



Essential Oils in Livestock Health and Production: A Review of Mechanisms, Applications, and the Transition to Antibiotic-Free Systems

Madhu Mishra¹ and Deepak Upadhyay^{2*}

¹Veterinary Assistant Surgeon, Govt. of Madhya Pradesh, Niwari, M.P., INDIA

²Associate Professor, College of Veterinary and Animal Sciences, RLBCAU, Jhansi, Uttar Pradesh, INDIA

*Corresponding author: D Upadhyay; E-mail: dpkvet@gmail.com

Received: 08 Oct., 2025

Revised: 18 Nov., 2025

Accepted: 25 Nov., 2025

ABSTRACT

The escalating challenge of antimicrobial resistance (AMR) in livestock production, exacerbated by the global restrictions on antibiotic growth promoters, has intensified the search for natural alternatives. Essential oils (EOs), derived from aromatic plants, have emerged as promising phytogetic feed additives due to their multifaceted bioactive properties, including antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory effects. This review explores the applications of EOs in livestock health and production, spanning poultry, swine, ruminants, and aquaculture. Key mechanisms involve disruption of microbial cell membranes, modulation of gut microbiota, enhanced nutrient digestibility, and rumen fermentation optimization, leading to improved growth performance, feed efficiency, and reduced methane emissions in ruminants. As feed additives, EOs from sources like oregano, thyme, cinnamon, garlic, and rosemary promote digestive enzyme secretion, mitigate enteric pathogens (e.g., *Salmonella*, *E. coli*, *Clostridium*), and support disease prevention against respiratory infections, mastitis, and parasitism. Species-specific benefits include enhanced egg production and immunity in poultry, better weight gain in swine, and improved milk yield in dairy animals. Advanced delivery systems, such as nanoencapsulation, address challenges like volatility and palatability, enhancing bioavailability and efficacy. Despite promising *in vitro* and *in vivo* evidence, variability in EO composition, optimal dosing, and long-term safety require further standardization. This review highlights EOs' potential as sustainable tools for antibiotic-free livestock systems, emphasizing future research directions for clinical translation and regulatory approval.

HIGHLIGHTS

- EOs are natural alternatives to antibiotics in livestock due to antimicrobial, antioxidant and immunomodulatory properties.
- EOs improve growth performance, feed efficiency, gut health and optimize rumen fermentation.
- Oregano, Thyme, Cinnamon, Garlic, and Rosemary Eos effectively control pathogens while preventing various livestock diseases.
- Use of EOs provides better egg production in poultry, weight gain in swine, and higher milk yield in dairy animals.
- Nanoencapsulation can help overcome EO volatility and palatability issues.

Keywords: Antimicrobial Resistance, Bioactive Metabolites, Essential oils, Phytogetic Feed Additives

Antibiotic resistance in livestock production represents a critical global threat, fueled by widespread antimicrobial use for therapeutic, prophylactic, and growth-promoting purposes in intensive farming. Globally, livestock consumed approximately 110,777 tons of antibiotics in 2019, projected to rise 29.5% to 143,481 tons by 2040, driven by increasing animal protein demand in Asia and Africa (Acosta *et al.*, 2025). Overuse selects for

resistant pathogens (e.g., *Escherichia coli*, *Salmonella*), transmitting to humans via food, direct contact, or the environment, complicating human treatments (WHO,

How to cite this article: Mishra, M. and Upadhyay, D. (2025). Essential Oils in Livestock Health and Production: A Review of Mechanisms, Applications, and the Transition to Antibiotic-Free Systems. *J. Anim. Res.*, 15(06): 247-255.

Source of Support: None; **Conflict of Interest:** None





2017). The European Union's (EU) 2006 ban on antibiotic growth promoters reduced resistance in animals (e.g., diminished vancomycin-resistant enterococci in humans) and demonstrated feasible alternatives, though it initially increased therapeutic antibiotic use due to health challenges like post-weaning diarrhea in pigs (Casewell *et al.*, 2003). India ranks among top global consumers of veterinary antimicrobials, with rising AMR in livestock pathogens. Recent 2025 measures include banning non-therapeutic uses, prohibiting 37 drugs in food animals, and phasing out growth promoters to curb resistance and align with international standards (GOI., 2025). As regulatory frameworks, India's 2025 National Action Plan restricts conventional antimicrobial use, therefore the search for high-potency alternatives has become a strategic paradigm shift for global food security. In developing regions, inconsistent regulations sustain high usage, highlighting the urgent need for alternatives like phytochemicals and improved biosecurity to mitigate antimicrobial resistance (AMR) while ensuring sustainable production. This review aims to evaluate the applications of essential oils as natural alternatives to antibiotics in livestock production, focusing on their roles in enhancing growth performance, gut health, immunity, and disease prevention across poultry, swine, ruminants, and aquaculture.

