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HAFİZE FİDAN

TONCHO KOLEV

DENİS DERVİSH

İVAYLA DİNÇEVA

İRA TANEVA

See next page for additional authors

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HAFIZE FIDAN, TONCHO KOLEV, DENIS DERVISH, IVAYLA DINCHEVA, IRA TANEVA, SERKAN YILMAZ, YUSUF ŞAVŞATLI, and ALBENA STOYANOVA

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Hafize FİDAN^{1,*}, Toncho KOLEV², Denis DERVISH¹, Ivayla DINCHEVA³, Ira TANEVA², Serkan YILMAZ⁴, Yusuf ŞAĞSATLI⁵, Albena STOYANOVA⁶

¹Department of Tourism and Culinary Management, Faculty of Economics, University of Food Technologies, Plovdiv, Bulgaria

²Department of Food Technology, Faculty of Technics and Technologies, Trakia University, Yambol, Bulgaria

³Department of Agrobiotechnology, AgroBioInstitute, Agricultural Academy, Sofia, Bulgaria

⁴Department of Midwifery, Faculty of Nursing, Ankara University, Ankara, Türkiye

⁵Department of Field Crops, Faculty of Agriculture, Recep Tayyip Erdoğan University, Rize, Türkiye

⁶Department of Technology of Tobacco, Sugar, Vegetable and Essential Oils, Technological Faculty, University of Food Technologies, Plovdiv, Bulgaria

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Abstract: Curd cheese is a traditional dairy product that, in recent years, has increasingly been supplemented with various functional additives aimed at enhancing its aroma and flavor profile, improving overall quality, and extending shelf-life. The objective of the present study was to conduct a comparative evaluation of changes in selected physicochemical, microbiological, and sensory parameters of curd cheese enriched with 0.01% essential oils derived from dill (*Anethum graveolens* L.), cumin (*Cuminum cyminum* L.), and caraway (*Carum carvi* L.) fruits. Fatty acid profiling revealed a reduction in saturated fatty acids and an increase in oleic and linoleic acids in essential oil-enriched curds compared with the control. Amino acid analysis showed higher levels of essential amino acids, particularly leucine and lysine, suggesting enhanced protein retention and balanced proteolysis. Organic acid content, including lactic acid, was slightly lower in treated samples, indicating moderate fermentation activity, while microbiological analyses confirmed the absence of spoilage or pathogenic organisms. Essential oils also contributed to higher moisture retention, reflected in slower increases in dry matter during storage. Sensory evaluation by a consumer panel indicated that all curds were well accepted. The findings demonstrate that dill, cumin, and caraway essential oils can be used as functional additives in low-fat curd to enhance nutritional value, improve product stability, and maintain consumer acceptance during storage.

Key words: Curd cheese, essential oils, sensory characteristics

1. Introduction

Today, interest in functional dairy products is quite high. Curd cheese represents a suitable model matrix for assessing the efficacy of natural additives owing to its low fat content and mild sensory characteristics. Nevertheless, its high moisture content and nearly neutral pH make it particularly prone to microbial growth and oxidative degradation, posing a major technological challenge for product preservation. This limitation can be mitigated by incorporating essential oils, whose antimicrobial and antioxidant activities not only prolong shelf life but also enhance the aroma and flavor profile of the resulting functional dairy product. Given their well-documented bioactive properties, essential oils contribute to improved product stability and overall quality. A common approach to developing these products is adding essential oils from

various plants to enhance aroma and flavor profiles, thereby improving overall quality (Kostova et al., 2014; Wedad et al., 2017). Extracts (Ivanova et al., 2020a, 2020b) and essential oils from dill (Kostova et al., 2017; Dimitrova and Koleva, 2024) and caraway (Trifonov et al., 2012; Kostova et al., 2015; Kostova et al., 2016) have also been used in dairy products. These ingredients have shown positive effects on both sensory characteristics and the technological aspects of the final products.

