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Application of quinoa oil emulsions in fresh goat cheese: effects on lipid profile, technological properties and microstructure

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ABSTRACT

This study investigates the use of quinoa oil emulsion as a novel plant-based ingredient to improve the nutritional quality of fresh goat cheese. Quinoa oil emulsions (3 and 6 g/L) were characterized and incorporated in fresh cheese. The effects on nutritional composition, lipid oxidation, microbiological and sensory attributes, texture and microstructure were evaluated.

The addition of quinoa oil emulsion to milk before the cheesemaking improved the lipid profile of the cheeses by increasing the content of linoleic and a-linolenic acids. Overall, the microstructure of the fortified cheeses looked like the typical protein-lipid network of cheese. Additionally, the addition of quinoa oil did not increase oxidative deterioration, and microbial growth was unaffected. Textural changes were minor and unlikely to impair consumer perception as sensory evaluation confirmed that fortified cheeses were well accepted, with overall acceptance similar to that for traditional formulation.

1. Introduction

In the recent years, there has been a significant growth in the global food market for functional and fortified foods due to an increased awareness of the relationship between nutrition, health, and disease prevention (Minj & Dogra, 2020). In fact, the fortified food market was valued at around USD 96 billion in 2023, and is expected to more than double by 2032, highlighting the consumer, economic and public health importance of this growing market (Straits Research, 2024). This rising trend led to fortified foods with bioactive compounds and/or nutrients; hence the food industry is on its way to create novel fortified food products in response to consumer demands and/or help in the management and prevention of diseases associated with nutrient deficiencies (Gharehcheshmeh et al., 2021; Picciotti et al., 2022).

The fortification process consists of adding a nutrient or bioactive compound found in small amounts or not present in the food matrix (Picciotti et al., 2022). PUFAs (Ω-3, 6 and 9) are important nutrients widely recognized for their beneficial roles in maintaining cardiovascular, neurological, and immune health (Bermúdez-Aguirre & Barbosa-Cánovas, 2011). These essential fatty acids are one of the most extensively studied and commonly used for foods fortification, as evidence supports that their regular intake helps to prevent several diseases such as hypertension, cardiovascular diseases or diabetes as well as autoimmune and inflammatory disorders (Gumus & Gharibzahedi, 2021). In this context, milk and dairy products are suitable carriers for PUFA fortification, due to their high nutritional value and wide consumption, and their physicochemical properties that promote the stability and incorporation of these fatty acids (Bhtoya et al., 2025).

Among dairy products, cheese has become one of the best delivery systems for PUFAs due to its popularity and its storage conditions that promote their stability (Suwannasang et al., 2022; Villamil et al., 2021). Goat milk fat globules are smaller than cow milk, while goat milk contains a greater proportion of short- and medium-chain fatty acids that enhance digestibility and energy availability. The structure of their proteins also contributes to a lower allergenicity, making goat milk and cheese more tolerated by those who are sensitive to cow milk proteins.

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Furthermore, goat cheese is mild and pleasant tasting improving consumer acceptance beyond traditional niche markets (Miloradovic et al., 2021; Pappa et al., 2022). Traditionally, fish oils have been used for PUFA fortification; however, due to their characteristic odor and undesirable taste, they have been replaced in recent years by plant and seed oils, which are also characterized by containing high amounts of essential fatty acids (Dal Bello et al., 2017).

In this sense, quinoa oil is well known for its high nutritional value, with more than 80% of its fatty acids being unsaturated—mainly linoleic and α-linolenic acids—making it a promising ingredient to enhance the lipid profile of dairy products (Filho et al., 2017; Marques et al., 2024). Oils are typically directly incorporated in milk prior to the cheesemaking to achieve PUFA fortification of cheeses (Calligaris et al., 2015; Shamil et al., 2023). However, due to their high content of PUFAs they are highly susceptible to oxidation, causing stability issues and undesirable sensory changes when used directly (Marques et al., 2024). Therefore, encapsulation strategies such as emulsification have been used to overcome these limitations. Emulsification is a method in which two immiscible liquids, typically oil and water, are blended to create a stable system where fine oil droplets are dispersed within an aqueous phase (Bhtoya et al., 2025; Gharehcheshmeh et al., 2021). This technique improves the dispersion, stability, and availability of lipophilic compounds, being a great way to incorporate oils into dairy matrices (Gumus & Gharibzahedi, 2021). Oil emulsification not only improves their oxidative stability but also facilitates their homogeneous distribution in the dairy products, without compromising the texture or sensory attributes (Bhtoya et al., 2025; Marques et al., 2024; Picciotti et al., 2022). However, no studies have been found so far regarding the addition of quinoa oil emulsion on fresh goat cheese, given that the existing research has carried out on different types of cheeses and dairy products—mainly yogurts—fortified with emulsions prepared with different plant and seed oils such as chia, olive, sweet almond and sesame, walnut and flaxseed (Baba et al., 2018; Gharehcheshmeh et al., 2021; Irfan et al., 2023; Muñoz-Tébar et al., 2019). Therefore, the objectives of this study were: i) to characterize the stability and physicochemical properties of quinoa oil emulsion and ii) to evaluate the effect of its incorporation on the nutritional composition, physicochemical properties, microbiological quality, lipid profile and oxidation, texture, sensory characteristics, and microstructure of fresh goat cheese.

2. Materials and methods

2.1. Materials

Goat milk was freshly collected from the farm of the Miguel Hernández University (Orihuela, Alicante, Spain) and quinoa oil was purchased from the company Bela Vizago Ingredientes Naturales (Murcia, Spain). Calcium caseinate (food grade) was acquired from HSN Store (Granada, Spain). Mesophilic starter culture CHOOZIT MA4001 was purchased from Danisco (Sassenage, France) while rennet (1:15000 strength) and calcium chloride ($CaCl_2$) were obtained from Arroyo Laboratories (Santander, Spain).

2.2. Fatty acid profile of quinoa oil

Fatty acid profile of quinoa oil was analyzed by direct methylation of the lipids and quantified by gas chromatography (GC) under the same conditions described by Pellegrini et al. (2018). The samples were measured in triplicate, and the results were expressed as g fatty acid methyl esters (FAME)/100 g of fat.

2.3. Quinoa oil emulsion

The emulsion was prepared following the procedure described by Muñoz-Tébar et al. (2019). Briefly, calcium caseinate suspension (3% *w/*w) was prepared at 40 °C, mixed with quinoa oil (ratio 30:70 w/w) and emulsified at the same temperature in an Ultra-Turrax T25 BASIC for 2 min at 17,000 rpm.