Role of Phytochemicals and EOs as Natural Alternatives

Phytochemicals, encompassing plant-derived compounds such as herbs, spices, essential oils (EOs), and oleoresins, have gained prominence as natural alternatives to antibiotic growth promoters (AGPs) in livestock production amid rising antimicrobial resistance concerns. Derived from bioactive secondary metabolites like phenols (e.g., carvacrol, thymol), terpenoids, and flavonoids, these additives exhibit multifaceted properties, including antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory effects (Abdelli *et al.*, 2021, Stevanović *et al.*, 2024). EOs disrupt microbial cell membranes, inhibit pathogen adhesion, and modulate gut microbiota, reducing loads of enteric bacteria (e.g., *Escherichia coli*, *Salmonella*, *Clostridium*) while favoring beneficial species like *Lactobacillus* (Yang *et al.*, 2015). This enhances nutrient digestibility, feed efficiency, and growth performance in poultry, swine, and ruminants, often comparable to AGPs (Gadde *et al.* 2017). In poultry, blends of oregano, thyme, and cinnamon EOs improve

body weight gain, lower feed conversion ratios, and bolster immunity against challenges like Newcastle disease. In swine, they mitigate post-weaning diarrhea and oxidative stress; in ruminants, they optimize rumen fermentation and reduce methane emissions (Benchaar, 2023). Advanced formulations, such as microencapsulation, improve bioavailability and overcome volatility issues. Overall, phytochemicals support sustainable, antibiotic-free systems by promoting health, welfare, and productivity without residue risks.

Historical and Current Use of EOs in Animal Husbandry

EOs have been utilized in animal husbandry for centuries, rooted in ethnoveterinary practices across ancient civilizations, including Egypt, China, India, and Europe, where aromatic plants served as remedies for animal health, parasite control, and wound treatment (Lans, 2012; Franz *et al.*, 2010). Historically, herbs and spices containing EOs were incorporated into feeds or applied topically for their digestive benefits and antimicrobial effect. In modern times, particularly following the European Union's 2006 ban on antibiotic growth promoters, EOs have surged as phytochemical feed additives in livestock production. Currently, EOs from oregano, thyme, cinnamon, and garlic are widely used to enhance growth performance, gut health, immunity, and feed efficiency in poultry, swine, and ruminants, while reducing methane emissions and serving as sustainable alternatives amid antimicrobial resistance concerns.

Chemical Composition and Bioactive Compounds of EOs

EOs are complex mixtures comprising primarily terpenes (mono-, sesqui-, and diterpenes), phenols, aldehydes, alcohols, ketones, ethers, and esters with phenols and terpenes being the most abundant and bioactive classes relevant to livestock applications. Phenolic compounds (e.g., thymol, carvacrol in oregano/thyme; eugenol in clove) exhibit strong antimicrobial and antioxidant properties by disrupting microbial membranes and scavenging free radicals (Nazzaro *et al.* 2013). Terpenes (monoterpenes like limonene, pinene; sesquiterpenes) contribute to anti-inflammatory and immunomodulatory effects, while enhancing palatability. Aldehydes (e.g., cinnamaldehyde

in cinnamon, citral in lemongrass) demonstrate potent antibacterial and antifungal activity through protein denaturation and enzyme inhibition. Alcohols (e.g., linalool, menthol) and ketones offer milder antimicrobial action with calming effects. Phenylpropanoids (e.g., anethole) and oxides (e.g., 1,8-cineole in eucalyptus) further broaden the spectrum. Variability in composition depends on plant species, chemotype, and extraction method, influencing efficacy in animal husbandry (Dhifi *et al.* 2016).

