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Review Article

# Effects of essential oils on economically important characteristics of ruminant species: A comprehensive review

Cara Wessels Wells

*MicroBios, Inc., Houston, United States*

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ABSTRACT

Essential oils derived from plants can provide biological impacts to livestock species. Scientific studies researching essential oils in livestock have investigated various essential oils for prevention and treatment of microbial infection and parasites as well as to enhance milk production, animal performance and rumen function. Despite the availability of several commercial products containing essential oils to promote animal health and production, the vast amount of essential oils, modes of application, and effective concentrations of the essential oils suggest there are more opportunities for essential oils to be utilized in commercial livestock production and veterinary medicine. The objective of this review is to contribute to the understanding of the value that essential oils can provide to the ruminant diet and to examine the biological impact of various essential oils on economically important production traits of ruminant species.



## 1. Introduction

Animal production is defined as the production of animal goods such as meat, dairy, wool, and leather. The production of animal products is a multi-billion dollar-per-year industry and accounts for over half the value of United States agricultural products (NIFA, 2021). To reach full production potential, production animals must be in peak health. Optimizing animal health and performance includes the control of pathogens and disease while maximizing growth and feed efficiency. As modern livestock production practices move away from the use of antibiotics and ionophores to generate these outcomes, the use of natural feed additives, such as essential oils, is gaining attention as possible alternatives to antibiotics to modify ruminal fermentation and enhance feed efficiency of ruminants (Herago et al., 2017; Al-Suwaiegh et al., 2020). Cost of feed additives plays a critical role in developing diets for production animals, so additives must yield an economically favorable return. To further understand the value and benefits essential oils can provide to the ruminant diet, this review will examine the biological impact of various essential oils on economically important production traits such as growth performance, milk yield, and reproduction of ruminant species (Table 1).

## 2. Effects of essential oils to replace conventional antimicrobial agents

Conventional antimicrobials have made a remarkable impact on the livestock industry due to their effectiveness therapeutically, prophylactically and as a growth promoter (Laxminarayan, 2015). Antimicrobials were widely adopted in modernized countries in the 1950s to reduce animal mortality, prevent disease, reduce food spoilage, reduce meat prices, enable fast and efficient food production, and compensate for sub-optimal hygiene practices (Castanon, 2007; Cromwell, 2002; Kirchhelle, 2018; Laxminarayan, 2015; Meek et al., 2015; National Research Council, 1980). However, antimicrobial use is a contributing factor to antibiotic resistance. Therefore, global efforts to phase out routine use of antimicrobials are in effect in effort to preserve the effectiveness of antibiotics for veterinary and human medicine (Wierup, 2001). This presents an opportunity to explore the use of essential oils as a nutraceutical agent to control microbial growth and infection in livestock (Funston et al., 2013; Lubbe et al., 2019).

Essential oils have the potential to be used in livestock as an antimicrobial agent due to their antibacterial, antiviral, antibiotic, and antifungal properties (Bakkali et al., 2008; Kasaian et al., 2016).

*E-mail address:* cara@emgenisys.com.

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**Table 1**
Classification, use and application of essential oils.