2.4. Characterization of quinoa oil emulsion

2.4.1. Particle size distribution, polydispersity index and zeta (ζ) - potential

A dynamic light scattering (DLS) instrument (Zetasizer Nano ZS Zen 3600, Malvern Panalytical Instruments, UK) was used to determine the particle size distribution, the polydispersity index (PDI) and the ζ-potencital (ζ) of the emulsion. Emulsion was analyzed one day after its preparation and all these parameters were measured in a cuvette at 25 °C. Particle size was obtained from particle size distribution curves (percentage of intensity vs. diameter), and ζ-potential was measured directly in zeta cell DTS1070 and expressed as mV. All measurements were performed in triplicate.

2.4.2. Physicochemical properties

pH of the emulsion was measured using a GLP21 pH meter (Crison, Barcelona, Spain). CIELAB color coordinates of the emulsion were measured directy in rectangular tray using a CM-700 Minolta spectrophotocolorimeter (Minolta, Osaka, Japan) with a D65 illuminant and a 10° observer angle. All measurements were performed in triplicate.

2.5. Fresh goat cheese fortified with quinoa oil emulsion

2.5.1. Cheese making

Cheese was manufactured under the same conditions described by Muñoz-Bas et al. (2024) with slight modifications adapted to quinoa oil emulsion. Before processing, goat milk (36 L) was pasteurized (72 °C/15 s) and separated into three batches of 12 L each (control, QE3: 3 g/L quinoa emulsion added, and QE6: 6 g/L quinoa emulsion added). Then milk was cooled and inoculated with the starter culture (CHOOZIT MA 4001) followed by the incorporation of quinoa oil emulsion, rennet, $CaCl_2$ and salt. Finally, after coagulation was performed, the curd was cut and molded and the fresh cheeses were stored at 8 °C/85% RH until analysis. Cheese yield was also calculated and expressed as percentage.

2.5.2. Proximate composition

Proximate composition (moisture, fat, protein and dry matter, DM) was determined in triplicate using a NIRS FoodScan analyzer (Foss Iberia, Barcelona, Spain) and the results were expressed in g/100 g cheese.

2.5.3. Fatty acid profile

Fatty acid profile of milk and cheese was analyzed by direct methylation following the method described by Muñoz-Tébar et al. (2019). The resulting fatty acid methyl esters (FAMEs) were quantified using gas chromatography (GC) following the conditions described by Pellegrini et al. (2018).All measurements were performed in triplicate and the results were reported as g FAME/100 g of sample.

2.5.4. Lipid oxidation

Primary oxidation (measured as peroxide values) of the cheeses was assessed following the ISO 3976-IDF 74 standard procedure (ISO-IDF, 2006) and the conditions described by Muñoz-Tébar et al. (2019). Peroxide values were determined in triplicate and expressed as milliequivalents (mEq) O_2/kg of cheese. Calibration curve used for quantification was performed using five Fe^{3+} standard solutions (1–9 μg/mL).

2.5.5. Physicochemical properties

pH of cheeses was measured with a pH-meter Sension + pH 31 (HACH, Spain) and water activity using a NOVASINA TH-200 hygrometer (Novasina; Lachen, Switzerland). CIELAB color coordinates were determined directly in the cheese as described in section 2.4.2. The color differences (ΔE) respect to control cheese were calculated with the following equation: $\Delta E^* = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$. All measurements were performed in triplicate.

2.5.6. Texture

A Texture Profile Analysis (TPA) was conducted using a TA-XT2i texturometer (Stable Micro Systems Ltd., Godalming, Surrey, UK), equipped with a 5 kg load cell and a cylindrical aluminum P/100 probe, following the procedure described by Muñoz-Bas et al. (2024). Briefly, cheese samples were cut into 1.5 cm cubes compressed twice to 25% of its original height at a speed of 1.3 mm/s, with a 5-s recovery time between compressions. The results were showed as the mean of ten measurements expressed as firmness (N), adhesiveness (N·s), springiness, cohesiveness and resilience.

2.5.7. Microbiological quality

Microbiological quality (total aerobic count, LAB, enterobacteria and molds and yeasts) of the cheeses was evaluated following the procedure described by Muñoz-Bas et al. (2024). Samples were aseptically inoculated in triplicate onto MRS agar for the enumeration of *Lactobacillus* spp. and onto M17 agar for *Streptococcus* spp., followed by incubation at 37 °C for 48 h. *Streptococcus* spp. Plates were incubated under aerobic conditions, while those for *Lactobacillus* spp. were incubated under anaerobic conditions with an Anaerocult A system (Merck, Darmstadt, Germany). Total aerobic mesophilic bacteria, Enterobacteriaceae, as well as molds and yeasts, were analyzed using Petrifilm plates (3 M, Madrid, Spain). Plates (30–300 colony-forming units (cfu)) were manually counted expressing the results as $\log_{10}$ cfu/g of cheese.

2.5.8. Confocal laser scanning microscopy (CLSM)

The microstructure of the fresh goat cheese samples was analyzed using a Leica SP5 confocal laser scanning microscopy (TCS-SPE, Leica Microsystems, Heidelberg, Germany) following the method described by Muñoz-Bas et al. (2024).The staining was performed using a combination of Fast Green FCF and Nile Red (Sigma-Aldrich, Madrid, Spain). Nile Red (channel red) was excited at 488 nm, while Fast Green (channel green) was excited at 633 nm. The emission filters were set to 520–590 nm for Nile Red and 660–750 nm for Fast Green.

2.5.9. Sensory analysis

Sensory acceptability of cheeses was carried out using the same conditions described by Muñoz-Bas et al. (2024). Fifty consumers (68% female, 32% male, aged 18 to over 65) were recruited from the Orihuela Polytechnical High School at Miguel Hernández University (UMH). Sensory evaluations were conducted in the standardized sensory laboratory at UMH, which complies with international standards (Eggert & Zook, 1986). Prior to the sensory analysis, participants were informed of what they were going to taste and the characteristics of the analysis providing their written informed consent. This sensory evaluation is approved by the Responsible Research Office at Miguel Hernández University (OIR-Reg. 211,128,200,759, Ref. PRL.DTA.JPA.05.21, UMH, Elche, Alicante, Spain). Consumers were asked to evaluate odor, taste, color, sweetness, salty, firmness, fracturability, granularity, and overall acceptability, using a 9-point hedonic scale ranging from "dislike extremely" (1) to "like extremely" (9). They were also asked to rate the rancidity intensity on a 9-point scale from "very slight" (1) to "extremely high" (9).

2.6. Statistical analysis

Data analysis was conducted using SPSS (IBM SPSS Statistics version 26). A one-way ANOVA was applied with a 95% confidence level to identify any significant differences between the control cheese and those fortified with quinoa oil emulsion. When significant differences were found ($p < 0.05$), Tukey's test was performed to identify specific differences between the cheese formulations.

