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The influence of plant additives on the fatty acid profile, textural matrix, and sensory properties of Diyarbakır Örgü cheese during ripening

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Abstract

This study investigated the effects of *Capsicum annuum* L. (CA) and *Nigella sativa* L. (NS) enrichment on the fatty acid profile, textural attributes, and sensory characteristics of Diyarbakır Örgü cheese (DÖC) during ripening. Three cheese groups (CA, NS, and control (C)) were produced and ripened at 5 °C for 120 days. Fatty acid composition and lipid quality indices (AI, TI, DFA, OFA, H/H, NVI, and HPI) were evaluated at specific ripening stages, along with instrumental texture parameters and sensory properties. CA and NS supplementation notably modified ripening behaviour. Enriched cheeses retained higher MUFA and PUFA levels than the control, indicating reduced lipid oxidation and improved lipid-related health indices ($p<0.05$). NS cheeses, in particular, displayed superior HPI and H/H values at the end of storage. Texture results showed decreasing hardness, gumminess, and chewiness in all groups, while CA accelerated softening and NS promoted structural stability. Sensory scores increased over time, with stronger aromatic development in CA cheeses and enhanced late-stage flavor harmony in NS samples. Overall, CA and NS improved the chemical, textural, and sensory attributes of DÖC during ripening, indicating that these plant additions are promising tools for enhancing the functionality, quality, and consumer appeal of traditional cheeses.

Keywords: *Capsicum annuum*; consumer appeal; lipid quality; *Nigella sativa*; TPA

Introduction

Diyarbakır Örgü cheese (DÖC) is a semi-fat, firm-textured, and typically ripened traditional pasta-filata type cheese from Türkiye. Although its production technique resembles that of mozzarella and kashar cheeses, it differs in its characteristic braided form, brine-ripening process, and region-specific microbiota. During DÖC production, milk is coagulated at 29–30 °C for 54-70 minutes, the curd is drained and pressed, and fermentation is allowed to proceed. The fermented curd is then stretched and heated at 78-87 °C for approximately 5 minutes, after which the curd strips are braided to obtain the traditional form. Following brine maturation, the cheese is stored at 6±1 °C for approximately 4-6 months (Hatipoğlu and Çelik, 2020).

The use of spices and plant-derived additives in traditional cheese production has become increasingly widespread worldwide. These plant additives - spices influence not only the sensory quality attributes of cheese - such as colour, flavor - aroma, consistency, and texture - but also enhance shelf life, oxidative stability, and consumer acceptance. Moreover, owing to their phenolic compounds, vitamins, and essential oils, such plant materials can contribute to the functional properties and nutritional value of dairy products (Hayaloglu and Fox, 2008; Tarakci and Temiz, 2009; El-Sayed and Youssef, 2019).

In this context, *Capsicum annuum* L. (CA) and *Nigella sativa* L. (NS) are among the prominent plant-based ingredients due to their rich biochemical composition and well-documented beneficial effects on human health (Korkmaz et al., 2019; Li et al., 2023). CA is one of the most widely cultivated and consumed pepper species globally and is particularly rich in carotenoids, ascorbic acid, flavonoids, and phenolic compounds (Castro et al., 2008; Korkmaz et al., 2019; Tripodi and Kumar, 2019; Hernández-Pérez et al., 2020). Owing to the antioxidant capacity of these constituents, CA is associated with reducing oxidative stress, supporting immune function, and reducing the risk of certain cancers, age-related macular degeneration, cataracts, gastric ulcers, and cardiovascular diseases (Cvetković et al., 2022). These properties suggest that CA may delay oxidative deterioration in cheese fat and enhance storage stability.

NS, on the other hand, is a spice with a broad geographical distribution and a strong medicinal background. Its seeds are rich in thymoquinone as well as various phenolic and aromatic compounds (Hannan et al., 2021). The antimicrobial and antioxidant properties of NS make it valuable for investigation as a functional additive in cheese, as it can limit microbial growth and slow lipid oxidation in traditional products. Additionally, NS has been reported to possess neuroprotective, anticancer, diuretic, antihypertensive, antidiabetic, immunomodulatory, antihelminthic, analgesic, anti-inflammatory, spasmolytic, bronchodilatory, gastroprotective, hepatoprotective, and nephroprotective activities, highlighting its relevance as a health-promoting spice (Abd El-Hack et al., 2016; Yimer et al., 2019).

During cheese ripening, flavor development is governed by complex biochemical processes such as glycolysis, lipolysis, and proteolysis; consequently, the ripening process directly influences textural structure, volatile aroma profile, and fatty acid composition (Chen et al., 2020; Tudor Kalit et al., 2020; Yavuz et al., 2021). Fat in cheese is known to be one of the primary carriers of aroma. More than 400 fatty acid constituents present in milk fat undergo progressive changes throughout ripening, playing a critical role in shaping the sensory profile (Białek et al., 2020; Ioannidou et al., 2022). In particular, saturated fatty acids such as myristic and palmitic acid have important health implications, making it essential to monitor lipid quality during ripening (Paszczyk et al., 2022).

Therefore, determining how fatty acid profiles of cheeses change during storage is important both for assessing product quality and for addressing nutrition-oriented dietary concerns. Furthermore, lipid composition is known to influence textural development and sensory characteristics. However, studies that comprehensively evaluate the relationships among lipid profile, texture, and sensory attributes within a single research framework remain limited.

This study aims to investigate changes in fatty acid profiles, textural properties, and sensory parameters of DÖC produced with CA and NS throughout ripening. A comprehensive review of the literature revealed no scientific study that simultaneously monitored fatty acid profiles and evaluated textural and sensory parameters of DÖC during ripening. In this respect, the present study fills an existing gap in cheese science and provides a valuable scientific contribution by characterizing the chemical and sensory attributes of DÖC during maturation.

Materials and methods

Cheese production

Diyarbakır Örgü cheese samples were produced using cow's milk obtained from the Karacadağ Basin (Diyarbakır, Türkiye) (Figure 1). *Nigella sativa* and *Capsicum annuum* were incorporated at 1 % during production. The DÖC samples were packed into 2-kg plastic containers and stored at 5 °C for four months to complete ripening. Analyses were conducted on days 1, 30, 60, and 120 of storage.