| Essential oil | Common name or common origin | Effects | Disease | Application | Ruminant type | Reference |
|---|---|---|---|---|---|---|
| *Allium stavium* | Garlic | antimicrobial, anti- parasitic | neonatal diarrhea, internal parasites | feed additive | Bovine, sheep | Campolina et al. (2021); Mashamha et al. (2010) |
| *Artemisia afra* | African wormwood | anti-parasitic | internal parasites, nematodes | oral drench | Sheep | Molefe et al. (2012) |
| *Azadirachta indica* | Neem oil | acaricidal | parasite infection | external | Bovine | Ellse and Wall (2014); Fang et al. (2016); Macchioni et al. (2006); Pasay et al. (2010); Seddiek et al. (2013); Shang et al. (2013); Shang et al. (2016); Wall (2011) |
| Capsaicin | Chili Peppers | milk production, rumen function, heat stress | | feed additive | Bovine, sheep | Abulaiti et al. (2021); McCarty et al. (2015); Cunha et al. (2020); Rodríguez-Prado et al. (2012) |
| Capsicum oleoresin | Chili Peppers | milk production, rumen function, methane reduction, heat stress | | feed additive | Bovine | Cardozo et al. (2006); Fandiño et al. (2006); Fandiño et al. (2008); Oh et al. (2017); Rodríguez-Prado et al. (2012) |
| Carvacrol | Thyme, oregano | antimicrobial, fungicidal, milk production, rumen function, methane reduction | mastitis, BRD, *Salmonella* foodborne illness | feed additive, external, fumigation | Bovine, poultry, swine, humans | Calo et al. (2015); Cirino et al. (2014); Danning et al. (2020); Grzesiak et al. (2018); Gupta et al. (2020); Kissels et al. (2017); de Silva et al. (2020) |
| Cinnamaldehyde | Cinnamon | antimicrobial, milk production, rumen function, methane reduction, heat stress | mastitis, *Salmonella* foodborne illness | feed additive, external | Bovine, poultry, swine, humans | Baskaran et al. (2009); Calo et al. (2015); Danning et al. (2020); Dal Pozzo et al. (2012); Reza-Yazdi et al. (2014) |
| *Cinnamomum zeylanicum* | Cinnamon | bacteriostatic, bactericidal, antimicrobial, rumen function | mastitis | feed additive, external | Bovine | Ornaghi et al. (2017); Dal Pozzo et al. (2012) |
| Citral | Citrus fruit peel | antimicrobial, rumen function | mastitis | feed additive, external | Bovine | Gupta et al. (2020) |
| *Citrus aurantium* | Bitter orange | anti-parasitic | mosquitoes, ticks | external | Bovine | Pazinato et al. (2016) |
| *Coriandrum sativum* | Coriander | rumen function, methane reduction, heat stress | | feed additive | Bovine | Belanche et al. (2020); Guash et al. (2016); Reza-Yazdi et al. (2014); Rossi et al. (2022) |
| *Cedrus atlantica* | Cedar | anti-parasitic | cattle tick, insecticidal | external | Bovine | Pazinato et al. (2016) |
| *Cymbopogon citratus* | Lemongrass | anti-parasitic | cattle tick | external | Bovine | Pazinato et al. (2016) |
| *Cymbopogon martini* | Palmarosa | anti-parasitic | cattle tick | external | Bovine | Pazinato et al. (2016) |
| Eugenol | Clove oil, cinnamon | antimicrobial, milk production, rumen function, methane reduction, heat stress | mastitis, hypocalcemia | feed additive, external, fumigation | Bovine | Belanche et al. (2020); Danning et al. (2020); Ornaghi et al. (2017); Dal Pozzo et al. (2012); Reza-Yazdi et al. (2014); Rossi et al. (2022); Al-Suwaiegh et al. (2020); de Silva et al. (2020); de Souza et al. (2019) |
| Fennel | Fennel plant | antimicrobial | BRD | intra-nasal (BRD), feed additive | Bovine | Amat et al. (2019) |
| *Gardenia* sp. | Gardenia | anti-parasitic | internal parasites | oral drench | Sheep | Chitura et al. (2019) |
| Geranyl acetate | *Ceylon citronella*, palmarosa, lemon grass | rumen function, methane reduction, heat stress | | feed additive | Bovine | Belanche et al. (2020); Guash et al. (2016); Reza-Yazdi et al. (2014); Rossi et al. (2022) |
| *Juniperus communis* | Juniper | milk production, anti-parasitic | cattle tick | feed additive | Bovine | Pazinato et al. (2016) |
| *Lavandula angustifolia* | Lavender | antimicrobial, acaricidal | mastitis | mammary infusion, external | Bovine | Abboud et al. (2015); Ellse and Wall (2014); Fang et al. (2016); Laabouri et al. (2017); Macchioni et al. (2006); Seddiek et al. (2013); Shang et al. (2013); Shang et al. (2016); Pasay et al. (2010); Wall (2011) |

**Table 1** (*continued*)

| Essential oil | Common name or common origin | Effects | Disease | Application | Ruminant type | Reference |
|---|---|---|---|---|---|---|
| *Melaleuca alternifolia* | Tea tree oil | acaricidal | parasite infection | external | Bovine | Ellse and Wall (2014); Fang et al. (2016); Macchioni et al. (2006); Pasay et al. (2010); Seddiek et al. (2013); Shang et al. (2013); Shang et al. (2016); Wall (2011) |
| Menthol | Mint | milk production, heat stress, anti-parasitic | hypocalcemia, internal parasites | feed additive | Bovine, Sheep | Braun et al. (2019); Molefe et al. (2012); Reza-Yazdi et al. (2014) |
| *Pelargonium graveolens* | Sweet scented geranium | anti-parasitic | ticks | external | Bovine | Jaenson et al. (2006); Maske et al. (1996); Pazinato et al. (2016); Slathia et al. (2007); Weldon et al. (2011) |
| *Pimpimella anisum* | Anise | antimicrobial, milk production | neonatal diarrhea, hypocalcemia | feed additive | Bovine | Campolina et al. (2021) |
| *Salvia rosmarinus* | Rosemary | antimicrobial, rumen function | neonatal diarrhea | feed additive | Bovine | Campolina et al. (2021); de Souza et al. (2019) |
| *Senecio barbertonicus* | *Succulent Bush Senecio* | anti-parasitic | internal parasites | oral drench | Sheep | Chitura et al. (2019) |
| *Sonchus congestus* | | anti-parasitic | internal parasites | oral drench | Sheep | Chitura et al. (2019) |
| Thymol | Thyme, ajowan | antimicrobial, rumen function, methane reduction | mastitis, BRD | intra-nasal (BRD), external (mastitis), feed additive | Bovine | Cirino et al. (2014); Danning et al. (2020); Gupta et al. (2020); Kissels et al. (2017); de Souza et al. (2019) |
| *Thymus vulgaris* | Thyme | antimicrobial, rumen function, methane reduction | mastitis | mammary infusion, external | Bovine | Abboud et al. (2015) |
| *Zingiber officinale* | Ginger | anti-parasitic, bactericidal | mosquitoes, mites | external | Bovine | Hanifah et al. (2012); Nerio et al. (2010); Pazinato et al. (2016); Al-Suwaiegh et al. (2020); Silva et al. (2007); Silva et al. (2009) |

BRD = bovine respiratory disease.