3. Results and discussion

3.1. Lipid profile of quinoa oil

Fig. 1 illustrate that the main fatty acids identified in quinoa oil were linoleic acid (C18:2, ω-6), oleic acid (C18:1, ω-9), palmitic acid (C16:0), α-linolenic acid (C18:3, ω-3), and stearic acid (C18:0). Polyunsaturated fatty acids (PUFAs) represent 57% of the total content, 29% monounsaturated fatty acids (MUFAs) and 13% saturated fatty acids (SFAs). Linoleic acid was the majority of the PUFAs, while oleic acid was the predominant MUFA. Other authors have reported similar fatty acid profiles, with linoleic, oleic, palmitic and α-linolenic acid as the majority fatty acids present in quinoa (Pellegrini et al., 2018; Tang et al., 2015).

3.2. Characterization of quinoa oil emulsion

The emulsion properties, such as their stability, appearance, texture, optical properties and sensory characteristics are determined by the size of the droplets they contain (Xiao et al., 2025). Therefore, the analysis of particle size distribution plays an important role in the development of emulsion-based food products. Quinoa oil emulsion showed a bimodal particle size distribution with two peaks: one at 1443.33 nm and another at 240.90 nm, reflecting the polydispersibility of the particles (Table 1).

The larger particle size in the second peak could be related to the coalescence of fat globules or the formation of covalent aggregates between proteins adsorbed on the surfaces of fat droplets (Goyal et al., 2015). The polydispersity index (PDI), a dimensionless parameter ranging from 0 to 1, describes the degree of particle size heterogeneity in an emulsion. PDI value of quinoa emulsion was 0.56, suggesting a moderately broad droplet size distribution and some degree of heterogeneity in droplet size. A PDI above 0.4 indicates a wide particle size distribution in line with the values reported by Kampa et al. (2022) for emulsions prepared with different vegetable oils (0.448–0.495).

The ζ-potential is another important parameter in the emulsion's quality, as it provides information about their stability and rheological behavior. High zeta-potential values (positive or negative) in emulsions generally indicate electrostatic stabilization, while low values are related to coagulation or flocculation processes. Likewise, a negative potential might indicate the presence of ionic impurities in the emulsion, such as free fatty acids or the adsorption of hydroxyl groups on the surface of the droplets (Kampa et al., 2022). Quinoa oil emulsion had a ζ-potential of −30.83 mV (Table 1), which suggests good electrostatic stability. In this regard, similar zeta-potential values have been reported for emulsions formulated with olive oil and rapeseed oil (Kampa et al., 2022) as well as with flaxseed oil (Goyal et al., 2015).

The pH of the quinoa oil emulsion (6.35) is close to neutral, a range generally regarded as suitable for food-grade emulsions, as it supports microbial stability, ensures safety, and is compatible with the dairy matrix. The value obtained is similar to that reported by Almasi et al. (2021) for emulsions formulated with flaxseed oil. Regarding color coordinates, the quinoa emulsion exhibited high lightness (L*) and chromatic values indicating a slight green–yellow hue. (Table 1). The color of the emulsion can be affected by the type of oil used, the particle size, and the concentration of pigments (i.e., carotenoids in the case of quinoa) present in the oil.

3.3. Effect of adding quinoa emulsion to fresh goat cheese

3.3.1. Cheese yield

Cheese yield is a key parameter in the development of fortified cheeses as it helps to measure efficiency and determine the economic viability of the production as well as the potential of a new product (Fox et al., 2016). In this study, the incorporation of quinoa emulsion led to an increase in cheese yield from 19.9% in the control to 21.9% and 22.1% in the formulations fortified with 3 and 6 g/L of emulsion, respectively. The similar yields observed for QE3 and QE6 formulations

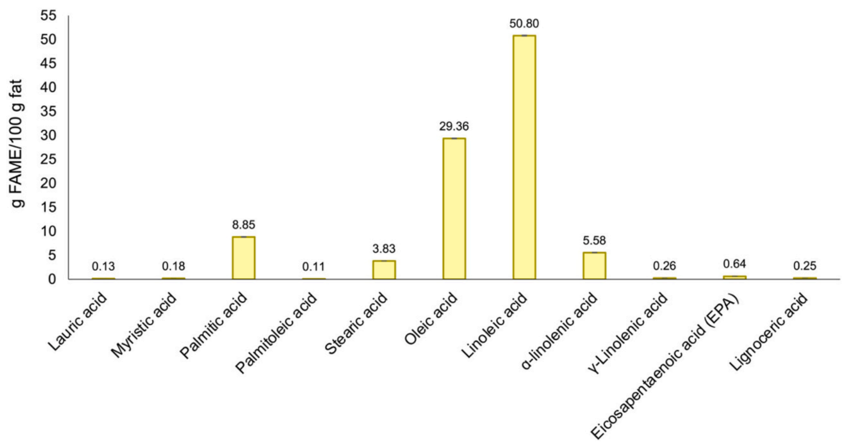

Fig. 1. Fatty acid profile of quinoa oil.

Table 1
Characterization of quinoa emulsion.

Parameter	
Particle sizes (nm)	1443.33 ± 22.74 240.90 ± 5.20
PDI	0.56 ± 0.04
ζ - potential (mV)	−30.83 ± 0.67
pH	6.35 ± 0.01
L*	87.61 ± 0.45
a*	−0.54 ± 0.01
b*	3.89 ± 0.32

Data (n = 3; Mean ± standard deviation).

Table 2
Chemical composition of goat fresh cheese fortified with quinoa oil emulsion.

Parameter	Control	QE3	QE6	*p*-value
% Moisture	60.33 ± 0.46	59.60 ± 0.27	60.19 ± 0.65	0.232
% Protein	13.43 ± 0.13	13.73 ± 0.09	13.53 ± 0.18	0.092
% Fat	20.29 ± 0.17^{b}	21.00 ± 0.12^{a}	21.53 ± 0.38^{a}	0.003
% DM	39.34 ± 0.22^{b}	40.40 ± 0.27^{a}	40.40 ± 0.10^{a}	0.001
% Ash	2.15 ± 0.05	2.12 ± 0.03	2.12 ± 0.13	0.844

a-b Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data (n = 3; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

can likely be explained by a saturation effect within the paracasein protein network. As the system becomes more crowded, this may induce microstructural changes such as coalescence or the formation of larger serum pockets (Lorenzen et al., 2024), as confirmed by the confocal micrographs (Fig. 3).

