https://doi.org/10.31925/farmacia.2023.5.3 **REVIEW**

# OPTIMIZING MILK PRODUCTION, QUALITY AND SAFETY THROUGH ESSENTIAL OIL APPLICATIONS

LAURENȚIU TUDOR [#], MARIA-TEODORA PIȚURU [#], RALUCA-ANIELA GHEORGHE-IRIMIA [1]*, COSMIN ȘONEA [#], DANA TĂPĂLOAGĂ

*[1]Faculty of Veterinary Medicine, University of Agronomic Sciences and Veterinary Medicine Bucharest, 105 Blvd, Splaiul Independenței, 050097 Bucharest, Romania*

**corresponding author: raluca.irimia@fmv.usamv.ro*
*[#]Authors with equal contribution.*

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**Abstract**

This study comprehensively explores the integration of essential oils (EOs) into dairy livestock nutrition and milk production, focusing on optimising various facets of dairy farming. Food safety and biosecurity are paramount when introducing EOs into dairy farming practices. Rigorous safety assessments, including toxicity, allergenicity and potential adverse effects on animal health, are essential for the welfare of both livestock and consumers. Additionally, managing EO residues is challenging due to their potential impact on dairy product composition. Moreover, the variable effects of EOs on dairy animals` performance add complexity. While EOs show potential for inhibiting oxidative reactions and microbial spoilage, their influence on nutrient utilisation, ruminal fermentation and milk performance varies. Extensive research is required to optimise EO dosage and formulation for consistent performance benefits. Sustainability is a critical concern, requiring the alignment of EO utilisation with sustainable agricultural practices to address environmental and resource constraints. Lastly, consumer perception and acceptance are vital, necessitating transparent communication and an understanding of consumer preferences to maintain trust in dairy products. Addressing these challenges enables the dairy industry to harness the full potential of EOs, ensuring ongoing safety, quality and sustainability in dairy product production. This study provides practical insights and outlines future research directions to advance dairy production, quality and safety.

**Rezumat**

Acest studiu explorează integrarea uleiurilor volatile (OE) în nutriția animalelor de lapte și în producția de lapte, concentrându-se pe optimizarea diferitelor aspecte. Siguranța alimentară și biosecuritatea sunt primordiale atunci când se introduc uleiurile volatile în practicile de creștere ale animalelor care produc lapte. Evaluările riguroase privind siguranța, inclusiv toxicitatea, potențialul alergen și potențialele efecte adverse asupra sănătății animalelor, sunt esențiale pentru bunăstarea animalelor și a consumatorilor. În plus, gestionarea reziduurilor de OE reprezintă o provocare din cauza potențialului impact al acestora asupra compoziției produselor lactate. În plus, efectele variabile ale OE asupra performanțelor animalelor care produc lapte reprezintă un factor de interes. În timp ce OE prezintă un potențial de inhibare a reacțiilor oxidative și a alterării microbiene, influența lor asupra utilizării nutrienților, a fermentației ruminale și a performanței laptelui variază. Sunt necesare cercetări aprofundate pentru a optimiza dozajul și formularea OE pentru a obține beneficii consistente în ceea ce privește performanța. Sustenabilitatea este o preocupare esențială, necesitând alinierea utilizării OE la practicile agricole durabile pentru a aborda constrângerile de mediu și de resurse. În cele din urmă, percepția și acceptarea de către consumatori sunt vitale, necesitând o comunicare transparentă și o înțelegere a preferințelor consumatorilor pentru a menține încrederea în produsele lactate. Abordarea acestor provocări permite industriei produselor lactate să valorifice întregul potențial al OE, asigurând în permanență siguranța, calitatea și durabilitatea producției de produse lactate. Acest studiu oferă perspective practice și subliniază direcțiile viitoare de cercetare pentru a avansa producția, calitatea și siguranța produselor lactate.

**Keywords**: essential oils, milk production, milk quality, milk safety, livestock feed

## Introduction

The global dairy industry holds a pivotal position within the broader food market due to the widespread consumption of milk and dairy products. However, the complexities involved in milk production and processing incur a spectrum of costs that exert a substantial influence on the economic viability of dairy enterprises. These costs encompass both production-related outlays, such as those associated with feed, labour and livestock health, as well as processing-related expenditures, including pasteurisation, packaging and transportation. Recognising and effectively managing these cost factors are imperative for dairy farmers and processors alike [1-5]. In this regard, a possible way of benefiting both dairy producers and consumers is through the use of essential oils (EOs). These plant extracts have garnered substantial attention across diverse industries owing to their multiple applications and beneficial attributes. EOs are concentrated liquids derived from plant sources, encapsulating an intricate mixture of volatile compounds endowed with bioactive properties encompassing antimicrobial, antioxidant and medicinal attributes [6–10]. In this direction, it is important to note that EOs can be used both in dairy animals' diets and in dairy products.