Therefore, they may be implemented into cattle production systems to control for diseases which cause serious economic losses such as mastitis and bovine respiratory disease (BRD). Over 3000 essential oils have been discovered, with 10 % of them having commercial and economic relevance (Nehme et al., 2021). Essential oils may induce an effect alone, or have an additive, synergistic or antagonistic effect on the animal when administered in combination (Benchaar et al., 2009; Blanch et al., 2016; Braun et al., 2019; Elcoso et al., 2019; Suksombat et al., 2017).

In the dairy industry, mastitis is an economically draining disease with the highest relative costs to control the disease consisting of culling and mortality (48 %), milk yield reduction (34 %) and labor (3 %) (Aghamohammadi et al., 2019). Worldwide economic losses from mastitis have been estimated at $35 billion (Wellenberg et al., 2002). Pathogens causing mastitis include *Listeria monocytogenes*, *Salmonella typhimurium*, *Escherichia coli* and *Staphylococcus aureus* (Burt, 2004). Many studies have investigated the use of various essential oils in vitro and in vivo as potential therapeutic agents against mastitis due to their ability to penetrate the lipid bilayer of the bacterial cell membrane, causing loss of integrity and structural organization (Aiemsaaed et al., 2011; Tavares et al., 2020). In vivo experiments using a 10 % mixture of *Thymus vulgaris* (thyme) and *Lavandula angustifolia* (lavender) administered through mammary infusions and external application significantly decreased bacterial counts (Abboud et al., 2015). In a study investigating the antimicrobial properties of *Cinnamomum zeylanicum* (cinnamon) and trans-cinnamaldehyde against isolates of *Staphylococcus* spp., the authors demonstrated both compounds had bacteriostatic and bactericidal activity with trans-cinnamaldehyde being more effective at reducing bacterial counts (Dal Pozzo et al., 2012). Comparable results reported that the majority fraction of cinnamaldehyde was more effective than eugenol against 5 species of bovine mastitis pathogens (Baskaran et al., 2009). Additionally, trans-cinnamaldehyde, carvacrol, citral, and thymol have been effective with lower minimum inhibitory concentration against all pathogens causing mastitis (Gupta et al., 2020).

Essential oils can also be used to control fungi, including the protothecosis, *Prototheca zopfii*, which is a common pathogen causing mastitis in animals (Lass-Flörl and Mayr, 2007). In a study to evaluate the effects of thyme, marjoram, mint, oregano, and bear garlic oils against *P. zopfii*, it was found all tested strains of *P. zopfii* were insensible to peppermint and bear garlic oils and sensitive to thyme, marjoram, and oregano which all contain carvacrol as an active compound (Grzesiak et al., 2018). Due to the efficacy of the carvacrol containing thyme, marjoram, and oregano to inhibit the growth of *P. zopfii*, it is believed carvacrol induces an anti-algal effect due to the ability of carvacrol to dissolve the cell algal cell wall, penetrate the cytoplasm, release proton propulsion, and coagulate cytoplasmic contents (Grzesiak et al., 2018). Previous studies by these researchers testing the anti-algal effect against *P. zopfii* from milk isolates demonstrated that cinnamon, clove and thyme had the greatest effectiveness as compared to geranium, lavender, basil, rosemary, and clary sage (Gzresiak et al., 2016).

BRD is viral and bacterial disease affecting newly weaned or received cattle (Duff and Galyean, 2007). BRD is considered to be the costliest health problem in the North American feedlot sector, as it is the leading cause of cattle morbidity and mortality, attributes to poor feedlot performance and carcass merit and is costly to treat (Amat et al., 2019; Babacock et al., 2006; Duff and Galyean, 2007; Gardner et al., 1999; Woolums et al., 2005). *Mannheimia* *haemolytica, Pasteurella multocida, Histophilus somni* and *Mycoplasma bovis* are the main bacterial pathogens associated with BRD (Griffin et al., 2010). In a study investigating 16 essential oils against *M. haemolyticam*, *P. multocida* and *H. somni*, it is found that ajowan, thyme (carvacrol) and fennel (which contain thymol and eugenol) displayed the strongest antimicrobial activity against these pathogens and have potential to mitigate BRD through intra-nasal administration (Amat et al., 2019). These findings are consistent with findings from multiple studies suggesting carvacrol and thymol appear to be highly effective anti-bacterial agents (scientific literature survey; Andrade-Ochoa et al., 2021).

Essential oils can also be used as adjuvants to traditional antibiotic drugs such as tetracycline, doxycycline and tilmicosin to reduce the effective dose and decrease bacterial resistance (Kissels et al., 2017). Carvacrol and thymol have demonstrated additive and synergistic effects when combined with each other or with doxycycline or tilmicosin against *P. multocida* and *M. haemolytica*, indicating these essential oils can be used as a feed additive as a novel therapy against multi-drug resistant bacteria (Kissels et al., 2017). Similar findings by Cirino et al. (2014) showed that carvacrol and thymol enhance tetracycline effects against *S. aureus* by inhibiting the activity of efflux pumps (Cirino et al., 2014).

Other bacterial strains associated with tremendous economic loss include gram-negative bacteria such as *E. coli*, *Salmonella* spp., *Pseudomonas* spp., *Campylobacter* spp. and gram-positive bacteria such as *Staphylococcus* spp., *Enterococcus* spp., *Mycobacterium* spp. Anti-*E. coli* activity has been demonstrated by many essential oils containing carvacrol and eugenol including oregano, thyme, cinnamon, and clove being amongst the most effective (Ebani and Mancianti, 2020).