One of the most commonly used spices is dill (*Anethum graveolens* L.) (Baeva et al., 2013; Altameme et al., 2017). Its aerial parts and their fruits contain essential oils with different compositions. In the aerial parts (dill weed), the main ingredients are linalool, β -phellandrene, and carvone, each making up about 30%. In the dill fruits, carvone is the major compound (Jirovetz et al., 2003;

* Correspondence: h_fidan@uft-plovdiv.bg

Dimov et al., 2019; Gandova et al., 2022). The essential oil content ranges from 1% to 5%, influenced by various factors, such as soil and geographical conditions (Vokk et al., 2011; Hah and Ea, 2016), harvest season (Radulescu et al., 2010; Saleh-e-in et al., 2010), fruit storage duration (Jirovetz et al., 2003), and processing methods (Stoyanova, 2022). The monoterpene ketone carvone has several biological activities (Chahal et al., 2017; Koleva et al., 2023). Carvone and other oxygenated compounds mainly determine the functional properties of dill oil, which include antimicrobial (Mahmoodi et al., 2012; Kostova et al., 2017), antioxidant (Ayoughi et al., 2009; Leahu et al., 2013; Gandova et al., 2022), and other bioactive effects (Rathore et al., 2013; Koleva and Dimov, 2023).

Other commonly used plant materials include cumin (*Cuminum cyminum* L.) and its essential oil, a pale yellow liquid known for its distinctive flavor and aroma (Kan et al., 2007; Mohammed et al., 2024). Its composition is mainly made up of aldehydes such as cuminaldehyde (15.7–71.9%), *p*-menthadien-1,4-al-7 (2.2–27.4%), and *p*-menthadien-1,4-al-7 (0.3–17.4%), along with hydrocarbons such as β -pinene (0.8–21.0%), *p*-cymene (4.2–23.2%), and γ -terpinene (1.5–23.9%). The levels of these compounds vary with harvest time and fruit maturity (Kan et al., 2007), the origin of the raw materials (Dobrev, 2010), and processing methods (Romagnoli et al., 2010). The high aldehyde content contributes to the strong antimicrobial activity of cumin oil (Gachkar et al., 2007; Chaudhary et al., 2014; Abbaszadegan et al., 2016; Sharifi et al., 2021) and its biological activities (Kedia et al., 2015; Mohammed et al., 2024).

Caraway (*Carum carvi* L.) essential oil is a clear, colorless to amber-yellow liquid with a spicy aroma and pungent taste (Laribi et al., 2010; Ćimović et al., 2014). It shows antimicrobial (Fekry et al., 2022; Ghannay et al., 2022; Liu et al., 2023), antioxidant (Ghannay et al., 2022), and other biological properties (Laribi et al., 2013). These effects arise from its complex mixture of aromatic compounds (Gwari et al., 2012; Ćimović et al., 2014), which vary by geographical origin (Laribi et al., 2013; Fidan et al., 2025a, 2025b, 2025c). The goal of this study is to compare changes in selected physicochemical, microbiological, and sensory parameters during storage of curd cheese supplemented with essential oils from dill, cumin, and caraway seeds.

2. Materials and methods

The raw materials for this study were purchased from the commercial retail network. Skimmed cow's milk (0.1% fat, 3.3% protein, 4.8% lactose) was the main ingredient for making curd cheese. A commercial freeze-dried starter culture containing *Lactococcus lactis* subsp. *lactis* and *L. lactis* subsp. *lactis/cremoris* was used to ferment the milk. Calcium chloride (33% stock solution, food grade)

helped with milk coagulation. A rennet enzyme with a clotting activity of 1:15,000 was added to induce clotting. Essential oils (EOs) from dill, cumin, and caraway fruits (food grade) were mixed (0.01%) into the curd cheese formulations. Commercial food-grade EOs derived from dill, cumin, and caraway were incorporated at 0.01% into the curd cheese formulations. All reagents and additives used in the experiments were of analytical or food-grade quality.