The incorporation of EOs into the diet of dairy animals presents a diverse array of potential advantages that can exert a favourable influence on both the physiological well-being of the animals and their milk production. These volatile organic compounds, derived from botanical sources, harbour distinctive pharmacological attributes, rendering them pertinent dietary supplements for dairy livestock. Firstly, EOs have demonstrated a capacity to augment digestive processes and enhance nutrient utilisation. Through mechanisms that enhance enzymatic activities and modulate gastrointestinal physiology, resulting in heightened milk yield. Moreover, EOs frequently manifest inherent antimicrobial and anti-inflammatory characteristics, thereby contributing substantively to the overall health status of the animals. Their anti-microbial properties aid in countering digestive problems and curtailing the proclivity for infectious outbreaks, which can potentially undermine milk production efficiency. Furthermore, specific EOs possess anxiolytic properties. Reduced stress levels culminate in sustained milk production and prevent the diversion of energy away from milk synthesis during times of stress. Additionally, the use of EOs offers an ecologically sound alternative to conventional antibiotics and growth-promoting agents, aligning with the contemporary trend towards sustainable and organic agricultural practices [11, 12]. However, it's worth acknowledging that long-term *in vitro* investigations, such as continuous cultures, have indicated a waning of the benefits associated with EOs over time. This decline is attributed to shifts in microbial populations or the adaptation of individual microbial species to the EOs [12]. The extent to which microbial pathogens undergo similar adaptive responses to EOs *in vivo* remains an area of ongoing exploration [14, 15].

Furthermore, the introduction of EOs into animal feed has undergone rigorous investigation on its potential to influence the milk flavour. Aromatic compounds inherent to EOs can traverse the gastro-intestinal tract and respiratory system of animals, potentially imprinting their sensory qualities onto dairy products [9]. A profound comprehension of the impact of EOs on milk flavour is pivotal for fine-tuning the sensory attributes of dairy products, thereby aligning them with consumer preferences.

On the other hand, considering the addition of EOs in dairy products, the antimicrobial, antifungal and sensory properties of these extracts hold immense promise in safeguarding the quality and safety of milk and milk products by inhibiting the growth of both spoilage and pathogenic microorganisms [7].

In light of the aforementioned information, this paper aims to comprehensively explore the use of EOs in dairy livestock nutrition and dairy products. It seeks to elucidate the mechanisms underpinning essential oil use, considering their potential benefits and challenges. The research will investigate how EOs affect nutritional requirements, milk production and the health of dairy cattle, emphasising their role in optimising these aspects. It will also scrutinise the critical factors influencing milk quality, emphasising the importance of quality control. The study aims to provide practical insights and outline future research directions, ultimately advancing milk production, quality and safety in the dairy industry.

## Enhancing Dairy Animal Performance - EOs in Milk Production

Collective findings suggest that dietary supplementation with EOs holds promise for positively impacting milk yield in dairy livestock (Table I). For example, Anam *et al*. demonstrated that a blend of mineral-enriched EOs (eucalyptus, orange, lavender, soybeans, walnuts, sesame seeds, olives and minerals) led to an increase in milk yield among lactating dairy cows [16]. Similarly, Davoodi *et al*. reported heightened milk production in Holstein cows when administered a mixture of thyme, mint and savoury EOs [17]. Additionally, in their study, Braun *et al*. observed that the incorporation of a blend of EOs containing eugenol, menthol and anethol (BTX12; PerformaNat GmbH, Berlin, Germany, patent US 9693971), administered at a dosage of 1.2 g *per* cattle *per* day, resulted in a notable augmentation of milk production, milk fat content and protein content, all within the context of a dry feed consumption regimen [18].

In a separate investigation by Drong *et al.*, aimed at inducing ketogenic inhibition in cattle feeding, the utilization of a blend of EOs (CRINA ruminants, DSM, Basel, Switzerland) exhibited a significant enhancement in milk fat content, corrected milk energy and feed efficiency. However, it also led to elevated levels of β-hydroxybutyrate (BHB) and non-esterified fatty acid (NEFA), implying an adverse impact on the energy balance of lactating cows [19]. Nonetheless, contrasting findings were observed by other researchers, who found that the supplementation of essential oil mixtures in the diet of milking cows did not exert any discernible effects on BHB and NEFA [20]. These outcomes underscore the complexity and context-specific nature of essential oil impacts on dairy cattle physiology and energy metabolism.