*Salmonella* is highly associated with foodborne illness but may be inhibited through use of essential oils as studies showed carvacrol and trans-cinnamaldehyde completely inhibited the growth of all *Salmonella enterica* strains isolated from turkey, poultry, cattle, swine and humans (Calo et al., 2015). *Pseudomonas aeruginosa* is a common cause of pneumonia, urinary tract infections, genital tract infections and skin infections and is resistant to many antibiotics (Mancianti and Ebani, 2020). Cinnamon bark, lemongrass and clove oil have all showed anti-bacterial activity against *P. aeruginosa*, especially when cinnamon oil is associated with cinnamaldehyde (Bouhdid et al., 2010; Prabuseenivasan et al., 2006; Utchariyakit et al., 2016). Thyme did not show anti-bacterial activity against *P. aergunosa* (Mancianti and Ebani, 2020). Members of the genus *Staphylococcus* are well-known opportunistic pathogens inflicting economic losses to livestock producers. Essential oils containing carvacrol and thymol have demonstrated anti-staphylococcal activity in multiple studies (Ebani et al., 2017, 2020; Kot et al., 2019; de Oliveira et al., 2009; Sakkas et al., 2018).

The genus *Enterococcus* belongs to the gastrointestinal microflora of animals and humans and serves both probiotic and pathogenic roles (Byappanahallo et al., 2012; Mancianti and Ebani, 2020). Pathogenic implications of *Enterococcus* include mastitis and diarrhea in cattle (Liu et al., 2020; Nilsson et al., 2012). Thyme oil (carvacrol) has been shown to inhibit the biofilm formation of enterococci by effecting call adherence and exopolysaccharide synthesis (Liu et al., 2020). Thyme oil can be improved in veterinary medicine as a natural alternative to antibiotics, but oral administration should be limited to maintain the probiotic effect of these bacteria (Mancianti and Ebani, 2020).

Regarding calves, essential oils can have a positive impact pre- and post-weaning. Adding a blend of essential oils (anise, cinnamon, garlic, rosemary, and thyme) to milk replacer contributed to immunity improvement (as determined by weekly blood samples). This essential oil blend decreased morbidity of neonatal diarrhea without affecting feed intake, animal performance characteristics, body development or blood metabolites (Campolina et al., 2021).

## 3. Effects of essential oils on milk yield

Improved nutrition, genetic progression and dairy management systems have allowed milk production to double per cow in the last 40 years (CIWF, 2021). These advancements in genetic gains and rearing practices improve animal health, confirmation, and nutrient utilization to increase the volume and improve the quality of milk produced. Increasing productivity per animal has positive economic and sustainability benefits. To further improve dairy cattle performance and health, several studies have investigated the role essential oils play when implemented into the diet of dairy cows. Various studies have reported inconsistent and inconclusive findings (Benchaar et al., 2008; Hashemzadeh-Cigari et al., 2014; Hristov et al., 2013; Santos et al., 2010; Spanghero et al., 2009; Tager and Krause, 2011; Tassoul and Shaver, 2009; Tekippe et al., 2013). To best understand how essential oils can improve the dairy industry, this present review will examine current literature to identify compounds with high potential to influence a positive biological impact and report associated findings. It is also understood that essential oils may have a greater effect when administered in combination, so it is likely additive and synergistic effects of multiple essential oils will be necessary to generate a favorable biological impact for the dairy industry.

In a study comparing the effects of a low dosage blend of clove, oregano, and juniper (2.5 g/head per day), high dosage blend of clove, oregano and juniper (5.0 g/head per day) and a control which received no treatment, it was found that cattle consuming the low dosage blend produced 4.3 % more milk than the non-supplemented cows during the treatment period, as well as demonstrated improved feed efficiency, increased milk protein, increased milk lactose and reduced bacterial cell and somatic cell counts (Al-Suwaiegh et al., 2020). The authors of this study recommend supplementing lower doses of essential oils to induce positive production traits without compromising or inhibiting rumen microbial populations (Al-Suwaiegh et al., 2020). Another study examined a microencapsulated blend of pepper extract containing capsaicin and pure forms of carvacrol, cinnamaldehyde and eugenol (150 mg/kg of diet dry matter for 56 d). Results suggest this blend of essential oils can increase feed efficiency, as cows fed the essential oil blend had a reduced dry matter intake (consuming 19.5 kg/d with the blend of essential oils as compared to 20.1 kg/d on control diet) and increased milk yield (30.8 kg/d when fed the essential oil blend compared to 30.1 kg/d when on control diet). Milk solids were not affected by the essential oil blend, but the supplementation of the essential oils reduced molar proportions of acetate and increased the proportion of propionate, which is suggestive of a lower methane energy loss. However, the effect of the essential oils on the feed efficiency was not consistent throughout the duration of the study and results may have been impacted by environmental conditions (da Silva et al., 2020).