Curd cheese was prepared using a mixed-type coagulation technology. Skimmed cow's milk was pasteurized at 72 °C to 75 °C for 15 to 20 s, cooled to 30 °C to 32 °C, and fortified with a 1% starter culture, 30 to 40 mL calcium chloride, and 15 to 20 mL rennet enzyme. EOs from dill, caraway, and cumin fruits were added at a concentration of 0.01%. This dosage was chosen based on unpublished data from our preliminary studies and supported by literature reports (Keshavarzi et al., 2021). The mixtures were homogenized and incubated at 30–32 °C for 45 min until the pH reached 5.0–5.2. Next, rennet enzyme was added at a concentration of 0.02–0.03%, and the milk was allowed to coagulate at 30–32 °C for 30–45 min. The coagulated curd was cut into uniform pieces to promote whey expulsion, followed by pressing to facilitate further moisture removal and curd consolidation.

The obtained curd cheese samples were analyzed for titratable acidity (Bulgarian State Standard, 1980), active acidity (pH), which was measured potentiometrically using a WTW 7110 pH meter (Germany), dry matter (ISO 5534:2004), fat content (ISO 19662:2018), fatty acid profile (ISO 12966-1:2014; ISO 12966-2:2017), amino acid composition (Otter, 2012), and organic acids (Murtaza et al., 2012).

Antibacterial activity was evaluated against selected test cultures, following established methods (Abbaszadegan et al., 2016; Sharifi et al., 2021). Standard microbiological parameters were determined, including total plate count per gram of sample, total counts of yeasts and molds per gram, coliforms per gram, *Salmonella* spp. in 25 g of sample, and coagulase-positive staphylococci per gram of product (IDF Standard 117B:1997).

Sensory evaluation was conducted according to the Bulgarian State Standard (1983), consistent with previous dairy studies (Ivanova et al., 2020a, 2020b).

All experiments were conducted in triplicate, and values in the tables were averaged and reported as the mean $\pm$ standard deviation. The experimental data were subjected to statistical analysis using analysis of variance in Statgraphics Centurion XVI Version 16.2.04 (StatPoint Technologies, Inc., USA). Duncan's multiple-range tests were used to determine differences between means, and significance was set at $p < 0.05$.

3. Results and discussion

The fatty acid composition of the control sample and curd cheese with added EOs is shown in Table 1. The results show that adding EOs reduced the amount of saturated fatty acids in the experimental samples, while increasing the amount of unsaturated fatty acids. The most significant increase was seen in oleic acid in the sample with cumin EO (80.52%). This was followed by the sample with dill EO (57.14%) and the one with caraway EO (33.77%). Bodas et al. (2010) reported similar changes in the fatty acid composition of cheeses made from milk enriched with other vegetable oils. In all EO-enriched samples, the proportion of medium-chain saturated fatty acids ($C_{4:0}$ to $C_{12:0}$) was slightly reduced compared with the control. For instance, butyric acid ($C_{4:0}$) in the dill EO curd cheese was 0.16%, lower than 0.25% in the control, with similar trends for caproic ($C_{6:0}$), caprylic ($C_{8:0}$), and capric ($C_{10:0}$) acids. Long-chain saturates like myristic ($C_{14:0}$), palmitic ($C_{16:0}$), and stearic ($C_{18:0}$) fatty acids were also lower in the EO-supplemented curd cheeses. Conversely, the curd cheeses fortified with EOs showed increased levels of unsaturated fatty acids. Monounsaturated palmitoleic acid ($C_{16:1}$) and oleic acid ($C_{18:1}$) were higher in the EO samples (e.g., oleic acid reached 1.21% with dill EO vs. 0.77% in the control). EOs are known to contain antioxidant compounds (e.g., terpenoids) that can retard lipid oxidation. As a result, fewer unsaturated fatty acids would be oxidized during

processing and storage, leading to a relatively higher unsaturated fatty acid content in the final product. This aligns with the findings of Ivanova et al. (2020a), who reported a significantly higher proportion of unsaturated fatty acids and a lower peroxide value in fresh cheese when a dill extract antioxidant was added. In nutritional terms, the slight shift toward more oleic and linoleic acids is desirable, as these unsaturated fats are considered beneficial for health. Thus, even at the low inclusion level (0.01%), the EOs may enhance the fat stability and nutritional profile of curd cheese by protecting unsaturated lipids from oxidation.