Milk composition, particularly its casein and fat content, is one of main factors influencing cheese yield (Fox et al., 2016). For this reason, the increase observed in cheese yield is likely related to the incorporation of fat from quinoa oil. In addition, emulsified oil droplets stabilized by caseinate proteins can be effectively entrapped within the casein matrix, reducing the loss of lipid material in the whey and increasing the overall recovery of fat in the cheese. Despite the differences in fat content, all values were within the normal range reported for artisanal fresh goat cheese (Vacca et al., 2018). In a similar study conducted on sheep's cheese fortified with chia emulsion, cheese yield also increased from 15.4% to 16.8% in the formulation containing the highest concentration of emulsion (5 g/L) (Muñoz-Tébar et al., 2019).

3.3.2. Proximate composition

The nutritional composition of cheese depends mainly on the nutritional characteristics of the milk used and the cheesemaking process (i.e., pasteurization, starter cultures, or salting). In addition, the composition of goat's milk can be affected by the breed, lactation stage, physiological aspects, storage, or feed composition (dos Santos et al., 2023). Table 2 shows the composition of cheeses fortified with quinoa emulsion, noticing that the emulsion contributed to the nutritional value. Cheeses fortified with the emulsion had higher fat and DM content ($p < 0.05$) than the control, although no significant differences ($p > 0.05$) were found between the two fortified formulations (QE3 and QE6). This increase in fat (from 20.20% to 21.53%) can be attributed mainly to the quinoa oil incorporated through the emulsion. Given that the dry matter of cheese is composed primarily of protein and fat, a slight increase in DM (from 39.39% to 40.40%) was expected following the increase in fat in the fortified cheeses. Similar findings have been reported in other studies where cheese and yogurt were fortified with vegetable oils, including chia oil (Muñoz-Tébar et al., 2019), flaxseed oil (Dal Bello et al., 2017), olive oil (Irfan et al., 2023), canola and almond oil (Hernández-Ruiz et al., 2025), and walnut oil (Turek et al., 2023).

On the other hand, the incorporation of the emulsion did not significantly affect ($p > 0.05$) the moisture, protein, and ash content, which remained comparable across all formulations. Furthermore, moisture, fat, protein, and ash values recorded for all formulations were within the typical ranges reported for fresh goat cheese (García et al., 2012; Kawęcka & Pasternak, 2022; Muñoz-Bas et al., 2024).

3.3.3. Fatty acids profile

The effect of adding quinoa emulsion on fatty-acid profile (FAMEs) in milk and cheese is summarized in Table 3. Across all milk samples, the most abundant fatty acid was palmitic acid (C16:0), followed by oleic acid (C18:1, Ω-9). The incorporation of the emulsion did not cause a significant change in the levels of capric acid (C10:0), lauric (C12:0), myristic (C14:0), and palmitoleic acid (C16:1). However, it had a positive effect on the content of palmitic acid (C16:0), stearic (C18:0), oleic, linoleic (C18:2, Ω-6), and α-linolenic acid (C18:3, Ω-3, ALA), with greater values being achieved in the formulation fortified with the highest concentration of the emulsion (QE6). Likewise, a significant increase was observed in the content of saturated fatty acids (SFAs), monounsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFAs). This increase is mainly due to the FAMEs composition of the quinoa oil used to prepare the emulsion (Fig. 1).

As expected, the same pattern observed in milk also appeared in the cheese. The cheeses fortified with the quinoa emulsion showed the highest levels of palmitic, stearic, oleic, linoleic, and α-linolenic acid ($p < 0.05$). Across all cheeses, palmitic and oleic acids were the most abundant, ranging from 11.63 to 13.33 g/100 g. A similar composition was obtained in our previous study on the enrichment of fresh goat

Table 3
Fatty acid profile of goat milk and fresh cheese fortified with quinoa oil emulsion.

FAMEs (g/100 g)	Control	QE3	QE6	*p*-value
Milk				
Capric acid (C10:0)	0.16 ± 0.01	0.16 ± 0.02	0.17 ± 0.01	0.422
Lauric acid (C12:0)	0.11 ± 0.01	0.12 ± 0.00	0.12 ± 0.00	0.132
Myristic acid (C14:0)	0.36 ± 0.01	0.36 ± 0.01	0.37 ± 0.01	0.310
Palmitic acid (C16:0)	1.34 ± 0.02^{c}	1.45 ± 0.00^{b}	1.53 ± 0.00^{a}	0.000
Palmitoleic acid (C16:1)	0.04 ± 0.00	0.04 ± 0.00	0.05 ± 0.00	0.073
Stearic acid (C18:0)	0.49 ± 0.01^{c}	0.55 ± 0.01^{b}	0.60 ± 0.01^{a}	0.000
Oleic acid (C18:1, Ω-9)	1.27 ± 0.00^{c}	1.38 ± 0.01^{b}	1.55 ± 0.02^{a}	0.000
Linoleic acid (C18:2, Ω-6)	0.20 ± 0.00^{c}	0.30 ± 0.02^{b}	0.46 ± 0.01^{a}	0.000
α-linolenic acid (C18:3, Ω-3)	0.04 ± 0.00^{c}	0.05 ± 0.00^{b}	0.06 ± 0.00^{a}	0.000
∑ SFAs	2.47 ± 0.03^{c}	2.63 ± 0.02^{b}	2.79 ± 0.01^{a}	0.000
∑ MUFAs	1.32 ± 0.00^{c}	1.43 ± 0.01^{b}	1.59 ± 0.02^{a}	0.000
∑ PUFAs	0.24 ± 0.01^{c}	0.35 ± 0.02^{b}	0.52 ± 0.01^{a}	0.000
Cheese				
Capric acid (C10:0)	0.76 ± 0.06	0.75 ± 0.02	0.83 ± 0.05	0.195
Lauric acid (C12:0)	0.57 ± 0.06	0.49 ± 0.00	0.51 ± 0.06	0.182
Myristic acid (C14:0)	1.55 ± 0.04	1.59 ± 0.00	1.63 ± 0.09	0.288
Palmitic acid (C16:0)	6.13 ± 0.02^{c}	6.46 ± 0.01^{b}	6.77 ± 0.02^{a}	0.000
Palmitoleic acid (C16:1)	0.23 ± 0.05	0.25 ± 0.05	0.26 ± 0.05	0.722
Stearic acid (C18:0)	2.29 ± 0.01^{c}	2.55 ± 0.00^{b}	2.71 ± 0.04^{a}	0.000
Oleic acid (C18:1, Ω-9)	5.50 ± 0.02^{c}	6.29 ± 0.00^{b}	6.56 ± 0.02^{a}	0.000
Linoleic acid (C18:2, Ω-6)	0.65 ± 0.02^{c}	1.10 ± 0.01^{b}	1.86 ± 0.11^{a}	0.000
α-linolenic acid (C18:3, Ω-3)	0.12 ± 0.01^{c}	0.24 ± 0.00^{b}	0.45 ± 0.01^{a}	0.000
∑ SFAs	11.30 ± 0.04^{c}	11.84 ± 0.04^{b}	12.42 ± 0.31^{a}	0.001
∑ MUFAs	5.73 ± 0.06^{c}	6.54 ± 0.04^{b}	6.82 ± 0.04^{a}	0.000
∑ PUFAs	0.78 ± 0.02^{c}	1.34 ± 0.01^{b}	2.31 ± 0.10^{a}	0.000

a-c Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data (n = 3; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

cheese, in which palmitic and oleic acids were the most abundant in all formulations, representing more than 50% of the total fatty acids (Muñoz-Bas et al., 2024).