Studies supplementing capsicum oleoresin demonstrated inconsistent results between trials, noting that supplementation of capsicum through the feed or directly into the abomasum in dairy cows did not affect dry matter intake, although capsicum supplementation increased dry matter intake and water consumption in studies with beef cattle (Cardozo et al., 2006; Oh et al., 2017; Rodríguez-Prado et al., 2012). However, it is acknowledged that the amount of capsicum supplemented in these studies was lower in the dairy model, which further emphasizes the need to determine the effective dose of capsicum required to yield an economic benefit (Oh et al., 2015, 2017). These findings warrant further investigation and suggest capsicum may have an impact on milk yield or could be utilized in combination with other essential oils to yield a synergistic effect which can result in economic productivity.

In addition to increasing milk production, essential oils may play a role to enhance the transport of $Ca^{2+}$, which can aid in the prevention of hypocalcemia or milk fever (Nilius and Szallasi, 2014). To further examine these potential effects, a commercially available mix of menthol, eugenol and anethol (PerformaNat GmbH) was fed to Holstein cattle and it was found that the PerformaNat GmbH significantly increased milk yield (Braun et al., 2019). Additionally, these researchers found the essential oil blend was associated with increased rise in plasma calcium levels, likely due to stimulated ruminal uptake of dietary calcium from the rumen into the blood. An increase of availability of blood $Ca^{2+}$ can prevent hypocalcemia after calving (Goff, 2008).

## 4. Effects of essential oils on rumen function, metabolism and feeding patterns

Evaluating rumen function can be complex as rumen function includes many factors such as energy metabolism, rumen microbiome and methanogenesis. These factors can be assessed by measuring dry matter intake, laboratory analysis of ruminal fluid and evaluating methane emissions.

Dry matter intake is important because increased dry matter intake directly provides more nutrients to rumen microbes, which in turn provide more nutrients for milk production, milk composition, growth, reproduction, and body condition (Department of Agriculture and Fisheries, 2013). Therefore, understanding the effect of consumption of essential oils on dry matter intake is critical to evaluate the nutrition the animals are consuming. Several studies have demonstrated capsicum oleoresin, fed at increasing dosages at 125, 250 and 500 mg/d and a control (no treatment) results in a linear increase in straw concentrate and total dry matter intake in both Holstein and beef cattle (Cardozo et al., 2006; Fandiño et al., 2006; Fandiño et al., 2008; Rodríguez-Prado et al., 2012). Rodríguez-Prado et al. (2012) also demonstrated a strong correlation between water consumption and dry matter intake, with an increase in 0.39 kg in dry matter intake for each liter increase in water consumption ($R^2 = 0.98$) (Rodríguez-Prado et al., 2012). Capsicum oleoresin changed feed intake patterns and increased volatile fatty acid concentrations at all treatment doses between 6 and 10 h after feeding (Rodríguez-Prado et al., 2012).

Other studies have examined the effects of capsaicin, pure forms of carvacrol, cinnamaldehyde and eugenol and found similar results, showing a gain in feed efficiency induced by this combination of essential oils was associated with reduced acetate-to-propionate ratio in ruminal fluid and altered eating behavior, overall suggesting a positive effect on ruminal fermentation (de Silva et al., 2020). In addition to blends containing capsaicin and capsicum oleoresin, other essential oils have demonstrated a positive biological impact in feedlot animals. Studies utilizing various dietary treatments with essential oils, including rosemary (ROS), protected blend of eugenol, thymol, and vanillin (BLE), protected blend + clove essential oil (BCL) and protected blend + rosemary essential oil + clove essential oil (BRC), demonstrated each combination resulted in greater average daily gain and dry matter intake than the control (no treatment) or the rosemary blend alone (de Souza et al., 2019). Clove and cinnamon generated similar results as studies have suggested that clove and cinnamon essential oils can be added at levels from 3.5 to 7.0 g/d per animal in high-grain finished diets because they improve animal growth performance up to 11 % compared with a control diet without changing feed efficiency, digestibility of nutrients, temperament, animal feeding behavior or carcass characteristics (Ornaghi et al., 2017)

A commercially available combination of microencapsulated essential oils (Agolin Ruminant) containing coriander oil, geranyl acetate and eugenol has been demonstrated to improve feed efficiency of lactating Holstein cattle, as animals supplemented with 1 g/d increased milk production and decreased feed intake ($P < 0.01$) (Guash et al., 2016). Additionally, this blend decreased methane production by 8.8 % per day, suggesting environmental benefits and reduced energy wastage (Belanche et al., 2020). Because methane is a by-product of enteric fermentation, the measurement of expelled methane allows researchers to gauge the feed efficiency, and therefore rumen function of an animal, in addition to providing environmental benefits.

A similar blend of essential oils to Agolin Ruminant containing cloves, coriander seeds and geranium effectively modulated the ruminal microbiota toward more efficient fermentation, which reduced the total methane production of the Holstein cows in this study (Rossi et al., 2022). In other studies, the addition of thyme essential oil to the basic ration reduced methane emissions on average by 21.6 % when the feed additive was added with an amount of 7.15 g/kg dry matter, and a reduction on average of 31.8 % with the amount was of 14.3 g/kg dry matter, suggesting thyme is a powerful essential oil to mitigate methane production in ruminant cattle (Laabouri et al., 2017). Other reported essential oil blends containing thymol, eugenol, cinnamaldehyde and carvacrol in dairy feed decreased the population of protozoa, methanogens, proteolytic and biohydrogenase bacteria, which leads to optimal ruminal fermentation and decreased methanogenesis (Danning et al., 2020).