The amino acid composition of the curd cheese samples is presented in Table 2. Of the 19 amino acids detected, nine were essential amino acids. Proline, leucine, aspartic acid, and lysine content were comparatively high in all the curd cheese samples, with the highest being observed in the sample incorporated with dill EO. Among the indispensable amino acids, the greatest gain relative to the control was observed for leucine, with the highest content in the dill EO sample (28.8%). The amino acid profiles of all curd cheese samples were dominated by glutamine/ glutamic acid, proline, leucine, and lysine, reflecting the typical composition of milk proteins. Both essential and nonessential amino acids were increased in the presence of EOs. These consistent increases across amino acids suggest that the protein content or retention in the curd cheese

Table 1. Fatty acid composition of curd cheese supplemented with essential oils from dill, cumin, and caraway fruits (%).

Fatty acid	Control sample	Curd cheese		
		Dill EO	Cumin EO	Caraway EO
Medium-chain fatty acids				
Butyric acid, C _{4:0}	0.25 ± 0.03 ^a	0.16 ± 0.02 ^b	0.19 ± 0.02 ^b	0.22 ± 0.02 ^a
Caproic acid, C _{6:0}	0.20 ± 0.02 ^a	0.13 ± 0.01 ^b	0.15 ± 0.01 ^b	0.17 ± 0.02 ^b
Caprylic acid, C _{8:0}	0.11 ± 0.01 ^a	0.07 ± 0.01 ^b	0.08 ± 0.01 ^b	0.09 ± 0.01 ^b
Capric acid, C _{10:0}	0.18 ± 0.02 ^a	0.12 ± 0.01 ^b	0.14 ± 0.01 ^b	0.16 ± 0.02 ^a
Lauric acid, C _{12:0}	0.13 ± 0.01 ^a	0.08 ± 0.01 ^b	0.10 ± 0.01 ^b	0.11 ± 0.01 ^b
Long-chain fatty acids				
Myristic acid, C _{14:0}	0.67 ± 0.07 ^a	0.44 ± 0.0 ^b	0.50 ± 0.05 ^b	0.58 ± 0.06 ^c
Palmitic acid, C _{16:0}	1.73 ± 0.17 ^a	1.14 ± 0.11 ^b	1.31 ± 0.13 ^b	1.51 ± 0.15 ^b
Stearic acid, C _{18:0}	0.55 ± 0.06 ^a	0.36 ± 0.04 ^b	0.42 ± 0.04 ^b	0.48 ± 0.05 ^a
Monounsaturated fatty acids				
Palmitoleic acid, C _{16:1}	0.10 ± 0.01 ^a	0.16 ± 0.02 ^b	0.18 ± 0.02 ^b	0.14 ± 0.01 ^a
Oleic acid, C _{18:1 9nc}	0.77 ± 0.08 ^a	1.21 ± 0.12 ^b	1.39 ± 0.14 ^b	1.03 ± 0.10
Polyunsaturated fatty acids				
Linoleic acid, C _{18:2n6c}	0.11 ± 0.01 ^a	0.17 ± 0.02 ^b	0.19 ± 0.02 ^b	0.14 ± 0.01 ^a

Values with different letters in the same row indicate significant differences ($p < 0.05$).

Table 2. Composition of amino acids of curd cheese enriched with dill, cumin, and caraway fruit essential oils (%).