The largest increases were found in linoleic and α-linolenic acids, which despite being present in smaller amounts than the main fatty acids, their levels were nearly four times those of the control in the cheese with the highest emulsion concentration (QE6). In fact, linoleic acid increased by 1.21 g/100 g, while α-linolenic acid increased by 0.33 g/100 g (Table 3). SFAs were the main fraction followed by MUFAs and a small proportion of PUFAs.

These results indicate that the emulsion was successfully incorporated into the curd. Increases in MUFAs and PUFAs after adding vegetable oils—whether emulsified or not—have also been achieved in previous studies. For instance, Lehaçani and Al-Abdullah (2022) reported higher levels of linoleic and α-linolenic acids in cow's cheese enriched with flaxseed oil. Similarly, Dal Bello et al. (2017) found increased omega-3 and omega-6 concentrations in fresh cheese when flaxseed oil was added. On the other hand, in a similar study in which pressed sheep's cheese was enriched with chia oil emulsion, higher ALA (α-linolenic acid) values were achieved in the fortified cheeses (Muñoz-Tébar et al., 2019).

3.3.4. Lipid oxidation

The peroxide value (PV) is one of the most widely used parameters in the food industry to assess the degree of oxidation in fats and oils as it reflects the hydroperoxides formed during the early stages of this process. In addition, it is closely linked to the formation of peroxides in unsaturated fats, a process triggered when the double bonds break, generating short-chain volatile compounds responsible for rancid odors (Duduzile Buthelezi et al., 2019). The PV obtained for both the control cheese and the cheeses fortified with quinoa oil emulsion are shown in Fig. 2.

The incorporation of the emulsion caused a significant ($p < 0.05$) increase in the peroxide value from 1.36 ± 0.03 mEq O_2/kg cheese to 1.84 ± 0.03 and 2.04 ± 0.04 mEq O_2/kg cheese in cheeses formulated with 3 g/L and 6 g/L of emulsion, respectively. In this sense, similar studies have also reported increases in the peroxide value of milk and dairy products fortified with vegetable oils. For instance, in fresh cheese fortified with flaxseed oil (Dal Bello et al., 2017), in pressed sheep cheese fortified with emulsified chia oil (Muñoz-Tébar et al., 2019), and in pasteurized milk enriched with emulsified grape seed oil (Sepeidnameh et al., 2025). Despite the increase in the peroxide value, all cheeses showed values far below 10 mEq 0_2/kg, indicating that the emulsion was stable and did not negatively affect lipid oxidation in the cheeses.

Since values above than 10 mEq 0_2/kg are associated with rancidity (Jagtap et al., 2021), and although no specific peroxide value limit exists for dairy products, the Codex Alimentarius Commission (1999) establishes this threshold for cold-pressed oils as an indicator of oxidative stability. Taking this limit as a reference, the results suggest that no rancidity occurred during emulsion preparation or in any of the cheese formulations, indicating a low degree of oxidation in all samples.

3.3.5. Physicochemical properties

Physicochemical characteristics of the control and QE-fortified cheeses are presented in Table 4. A significant decrease in pH ($p < 0.05$) was observed with the addition of quinoa emulsion, being more pronounced in cheeses formulated with the highest emulsion concentration (from 6.56 to 6.23). However, all cheeses showed values within the typical pH range reported for fresh goat cheese (6.47–6.70; Mladenović et al., 2022; Pawlos et al., 2023).

This reduction in pH seems to be directly related to the components of the emulsion. On the one hand, the carboxylic groups of calcium

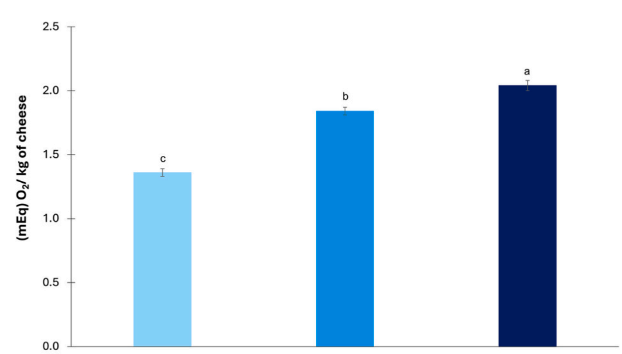

Fig. 2. Lipid oxidation of goat fresh cheese fortified with quinoa oil emulsion. a-c Different superscripts means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data (n = 3; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

Table 4
Physico-chemical properties of goat fresh cheese fortified with quinoa oil emulsion.

Parameter	Control	QE3	QE6	p-value
aw	0.974 ± 0.000	0.974 ± 0.001	0.975 ± 0.002	0.787
pH	6.56 ± 0.00^{a}	6.29 ± 0.01^{b}	6.23 ± 0.01^{c}	0.000
L*	85.91 ± 1.22	86.03 ± 0.43	85.14 ± 0.21	0.123
a*	−1.89 ± 0.10	−1.94 ± 0.05	−1.88 ± 0.03	0.319
b*	6.37 ± 0.27^{a}	5.82 ± 0.18^{b}	5.70 ± 0.17^{b}	0.000
ΔE	–	0.90 ± 0.29^{b}	1.56 ± 0.19^{a}	0.000

a-c Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data (n = 3; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

caseinate can contribute to a reduction in pH as stated by Irfan et al. (2023). These authors reported a reduction in the pH of processed Cheddar cheese when they incorporated olive oil emulsified with whey protein isolate. On the other hand, it has also been observed that the content of polyunsaturated fatty acids can affect the acidity and pH of dairy products. Gharehcheshmeh et al. (2021) reported this effect in yogurts incorporated with sesame oil.

Water activity (aw) is an important parameter in any food product, as it is closely related to microbiological safety and the chemical reactions that can occur (Trmčić et al., 2017). In the present study, the addition of the emulsion did not significantly ($p > 0.05$) modify the aw, and all the cheeses showed similar values (Table 4). Besides, this finding is consistent with the moisture values, which were also unaffected by the incorporation of the emulsion (Table 2).