Table 1: Classification of Major Bioactive Compounds

Class	Key Examples	Biological Functions
Phenols	Thymol, Carvacrol, Eugenol	Potent antimicrobial action; disrupts microbial membranes; antioxidant scavenging.
Terpenes	Limonene, Pinene	Anti-inflammatory and immunomodulatory effects; enhances palatability.
Aldehydes	Cinnamaldehyde, Citral	Potent antibacterial and antifungal activity; induces protein denaturation and enzyme inhibition.
Alcohols	Linalool, Menthol	Milder antimicrobial action; calming/sedative effects in specific species.
Ketones	Carvone, Menthone	Antimicrobial properties; impact on metabolic rate and digestive secretions.
Phenylpropanoids	Anethole	Broad-spectrum antimicrobial activity; supports gut barrier function.

Factors influencing composition of EOs (plant source, extraction method and chemotypes): The composition of essential oils (EOs) is highly variable and influenced by multiple factors. Plant source (species, cultivar, and geographical origin) determines baseline chemoprofiles due to genetic and environmental adaptations. Chemotypes—genetically distinct variants within the same species (e.g., thymol-rich vs. linalool-rich thyme)—produce markedly different dominant compounds. Extraction methods (steam

distillation, hydrodistillation, cold pressing, or solvent extraction) affect yield and selectivity, with distillation preserving volatiles while solvent methods may retain heavier compounds or introduce residues. Harvest time, plant part, and post-harvest handling further contribute to compositional variability, impacting efficacy in livestock applications (Tongnuanchan & Benjakul 2014).

Commonly Used EOs in Livestock

Several EOs are widely used in livestock production as phytogetic feed additives, valued for their antimicrobial, antioxidant, digestive, and growth-promoting properties. The most common include oregano, thyme, cinnamon, garlic, and eucalyptus, often applied in poultry, swine and ruminants to enhance performance and reduce antibiotic reliance (Gadde *et al.* 2017). Oregano oil (rich in carvacrol and thymol) is among the most researched and commercially applied, improving gut health, feed efficiency, and immunity in broilers and pigs, while reducing pathogens like *Salmonella* and *E. coli* (Abdelli *et al.* 2021). Thyme oil (high in thymol) offers similar strong antimicrobial effects, supporting growth in poultry and swine, and modulating rumen fermentation in ruminants (Gadde *et al.* 2017, Benchaar 2023). Cinnamon oil (cinnamaldehyde-dominant) exhibits potent antibacterial activity, enhancing digestion and reducing methane emissions in ruminants, with benefits in monogastrics (Stevanović *et al.* 2024; Yang *et al.* 2015). Garlic oil (allyl sulfides) provides broad-spectrum antimicrobial and immunomodulatory effects, commonly used against enteric pathogens in poultry and swine (Abdelli *et al.* 2021). Eucalyptus oil (1,8-cineole) aids respiratory health and antioxidant status, particularly in poultry and as a rumen modifier (Benchaar, 2023). These EOs are often blended for synergy and encapsulated for stability (Yang *et al.* 2015).

Mechanisms of Action of EOs in Livestock

EOs exert diverse bioactive effects in livestock through their lipophilic compounds, primarily phenols (e.g., carvacrol, thymol), terpenes, and aldehydes, influencing microbial populations, oxidative status, inflammation, immunity, and digestion.