Amino acids	Control sample	Curd cheese		
		Dill EO	Cumin EO	Caraway EO
Alanine	0.33 ± 0.03 ^a	0.43 ± 0.04 ^b	0.40 ± 0.04 ^b	0.36 ± 0.04 ^a
Arginine*	0.44 ± 0.04 ^a	0.57 ± 0.06 ^b	0.53 ± 0.05 ^b	0.47 ± 0.05 ^a
Aspartic acid	0.80 ± 0.08 ^a	1.03 ± 0.10 ^b	0.97 ± 0.10 ^b	0.86 ± 0.09 ^a
Cystine	0.06 ± 0.01 ^a	0.08 ± 0.01 ^a	0.07 ± 0.01 ^a	0.07 ± 0.01 ^a
Glycine	0.19 ± 0.0 ^a	0.24 ± 0.02 ^b	0.23 ± 0.02 ^b	0.20 ± 0.02 ^a
Glutamine	0.59 ± 0.06 ^a	0.75 ± 0.08 ^b	0.71 ± 0.07 ^b	0.63 ± 0.06 ^a
Histidine	0.29 ± 0.03	0.37 ± 0.04	0.35 ± 0.04	0.31 ± 0.03
Isoleucine*	0.52 ± 0.05 ^a	0.67 ± 0.07 ^b	0.63 ± 0.06 ^b	0.56 ± 0.06 ^a
Leucine*	0.99 ± 0.10 ^a	1.27 ± 0.13 ^b	1.19 ± 0.12 ^b	1.06 ± 0.11 ^a
Lysine*	0.82 ± 0.08 ^a	1.05 ± 0.11 ^b	0.99 ± 0.10 ^b	0.88 ± 0.09 ^a
Methionine*	0.24 ± 0.02 ^a	0.31 ± 0.03 ^b	0.29 ± 0.03 ^b	0.26 ± 0.03 ^a
Phenylalanine*	0.51 ± 0.05 ^a	0.66 ± 0.07 ^b	0.62 ± 0.06 ^b	0.55 ± 0.05 ^a
Proline	1.08 ± 0.11 ^a	1.39 ± 0.14 ^b	1.31 ± 0.13 ^b	1.17 ± 0.12 ^c
Serine	0.56 ± 0.06 ^a	0.73 ± 0.07 ^b	0.68 ± 0.07 ^b	0.61 ± 0.06 ^a
Threonine*	0.44 ± 0.04 ^a	0.57 ± 0.06 ^b	0.53 ± 0.05 ^b	0.47 ± 0.05 ^a
Tryptophan*	0.13 ± 0.01 ^a	0.17 ± 0.02 ^b	0.16 ± 0.02 ^b	0.14 ± 0.01 ^a
Tyrosine	0.53 ± 0.05 ^a	0.68 ± 0.07 ^b	0.64 ± 0.06 ^b	0.57 ± 0.06 ^a
Valine*	0.66 ± 0.07 ^a	0.85 ± 0.08 ^b	0.80 ± 0.08 ^b	0.71 ± 0.07 ^a

*essential amino acids; values with different letters in the same row indicate significant differences ($p < 0.05$).

was improved by adding EOs. One possible explanation is that the EOs may have subtly affected microbial or enzymatic proteolytic activity. Although these curd cheeses were fresh, some proteolytic breakdown of casein can occur during the early storage period. The presence of EOs might have promoted a slight increase in proteolysis, thereby releasing more free amino acids into the curd cheese matrix. Essential amino acids such as lysine and leucine being higher in the EO-enriched curd cheeses is nutritionally advantageous, as it could improve the curd cheese's amino acid balance. This result is in line with previous research showing that plant additives can enhance the nutritional profile of dairy products by either increasing protein retention or increasing the production of peptides and free amino acids during fermentation (Ivanova et al., 2020a, 2020b).

Organic acids are known to determine the aroma-flavor profile of most dairy products. The contents of the curd cheese samples are presented in Table 3. The findings reveal that adding EOs did not appreciably alter the organic acid profile. However, the lactic acid content

decreased from 1.49% in the control to 1.12% in the sample containing dill EO. Relatively higher lactic acid concentrations in our samples are consistent with the findings of other authors (Murtaza et al., 2012; Ivanova et al., 2020a).

Lactic acid and other metabolic organic acids, such as isocitric, malic, pyruvic, succinic, and fumaric acids, were all reduced in the presence of EOs (each decreased by roughly 15–25% relative to the control). This trend indicates that the EOs slightly attenuated the acidification and metabolic activity of the starter culture. The EOs used (particularly cumin and caraway oils) are rich in compounds such as cuminaldehyde, carvone, and limonene, which are known to exhibit antimicrobial activity (Mahmoodi et al., 2012; Kostova et al., 2017). Past studies have shown that certain spice EOs can be compatible with dairy starter cultures at low doses, sometimes even stimulating acid production or having little effect (Kostova et al., 2014). In our case, however, a slight reduction was observed. It is worth noting that the differences here did not spoil the fermentation process, as

Table 3. Organic acid content in dill, cumin, and caraway fruit essential oil-enriched curd cheese (mg/100 g).