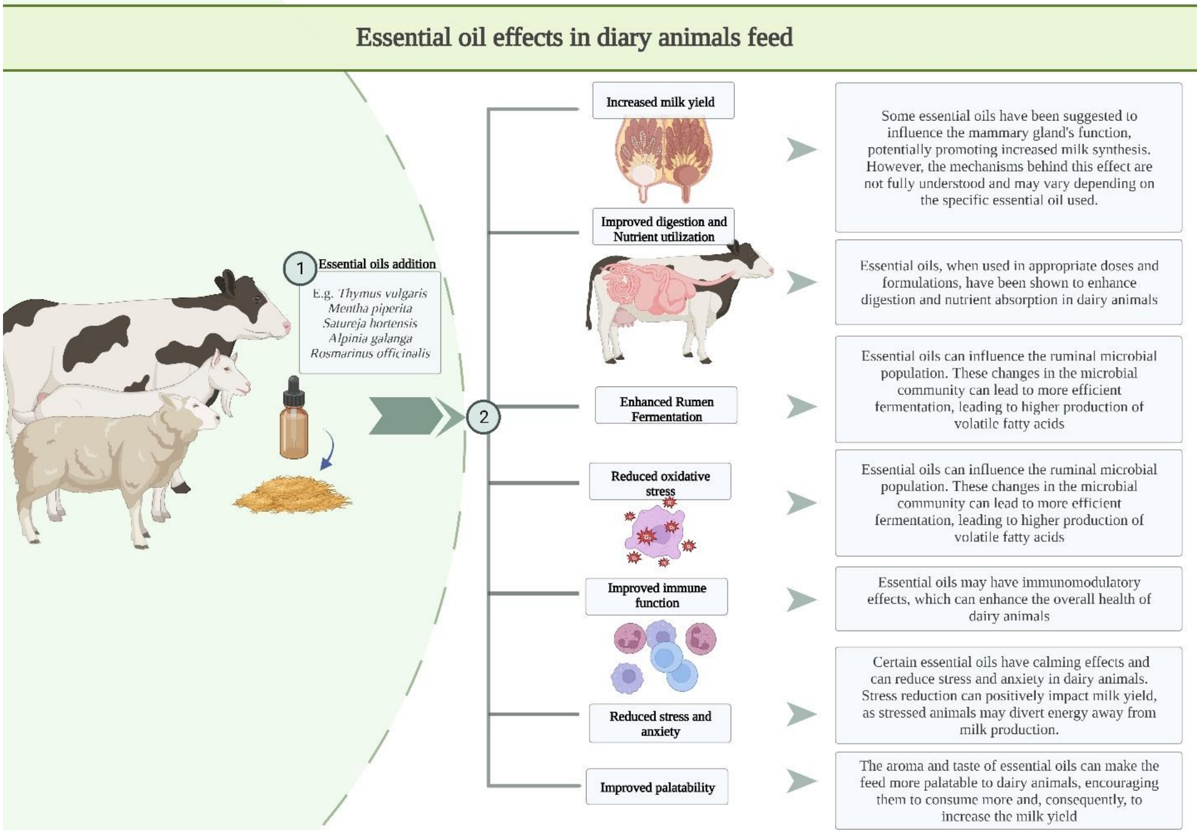


**Figure 1.**
EOs effects in dairy animals' feed (illustration made *via* BioRender$^{TM}$)

On the other hand, Daning *et al*. conducted a comprehensive meta-analysis that revealed a notable impact of specific essential oil dosages on milk production, leading to an average increase of 29.06 kg in milk yield and a 3.5% increase in fat-corrected milk, with an average value of 30.1 kg. However, the analysis also indicates that feed consumption does not exhibit a significant difference, with an average value of 22.76 kg. Furthermore, the meta-analysis scrutinised the utilisation of EOs in relation to milk composition parameters, specifically lactose, protein and fat content. The findings demonstrate that there is no statistically significant effect on these three parameters, with average values of 4.83% for lactose, 3.32% for protein and 3.58% for fat. These variations in milk composition outcomes underscore the complexity and diverse nature of essential oil supplementation's influence on dairy cow physiology and milk biosynthesis (Figure 1). Moreover, the same study unearthed intriguing evidence that underscores the transformative impact of EOs on the intricate ecosystem within the rumen of dairy cows. These compounds have been shown to possess the capability to exert substantial modifications on the rumen microbial population. Such microbial alterations, when judiciously harnessed, result in the facilitation of optimal rumen fermentation processes. Consequently, this optimisation yields tangible benefits in the form of heightened feed efficiency in dairy cows [21].