Antimicrobial and anti parasitic effects: EOs disrupt

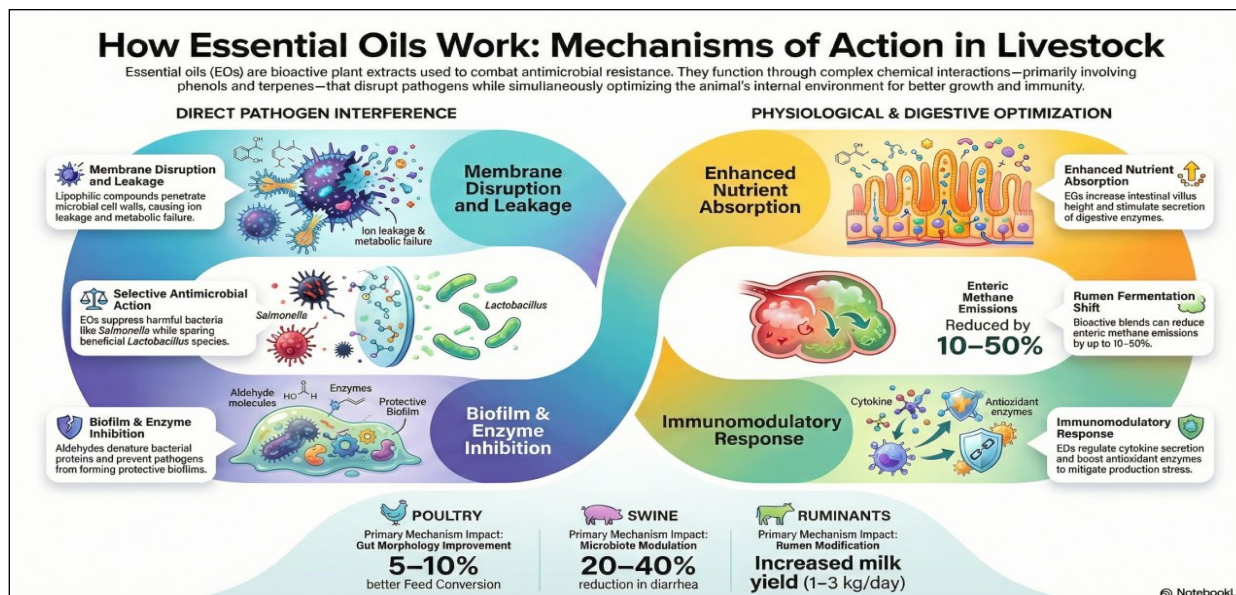


Fig. 1: Mechanism of action of Essential oils in livestock and their impact

microbial cell membranes due to their hydrophobicity, increasing permeability, causing leakage of ions, proteins, and ATP, and inhibiting enzymes. Phenolic compounds like thymol and carvacrol target Gram-positive and Gram-negative bacteria (e.g., *E. coli*, *Salmonella*, *Clostridium*), fungi, and protozoa by partitioning into lipid bilayers (Nazzaro *et al.* 2013; Benchaar, 2023). Antiparasitic activity includes inhibition of coccidia and internal/external parasites, as seen with garlic oil’s allicin derivatives, reducing parasite loads in poultry and ruminants. In the gut, EOs selectively suppress pathogens while sparing beneficial bacteria like *Lactobacillus*, lowering enteric disease risk (Abdelli *et al.* 2021).

Antioxidant and anti-inflammatory properties: EOs scavenge free radicals, enhance endogenous enzymes (e.g., SOD, GSH-Px), and protect against lipid peroxidation. Compounds like eugenol and cinnamaldehyde reduce oxidative stress in blood and tissues, improving meat/milk quality and animal resilience (Nehme *et al.* 2021). Anti-inflammatory effects involve down regulation of pro-inflammatory cytokines (e.g., via NF-κB pathway inhibition) and reduced oxidative damage, mitigating stress in intensive production.

Immunomodulatory and gut health-promoting mechanisms: EOs modulate immune responses by altering

cytokine secretion (e.g., increasing IL-10, decreasing TNF-α) and enhancing macrophage activity/antibody titers. In the gut, they improve morphology (increased villus height: crypt depth ratio), stimulate digestive enzyme secretion (amylase, trypsin), boost nutrient absorption, and favor beneficial microbiota (e.g., Bacteroides, *Lactobacillus*), reducing diarrhea and pathogen adhesion (Abdelli *et al.* 2021).

Impact on rumen fermentation and digestion (especially in ruminants): In ruminants, EOs selectively inhibit hyper-ammonia-producing bacteria and protozoa, reducing ammonia N and shifting fermentation toward propionate (energy-efficient) over acetate, while decreasing methanogenesis (Patra, 2016). Methane reduction (up to 20–50% *in vitro*) occurs via direct inhibition of methanogens or protozoa-associated archaea, with blends enhancing VFA production without impairing digestibility (Nasir *et al.* 2025). Overall, EOs optimize rumen pH, reduce protein degradation, and improve feed efficiency (Kholif *et al.* 2023). These mechanisms position EOs as sustainable alternatives, though dose-dependent and variable due to composition (Nehme *et al.* 2021).

Effects on growth performance and feed efficiency: Dietary supplementation with EOs consistently enhances growth performance in livestock by improving average

daily gain (ADG) and feed efficiency. Meta-analyses show that EOs increase body weight gain (BWG) linearly with dosage, often comparable to or exceeding antibiotic growth promoters (Putra *et al.* 2024). In broilers, EOs like oregano, thyme, and blends (100–500 mg/kg) improve ADG by 5–10% and reduce feed conversion ratio (FCR) by enhancing nutrient utilization and gut health. Similar effects occur in swine, where EOs mitigate post-weaning stress, boosting ADG and gain: feed ratio (G:F), particularly in low-energy diets (Omonijo *et al.* 2018). In beef cattle, phytogetic EOs yield greater ADG and a tendency for improved feed efficiency, with males and females responding similarly. Overall, EOs promote lean growth, reduce lipid oxidation in tissues, and support antibiotic-free systems without compromising productivity (Khurana *et al.*, 2023).