These studies present promising data suggesting rumen function can be enhanced through the use of various essential oils, which can provide a direct positive impact to animal growth, milk production and the environment through increased feed efficiency and decreased methane production. With the demonstrated effectiveness of many essential oils, selected oils and blends can be curated to optimize the biological performance according to the cattle producer's production goals.

## 5. Effects of essential oils to mitigate heat stress

Heat stress is defined as the magnitude of forces external to the bodily system which tend to displace that system from its resting or ground state, and strain is the internal displacement from the resting or ground state brought about by the application of the stress. Therefore, the environmental factors external to the cow would contribute to stress (in this case heat stress) while the displacement of the cow from the cow's resting state would be the response to the external stress, or heat strain (Lee, 1965; West, 2003). The physiological stress response in cattle typically occurs when climate conditions are outside of their optimal range of −0.5 to 20 °C, above the upper critical air temperature of 25 to 26 °C, are of high relative humidity or is caused by the elevated body temperature of animals with high metabolic activity (Berman, 1985; Johnson, 1987). During heat stress cows exhibit reduced feed intake, decreased activity, increased respiratory rate, increased peripheral blood flow and sweating, and seek shade and wind (West, 2003). These conditions result in a deterioration of the physiological status of the cow and reduced growth and milk production. This is a widespread problem affecting a vast proportion of the globe, including the prominent cattle regions in the United States. In 2003, it was estimated that “heat stress impacts a variety of performance parameters in dairy cattle including milk yield, growth and reproduction and therefore possesses a significant financial burden of approximately $900 million/year for the dairy sector in the U.S.A.” (St-Pierre et al., 2003). Animal husbandry strategies can mitigate the deleterious impacts of heat stress. These strategies include providing animals with shade and fans, genetically selecting animals for heat tolerance and nutritional approaches. As essential oils are known to elicit biological responses in cattle, this review aims to understand prospective values essential oils can provide to animals during heat stress conditions.

Based on data from previous studies during mild or optimal environmental conditions demonstrating essential oils can improve milk production and rumen function, it was hypothesized similar effects could be present in heat stress conditions. Several essential oils including cinnamaldehyde, eugenol, peppermint, coriander, cumin, and lemongrass have been discovered to help animals maintain growth and performance under heat stress conditions, but existing literature has repeatedly demonstrated the promising impacts of capsaicin.

Capsaicin is a well-studied essential oil and a known activator of the vanilloid receptor, which is found in a variety of tissues throughout the body. Activation of the vanilloid receptor can invoke many reactions, but the ability of capsaicin to induce vasodilation may provide a thermoregulatory mechanism by allowing heat to dissipate (McCarty et al., 2015). Use of dietary capsaicin to assist in thermoregulation may improve the comfort of the animal which can have a positive effect on performance. Other production effects may include performance effects of dietary capsaicin comparable to studies in non-heat stress conditions.

In a study conducted during July 10th to August 24th, 2018, in the subtropical zone of central China, 109 cattle were randomly divided into 4 groups and fed a control diet (no treatment), 20, 40 and 60 mg dose of capsaicin per kilogram of total mixed ration daily. After 20 d of the study, these researchers found the addition of capsaicin to the diet yielded higher milk production and higher milk fat, suggesting capsaicin in heat stressed cows might improve the utilization of protein by enhancing rumen efficiency. Enhanced metabolic function during heat stress conditions can mitigate losses and maintain the performance of lactating dairy cattle. This study also reported significant increases in estrus response, ovulatory follicle size, ovulation rate and pregnancy rate in animals fed the capsaicin (40 mg/kg of total mixed ration daily), possibly due to capsaicin's role as a vasodilator and ability to increase blood flow to improve follicle development, meiotic maturation and embryonic development in heat stressed cows. As heat stress typically poses a negative impact on fertility, these findings support the use of capsaicin as an ameliorative strategy to improve summer breeding programs (Abulaiti et al., 2021).

Other research in cattle supports the use of capsaicin as a strategy to alleviate negative impacts of heat stress as capsaicin increased dry matter intake, which provides a fundamental value in field conditions during stressful periods when intake is depressed (Rodríguez-Prado et al., 2012). Studies in lactating ewes mimicked these findings, showing the inclusion of capsaicin in sheep concentrate in the middle of lactation minimized the reduction of milk production, improved the quality of the milk, and stimulated an antioxidant response system (Cunha et al., 2020).

Capsaicin can also modify feeding frequency and increase water intake as demonstrated by cattle ingesting a capsicum extract. These cattle ate more frequent meals throughout the day, as compared to the control, which can stabilize the ruminal environment, reduce the drop in pH and prevent rumen acidosis (Rodríguez-Prado et al., 2008; Sebastian, 2020). Additionally, regulation of the feeding pattern limits the peak heat after a large meal and maximizing water intake provides a cooling effect to maintain body temperature (Sebastian, 2020). These properties allow animals to better cope with heat stress.