Organic acids	Control sample	Curd cheese		
		Dill EO	Cumin EO	Caraway EO
Adipic acid	0.31 ± 0.03 ^a	0.23 ± 0.02 ^b	0.26 ± 0.03 ^c	0.28 ± 0.03 ^c
Azelaic acid	0.32 ± 0.03 ^a	0.24 ± 0.0 ^b	0.27 ± 0.03 ^c	0.29 ± 0.03 ^c
Fumaric acid	0.18 ± 0.02 ^a	0.14 ± 0.01 ^b	0.15 ± 0.02 ^b	0.16 ± 0.02 ^b
Isocitric acid	0.58 ± 0.06 ^a	0.44 ± 0.04 ^b	0.49 ± 0.05 ^c	0.52 ± 0.05 ^c
Lactic acid	1.49 ± 0.15 ^a	1.12 ± 0.11 ^b	1.24 ± 0.12 ^b	1.32 ± 0.13 ^c
Malic acid	0.61 ± 0.06 ^a	0.46 ± 0.05 ^b	0.51 ± 0.05 ^c	0.54 ± 0.05 ^c
Oxalic acid	0.53 ± 0.05 ^a	0.40 ± 0.04 ^b	0.45 ± 0.04 ^c	0.47 ± 0.05 ^c
Pyruvic acid	0.45 ± 0.04 ^a	0.34 ± 0.03 ^b	0.37 ± 0.04 ^b	0.40 ± 0.04 ^a
Succinic acid	0.26 ± 0.03 ^a	0.20 ± 0.02 ^b	0.22 ± 0.02 ^b	0.23 ± 0.02 ^b

Values with different letters in the same row indicate significant differences ($p < 0.05$).

all curd cheese samples achieved the desired coagulation and acidity for a proper curd. The results simply suggest a tempered fermentation rate in the presence of EOs. This effect could be beneficial for controlling overly rapid acid development, and it underscores the need to optimize EO concentration: at higher doses, EOs could potentially inhibit starter cultures too strongly. Although our curd samples were not inoculated with pathogens, the inclusion of dill, cumin, and caraway oils at 0.01% likely provided an additional hurdle to microbial contamination. This is supported by our microbiological analyses, in which no coliforms, yeasts, or molds were detected in any sample throughout 14 days of storage, and total viable counts remained within the normal range for a fresh curd product. The absence of spoilage microorganisms and pathogens (*Salmonella* spp. and coagulase-positive staphylococci were not found in 25 g samples) across all treatments attests to the good hygienic quality.

Dry matter contents are presented in Figure 1. As observed in the data, dry matter content increased slightly over storage time in the control sample, likely due to the evaporation of free water. In the samples supplemented with EOs, the increase in dry matter values was slower. This may be attributed to the emulsifying effect of the oils and their water-retention ability in the protein matrix (Kostova et al., 2016). Regardless of the type of EO added, the 0.01% concentration did not have any significant effect on fat content during storage (0.03–0.05%), pH (4.51–4.64), or titratable acidity (60–80 °T).

The curd cheese samples were evaluated over a refrigerated storage period of 14 days (with analyses at 0, 7, and 14 days) to assess changes in composition and quality. One notable physicochemical parameter

monitored was the dry matter content (Figure 1). All curd samples showed a gradual increase in dry matter during storage, which is expected as slight moisture loss or whey syneresis occurs even under refrigeration. Interestingly, the EO-enriched curds had a lower initial dry matter content than the control at day 0, indicating higher moisture retention. This can be attributed to the influence of EOs on curd structure and syneresis. This observation is consistent with the report by Abbaszadegan et al. (2016), who found that cheese supplemented with caraway or dill oil remained softer and showed less whey drainage than the control. By day 14, however, the dry matter of the EO samples increased and partially caught up to the control due to ongoing slow moisture release. Even with this increase, the EO-fortified curds maintained a slightly higher moisture content than the control at the end of storage. Thus, from a technological perspective, the inclusion of these EOs helped achieve a curd with a higher yield (since less weight was lost as whey) and did not cause any spoilage issues over two weeks of storage. Such an outcome is advantageous for producers, as it can improve product yield and possibly extend the shelf-life, provided the product is kept refrigerated.