Lipid extraction and preparation of fatty acid methyl esters

Cheese samples were homogenized in a chloroform/methanol solution (2:1, v/v) and kept in the dark for 48 hours. The extracted lipids were converted into methyl esters using a reflux system (conversion of fatty acid methyl esters was achieved by adding 3-5 drops of sulfuric acid to 4 mL of methanol and incubating it at 85 °C for 2 hours in a reflux system), and the resulting fatty acid methyl esters were extracted with hexane and transferred into vials. The samples were transferred into vials and analyzed using a gas chromatography system (Kizmaz, 2022).

Raw cow's milk
↓
Filtering through cheesecloth
↓
Coagulation (30 °C, 1:10.000)
↓
Cutting the curd and removing the whey
↓
Pressing and fermentation (for 120-160 minutes)
(Scalding maturity was determined by the string-pulling method)
↓
Slicing and scalding
(In water, 80 °C for 5 minutes)
↓
Portioning, shaping, and adding CA and NS
(Kneading, stretching, and braiding)
↓
Keeping in brine (12 °Bé, for 30 minutes)
↓
Packaging and addition of brine (Into plastic drums)
↓
Ripening (in a 17 °Bé brine, 5 °C for 120 days)

Figure 1. *Production flow chart of Diyarbakır Örgü cheese enriched with CA and NS*

Gas chromatographic analysis of fatty acids

Fatty acid methyl esters were analyzed using a gas chromatography system (SHIMADZU GC-2010 PLUS, Shimadzu Corp., Kyoto, Japan) equipped with a flame ionization detector (FID) and a DB-23 capillary column (Bonded 50 % cyanopropyl; 30 m × 0.25 mm i.d. × 0.25 µm film thickness; J & W Scientific, USA). The detector and injector temperatures were set at 250 °C, and injections were performed in split mode (1:50). The carrier gas was helium at a flow rate of 0.5 mL/min for a 30 m column, while hydrogen and dry air were supplied at flow rates of 30 mL/min and 400 mL/min, respectively.

The oven temperature program was as follows: initial temperature of 170 °C for 2 min, increased to 210 °C at 2 °C/min, and held for 20 min, resulting in a total run time of 42 min. A 1 µL sample was manually injected into the system. Identification of fatty acids was accomplished using a certified fatty acid methyl ester standard mixture containing 37 components (Sigma-Aldrich, USA). Chromatograms and total fatty acid compositions were processed using GC Solution software (Version 2.4).

Individual fatty acids in the chromatograms of the analyzed samples were identified by comparing their retention times with those of the standards. Quantification was performed using nonanoic acid (Sigma-Aldrich, USA) as an internal standard, and retention time comparisons with reference standards were used to determine qualitative fatty acid composition.

Assessment of lipid quality indices

To evaluate the nutritional and health-related lipid profile of the cheese samples, several fatty acid–based lipid quality indices were calculated. First, the atherogenicity (AI) and thrombogenicity (TI) indices were determined to characterize lipid patterns associated with atherosclerosis and thrombosis risk (Ulbricht and Southgate, 1991; Osmari et al., 2011):

$$AI = (C\ 12{:}0 + (4 \times C\ 14{:}0) + C\ 16{:}0)/(\Sigma\omega\text{-}3\ PUFA + \Sigma\omega\text{-}6\ PUFA + \Sigma\ MUFA)$$

$$TI = (C\ 14{:}0 + C\ 16{:}0 + C\ 18{:}0)/((0.5 \times C\ 18{:}1) + (0.5 \times \Sigma MUFA) + (0.5 \times \Sigma\omega\text{-}6\ PUFA) + (3 \times \Sigma\omega\text{-}3\ PUFA) + \Sigma\omega\text{-}3\ PUFA/\Sigma\omega\text{-}6\ PUFA)$$

Additionally, the hypocholesterolemic fatty acids (DFA) index and the hypercholesterolemic fatty acids (OFA) index were calculated to evaluate the cardiometabolic orientation of the fatty acid profile (Pietrzak-Fiećko and Kamelska-Sadowska, 2020):

$$DFA = \Sigma\ MUFA + \Sigma\ PUFA + C\ 18{:}0$$

$$OFA = C12{:}0 + C14{:}0 + C16{:}0$$

Furthermore, the H/H ratio (Akinbule et al., 2022) and the nutritional value index (NVI) (Chen et al., 2016) were calculated to provide additional insight into the nutritional status and lipid balance of the cheeses:

$$H/H = (C\ 18{:}1\ \omega\text{-}9 + C\ 18{:}2\ \omega\text{-}6 + C\ 18{:}3\ \omega\text{-}3 + C\ 20{:}4\ \omega\text{-}6 + C\ 20{:}5\ \omega\text{-}3 + C\ 22{:}5\ \omega\text{-}3 + C\ 22{:}6\ \omega\text{-}3)/(C\ 14{:}0 + C\ 16{:}0)$$

$$NVI = (C\ 18{:}0 + C\ 18{:}1)/C\ 16{:}0$$

Finally, the health-promoting index (HPI) was used to assess lipid health capacity by comparing total unsaturated fatty acids (UFA) levels with atherogenic fatty acids (Chen and Liu, 2020):

$$HPI\ (Health\text{-}Promoting\ Index) = \Sigma\ UFA/[C\ 12{:}0 + (4 \times C\ 14{:}0) + C\ 16{:}0]$$

Texture profile analysis

Texture Profile Analysis (TPA) of the cheese samples was performed using a Texture Analyzer (TA.XT Plus, Stable Micro Systems Ltd., Godalming, Surrey, UK) following the procedure described by Hatipoğlu et al. (2023). Cheese samples were cut into cubes measuring 3 cm on each side. Texture measurements were performed in quadruplicate for each treatment and sampling day. A 50-kg load cell equipped with a stainless-steel cylindrical probe (P/50; 50 mm diameter, Stable Micro Systems Ltd., Surrey, UK) was used to conduct the analysis. Samples with a height of 15 mm were tested at 25 °C using a double-compression cycle to 80 % deformation, with a pre-test speed of 10 mm/s and a test speed of 1 mm/s.