Building upon this foundation, Ozcinar *et al*. probed the utilisation of EOs in sheep farming. Their study unveiled promising findings, demonstrating that EOs have the capacity to enhance both the yield and quality of sheep milk. These results undoubtedly herald a potential avenue for enhancing milk production and quality in the ovine dairy sector. However, it is noteworthy that the efficacy of EOs in this regard remains subject to variability, as evidenced by inconsistent outcomes in different studies [22]. These inconsistencies, which manifest particularly in milk production and milk fat, underscore the exigency of further research. The quest for a nuanced understanding necessitates investigations into factors such as dosage and the specific types of EOs employed, which invariably impact dairy cow performance.

However, as El-Aziz *et al*. point out, despite the tantalising potential of EOs in the dairy sector, widespread adoption remains elusive. This is largely attributed to the challenges associated with controlling the concentration of bioactive ingredients within these oils and optimising their efficiency [23]. The inherent variability in plant extracts and EOs, compounded by their sensitivity to factors such as source, extraction methods and storage conditions, poses formidable hurdles. Consequently, the integration of EOs into mainstream dairy production demands meticulous attention to these challenges to unlock their full potential.

On the other hand, other vegetal oils influenced dairy cattle performance. A study conducted by Vargas-Bello-Pérez *et al*. delved into the intricacies of augmenting the diets of dairy cows with soybean and hydrogenated vegetable oils, focusing on their consequential impacts on milk composition and sensory attributes. The findings revealed that dietary supplementation with soybean oil elicited a discernible increase in milk yield among dairy cows. Notably, the inclusion of hydrogenated vegetable oils, strategically employed to enhance dietary energy density, manifested in elevated milk and fat yields within grazing systems [24]. Another investigation, spearheaded by Côrtes *et al*., delved into the effects of flax oil supplementation on milk yield, concentrating on mid-lactating dairy cows. Intriguingly, the study discerned that abomasal infusions of flax oil failed to impart any statistically significant influence on milk yield. Nevertheless, when flax oil supplementation was administered at a higher dosage, it led to a reduction in dry matter intake and, subsequently, milk yield [25]. Furthermore, the inclusion of canola oil in the diets of lactating dairy cows, as elucidated by Welter *et al*., manifested in a reduction of milk saturated fatty acids while concurrently enhancing the content of omega-3 and oleic fatty acids [26].

**Table I**

Summary of key EOs used in dairy animals' nutrition

| EOs used | Breed/Species | Dose | Measured outcome | Summary | Ref. |
|---|---|---|---|---|---|
| Thyme, mint and savory (*Thymus vulgaris, Mentha piperita, Satureja hortensis*) | Holstein lactating dairy cows | Mixture of thyme, mint and savory at the rate of 1:1:1 for two levels of 5 and 10 mL/day/cow | Dry Matter Intake, milk yield, milk fat, protein, lactose, total solid, urea nitrogen concentration, rumen pH value | The addition of EOs to the diet influenced feed palatability and increased dry matter intake of Holstein lactating dairy cows. Additionally, it influenced the milk yield | [17] |
| Galangal essential oil (*Alpinia galanga)* | Holstein-Friesian cows | 0, 1.25 and 2.50 g/head/day | Milk production Composition Fatty acids characteristics | Galangal EO supplementation increased the polyunsaturated fatty acids ratio at level 1.25 g/head/day of galangal EO, but did not affect milk production, lactose, protein and fat content | [27] |
| A blend of EOs synthesized from eucalyptus (*Eucalyptus globulus)*, orange (*Citrus sinensis)*, lavender (*Lavandula angustifolia)*, soybeans (*Glycine max)*, walnuts (*Juglans regia)*, sesame seeds (*Sesamum indicum*) and olives (*Olea europea)* and minerals – Agromix Booster | 48 lactating Holstein-Friesian | 0.5% | Dry Matter Intake, milk yield, milk fat, protein, lactose, total solids, and yield, solid non-fat content and yield, feed efficiency | The supplementation of mixed mineral enriched EOs in the Total Mix Ration could improve milk yield of Holstein-Friesian dairy cows | [16] |
| Mixture of essential oil compounds (*Crina* S.A. *ruminants*, DSM, Basel, Switzerland) | Holstein-Friesian cows | 750 mg/day | Rumen pH, volatile fatty acid concentrations, estimated microbial protein synthesis, ammonia concentration, methane production *per* unit of Dry Matter Intake, milk yield, and others | OEs supplementation had no effect on rumen pH, volatile fatty acid concentrations, and estimated microbial protein synthesis in dairy cows | [28] |
| Mixture of essential oil compounds (*Crina* S.A. *ruminants*, DSM, Basel, Switzerland) | Chios breed ewes | 50, 100 and 150 mg/kg | Milk yield, chemical composition, Somatic Cell Count, urea content | EO supplementation may improve feed utilization and performance of the high-yielding dairy Chios ewes | [29] |
| *Rosmarinus officinalis* L. *EOS (REO)* | Tunisian native goat breeds | 0.6 g/kg of REO | Milk yield and chemical composition | Daily milk production was significantly higher (P = 0.007) for rosemary groups | [30] |