Color is an important attribute due to that not only defines the quality of the product, but also has economic implications by influencing sensory perception and driving the consumer acceptance of the product (Kasprzak et al., 2025). Therefore, the effect of incorporating quinoa oil emulsion on the color of the formulated fresh goat cheeses was evaluated (Table 4). The results show that the incorporation of the emulsion did not modify lightness (L*) or coordinate a* (+ red/− green). L* values varied from 85.15 to 86.03, while a*coordinate ranged between −1.88 and − 1.94. However, a slight decrease in b* coordinate (+ yellow/− blue) was observed in the cheeses fortified with the emulsion, although no significant differences were found between the two formulations (QE3 and QE6). The control showed a b* value of 6.37, while the QE-cheeses ranged from 5.70 to 5.82, which would indicate that the emulsion tends to reduce yellowness. This reduction in the coordinate b*due to the incorporation of oils was also observed by Hughes et al. (2012) in soft goat cheese with fish oil, who attributed this behavior to the light-scattering properties of homogenized oil droplets in the emulsion.

These small color changes in cheeses were also reflected in the color differences (ΔE) between the QE-fortified cheeses and the control cheese. Despite the differences observed, both formulations had color differences well below 3 units, which is considered imperceptible to the human eye (Martínez et al., 2001). Consequently, consumers would be unlikely to perceive visual differences between the cheeses fortified with quinoa emulsion and a conventional fresh goat cheese.

3.3.6. Texture

As color, texture attributes are key in evaluating cheese quality, since both of them are fundamental parameters in consumer selection criteria. Texture influences not only the mouthfeel and visual appearance of the cheese but also its suitability for different uses such as cutting, grating, spreading or melting. It can also be affected by moisture, fat, or salt contents, pH, or protein degradation (Fresno & Álvarez, 2012; Pinho et al., 2004). Therefore, it is important to evaluate the texture of cheese when non-dairy ingredients are incorporated. The texture parameters (firmness, adhesiveness, springiness, cohesiveness, and resilience) of control and fortified cheeses with quinoa emulsion are presented in Table 5. Only firmness and adhesiveness were significantly affected ($p < 0.05$) by the addition of the quinoa emulsion. Firmness decreased from 2.11 to 1.67–1.73 N in the fortified cheeses, with no significant differences between the QE3 and QE6 formulations.

However, adhesiveness increased when the emulsion was incorporated, with a tendency to increase with increasing emulsion concentration (CT: −0.06 N.s, QE3: −0.05 N.s and QE6: −0.03 N.s). The lower firmness values observed in this study may be attributed to the higher proportion of unsaturated fatty acids in the formulations fortified with emulsified quinoa oil (Table 3). These fatty acids have a lower melting point than milk fat, which could contribute to the softer texture (Pandule et al., 2021; Turek et al., 2023). In addition, the pH reduction in fortified cheeses (Table 4) and its interaction with rennet enzymes and starter cultures determine the moisture retention and curd formation. These processes influence the firmness and the elasticity of the curd, ultimately defining the final texture of the cheese (Muñoz-Bas et al., 2024).

Regarding adhesiveness, the increased observed in the fortified cheeses may be linked to their higher fat content compared to control (Table 2), as previous studies have shown that adhesiveness tends to decrease when fat content decrease (Bryant et al., 1995; Sánchez-Macías et al., 2010). Similar to the effect observed on firmness, this behavior may also be associated with the MUFAs present in quinoa oil, as similar results have been reported in mozzarella cheese analogue formulated with canola oil (Bano et al., 2025) and in spreadable processed cheese analogue with vegetable fat that contained 71.41% of oleic acid (Cunha et al., 2010).

On the other hand, the emulsion did not significantly ($p > 0.05$) modify the springiness, cohesiveness, or resilience of the cheeses, consistent with the findings of a similar study conducted on sheep cheese fortified with chia oil emulsion (Muñoz-Tébar et al., 2019).

3.3.7. Microbiological quality

As shown in Table 6, the addition of the quinoa oil emulsion did not negatively affect ($p > 0.05$) the development and growth of the starter strains, with similar values in all formulations. Total aerobic counts ranged from 8.01 to 8.07 $\log_{10}$ cfu/g, *Lactobacillus* spp. counts from 8.19 to 8.21 $\log_{10}$ cfu/g, and *Streptococcus* spp. counts from 6.92 to 6.93 $\log_{10}$ cfu/g.

On the other hand, no *Enterobacteriaceae*, molds, or yeasts were detected in any of the cheeses, which would confirm that the manufacturing process and the hygienic-sanitary conditions used were adequate to produce a fresh goat cheese with high microbiological quality.

In the study carried out by Dal Bello et al. (2017) on fresh cow's milk cheese, no significant differences were found in the growth of total bacteria between the control and the cheese fortified with sesame oil. Bermúdez-Aguirre and Barbosa-Cánovas (2011)reported similar growth of LAB in Cheddar fortified with flaxseed oil. Later, Muñoz-Tébar et al.

Table 5
Texture of goat fresh cheese fortified with quinoa oil emulsion.

Parameter	Control	QE3	QE6	p-value
Firmness (N)	2.11 ± 0.33^{a}	1.67 ± 0.25^{b}	1.73 ± 0.33^{b}	0.011
Adhesiveness (N*s)	−0.06 ± 0.03^{b}	−0.05 ± 0.02^{ab}	−0.03 ± 0.02^{a}	0.018
Springiness	0.96 ± 0.02	0.96 ± 0.02	0.94 ± 0.03	0.147
Cohesiveness	0.82 ± 0.01	0.82 ± 0.01	0.81 ± 0.01	0.054
Resilience	0.47 ± 0.03	0.47 ± 0.01	0.46 ± 0.01	0.439

a-c Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data ($n = 10$; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

Table 6
Microbial quality of goat fresh cheese fortified with quinoa oil emulsion.

Microorganism (log cfu/g)	Control	QE3	QE6	*p*-value
Total aerobic counts	8.07 ± 0.01	8.03 ± 0.02	8.01 ± 0.03	0.097
Lactobacillus spp	8.21 ± 0.01	8.19 ± 0.01	8.19 ± 0.01	0.245
Streptococcus spp	6.93 ± 0.01	6.92 ± 0.01	6.93 ± 0.01	0.854

a-b Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

(2019)confirmed that the incorporation of chia oil emulsion did not affect the microbial development (total bacteria and LAB) of pressed sheep's milk cheeses.

Overall, the present results suggest that the application of quinoa emulsion in fresh goat cheese would not modify the normal development of its microbiological profile, which plays an important role in its flavor, food safety, and texture.