Capsaicin may also provide synergistic effects when combined with other essential oils. In a study including capsicum oleoresin, cinnamaldehyde and eugenol, the profile of fatty acids produced in the rumen was optimized, resulting in a lower molar proportion of acetate and a higher proportion of propionate and butyrate (Sebastian, 2020). Propionate is a precursor in gluconeogenesis and provides more energy to the animal, even when dry matter intake is reduced (Sebastian, 2020). These findings are comparable to studies showing that essential oils can increase feed efficiency, which is an important economical characteristic.

To investigate the role of other essential oils in heat stress, a patented blend of cinnamaldehyde, eugenol, peppermint, coriander, cumin, lemongrass, and an organic carrier manufactured by Oars-Imen-Daru Herbal Medicines Development Company was fed at 2 g/cow per day for 4 weeks to Holstein dairy cows and compared to a control (Reza-Yazdi et al., 2014). Significant results were observed as dry matter intake was decreased in the control as compared to the cows fed the essential oil blend (Reza- Yazdi et al., 2014). These findings are further supported by research demonstrating that a blend of eugenol (28 %) and cinnamaldehyde (17 %) increased dry matter intake and milk production in dairy cattle (Tekippe et al., 2013).

These studies demonstrate that essential oils can stimulate production of lactating dairy cattle and feedlot beef cattle. Capsaicin has provided consistent results in various studies, whereas the blend of cinnamaldehyde, eugenol, peppermint, coriander, cumin, lemongrass may also provide improvements in animals under heat stress conditions. Further studies can refine the impact of these essential oils. Studies feeding a citrus extract to high producing dairy cattle had no effect on respiration rate, panting score, rump temperature, dry matter intake, whole tract digestibility of crude protein or milk production (Havlin and Robinson, 2015). These findings can help animal scientists determine optimal blends and dosages to mitigate the impacts of heat stress and provide relief to these animals. Data demonstrating production increases during non-heat stress conditions can provide more information regarding the role of essential oils in the ruminal environment. It is likely many essential oils can provide yearlong benefits and are not exclusive to the summer months.

## 6. Effects of essential oils to control parasites and reduce economic losses

Controlling parasites is critical to maintain animal health, welfare, and production. Parasites are a major cause of economic loss for cattle producers as they can cause reduced milk production, reduced weight gain, food safety concerns, disease, and mortality. Economic losses of all internal and external parasites are difficult to calculate but it is estimated internal parasites cost United States cattle producers over $3 billion in losses annually (Tarpoff, 2021). Stable flies, an external parasite, were estimated to cost United States cattle producers over $2.2 billion annually in 2012 (Kaufman et al., 2021). These economic losses are more devastating in subtropical and developing countries. In Brazil, combined annual economic loss due to internal and external parasites is estimated to be at least $13.96 billion, with ticks serving as one of the most destructive ectoparasites in livestock (Lopes et al., 2015). Treatment and prevention of both internal and external parasites is becoming increasingly difficult. Parasites have become resistant to many pharmaceutical and chemical compounds which make them difficult to control (Lopes et al., 2015). Despite the global market opportunity, many companies are not incentivized to solve this problem as introduction of a new product to market is time-consuming and is a huge economic burden; the cost of discovering and developing a novel product is estimated to cost $100 million, with an average duration of 10 years (Graf et al., 2004). Considering the urgent demand for effective anti-parasitic prevention and treatment in livestock, the use of essential oils either in vivo or in vitro to provide protection to livestock has been explored.

Several recent studies have examined the bioactive effects of essential oils against ectoparasites. Oregano, lavender, tea tree oil and neem oil have demonstrated a strong acaricidal activity (Ellse and Wall, 2014; Fang et al., 2016; Macchioni et al., 2006; Pasay et al., 2010; Seddiek et al., 2013; Shang et al., 2013; Shang et al., 2016; Wall, 2011). Topical application and fumigation of geraniol, eugenol and carvacrol demonstrated significant acaricidal activity against *Psoroptes ovis* mites (Chen et al., 2019). In vivo evaluation of carvacrol in cattle resulted in 98.5 % elimination of mites and only caused mild and transient local side effects, suggesting 2 % carvacrol can be a safe antiparasitic drug for cattle (Chen et al., 2019).

In vitro studies tested 7 essential oils against the cattle tick (*Rhipicephalus microplus*), which is known to cause animal stress, reduced growth, poor performance and negative economic impacts (Pazinato et al., 2016). This study found *Cymbopogon martini, Cymbopogon citratus* and *Cedrus atlantica* essential oils showed efficacy against cattle ticks higher than 99 % in all concentrations tested (Pazinato et al., 2016). *Juniperus communis, Zingiber officinale, Pelargonium graveolens* and *Citrus aurantium* oils showed efficiency ranging from 73 % to 95 %, whereas higher concentrations resulted in greater efficacy (Pazinato et al., 2016). These results are comparable to studies reporting *J. commuinis* is a rich source of anti-tick compounds with well-known repellent and insecticidal activities, and *C. citratus* oil had 100 % efficacy against *R. microplus* (Agnolin et al., 2014; Dietrich et al., 2006; Silva et al., 2007; Silva et al., 2009). *Z. Officinale* showed bactericidal effect on *S. aureus*, repellent activity against mosquitoes (*Culex quinquefasciatus*) and repellent effect against mites *(Leptotrombidium delicense*) suggesting broad spectrum usage (Hanifah et al., 2012; Nerio et al., 2010; Silva et al., 2007; Silva et al., 2009). Oils from the *Citrus* sp. resulted in a repellant effect against mosquitoes and ticks and *P. graveolens* oil showed 100 % repellency against host-seeking nymphs of *Ixodes Ricinus* (ticks) (Jaenson et al., 2006; Maske et al., 1996; Slathia et al., 2007; Weldon et al., 2011). This data supports the use of essential oils as a safe and effective repellant to protect livestock from external parasites.