| EOs used | Breed/Species | Dose | Measured outcome | Summary | Ref. |
|---|---|---|---|---|---|
| Garlic (*Allium sativum)*, Cinnamon (*Cinnamomum verum)* or Ginger (*Zingiber officinale)* EOs | Lactating Damascus goats | Control - Bersem clover (40:60 dry matter bases); (2) control + 2 mL/ head/day garlic oil; (3) control + 2 mL/head/day cinnamon oil; (4) control + 2 mL/ head/day ginger oil | Milk yield, milk composition (protein, fat, solids not fat, milk non protein nitrogen, total solids, ash), milk fatty acids profile (un-saturated fatty acids, C18:1N9C, conjugated linoleic acids, C18:3N3, C18:3N6) and others. | Plant EOs supplementation to ration of lactating goats had beneficial effects on milk yield and milk protein (especially cinnamon EO) | [31] |
| Mixture of thyme (*Thymus vulgaris)*, anise (*Pimpinella anisium)* and olive (*Olea europaea)* (MPBC) | Ewes | MPBC at 0.05%; MPBC at 0.025% and Control | Milk yield, composition, oxidation Stability, udder health | MPBC addition had a positive effect on sheep milk yield | [32] |
| *Euterpe oleracea* oil | Ewes | 2% of soybean oil or 2% of açai oil in the concentrate for 14 days - 0.65% of the total diet | Health and milk production and quality | Açai oil improved the anti-oxidant activity in serum and milk and improved milk production and quality | [33] |

**EOs in milk quality and safety**

The incorporation of EOs into milk and milk products bears profound ramifications with respect to both their quality and safety attributes. EOs have undergone extensive scientific inquiry, as documented in studies by Hyldgaard *et al*. and Gheorghe-Irimia *et al*. [7, 27, 28]. These investigations have shown their multifaceted properties, encompassing antimicrobial, antioxidant and flavour-enhancing attributes.

Within dairy products, one notable facet pertains to the potential utility of EOs as natural preservatives. According to the research conducted by Benchaar *et al*., there is empirical evidence supporting the extraordinary antibacterial activity of EOs against a diverse range of foodborne pathogens, including bacteria and fungi. This innate antimicrobial prowess serves as an efficacious mechanism for restraining the proliferation of spoilage microorganisms, thereby bestowing an appreciable extension of the shelf life of dairy products [28]. Nonetheless, it is imperative to underscore the contextual variability inherent in the effectiveness of EOs as preservatives, contingent upon factors such as concentration, the specific type of essential oil employed, and the compositional profile of the resident microflora.

In addition to their preservative function, EOs also wield a considerable influence on the sensory attributes of milk and its derivatives. Specific EOs, exemplified by oregano (*Origanum vulgare)*, caraway (*Carum carvi)* and clove oil (*Syzygium aromaticum*), have been the subject of meticulous scrutiny regarding their potential impact on the flavour and aroma of milk [28]. These oils possess the capacity to impart distinctive and desirable sensory nuances, thereby elevating the overall sensorial experience enjoyed by consumers. Nevertheless, it is imperative to employ discernment in the judicious selection and precise dosing of EOs, with the aim of mitigating the risk of overwhelming or undesirable flavours.

Furthermore, the prudent use of EOs in the realm of milk and milk products necessitates diligent consideration of safety parameters. While EOs are generally acknowledged as safe for human consumption, it is imperative to ensure their application within prescribed concentration limits and adherence to regulatory directives, as articulated in the studies by Hyldgaard *et al*. [27]. Notably, specific EOs may harbour distinct safety considerations, encompassing potential allergenicity or interactions with certain medications. As such, a comprehensive research approach, coupled with consultation with regulatory authorities, constitutes an indispensable prerequisite prior to the integration of EOs into the domain of milk and milk-based products (Figure 2).

In recent years, heightened consumer awareness regarding natural food products has spurred a significant surge in the quest for naturally occurring antimicrobial agents. Bio-preservatives are harnessed in the food industry to enhance product quality by prolonging shelf life and curbing the proliferation of pathogenic bacteria [29]. The effectiveness of EOs varies depending on several critical factors, including their application form, concentration, method of application and storage conditions. In this regard, the fat content of the medium exerts an inverse relationship with terpineol's antimicrobial activity, as evidenced in skimmed milk (7 log CFU/mL), low butterfat milk (4 log CFU/mL) and whole milk (3 log CFU/mL) [30]. The mode of application (*via* spray, encapsulation in lactose capsules, or immersion) and the applied concentration are pivotal determinants of bio-preservative efficacy.