Textural parameters, including hardness, adhesiveness, springiness, cohesiveness, gumminess, and chewiness, were obtained from force–time curves generated by Exponent

software (Version 6.1.16.0, Stable Micro Systems Ltd., Godalming, Surrey, UK).

Sensory evaluation

Sensory evaluation of the cheese samples was conducted by nine trained panelists (aged 30–50 years) from the Department of Nutrition and Dietetics at Mardin Artuklu University, Türkiye. A four-point hedonic scale was used to assess the sensory attributes. For colour appearance, scores ranged from 1 = poor, 2 = adequate, 3 = good, and 4 = very good. Texture was evaluated using the same scale, where 1 = soft, 2 = normal, 3 = hard, and 4 = very hard. Taste-aroma intensity was scored as 1 = mild, 2 = moderate, 3 = strong, and 4 = very strong (Awad, 2006).

Statistical analysis

Data were analyzed separately for each ripening stage using one-way ANOVA to compare treatment effects within the same sampling day. Tukey's multiple comparison test was applied to determine significant differences among means (Watkins, 2021). Statistical analyses were performed using SPSS® (Version 25, IBM, USA).

Results and discussion

Fatty acid profile and lipid quality indices

Significant effects of ripening time and spice supplementation on fatty acid composition and lipid quality indices were observed in DÖC samples ($p<0.05$) (Table 1). During ripening, short- and medium-chain fatty acids increased significantly in all groups, confirming progressive lipolysis. For instance, butyric acid (C4:0) increased from 1.22 to 1.67 mg/g in the control between day 1 and day 120, whereas the increase was more moderate in CA (1.09 → 1.36 mg/g) and NS cheeses (1.17 → 1.43 mg/g). Similarly, caproic acid (C6:0) rose markedly in the control (2.31 → 3.06 mg/g), while CA exhibited a more limited increase (1.41 → 1.86 mg/g). These results demonstrate that although lipolysis progressed in all treatments, spice supplementation moderated the extent of fatty acid release, consistent with the modulatory effects of plant-based additives reported by Paszczyk and Tońska (2025).

Fatty acids ranging from C12:0 to C16:0 also increased significantly during storage, with the control exhibiting the greatest rise. Palmitic acid (C16:0), the dominant SFA, increased from 31.80 to 35.01 mg/g in the control, whereas CA and NS remained relatively stable (29.00 → 29.94 mg/g and 29.10 → 29.96 mg/g, respectively). Consequently, total SFA increased substantially in the control (80.74 → 94.37 mg/g), while the increase was less pronounced in CA (69.32 → 75.52 mg/g) and NS cheeses (74.76 → 81.02 mg/g). In agreement with previous reports showing that palmitic, myristic, and stearic acids remain dominant during cheese ripening (Medeiros et al., 2014; Paszczyk et al., 2022; Ali et al., 2023), these findings indicate that spice incorporation limited the magnitude of saturated fatty acid accumulation.

Conversely, MUFA and PUFA levels were significantly higher in CA and NS cheeses throughout ripening compared with the control ($p<0.05$). Oleic acid (C18:1 n9) remained elevated in NS (19.23 → 19.86 mg/g) and CA cheeses (16.24 → 16.30 mg/g), whereas it declined in the control (9.84 → 8.86 mg/g). Accordingly, total MUFA at day 120 reached 21.15 mg/g in NS and 17.58 mg/g in CA, compared with only 9.35 mg/g in the control. PUFA content showed an even more pronounced divergence, increasing in NS from 4.32 to 6.35 mg/g and in CA from 2.33 to 3.60 mg/g, while slightly decreasing in the control (1.37 → 1.28 mg/g). The maintenance of unsaturated fatty acids in spice-treated cheeses aligns with documented increases in MUFA and PUFA content in cheese systems influenced by dietary or additive interventions (Santillo et al., 2016; Paszczyk and Tońska, 2025), suggesting that plant-derived phenolics may have exerted antioxidant or enzyme-modulating effects during ripening.

Lipid quality indices further reflected these treatment-dependent trends. The AI value in the control increased markedly from 8.02 to 9.86 during ripening, whereas CA remained relatively stable (4.16 → 4.04) and NS even decreased slightly (3.64 → 3.40). A similar pattern was observed for TI, which increased sharply in the control (10.50 → 13.44) but declined in NS (4.57 → 4.28). Given the established association of these indices with atherogenic and thrombogenic fatty acid patterns, these numerical differences confirm that spice-treated cheeses exhibited a more favourable lipid profile during storage.

The H/H ratio declined in the control (0.24 → 0.20) but increased in CA (0.45 → 0.47) and NS cheeses (0.55 → 0.59). Likewise, HPI decreased in the control (0.12 → 0.10) while increasing in NS (0.27 → 0.29). Parallel trends were observed for NVI, which remained consistently higher in spice-treated cheeses at later ripening stages. These results collectively demonstrate that ripening promoted progressive lipid modification in all samples; however, the magnitude and nutritional implications of these changes were strongly influenced by spice treatment. Comparable modifications of lipid indices in plant-enriched cheese systems have been reported previously (Paszczyk et al., 2020; Ali et al., 2023).