3.3.8. Microstructure

The microstructure of cheese consists of a protein matrix in which fat globules, water, and minerals are integrated. Analyzing cheese microstructure is essential when developing new dairy products, as it provides detailed information about its technological properties, texture, and the interactions between cheese components (Mehta, 2018). Therefore, the microstructure of both the control cheese and the cheeses fortified with the quinoa emulsion was evaluated using confocal laser scanning microscopy. As shown in Fig. 3, the protein matrix is visualized in green, fat in red, and the serum phase/air pockets in black.

The appearance of the protein matrix of the control cheese (Fig. 3A-C) is a sponge-like structure in which fat globules and small cavities of the serum phase are distributed throughout the protein matrix. In the control sample, the protein network showed fine and uniformly distributed pores, with small and mainly spherical fat globules dispersed throughout the matrix and no evident signs of coalescence.

Regarding the cheeses fortified with the emulsion (Fig. 3D-I), the protein-lipid matrix structure observed in the control cheese was maintained, however differences in the size and shape of the fat globules were observed. In fortified cheeses, several types of fat were detected within the protein matrix: individual spherical fat globules, coalesced fat globules, and non-globular fat. Fat globule coalescence occurs when two or more globules merge, forming irregularly shaped structures that still retain the native milk fat globule membrane, while non-globular fat

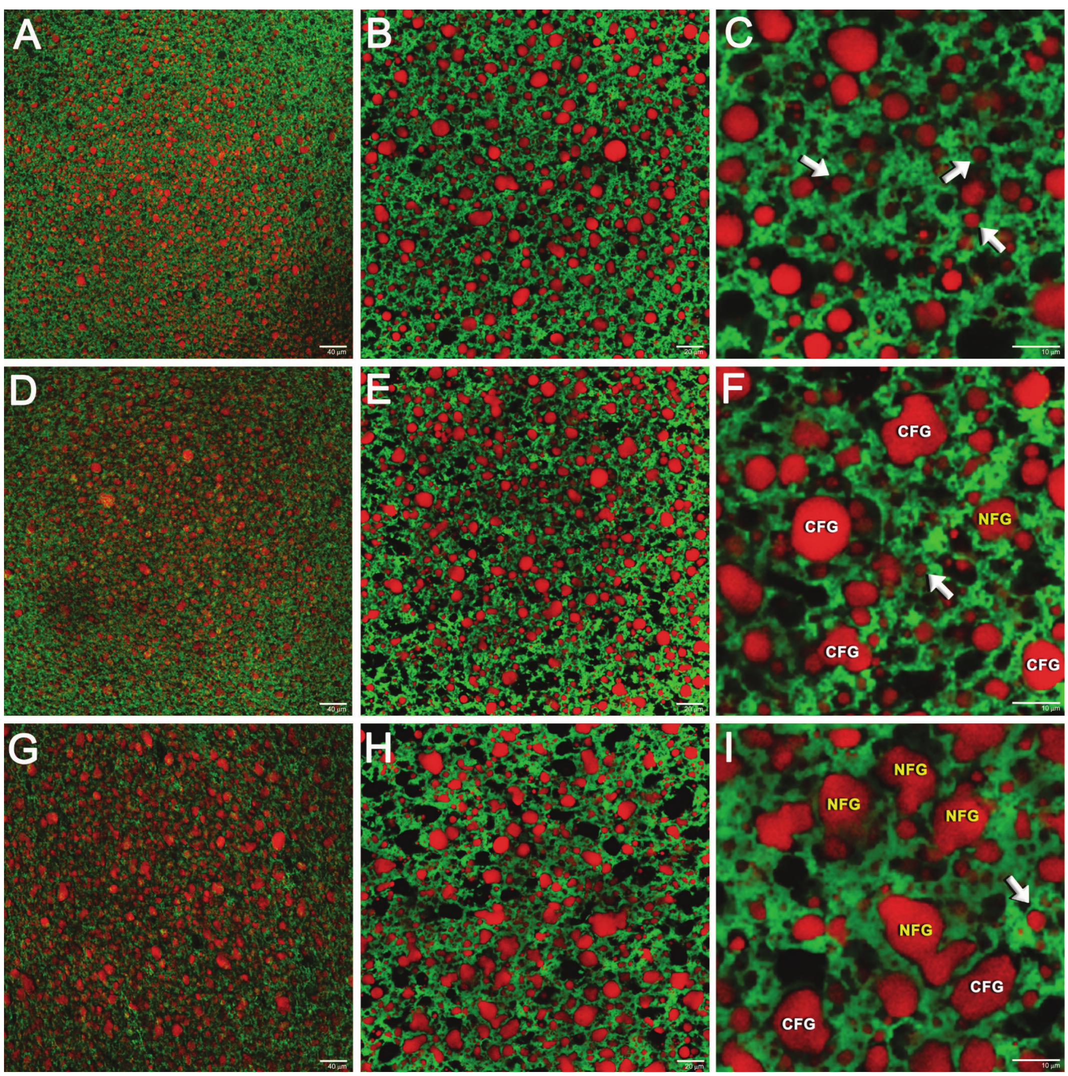

Fig. 3. Confocal scanning microscopy images of the microstructure of control cheese (A-C) and cheeses fortified with quinoa emulsion at 3 g/L (D—F) and 6 g/L (G-I). For each formulation, images are presented at increasing magnification from left to right. Proteins were stained with Fast Green FCF (green) and lipids with Nile Red (red) and serum pockets/air spaces appears in black. Arrows indicate representative fat globules (FG); CFG: Coalesced fat globules; NFG: Non-globular fat. Scale bars: 40 μm, 20 μm, 10 μm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

loses this protective membrane and is referred to as free fat (Hickey et al., 2015; Ong et al., 2011). Even though this occurred in both fortified cheeses, it was observed that cheeses fortified with the highest emulsion concentration (6 g/L) displayed a greater degree of coalescence (Fig. 3I), resulting in markedly larger and more irregular fat globules than those observed in the 3 g/L samples (Fig. 3F). This phenomenon is closely related to the fat content of the cheeses (Table 2), since an increase in fat content leads to a greater number of fat globules that are more likely to coalesce and form larger globules due to their proximity. Likewise, the fatty acid composition also plays a key role in this. As reported by Cunha et al. (2010), vegetable fats rich in fatty acids with more than 16 carbons have stronger hydrophobic characteristics promoting the formation of larger and irregular fat globules. In contrast, milk fat is mainly composed of SFAs that tend to weaken attractive forces between fat globules and enhance their affinity with the surrounding protein network.

The increase in the number of coalesced fat globules is also consistent with the behavior observed in the texture analysis (Table 5), since these coalesced globules cause more weak points in the microstructure, ultimately producing softer cheeses (Lou et al., 2025). In addition, fortified cheeses showed larger and more abundant serum pockets, a trend that was more noticeable in cheeses containing the highest concentration of emulsion (Fig. 3F, I). These larger serum pockets, which appear as black areas in the CLSM images, could be caused by the shearing and mixing of the casein gel network during the emulsification (Lorenzen et al., 2024).