Furthermore, to ensure the inhibition of microbial growth while preserving product organoleptic qualities, it is imperative to carefully consider the required concentration of Eos.

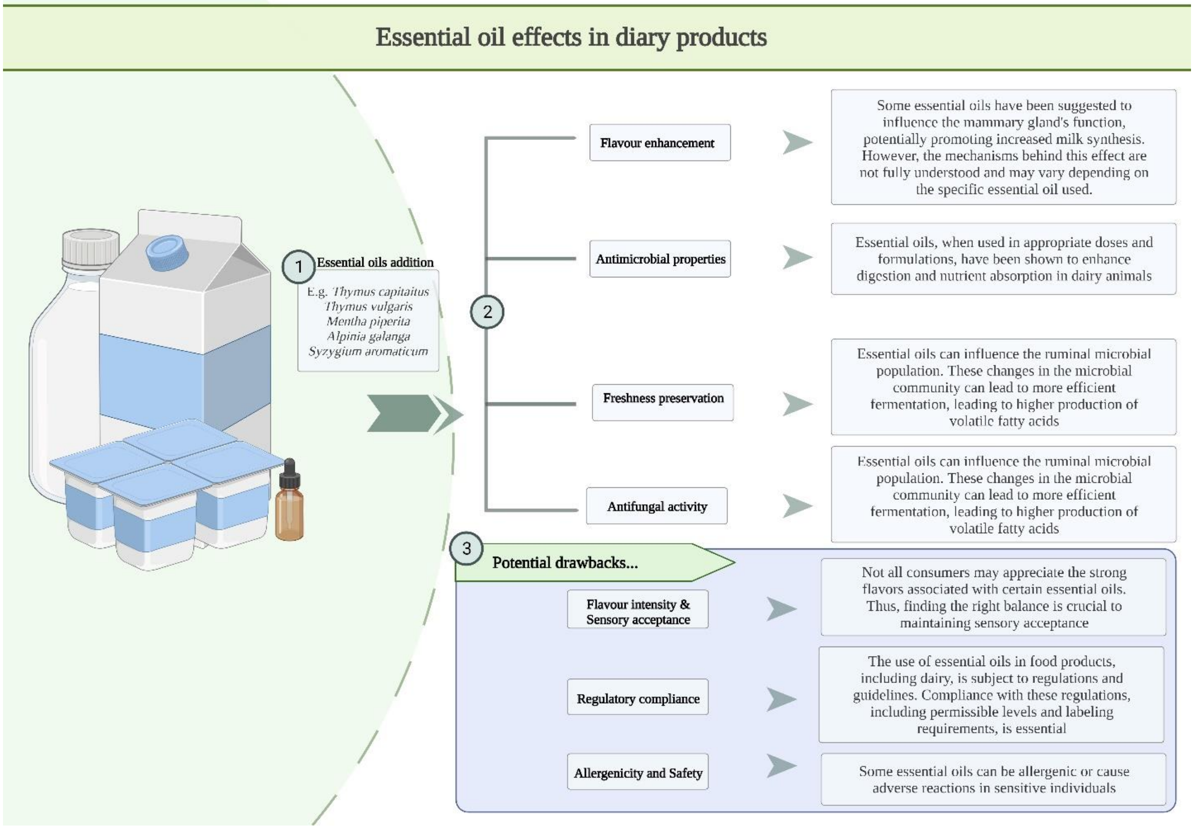


**Figure 2.**
EOs effects in dairy products (illustration made *via* BioRender$^{TM}$)

Incorporating EOs into food products necessitates a comprehensive understanding of the target micro-organism, minimum inhibitory concentrations (MICs), mechanisms of action and their potential interactions with the food matrix and sensory attributes. Eos primarily comprise volatile compounds such as mono-terpenes, sesquiterpenes, oxygenated byproducts, alcohols, esters and aliphatic aldehydes, with antimicrobial compounds categorized into terpenes, phenylpropenes, terpenoids and other chemical classes [34, 37]. The precise mode of action of Eos remains variable and not fully elucidated, with various locations within microorganisms being considered as potential sites of action. Generally, Eos display superior efficacy against Gram-positive bacteria due to their simpler cell wall composition in comparison to Gram-negative bacteria, which possess a more complex outer membrane. Additionally, cell shape may influence essential oil efficacy, with rod-shaped cells being more vulnerable than coccoid ones.