Improvement in nutrient digestibility and absorption: EOs enhance nutrient digestibility by stimulating digestive enzymes (e.g., amylase, lipase, trypsin), increasing villus height: crypt depth ratio, and improving intestinal morphology for greater absorptive surface (Bach A *et al.* 2023). Meta-analyses in poultry reveal increased digestibility of dry matter (DM), crude protein (CP), ether extract (EE) and energy, with positive shifts in cecal microbiota (higher *Lactobacillus*, lower *E. coli*) (Putra *et al.* 2024). In pigs, EOs improve apparent ileal digestibility of CP and amino acids, especially with menthol-based blends (Permata *et al.* 2023). For small ruminants, EOs boost DM, organic matter, CP, and fiber digestibility. Enhanced absorption stems from reduced pathogen load, better mucus secretion, and modulated gut barrier function (e.g., upregulated tight junction proteins) (Bach *et al.*, 2023). These effects are dose-dependent and more pronounced in encapsulated forms for targeted release.

Modulation of rumen microbiota and methane reduction: In ruminants, EOs selectively modulate rumen microbiota, inhibiting hyper-ammonia-producing bacteria, protozoa, and methanogens while favoring propionate-producing pathways. This shifts fermentation toward energy-efficient volatile fatty acids (VFAs), reducing acetate:propionate ratio and methane (CH₄) production by 10–50% *in vitro* and *in vivo*. Recent studies on blends (e.g., oregano, garlic, citrus) confirm synergistic CH₄ mitigation without impairing digestibility, with optimized mixtures enhancing VFAs and lowering emissions (Khurana *et al.*, 2023). Garlic-citrus extracts and Agolin-like blends reduce

enteric CH₄ while improving performance in dairy cows. Methane inhibition involves direct antimicrobial action on archaea and alternative hydrogen sinks (Benchaar, 2023). Environmental benefits include lower GHG intensity, supporting sustainable ruminant production.

Species-Specific Applications of EOs

EOs, volatile aromatic compounds from plants, are widely applied in livestock sectors as natural alternatives to antibiotics, enhancing growth, health, immunity, and sustainability. Their bioactive components like carvacrol, thymol, and cinnamaldehyde provide antimicrobial, antioxidant, and anti-inflammatory benefits. This review outlines applications in poultry, swine, ruminants (dairy/beef cattle, sheep and goats), aquaculture, and minor species.

Poultry production: In poultry production, EOs are key feed additives for antibiotic-free systems. Oregano, thyme, cinnamon, and clove blends reduce *Salmonella*, *E. coli*, and *Clostridium* loads, improving gut morphology and nutrient absorption (Rodrigues, 2025). They enhance feed conversion ratios (FCR) by 5–10%, increase body weight gain, and mitigate oxidative stress in broilers under heat or density challenges (Elbaz, 2022). Antiviral and anticoccidial effects support respiratory health and parasite control, with encapsulated forms ensuring stability in feed (Bao, 2023).

Swine production: Swine production utilizes EOs extensively post-weaning to combat digestive disorders. Carvacrol-thymol mixtures modulate gut microbiota, reducing diarrhea by 20–40% and improving average daily gain (ADG) and FCR in nursery pigs. Cinnamon and oregano oils target pathogens like *E. coli* and *Lawsonia intracellularis*, while anti-inflammatory properties alleviate weaning stress. Microencapsulated EOs protect against gastric degradation, promoting consistent performance in grow-finish phases and reducing antibiotic use (Luise, 2023).

Ruminants (dairy and beef cattle, sheep, goats): For ruminants, EOs optimize rumen fermentation. In dairy cattle, oregano and garlic oils increase milk yield (1–3 kg/day), enhance milk fat/protein, and reduce somatic cell counts via antimicrobial action. Beef cattle fed blends show improved ADG, feed efficiency, and reduced methane



emissions (10-30%) through methanogen inhibition. In sheep and goats, rosemary, thyme, and polyphenol-rich EOs boost antioxidant status, improve meat/milk fatty acid profiles, and control gastrointestinal nematodes. These support sustainable grazing systems and product quality.