Internal parasites also present detrimental effects to livestock species. Animals typically contract intestinal parasites during grazing, in which parasites are ingested and take up residency inside of the animals' internal organs. Gastrointestinal nematodes are one of the most common internal parasites worldwide, causing economic losses to the livestock industry as a result of the symptoms of infection which include irritation, loss of appetite, inflammation of the mucous membrane, diarrhea, loss of body mass and poor health (Hendrix, 1998; Hunter, 1996). Synthetic anthelmintics are the only known treatment against gastrointestinal parasites but are incurring resistance. If essential oils can provide anthelmintic activity against intestinal parasites, essential oils can be used either alone or as an adjuvant to prevent anthelmintic resistance and parasite infection, and provide more options in regions where veterinary anthelmintics are not available. This review utilized literature from the small ruminant model, as very limited information is available using essential oils for internal parasite control in cattle.

In vitro studies concluded *Artemisia afra* and *Mentha longifolia* crude extracts against gastrointestinal nematodes in sheep (*Haemonchus*, *Ostertagia*, *Chabertia*, *Nematodirus*, *Trichostrongylus*/*Teladorsagia*, *Bunostomum*) significantly decreased egg hatching and inhibited larval development, suggesting plant extracts may be potential candidates for treatment of gastrointestinal larval infections (Molefe et al., 2012).

To investigate the effectiveness of essential oils to control internal parasites, *Allium stavium* (garlic) was compared to a conventional de-wormer, Valbazen, in sheep. These researchers found there were no significant differences between the *A. stavium* treatments and the Valbazen, suggesting *A. stavium* is as effective as a conventional de-wormer (Mashamha et al., 2010). Comparable results were achieved in a study which demonstrated extracts of *Amaurobius ferox*, *Sonchus congestus*, *Senecio barbertonicus* and *Gardenia* sp. achieved larval mortality similar to the commercial drug, Thiabendazole, at concentrations of 2.5 and 5 mg/mL after 72 h of incubation, concluding that these plant derived essential oils are good candidates for livestock farmers for use in controlling internal parasites (Chitura et al., 2019).

These studies present promising data for future uses of essential oils to protect livestock species from external and internal parasites, prevent drug resistance and provide environmentally friendly alternatives to synthetic pharmaceuticals. Further studies are required to test specific essential oils against various parasite species, determine effective concentration and evaluate potential side effects.

## 7. Limitations to the use of essential oils in ruminant livestock production

Despite the potential role of essential oils to provide beneficial biological impacts on animal health, production and performance, there are limitations. With over 3000 discovered essential oils, studying the effects of each oil's effect on an animal's biological response is difficult. Additionally, many studies utilized a blend of essential oils, making it difficult to understand which essential oil induced the observed response or if it is necessary to administer the oils together to induce the desired response. Ruminant animals have complex organ systems, and it is critical that administration of any oral or topical agent does not negatively disrupt their normal physiological function, harm the beneficial microflora in the ruminant microbiome, or, in the case of antimicrobial purposes, cause pathogen resistance to nutraceutical agents.

Essential oils can be very expensive, and it is critical to define the effective dosage to elicit animal health, performance and economical gains. To date, many essential oils such as capsaicin, garlic, cinnamaldehyde, carvacrol, and eugenol are well studied in domestic ruminant livestock while others are rarely documented in the scientific literature. Without thorough understanding of the effects of these essential oils on the animal's heath and performance and the essential oil's mechanism of action, it is challenging to provide proper guidance for utilizing essential oils as a preventative or treatment in a livestock production system. More research is necessary to fully unlock the potential of essential oils to improve the health of ruminant animals.

## 8. Conclusion

Livestock producers strive to raise healthy animals to deliver high quality animal protein to feed the global population, but are confined by finite resources such as land, water, and feed, increasing regulation regarding pharmaceutical use and animal husbandry, increased parasite resistance to pharmacological compounds and consumer preferences trending towards treating animals with only naturally occurring substances. With these stringent demands, there is an immense need to understand the role of naturally occurring plant derived compounds such as essential oils to help livestock producers provide safe, effective, economically viable solutions to treat microbial infections, parasites, heat stress and enhance milk production and rumen function.

As many essential oils are safe for use on animals intended for human consumption, there is a large commercial opportunity to develop more feed additives and topical agents containing essential oils for prevention and treatment of infection and disease, to promote growth and milk yield, reduce heat stress and reduce methane emissions. This market potential will create a need for more research pertaining to the animal's response to essential oils which should address the limitations and unknowns to these compounds to optimize the use of essential oils most effectively in livestock production operations. In conclusion, many studies have demonstrated essential oils can provide a beneficial biological effect to ruminant animals without inducing detrimental effects to animal or human health and therefore should be considered as an important component in animal health programs.

## Author contributions

**Cara Wessels Wells**: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing original draft, Writing review and editing, and Project administration.

## Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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