.3 ± 0.4^{c}	4.0 ± 0.3^{cd}	3.7 ± 0.3^{d}
Yeast & Mold (log CFU/g)	Fresh	2.8 ± 0.3^{a}	2.5 ± 0.2^{ab}	2.2 ± 0.1^{b}	1.5 ± 0.2^{c}	1.5 ± 0.1^{c}
	1	3.2 ± 0.4^{a}	2.9 ± 0.3^{ab}	2.5 ± 0.2^{b}	2.1 ± 0.1^{bc}	1.8 ± 0.1^{c}
	2	3.8 ± 0.5^{a}	3.5 ± 0.4^{ab}	3.0 ± 0.3^{bc}	2.5 ± 0.2^{bc}	2.0 ± 0.1^{c}
	3	4.2 ± 0.6^{a}	3.9 ± 0.5^{ab}	3.4 ± 0.4^{b}	2.9 ± 0.3^{bc}	2.3 ± 0.2^{c}
Coliforms (log CFU/g)	Fresh	NIL	NIL	NIL	NIL	NIL
	1	NIL	NIL	NIL	NIL	NIL
	2	0.6 ± 0.3^{a}	NIL	NIL	NIL	NIL
	3	1.2 ± 0.4^{a}	0.8 ± 0.3^{b}	0.2 ± 0.2^{c}	NIL	NIL

[a-d]Means (n=3) within a row with different superscripts differ ($p < 0.05$).

C=100 % C, T1=75% C, T2=50% C+50 % P, T3=75 % P +25 % C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

TABLE 9. Effect processing on sensory profile of processed cheese analogue at 5°C.

Parameters	Storage period (month)	Treatments				
		Control	T1	T2	T3	T4
Appearance (20)	Fresh	15.35±0.32^{b}	16.75±0.52^{a}	16.66±0.51^{a}	16.05±0.36^{ab}	15.21±0.76^{b}
	1	14.89±0.33^{c}	16.35±0.43^{a}	16.14±0.55^{a}	15.93±0.56^{ab}	15.06±0.65^{b}
	2	14.56±0.46^{c}	15.86±0.62^{a}	15.98±0.59^{a}	15.73±0.34^{ab}	14.77±0.38^{b}
	3	14.13±0.65^{c}	15.42±0.73^{a}	15.63±0.64^{a}	15.26±053^{ab}	14.6±0.78^{b}
Body &Texture (40)	Fresh	31.24±0.42^{ab}	31.62±0.57^{a}	31.33±0.69^{ab}	30.81±0.64^{b}	30.12±0.68^{c}
	1	30.96±0.71^{ab}	31.38±0.71^{a}	30.88±0.93^{b}	30.59±022^{bc}	29.89±0.87^{c}
	2	30.78±0.51^{ab}	31.08±0.52^{a}	30.67±0.78^{ab}	30.26±0.33^{b}	29.73±0.79^{c}
	3	30.42±0.34^{b}	30.83±0.48^{a}	30.23±0.103^{bc}	30.04±0.46^{bc}	29.64±0.26^{c}
Flavor (40)	Fresh	32.21±0.46^{ab}	32.43±0.43^{a}	31.94±0.86^{b}	31.25±0.69^{c}	31.06±0.66^{c}
	1	32.07±0.42^{ab}	32.19±0.63^{a}	31.29±0.79^{b}	31.08±0.96^{bc}	30.67±0.91^{c}
	2	31.79±0.63^{ab}	31.97±0.37^{a}	31.19±0.58^{b}	30.67±0.34^{bc}	30.09±0.26^{c}
	3	31.31±0.75^{ab}	31.62±0.4^{a}	31.14±0.67^{b}	30.26±0.44^{c}	29.86±0.68^{d}
Total (100)	Fresh	78.8±0.28^{c}	80.8±0.41^{a}	79.93±0.75^{b}	78.11±0.22^{d}	76.39±0.38^{e}
	1	77.92±0.53^{c}	79.92±0.53^{a}	78.31±0.63^{b}	77.6±0.68^{d}	75.62±0.83^{e}
	2	77.13±0.36^{c}	78.91±0.45^{a}	77.84±0.55^{b}	76.66±0.69^{d}	74.59±0.91^{e}
	3	75.86±0.43^{c}	77.87±0.63^{a}	77±0.86^{b}	75.56±0.26^{d}	74.1±0.57^{e}

$^{a-d}$Means (n=3) within a row with different superscripts differ ($p<0.05$). C =100 % C, T1=75 % C, T2=50%C+50 % P, T3=75 % P+25% C, T4=100 % P, C=goat processed cheese, P= millet processed cheese base.

Conclusion

The fortification of processed goat cheese with a plant-based cheese base comprising zein protein, millet flour, and a coconut–corn oil blend offers a promising avenue for developing nutritionally enhanced and sensory-appealing cheese alternatives. Partial substitution, particularly at 50–75%, not only increases protein content and antioxidant activity but also improves meltability and texture, aligning with consumer preferences. These formulations maintain structural integrity and exhibit reduced oil separation over extended storage, indicating potential for longer shelf life. Microbiological assessments confirm the safety of these products, with no detection of common pathogens throughout the storage period. However, while in vitro digestion assays suggest improved nutrient bioavailability in the plant-fortified cheeses, further in vivo research is recommended to validate these findings. Overall, integrating plant-based components into traditional cheese matrices can meet the growing demand for sustainable and health-conscious dairy alternatives, contributing to a more diverse and resilient food system.

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