All curd cheese samples, regardless of the type of EO added, showed no microbial growth after 7 and 14 days of storage, indicating that the technological process was properly carried out.

Sensory evaluation results are presented in Figures 2–4. The results indicate that the curd cheese sample enriched with dill EO possessed the most preferred appearance, texture, and aftertaste. The three EOs' major components are oxygenated monoterpenes, carvone (dill and caraway), and cuminaldehyde (cumin), which are accountable for

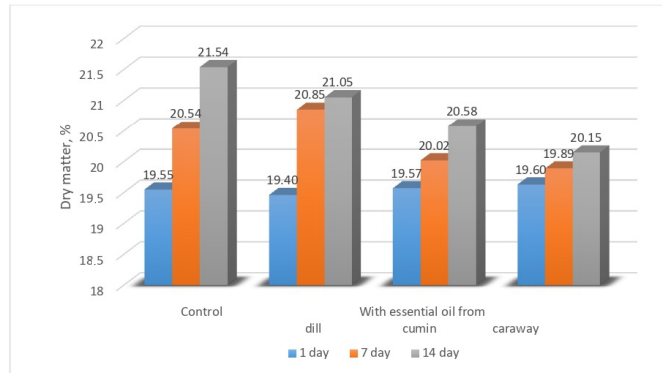


Figure 1. Changes in dry matter content of curd samples during storage.

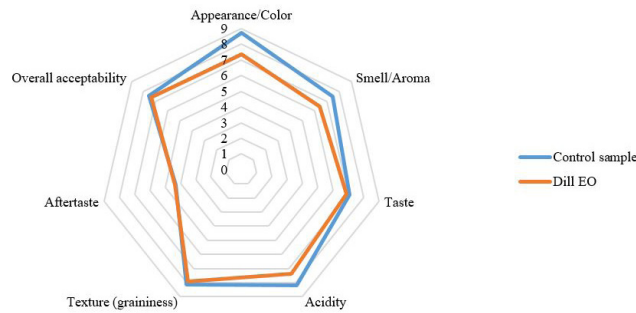


Figure 2. Sensory evaluation of curd cheese supplemented with essential oils (dill EO).

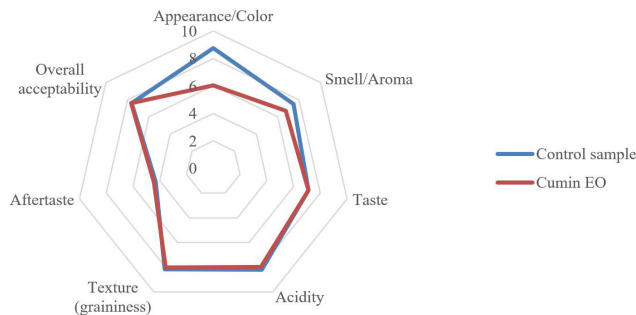


Figure 3. Sensory evaluation of curd cheese supplemented with essential oils (cumin EO).

their characteristic spicy aroma and their strong, warm, sweet flavor (Romagnoli et al., 2010; Chahal et al., 2017; Mohammed et al., 2024; Fidan et al., 2025a, 2025b, 2025c).

The results revealed how the addition of EOs influenced various sensory indicators. In terms of appearance/color, the control curd scored highest (8.74 ± 1.32) and was described as the most visually appealing. The curds with added oils had slightly lower appearance scores (7.34 for dill), suggesting that the oils may have

induced minor changes in color or surface moisture that were less preferred. Despite these differences, all samples were within an acceptable range for appearance, and no visible defects were noted. Regarding aroma, the control curd's smell was rated highest (7.49 ± 4.34), characterized by the clean, mild dairy aroma typical of fresh curd. The EO-enriched curds had distinguishable herbal/spice notes in their aroma profiles. Dill, cumin, and caraway oils each imparted their characteristic fragrance to the