Total fat content decreased significantly in all groups during storage ($p<0.05$), reflecting expected ripening-related lipolysis and moisture redistribution (Hatipoğlu and Çelik, 2020; Aydoğan et al., 2025). Quantitatively, CA decreased from 24.47 % on day 1 to 18.74 % by day 120 (-5.73 percentage points), while the control declined from 25.76 % to 19.82 % (-5.94 percentage points). In contrast, NS exhibited a comparatively smaller reduction, from 26.00 % to 22.38 % (-3.62 percentage points). Although lipid reduction is inherent to cheese ripening, the significantly lower fat loss observed in NS cheeses indicates that *Nigella sativa* supplementation modulated lipid dynamics during maturation. This difference may be associated with interactions between spice-derived bioactive compounds and the protein–lipid matrix, potentially influencing moisture

Table 1. Changes in fatty acid profile (mg/g), lipid quality indices, and total fat contents (%) of Diyarbakır Örgü cheese produced with different spices during the ripening

	Day 1			Day 30			Day 60			Day 120		
Lipid characteristics	CA	NS	C	CA	NS	C	CA	NS	C	CA	NS	C
4:0	1.09±0.05^{Bb}	1.17±0.04^{Ba}	1.22±0.04^{Ca}	1.15±0.04^{Bc}	1.24±0.05^{Bb}	1.36±0.05^{Ba}	1.31±0.06^{Ab}	1.36±0.06^{Cab}	1.42±0.08^{Ba}	1.36±0.05^{Ab}	1.43±0.08^{Cb}	1.67±0.07^{Aa}
6:0	1.41±0.05^{Cc}	2.11±0.09^{Bb}	2.31±0.09^{Ca}	1.76±0.06^{Bc}	2.58±0.07^{Ab}	2.85±0.08^{Ba}	1.83±0.05^{Ac}	2.62±0.09^{Ab}	3.02±0.08^{Aa}	1.86±0.09^{Ac}	2.62±0.09^{Ab}	3.06±0.15^{Aa}
8:0	1.10±0.05^{Cb}	1.45±0.05^{Ca}	1.40±0.05^{Da}	1.43±0.05^{Bc}	1.65±0.06^{Bb}	1.89±0.05^{Ca}	1.46±0.06^{Bc}	1.68±0.06^{ABb}	2.04±0.04^{Ba}	1.57±0.06^{Ac}	1.73±0.07^{Ab}	2.22±0.05^{Aa}
10:0	2.96 ±0.09^{Cc}	3.42±0.06^{Cb}	3.94±0.08^{Ca}	3.32±0.13^{Bc}	3.80±0.16^{Bb}	4.04±0.15^{BCa}	3.44±0.17^{ABb}	4.05±0.22^{Aa}	4.22±0.18^{ABa}	3.58±0.14^{Ab}	4.18±0.17^{Aa}	4.32±0.23^{Aa}
12:0	3.76±0.15^{Cb}	4.27±0.22^{Ba}	4.29±0.16^{Ca}	3.93±0.14^{BCb}	4.40±0.24^{ABa}	4.63±0.30^{Ba}	3.97±0.15^{Bc}	4.49±0.20^{ABb}	4.90±0.22^{ABa}	4.54±0.15^{Ab}	4.68±0.23^{Ab}	5.04±0.20^{Aa}
14:0	12.13±0.46^{Bb}	14.08±0.53^{Aa}	14.52±0.52^{Ca}	12.35±0.41^{ABc}	14.28±0.34^{Ab}	15.33±0.60^{Ba}	12.73±0.46^{Ac}	14.63±0.50^{Ab}	15.69±0.28^{ABa}	12.79±0.49^{Ac}	14.69±0.53^{Ab}	16.21±0.81^{Aa}
15:0	0.75±0.03^{Cc}	0.89±0.04^{Cb}	0.98±0.04^{Ba}	0.87±0.03^{Bb}	0.92±0.04^{ABb}	1.04±0.06^{Ba}	0.88±0.04^{Ac}	0.95±0.04^{Bb}	1.14±0.04^{Aa}	0.93±0.04^{Bc}	1.02±0.05^{Ab}	1.18±0.07^{Aa}
16:0	29.00±0.94^{Ab}	29.10±0.94^{Ab}	31.80±1.05^{Ba}	29.14±0.92^{Ab}	29.23±0.84^{Ab}	32.79±0.66^{Ba}	29.68±0.75^{Ab}	29.24±0.67^{Ab}	34.14±1.14^{Aa}	29.94±0.79^{Ab}	29.96±0.84^{Ab}	35.01±0.61^{Aa}
17:0	0.30±0.01^{Cb}	0.41±0.01^{Ba}	0.40±0.02^{Da}	0.34±0.01^{Bc}	0.43±0.01^{Bb}	0.47±0.02^{Ca}	0.36±0.01^{ABb}	0.47±0.03^{Aa}	0.50±0.02^{Ba}	0.38±0.02^{Ac}	0.50±0.02^{Ab}	0.62±0.02^{Aa}
18:0	16.81±0.48^{Bc}	17.86±0.39^{Cb}	19.86±0.76^{Ca}	17.26±0.58^{Bc}	19.36±0.55^{Bb}	21.05±0.97^{Ba}	18.34±0.44^{Ac}	20.04±0.63^{ABb}	24.14±0.69^{Aa}	18.57±0.58^{Ac}	20.22±0.71^{Ab}	25.04±1.03^{Aa}
SFA	69.32±1.81^{Cc}	74.76±1.59^{Cb}	80.74±1.88^{Da}	71.56±1.62^{Bc}	77.90±1.78^{Bb}	85.44±2.25^{Ca}	74.01±1.50^{Ac}	79.54±1.67^{ABb}	91.22±1.70^{Ba}	75.52±1.18^{Ac}	81.02±1.79^{Ab}	94.37±2.70^{Aa}