Emerging uses in aquaculture and minor species: Emerging aquaculture applications leverage EOs for disease resistance and growth in intensive farming. Oregano, tea tree, and cinnamon oils enhance immunity, antioxidant enzymes, and survival in tilapia, shrimp, and salmon against *Vibrio* and *Aeromonas*. They promote feed intake, weight gain, and stress mitigation during handling/transport, with nanoemulsions improving water dispersion. Antiparasitic effects target ectoparasites like sea lice, offering eco-friendly alternatives amid antibiotic restrictions. In minor species, EOs address specific needs. Rabbits benefit from oregano and thyme for digestive health and coccidiosis reduction, improving growth and welfare. Horses use lavender aromatherapy for calming (reducing heart rate during transport) and topical tea tree/peppermint for wound healing, insect repulsion, and hoof issues like thrush. These applications emphasize safety via non-ingestible routes. Overall, EOs promote sustainable livestock production by enhancing productivity and reducing chemical inputs, though standardization of dosage, delivery, and blends is essential for maximal efficacy.

Role in Disease Prevention and Health Management

Control of enteric pathogens: EOs offer natural antimicrobial strategies against enteric pathogens like *Salmonella* spp., *Escherichia coli*, *Clostridium difficile*, *Listeria* spp., and *Campylobacter jejuni*, combating antibiotic resistance through bioactive compounds such as terpenes and phenylpropenes. These disrupt bacterial cell membranes, enhance permeability, induce ion leakage, and inhibit biofilm formation and quorum sensing, leading to metabolic failure (Meenu *et al.*, 2023). Gram-negative bacteria (*E. coli*, *Salmonella*) show variable susceptibility due to outer membranes, while Gram-positive (*Listeria*, *Clostridium*) are often more vulnerable. Clove EO (*Eugenia caryophyllus*) exhibits bactericidal effects against *E. coli* and *Salmonella* at 0.19% v/v (Sitowski *et al.*, 2025). For *C. difficile*, clove and ginger EOs achieve MICs of 1.25–2.5 $\mu\text{L/mL}$ and 2.5–10 $\mu\text{L/mL}$, respectively, suppressing

spore outgrowth (Jerkovic-Mujkic *et al.*, 2024). Cinnamon and oregano EOs yield >50 mm inhibition zones against *Campylobacter jejuni*, with MICs of 0.2–4.0 mg/mL in nanoformulations (Pires *et al.*, 2024). *Taxodium distichum* leaf EO inhibits *Salmonella typhimurium* at 78.1 $\mu\text{g/mL}$ MIC (Meenu *et al.*, 2023). These applications enhance food safety and therapeutic potential, though formulation optimizes bioavailability.

Respiratory and mastitis management: For respiratory management, EOs like eucalyptus, peppermint, and cinnamon support airway health in poultry and swine by reducing inflammation, thinning mucus, and inhibiting pathogens such as *Mycoplasma gallisepticum* and *Escherichia coli*. (Erfan & Marouf 2019). Inhalation or dietary supplementation improves air quality and prevents infections, particularly in stressed flocks. In mastitis control for dairy cows, topical or intramammary applications of oregano, thyme, basil, and bergamot oils demonstrate antibacterial activity against *Staphylococcus aureus* and *E. coli*, lowering somatic cell counts and inflammation without antibiotic residues (Hunt, 2024).

Antiparasitic effects (internal and external parasites): Antiparasitic properties of EOs target both internal and external parasites. Oregano and clove oils show efficacy against gastrointestinal nematodes and coccidia (*Eimeria* spp.) in poultry, while tea tree, peppermint, and lemon oils combat monogeneans like *Dactylogyrus* in fish. Externally, neem, citronella, and tea tree repel ticks, fleas, and mites in livestock and pets (Panda, 2022).

Stress reduction and welfare improvement: EOs also promote stress reduction and welfare. Lavender and chamomile inhalation lowers cortisol in pigs and dogs, enhancing calm behavior and growth (Nehme, 2021). Dietary peppermint boosts antioxidant status under heat stress in livestock, supporting overall performance and immunity (Wells, 2023).