Thymol, a prominent constituent of thyme (*Thymus vulgaris)* essential oil, augments its antimicrobial potency by binding to membrane proteins, leading to membrane disruption and cell lysis [15]. Eugenol, a major component of clove (*Syzygium aromaticum*) essential oil, has demonstrated the capability to disrupt bacterial cell walls, inhibit amylase production and induce cell wall destruction [38, 39]. Furthermore, the essential oil from *Coriaria nepalensis* disrupts ergosterol biosynthesis and compromises membrane integrity in *Candida*, while *Curcuma longa* exhibits anti-aflatoxigenic and antifungal properties against *Aspergillus flavus*, potentially by inhibiting ergosterol biosynthesis [40]. Additionally, cinnamaldehyde from cinnamon plants, exhibited significant antimicrobial potential against various foodborne pathogens, including *Salmonella enterica*, *Bacillus cereus*, *Listeria monocytogenes*, *Clostridium perfringens*, *Campylobacter jejuni* and *Escherichia coli*, as elucidated in the review by Friedman [41].

In a study conducted by da Silva Dannenberg *et al.*, it was found that essential oils (EOs) extracted from green (*Capsicum annuum*) and mature pink pepper (*Schinus mole*) have significant antioxidant activity [42].

Notably, mature pink pepper (*Schinus mole*) displays the potential to significantly prolong the preservation of sensory attributes, thereby potentially extending the shelf life of the product [43, 44]. Furthermore, EOs offer versatile avenues for enhancing the flavour profile of milk [44].

The key findings regarding the addition of EOs to dairy and dairy products are summarised in Table II.

**Table II**

Summary of key EOs used in dairy products

| Dairy product | EOs/Components used | Dose | Measured outcome | Summary | Ref. |
|---|---|---|---|---|---|
| MILK | Cardamom (*Elettaria cardamomum*), cinnamon (*Cinnamomum verum*), lemongrass (*Cymbopogon citratus*), ginger (*Zingiber officinale*) | Minimum inhibitory concentrations - 0.004 and 0.125 μg/μL | Antimicrobial activity (*Streptococcus thermophilus, Lactobacillus plantarum, Escherichia coli)* | EOs have the potential to inhibit the growth of milk spoilage bacteria, exhibiting higher antimicrobial activity than gentamycin | [46] |
| | *Thymus capitatus* | 1 mg/L | Microbiological Stability Physicochemical Stability | EO acts as milk stabilizer | [47] |
| | *Thymus vulgaris* | 4.5 g/L | Antimicrobial properties (*Escherichia coli* O157:H7 and *Listeria monocytognes*) | Antimicrobial properties | [48] |
| | *Metasequoia glyptostroboides* | 2% and 5 % | Antimicrobial properties (*Listeria monocytognes*) | Antimicrobial properties | [49] |
| FERMENTED MILK | *Syzygium aromaticum* | 10, 20 and 30 μL/mL | Microbiological Stability Physicochemical Stability | The microbiological and physicochemical stability parameters were maintained during storage. The milk matrix did not interfere with the EOs | [50] |
| | *Xylopia aethiopica and Pimenta racemosa* | *Xylopia aethiopica* EO - 0.23 mg/mL and 0.46 mg/mL, *Pimentaracemosa* - 1.10 mg/mL and 0.55 mg/mL respectively for S*taphylococcus aureus* and *Escherichia coli* | Physicochemical characteristics Evolution of the microbial flora (mesophilic flora, lactic flora, coliforms, *Staphylococcus aureus*) | Both EOs were reported to have antimicrobial activities on *Staphylococcus aureus* and *Escherichia coli* strains | [51] |
| YOGURT | *Mentha piperita, Ocimum basilicum, Zataria multiflora* | 0.5% v/v | Antioxidant activity, sensory and physicochemical evaluation | EOs improved the antioxidant potential of the product, having a good sensory acceptability (except *Zataria multiflora* EO) | [52] |
| | *Pimpinella anisum* | 0.1 - 1.0 g/L | Physicochemical and microbiological qualities | Antimicrobial properties and no adverse effect on the physicochemical properties | [53] |
| CREAM | *Echinophora platyloba* | EO - 0.10%, 0.50% and lycopene (20 and 50 ppm) | Microbial characteristics, sensorial properties and lipid stability | Antimicrobial properties and stability | [54] |

**Challenges and Future Directions**

The incorporation of EOs into dairy farming practices offers promising avenues for improving various aspects of milk production and dairy product quality. However, the introduction of EOs into this context necessitates a comprehensive evaluation of several critical factors encompassing food safety, residue concerns, variability in animals` performance, sustainability and consumer perception.