16:1 (*n*7)	1.00±0.05^{Cb}	1.05±0.06^{Ca}	0.53±0.02^{Ac}	1.16±0.04^{Ba}	1.14±0.03^{Ba}	0.51±0.03^{ABb}	1.24±0.05^{Aa}	1.27±0.05^{Aa}	0.50±0.02^{ABb}	1.28±0.05^{Aa}	1.29±0.05^{Aa}	0.49±0.02^{Bb}
18:1 (*n*9)	16.24±0.55^{Ab}	19.23±0.57^{Aa}	9.84±0.16^{Ac}	16.25±0.43^{Ab}	19.70±0.64^{Aa}	9.89±0.19^{Ac}	16.61±0.33^{Ab}	19.69±0.51^{Aa}	9.12±0.19^{Bc}	16.30±0.54^{Ab}	19.86±0.68^{Aa}	8.86±0.27^{Bc}
MUFA	17.23±0.59^{Ab}	20.29±0.57^{Ba}	10.38±0.17^{Ac}	17.41±0.42^{Ab}	20.84±0.67^{ABa}	10.40±0.21^{Ac}	17.85±0.32^{Ab}	20.96±0.51^{ABa}	9.63±0.21^{Bc}	17.58±0.57^{Ab}	21.15±0.70^{Aa}	9.35±0.28^{Bc}
18:3 (*n*3)	0.22±0.00^{Cb}	0.38±0.02^{Da}	0.13±0.00^{Ac}	0.34±0.02^{Bb}	0.42±0.02^{Ca}	0.13±0.01^{Ac}	0.37±0.02^{Ab}	0.47±0.02^{Ba}	0.13±0.01^{Bc}	0.38±0.02^{Ab}	0.52±0.02^{Aa}	0.11±0.00^{Cc}
18:2 (*n*6)	2.11±0.03^{Db}	3.94±0.08^{Da}	1.23±0.02^{Ac}	2.46±0.01^{Cb}	4.11±0.04^{Ca}	1.23±0.04^{Ac}	2.71±0.14^{Bb}	5.42±0.20^{Ba}	1.22±0.04^{ABc}	3.23±0.13^{Ab}	5.83±0.13^{Aa}	1.18±0.04^{Bc}
PUFA	2.33±0.03^{Db}	4.32±0.08^{Da}	1.37±0.02^{Ac}	2.80±0.03^{Cb}	4.53±0.04^{Ca}	1.36±0.04^{Ac}	3.08±0.16^{Bb}	5.90±0.20^{Ba}	1.34±0.05^{Ac}	3.60±0.13^{Ab}	6.35±0.15^{Aa}	1.28±0.05^{Bc}
***n*3/*n*6**	0.10±0.00^{Ca}	0.09±0.00^{Bb}	0.11±0.00^{Aa}	0.14±0.00^{Aa}	0.10±0.00^{Ab}	0.10±0.00^{Ab}	0.14±0.00^{Aa}	0.09±0.00^{Cc}	0.10±0.01^{Bb}	0.12±0.01^{Ba}	0.09±0.00^{Cb}	0.09±0.00^{Bb}
AI	4.16±0.13^{Ab}	3.64±0.08^{Ac}	8.02±0.13^{Da}	4.08±0.11^{Ab}	3.58±0.07^{Ac}	8.39±0.24^{Ca}	4.04±0.06^{Ab}	3.44±0.07^{Bc}	9.29±0.16^{Ba}	4.04±0.14^{Ab}	3.40±0.08^{Bc}	9.86±0.20^{Aa}
TI	5.56±0.15^{Ab}	4.57±0.10^{Ac}	10.50±0.18^{Da}	5.30±0.11^{Bb}	4.54±0.10^{Ac}	10.96±0.22^{Ca}	5.27±0.08^{Bb}	4.35±0.07^{Bc}	12.60±0.18^{Ba}	5.26±0.13^{Bb}	4.28±0.13^{Bc}	13.44±0.22^{Aa}
DFA	36.37±0.85^{Cb}	42.47±0.94^{Ca}	31.60±0.84^{Bc}	37.47±0.66^{Bb}	44.73±1.03^{Ba}	32.82±1.17^{Bc}	39.26±0.59^{Ab}	46.89±1.19^{Aa}	35.11±0.77^{Ac}	39.76±1.04^{Ab}	47.72±0.73^{Aa}	35.68±1.30^{Ac}
OFA	44.84±1.27^{Cc}	47.45±1.20^{Bb}	50.62±1.38^{Ca}	45.42±0.97^{BCc}	47.92±1.07^{ABb}	52.74±1.14^{Ba}	46.38±1.03^{ABc}	48.36±1.14^{ABb}	54.74±1.41^{Aa}	47.27±1.06^{Ac}	49.33±1.28^{Ab}	56.27±1.31^{Aa}
H/H	0.45±0.01^{Ab}	0.55±0.02^{Ba}	0.24±0.00^{Ac}	0.46±0.01^{Ab}	0.56±0.01^{Ba}	0.23±0.00^{Bc}	0.46±0.01^{Ab}	0.58±0.01^{Aa}	0.21±0.00^{Cc}	0.47±0.02^{Ab}	0.59±0.02^{Aa}	0.20±0.00^{Dc}
NVI	1.14±0.02^{Ab}	1.28±0.05^{Ba}	0.93±0.04^{Ac}	1.15±0.02^{Ab}	1.34±0.03^{Aa}	0.94±0.03^{Ac}	1.18±0.03^{Ab}	1.36±0.04^{Aa}	0.98±0.04^{Ac}	1.17±0.05^{Ab}	1.34±0.03^{Aa}	0.97±0.03^{Ac}
HPI	0.24±0.01^{Ab}	0.27±0.01^{Ba}	0.12±0.00^{Ac}	0.25±0.01^{Ab}	0.28±0.01^{Ba}	0.12±0.00^{Bc}	0.25±0.00^{Ab}	0.29±0.01^{Aa}	0.11±0.00^{Cc}	0.25±0.01^{Ab}	0.29±0.01^{Aa}	0.10±0.00^{Dc}
Total fat	24.47±0.73^{Ab}	26.00±0.57^{Aa}	25.76±0.46^{Aa}	20.30±0.53^{Bc}	25.24±0.75^{ABa}	23.50±0.54^{Bb}	19.79±0.81^{Bc}	24.56±0.88^{Ba}	21.05±0.99^{Cb}	18.74±0.86^{Cc}	22.38±0.66^{Ca}	19.82±0.80^{Db}

Values (mean ± SD, n = 3); SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids; CA, cheese with Capsicum annuum; NS, cheese with Nigella sativa; C, control cheese; AI, atherogenicity index; TI, thrombogenicity index; DFA, hypocholesterolemic index; OFA, hypercholesterolemic index; H/H, hypocholesterolemic/ hypercholesterolemic ratio; NVI, nutritive value index; HPI, health-promoting index