The incorporation of non-dairy ingredients, such as vegetable fats, into cheese matrices has been extensively explored in the development of imitation or analog cheeses. These modifications significantly influence the protein-lipid network, as described by Cunha et al. (2010) in cheeses formulated with vegetable fats, and by Anvari and Joyner (2018) in Cheddar cheeses with varying fat levels. Furthermore, recent studies, such as the one conducted by Lorenzen et al. (2024), have analyzed how fat content and type modulate the microstructure of rennet casein gel emulsions, providing a framework for understanding how quinoa oil emulsions integrate into the dairy curd.

The results obtained in this study therefore provide valuable information on the effect of incorporating non-dairy ingredients into the microstructure of goat fresh cheese, how the components interact with each other, and how this can determine its texture.

3.3.9. *Sensory properties*

Sensory evaluation plays a crucial role in the development of new food products, as sensory quality informs about important technological and economic aspects related to product acceptability and viability in the market. The sensory quality of a product adds value, and sensory analysis is the main tool used for its evaluation (Fresno & Álvarez, 2012). Table 7 shows the nine sensory attributes evaluated by the panelists, with only significant differences ($p < 0.05$) in taste and sweetness between the control and fortified cheeses.

Table 7
Sensory properties of goat fresh cheese fortified with quinoa oil emulsion.

Parameter	Control	QE3	QE6	*p*-value
Odor	7.69 ± 1.39	7.47 ± 1.69	7.35 ± 1.91	0.608
Color	8.44 ± 0.94	8.28 ± 0.94	8.48 ± 0.89	0.599
Taste	7.65 ± 1.72[a]	6.72 ± 1.38[b]	7.50 ± 1.81[ab]	0.016
Sweetness	7.42 ± 1.71[a]	6.62 ± 1.64[b]	7.43 ± 1.76[a]	0.032
Salty	7.44 ± 1.88	6.66 ± 1.79	7.37 ± 1.64	0.065
Firmness	7.90 ± 1.32	7.60 ± 1.41	7.93 ± 1.37	0.428
Fracturability	7.94 ± 1.25	7.57 ± 1.19	7.78 ± 1.46	0.398
Granulosity	7.85 ± 1.30	7.32 ± 1.40	7.63 ± 1.47	0.174
Rancidity (Intensity)	2.85 ± 2.06	3.60 ± 2.26	2.89 ± 2.40	0.199
Overall acceptance	7.88 ± 1.44[a]	6.83 ± 1.51[b]	7.70 ± 1.40[a]	0.001

a-b Different superscripts between columns means significant differences ($p < 0.05$) due to quinoa oil emulsion addition.
Data ($n = 47$; Mean ± standard deviation). Control: cheese without quinoa emulsion; QE3: cheese with 3 g/L quinoa emulsion added; QE6: cheese with 6 g/L quinoa emulsion added.

The cheese fortified with the lowest emulsion concentration (QE3) received the lowest scores for taste and sweetness, while the QE6 formulation scored like the control for both attributes. The differences observed in the sweetness of the cheeses may be linked to the amino acid profile of calcium caseinate used in the emulsion. According to previous studies and the data from the manufacturer, caseinate contains 16 amino acids, including proline, alanine, threonine, serine, and glycine (Gorissen et al., 2018).These are classified as sweet-tasting amino acids (Wang et al., 2024; Wei et al., 2022) and are present in higher amounts in calcium caseinate than in goat's milk (Landi et al., 2021). Therefore, this could explain the subtle sweetness detected by the panelists in the cheeses fortified with the emulsion. Nevertheless, confirming this hypothesis would require analyzing the amino acid composition of the cheeses in future research studies.

The sensory results for color align with the results for color in the instrumental evaluation (Table 4), since the ΔE values between the fortified cheeses and the control were far below 3 and therefore imperceptible to the human eye. Similarly, the firmness scores suggest that, despite the instrumental differences observed for this parameter (Table 5), these variations would not be detected by consumers, as the panelists scored similarly all the formulations. On the other hand, the low scores recorded for rancidity across all cheeses are consistent with the peroxide value results (Fig. 2) and would confirm that none of the formulations showed any signs of rancidity.

The control cheeses and the QE6 cheese received similar overall acceptability scores, while the QE3 formulation obtained the lowest score (6.83 vs. 7.70–7.88). However, all scores were above 5, indicating that all fresh goat cheese formulations were well accepted by the panelists. In addition, the panelists noted in their comments that they would be willing to purchase the fortified cheeses. In line with these findings, several studies have reported positive sensory evaluations of cheese and dairy products fortified with vegetable oils (Hernández-Ruiz et al., 2025; Irfan et al., 2023; Khan et al., 2022; Muñoz-Tébar et al., 2019). This would support the viability of incorporating vegetable oils for the development of novel functional dairy products with sensory properties similar to those of traditional cheese.

4. Conclusions

The present study demonstrates that quinoa oil emulsions can be considered as an innovative approach to improve the nutritional value of fresh goat cheese while maintaining the quality attributes appreciated by consumers for any traditional cheese. The emulsion was successfully incorporated into the milk, increasing the MUFAs (from 1.32 to 1.59 g/100 g) and PUFAs content (from 0.24 to 0.52 g/100 g) without causing off-flavors, textural defects or microbiological issues. The cheeses maintained their characteristic freshness and typical microstructure with good sensory acceptance by the panelists.

The findings of this study are promising and prove that quinoa oil is a sustainable and clean-label plant alternative to conventional fish oils, overcoming the off-flavors that often limit their use and are unpleasant for consumers.

To sum up, quinoa oil emulsions open a new door for the food industry in the development of novel functional dairy products that not only align with current clean-label and plant-based trends but also meet consumer expectations for taste and quality.

CRediT authorship contribution statement

Nuria Muñoz-Tebar: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Raquel Lucas-González:** Methodology, Investigation, Data curation. **Clara Muñoz-Bas:** Investigation, Formal analysis. **Gema Martínez-Navarrete:** Methodology, Data curation. **Manuel Viuda-Martos:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Estrella Sayas-Barberá:** Writing – review & editing, Supervision. **Eduardo Fernández:** Resources. **José Ángel Pérez-Alvarez:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Juana Fernández-López:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

Ethical statement

Protocols for sensory analysis were approved (ref. PRL.DTA. JPA.05.21) by the Project Evaluation Office of the Miguel Hernández University (OEP, UMH, Elche, Alicante, Spain). Participants gave informed consent via the statement "I agree to participate in this survey" where an affirmative reply was required to enter the survey. They were able to withdraw from the survey at any time without giving a reason. The products tested were safe for sensory evaluation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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