While EOs are generally recognised as safe, their application in dairy farming mandates rigorous scrutiny. Barkema *et al*. advocate for heightened food safety and biosecurity standards within the dairy industry. Assessments are imperative to ascertain the potential for toxicity, allergenicity and adverse effects on animal health, thereby ensuring that EOs used in dairy farming pose no risks to either animals or human consumers [55].

Another prominent challenge arises in the form of environmental implications associated with the utilisation of EOs as feed supplements. Bampidis *et al*. have conducted a comprehensive investigation into the use of clove (*Syzygium aromaticum*) oils in animal feed, concluding that the environmental risk posed by such usage is generally low [56].

However, it is crucial to acknowledge that these oils should be handled with care due to their potential irritant properties towards the skin, eyes and respiratory tract, as well as their potential to induce skin sensitization [56]. Maes *et al*. has delved into the broader landscape of potential risks linked to the utilisation of EOs as bioherbicides in agricultural and horticultural contexts. This scrutiny highlights the nuanced nature of these molecules, which, while holding promise for their intended applications, also bear the potential for hazards to both human health and the environment [57]. In contrast, Hari Sankar *et al*. and Simitzis present a more positive perspective, proposing that EOs can provide advantages for animal health and production. Their reported impacts span various facets, including improvements in growth performance, digestive system function, suppression of pathogenic bacterial growth and mitigation of lipid oxidation, among other positive effects [58, 59]. However, it is important to note that a comprehensive understanding of the precise mechanisms of action and the establishment of standardised protocols for their incorporation into animal production are areas that warrant further investigation.

The impact of EOs on dairy cow performance is marked by variability. Simitzis concluded that the inclusion of EOs in livestock diets can impede oxidative reactions and microbial spoilage. Nevertheless, the influence on nutrient utilisation, ruminal fermentation and milk performance can fluctuate depending on the specific EO and diet composition [59]. Further research is imperative to elucidate the optimal dosage and formulation of EOs to maximise performance benefits.

The sustainability aspect of EO use in dairy farming warrants careful consideration. Keyserlingk *et al*. delineate the challenges faced by the dairy industry, encompassing environmental issues and the escalating dichotomy between industry practices and public perceptions [60]. It is imperative that the integration of EOs align harmoniously with sustainable agricultural practices and effectively address environmental concerns.

Consumer perception and acceptance of EO utilisation in dairy products emerge as notable limitations. Wolf *et al*. state that public support for production practice bans and limitations is influenced by factors such as age, gender, income and exposure to animal welfare narratives in the media [61]. Therefore, it is crucial to consider consumer preferences and maintain transparent communication about the use of EO in order to uphold consumer trust and confidence in dairy products that have been supplemented.

## Conclusion

Considering the comprehensive exploration undertaken in this paper, which delved into the integration of EOs into dairy cattle nutrition and milk production, we arrive at a culmination of insights and revelations that underscore the multifaceted nature of these endeavours.

First and foremost, our investigation underscored the critical importance of food safety and biosecurity. While EOs hold promise for enhancing various aspects of dairy farming, their introduction necessitates rigorous safety assessments to ensure the well-being of both animals and consumers. The evaluation of potential toxicity, allergenicity and adverse effects on animal health must remain a paramount concern.

Residue concerns also loom large on the horizon. The presence of EO residues in dairy products can impact their composition. Vigilant monitoring and control of EO residue levels are vital to meet food safety standards and safeguard the quality and safety of dairy products.

Additionally, the variable effects of EOs on dairy cow performance present a challenge. While EOs can inhibit oxidative reactions and microbial spoilage, their influence on nutrient utilisation, ruminal fermentation and milk performance can vary widely. Further research is essential to optimise EO dosage and formulation for consistent and maximised performance benefits.

The sustainability aspect is another critical consideration. In an era of growing environmental awareness and resource constraints, it is imperative to ensure that the use of EOs aligns with sustainable agricultural practices. Addressing challenges such as water resource availability and harmonising industry practices with public perceptions is essential for a sustainable future in dairy farming.

Lastly, consumer perception and acceptance cannot be overlooked. Public support for EO use in dairy products is influenced by various factors, including demographics and exposure to animal welfare narratives. Therefore, transparent communication and a thorough understanding of consumer preferences are pivotal for maintaining trust and confidence in dairy products.

In conclusion, the utilisation of EOs in milk production and dairy products is a promising endeavour, but it demands a holistic and scientifically informed approach. By addressing these challenges with diligence and adaptability, the dairy industry can harness the full potential of EOs while ensuring the continued safety, quality and sustainability of dairy products.

## Conflict of interest

The authors declare no conflict of interest.

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