$^{A–D}$: Means with different letters in the same line are significantly different between ripening time in the same sample (p<0.05)

$^{a–c}$: Means with different letters in the same line are significantly different between the same ripening times in different samples (p<0.05)

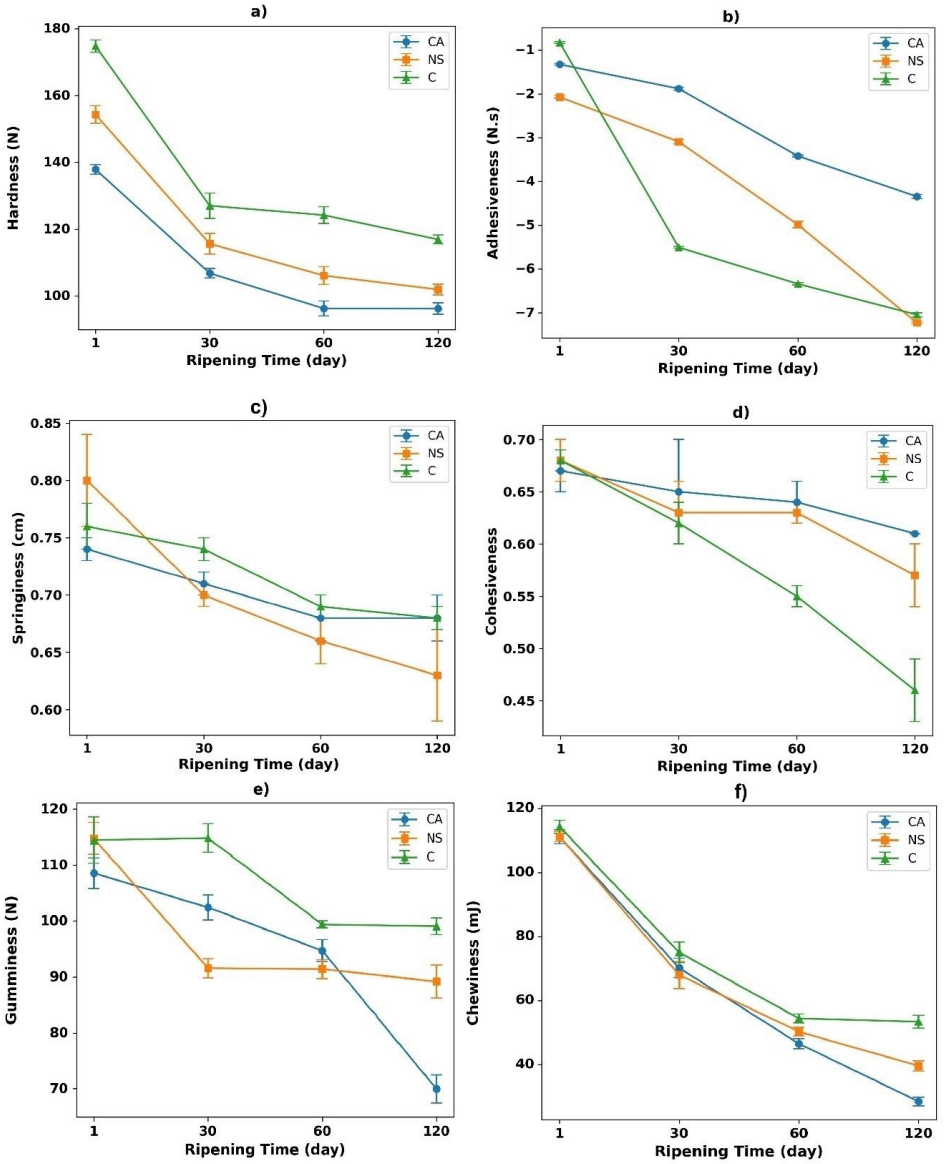


Figure 2. Changes in textural properties of cheese types during storage: Values (mean ± SD, n = 3); Hardness (a), Adhesiveness (b), Springiness (c), Cohesiveness (d), Gumminess (e), Chewiness (f). CA, cheese with Capsicum annuum; NS, cheese with Nigella sativa; C, control cheese

retention and lipolytic activity. Therefore, the progression of fat reduction was not solely time-dependent but was clearly modulated by the type of spice incorporated.

Texture profile

Texture profile analysis revealed that ripening time significantly affected all evaluated parameters, and the magnitude of change depended on spice supplementation ($p<0.05$) (Figure 2). The observed modifications reflect progressive proteolysis, moisture redistribution, and mineral equilibrium shifts occurring during maturation.

Hardness decreased significantly in all treatments throughout storage. Quantitatively, the control cheese declined from 174.78 N on day 1 to 116.90 N by day 120 (-33 %), while CA decreased from 137.87 to 96.20 N (-30 %) and NS from 154.29 to 101.92 N (-34 %). Although all groups exhibited marked softening, the control retained the highest absolute hardness values at each ripening stage. The progressive reduction in hardness confirms weakening of the casein matrix due to proteolytic activity and fat redistribution during ripening, consistent with previous reports describing structural breakdown in matured cheeses (Tarakçı and Yolaşan, 2024; López-Ruiz et al., 2025; Młynek et al., 2018). The slightly greater proportional decline in NS suggests that *Nigella sativa* components may have influenced proteolytic dynamics differently from Capsicum-derived compounds.

Adhesiveness increased markedly during ripening in all groups ($p<0.05$). In the control, values shifted from -0.83 N.s at day 1 to -7.05 N.s at day 120, representing more than an eight-fold increase in magnitude. NS exhibited the most pronounced final adhesiveness (-7.23 N.s), whereas CA reached -4.35 N.s. This dramatic increase reflects progressive protein network

disintegration and enhanced surface stickiness associated with moisture mobility changes during ripening (Młynek et al., 2018). The sharper increase observed in NS cheeses suggests that black seed constituents may have modified water-protein interactions, potentially influencing matrix cohesiveness and surface characteristics.