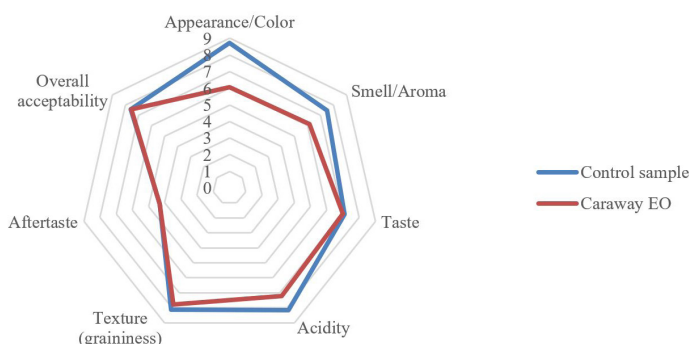


Figure 4. Sensory evaluation of curd cheese supplemented with essential oils (caraway EO).

curd cheese—dill EO gave a fresh, pickle-like herb aroma; cumin EO contributed a warm, pungent spice note; and caraway EO provided a sweet, rye-like spice aroma. Among the three, the cumin-supplemented curd had the highest aroma score (6.74), indicating cumin's aroma was the most acceptable. In contrast, caraway had the lowest score (6.14), possibly because its fragrance was perceived as overpowering or less familiar in a dairy context.

The taste scores, however, showed that flavor acceptance of the EO curds was quite comparable to that of the control. The cumin EO curd actually matched the control in taste score (around 7.1), and caraway EO (7.01) was only below the control sample. These results imply that, while the aroma of the EOs was polarizing, the curd's flavor on the palate remained pleasant. The dill and caraway flavors were mellow enough when blended into the curd matrix, and cumin's flavor might have even enhanced the taste for some consumers. The panel also evaluated the perceived acidity and texture of the samples. Consistent with the chemical measurements, the control curd was slightly more acidic and was well-liked (score 8.17). The EO curds, having slightly less lactic acid, were a bit less tangy; their acidity scores ranged from 7.2 to 7.98. The cumin oil curd's acidity score (7.98) was nearly equal to that of the control, suggesting that the presence of cumin might have masked the lower lactic acid or imparted a flavor that compensated for the milder tang. Texturally, all samples were well-received. The control curd had a texture score of 8.14, described as having ideal curd firmness, a fine granular structure, and juiciness. One area where the EOs did have a more pronounced effect was aftertaste. The control sample had a lower aftertaste score (4.32) on a scale where higher scores indicate a more pleasant or neutral aftertaste. In contrast, managing the aftertaste is important for consumer satisfaction, so this result suggests that at 0.01% concentration, the EOs do not leave a residual flavor. On a hedonic scale, consumers rated the EO samples as more acceptable than the control. Statistically, this is a

small difference, indicating that the enriched curds were generally well-liked. It might also reflect that EOs used in the study were familiar flavors in some traditional cheeses, making them broadly acceptable. These sensory outcomes revealed that EOs can be successfully integrated into curd cheese without compromising consumer acceptance. In fact, other research has found that incorporating EOs or extracts in cheese can be done in ways that maintain or even improve sensory properties. A concentration of 0.01% was low to maintain high overall liking. Still, future work could explore whether higher levels (or different blending techniques, e.g., emulsifying the oil) might increase acceptance while still providing the functional benefits.

4. Conclusion

Comparative characterization of curd enriched with three EOs derived from dill, cumin, and caraway revealed that the additives are suitable for use in dairy products. They improved the physicochemical parameters of the final product and its aroma-flavor profile, without adversely affecting the technological parameters during storage. Additionally, no undesirable microbiota were detected in any of the samples. Of the functional additives examined, dill EO was the most suitable for application in low-fat curd, followed by caraway and cumin EOs.

Author contributions

Conceptualization: Hafize Fidan, Ira Taneva, Albena Stoyanova; Data curation: Hafize Fidan; Formal analysis: Hafize Fidan; Methodology: Hafize Fidan, Toncho Kolev, Ivayla Dincheva, Albena Stoyanova; Supervision: Hafize Fidan, Ira Taneva; Visualization: Hafize Fidan; Writing – original draft: Hafize Fidan, Toncho Kolev, Denis Dervish, Ira Taneva, Albena Stoyanova; Writing – review and editing: Hafize Fidan, Serkan Yılmaz, Yusuf Şavşatlı.

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