Springiness showed a moderate but statistically significant decline ($p<0.05$). NS decreased from 0.80 to 0.63 cm, CA from 0.74 to 0.68 cm, and the control from 0.76 to 0.68 cm. Compared with hardness and chewiness, the percentage reduction in springiness was limited, indicating that elastic recovery was less sensitive to structural breakdown than compressive strength parameters. Nevertheless, the lower final elasticity in NS suggests treatment-specific effects on protein network resilience.

Cohesiveness decreased significantly over time, with the control cheese showing the most pronounced decline from 0.68 on day 1 to 0.46 by day 120 ($p<0.05$). In contrast, CA decreased from 0.67 to 0.61 and NS from 0.68 to 0.57. The sharper reduction in the control indicates more extensive internal structural fragmentation, whereas spice-treated cheeses exhibited comparatively moderated reductions. These findings suggest that plant-derived bioactive compounds may have partially stabilized protein–protein interactions within the cheese matrix, in agreement with studies reporting texture modulation by functional plant ingredients (López-Ruiz et al., 2025).

Parallel trends were observed for gumminess and chewiness, both of which declined substantially during maturation ($p<0.05$). Gumminess in CA decreased from 108.58 N to 69.99 N, in NS from 114.76 N to 89.19 N, and in the control from 114.48 N to 99.09 N. Chewiness demonstrated the greatest proportional reduction among all parameters: CA declined from 111.17 to 28.52 mJ (-74 %), NS from 111.22 to 39.62 mJ (-64 %), and the control from 114.30 to 53.39 mJ (-53 %). These pronounced decreases indicate a significant reduction in mastication energy requirement and reflect advanced matrix softening driven by proteolysis and mineral redistribution (Tarakçı and Yolaşan, 2024; Młynek et al., 2018). The more substantial chewiness decline in CA suggests intensified structural breakdown, possibly linked to Capsicum-derived phenolic interactions with microbial or enzymatic systems, as previously reported for spice-enriched cheese matrices (Andriot et al., 2024).

Collectively, the numerical integration of Figure 2 data confirms that ripening induced significant structural softening in all samples; however, the extent and kinetics of change were treatment-dependent. CA supplementation was associated with the most pronounced reduction in chewiness, whereas NS exhibited the greatest increase in adhesiveness. The control, despite higher absolute hardness retention, showed the strongest decline in cohesiveness. These results demonstrate that spice incorporation altered not only absolute texture values but also the trajectory of structural transformation during maturation, supporting previous findings that plant-derived bioactives modulate enzymatic activity and cheese matrix evolution (Andriot et al., 2024; López-Ruiz et al., 2025).

Sensory properties

Sensory evaluation revealed that storage time significantly affected taste–aroma, texture perception, and colour attributes in DÖC samples ($p<0.05$) (Figure 3). The changes observed during ripening reflected a progressive evolution of sensory quality rather than simple numerical variation.

Colour scores exhibited formulation-dependent differences throughout storage. The control cheese maintained consistently higher colour scores (3.22 → 3.33), whereas CA showed slightly lower values at later stages (2.85 → 2.74), and NS fluctuated between 2.93 and 3.19. The relatively lower colour perception in spice-containing cheeses may be attributed to the presence of plant particulates, which could have affected visual homogeneity and surface uniformity. Similar impacts of spice-derived particles on visual perception have been documented in herb- and spice-enriched cheeses (Tarakçı and Yolaşan, 2024).

Taste-aroma scores increased significantly in all formulations during ripening. CA improved from 1.89 on day 1 to 2.52 by day 120, NS from 1.56 to 2.58, and the control from 1.56 to 2.56. Notably, NS cheeses initially exhibited the lowest taste–aroma score; however, they showed the greatest overall increase (+1.02 units), ultimately reaching the highest final value among treatments. This pattern suggests a slower but more pronounced flavour development in NS cheeses. The progressive enhancement of flavour perception is consistent with the accumulation of free fatty acids and volatile aromatic compounds during ripening. In particular, the higher MUFA and PUFA levels maintained in spice-treated cheeses (Table 1) may have contributed to the formation of aroma-active compounds through oxidative and enzymatic pathways, as reported in previous studies (Andriot et al., 2024; López-Ruiz et al., 2025). Thus, the sensory improvement in taste–aroma appears directly linked to biochemical changes occurring in the lipid fraction during maturation.

Texture perception scores also increased significantly over time ($p<0.05$). CA increased from 1.56 to 1.89, NS from 1.44 to 1.52, and the control from 1.56 to 2.00. The highest final texture score was observed in the control sample, despite its comparatively higher instrumental hardness values (Figure 2). This apparent discrepancy can be explained by the fact that moderate structural integrity may positively influence consumer-perceived chewability and mouthfeel. Importantly, the overall improvement in sensory texture paralleled the marked decline in instrumental hardness (e.g., control: 174.78 → 116.90 N) and chewiness (114.30 → 53.39 mJ). This inverse relationship confirms that mechanical softening during ripening translated into enhanced oral perception, consistent with previously reported correlations between instrumental and sensory texture measurements in ripened dairy products (Półtorak et al., 2015; López-Ruiz et al., 2025).

Overall, sensory progression during ripening was characterized by significant improvements in taste–aroma and texture perception, with formulation-dependent differences in the rate and magnitude of change. CA cheeses demonstrated earlier enhancement in flavour intensity, whereas NS cheeses exhibited a more gradual but ultimately greater increase in taste–aroma scores. The control maintained superior colour perception and achieved the highest final texture score. These

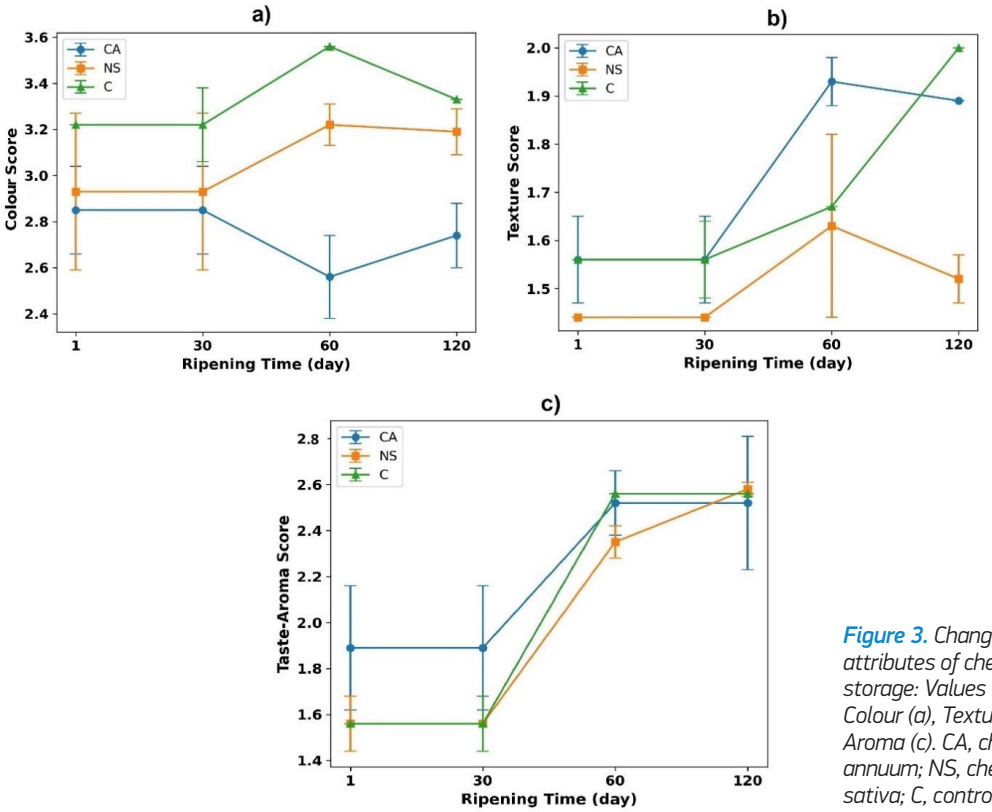


Figure 3. Changes in sensory attributes of cheese types during the storage: Values (mean ± SD, n = 9); Colour (a), Texture (b), and Taste-Aroma (c). CA, cheese with Capsicum annuum; NS, cheese with Nigella sativa; C, control cheese

findings indicate that spice supplementation influenced not only biochemical and structural transformations but also the kinetics of sensory development, highlighting the interconnected nature of lipid modification, matrix softening, and flavour evolution during cheese maturation.

Conclusion

This study demonstrated that storage time influenced the chemical, textural, and sensory properties of DÖC samples produced with different spices. As ripening progressed, changes were observed in the fatty acid profile, with a decline in total fat content and an increase in the proportion of saturated fatty acids. Cheeses enriched with *Capsicum annuum* and *Nigella sativa* showed a greater preservation of MUFA and PUFA levels during storage, which was accompanied by lower lipid oxidation and more favourable values of health-related lipid indices such as HPI, DFA, and H/H. In contrast, control cheeses exhibited more pronounced increases in AI, TI, and OFA values over time, indicating reduced lipid stability compared to spice-enriched samples.

Storage-related biochemical changes were also reflected in textural parameters. Hardness, gumminess, and chewiness decreased progressively throughout ripening, consistent with the gradual breakdown of the cheese matrix. While CA supplementation was associated with a more noticeable softening during storage, NS incorporation contributed to a comparatively better maintenance of structural integrity. Sensory evaluation further indicated that ripening enhanced taste–aroma and texture perception over time, with NS cheeses demonstrating a more balanced flavour development at later stages of storage.

Overall, storage duration was identified as the primary factor influencing quality changes during ripening, whereas spice incorporation modulated the extent and pattern of these time-dependent changes. Future research should focus on enzymatic lipolysis mechanisms, optimization of spice concentration levels, microstructural analysis, and consumer acceptance studies.

Utjecaj biljnih dodataka na profil masnih kiselina, teksturnu matricu i senzorska svojstva sira Diyarbakır Örgü tijekom zrenja

Sažetak

U ovom radu istražen je utjecaj dodatka *Capsicum annuum* L. (CA) i *Nigella sativa* L. (NS) na profil masnih kiselina, teksturalna i senzorska svojstva sira Diyarbakır Örgü (DÖC) tijekom zrenja. Proizvedene su tri skupine sireva (CA, NS i kontrolna skupina (C)) koje su pohranjene pri 5 °C tijekom 120 dana. U određenim fazama zrenja praćeni su sastav masnih kiselina i indeksi kvalitete lipida (AI, TI, DFA, OFA, H/H, NVI i HPI) zajedno s parametrima teksture i senzorskim svojstvima. Dodatak CA i NS značajno je utjecao na tijek zrenja. Obogaćeni sirevi zadržali su više MUFA i PUFA u odnosu na kontrolnu skupinu, što upućuje na smanjenu oksidaciju lipida i poboljšane zdravstvene indekse povezane s lipidima ($p<0,05$). Posebno su NS sirevi na kraju skladištenja pokazali više vrijednosti HPI i H/H. Rezultati teksturalne analize ukazali su na smanjenje tvrdoće, gumenosti i žvakljivosti u svim skupinama, pri čemu je CA ubrzao omekšavanje sira, dok je NS pridonio strukturnoj stabilnosti. Senzorske ocjene rasle su tijekom vremena, uz izraženiji razvoj arome u CA sirevima te poboljšanu harmoniju okusa u kasnijim fazama kod NS uzoraka. Sveukupno, dodatak CA i NS unaprijedio je kemijska, teksturalna i senzorska svojstva DÖC tijekom zrenja, što upućuje na njihov potencijal kao funkcionalnih dodataka za poboljšanje kvalitete i prihvatljivosti tradicionalnih sireva kod potrošača.

Ključne riječi: *Capsicum annuum*; prihvatljivost kod potrošača; kvaliteta lipida; *Nigella sativa*; TPA

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