Challenges and Limitations Hindering Widespread Adoption

EOs exhibit promising antimicrobial, antioxidant, and anti-inflammatory properties *in vitro*, but *in vivo* and long-term studies are limited, often producing inconsistent results. Factors like complex gut ecosystems, dosage issues, and environmental variables contribute to discrepancies

Table 2: Role of Essential oils in livestock disease management

Health Management Category	Essential Oil Source	Target Pathogens or Conditions	Specific Animal Species	Mechanism of Action / Benefits	Source
Enteric Pathogen Control	Oregano, thyme, cinnamon, garlic, clove	<i>Salmonella</i> , <i>E. coli</i> , <i>Clostridium</i> , <i>Listeria</i> , <i>Campylobacter jejuni</i>	Poultry, Swine	Disruption of microbial cell membranes, inhibition of pathogen adhesion, modulation of gut microbiota, and biofilm inhibition.	Abdelli <i>et al.</i> 2021; Meenu <i>et al.</i> , 2023; Sitowski <i>et al.</i> , 2025; Pires <i>et al.</i> , 2024
Respiratory Management	Eucalyptus, peppermint, cinnamon	<i>Mycoplasma gallisepticum</i> , <i>Escherichia coli</i>	Poultry, Swine	Reduction of inflammation, thinning of mucus, and down-regulation of virulence genes.	Erfan & Marouf 2019.
Mastitis Control	Oregano, thyme, basil, bergamot	<i>Staphylococcus aureus</i> , <i>E. coli</i>	Dairy Cows	Antibacterial activity via topical or intramammary application.	Hunt, 2024
Antiparasitic Effects	Oregano, clove, garlic, tea tree, neem, citronella	Gastrointestinal nematodes, <i>Eimeria</i> spp. (coccidia), <i>Dactylogyrus</i> , ticks, fleas, mites	Poultry, Ruminants, Fish	Direct inhibition of internal parasites and repellent action against external parasites.	Panda, 2022; Abdelli <i>et al.</i> 2021
Stress Reduction and Welfare	Lavender, chamomile, peppermint	Cortisol levels, heat stress, transport stress	Pigs, Dogs, Horses, General Livestock	Calming effects via inhalation (aromatherapy) and enhancement of antioxidant status.	Nehme, 2021; Wells 2023

between lab and field outcomes. This highlights the need for more rigorous, standardized research to assess sustained efficacy, potential toxicity, residue accumulation, and impacts on animal health over production cycles. Cost-effectiveness poses a major barrier, as EOs are pricier than synthetic alternatives due to extraction costs, raw material variability, and higher required doses. Economic benefits, such as improved feed efficiency, do not always offset expenses in large-scale operations. Scalability is challenged by supply chain fluctuations, production costs for stable forms like encapsulated EOs, and precise formulation needs. Innovations like nanoencapsulation could enhance delivery but increase costs, impeding widespread adoption. EOs interact with feed components like proteins, lipids, and minerals, potentially reducing bioavailability, stability, or activity through binding or degradation. High lipid or fiber diets may diminish efficacy, while strong odors affect palatability and intake. Interactions with other additives remain underexplored, risking synergies or antagonisms. Encapsulation helps mitigate issues, but optimal carriers and feed compatibility require further refinement. Overall, advancing research and cost innovations are crucial for

EOs' practical integration in animal nutrition. Research should expand beyond common EOs (e.g., oregano, thyme) to underexplored sources like lemon balm, arctic plants, or regional botanicals for unique bioactives. Synergistic combinations—EOs with organic acids, saponins, or probiotics—promise amplified effects, such as enhanced antimicrobial activity and reduced dosages. Novel blends targeting specific challenges (e.g., heat stress or methane emissions) and encapsulated multi-component formulations will drive innovation, offering broader-spectrum benefits.

CONCLUSION

EOs has emerged as versatile, natural tool in modern livestock production, offering multifaceted benefits as sustainable alternatives to synthetic antibiotics and chemicals. Their bioactive compounds such as carvacrol, thymol, and cinnamaldehyde demonstrate potent antimicrobial activity against enteric pathogens like *Salmonella*, *E. coli*, and *Clostridium* while supporting respiratory health, mastitis management, and antiparasitic



effects against internal and external parasites. EOs also promotes stress reduction and animal welfare through calming and antioxidant properties. Across poultry, swine, ruminants, aquaculture, and minor species, EOs enhance growth performance, feed efficiency, gut health, immunity, and product quality, while reducing methane emissions and antibiotic resistance. In organic and antibiotic-free systems, they align perfectly with consumer demands for clean, residue-free animal products. Despite challenges like compositional variability, limited long-term studies, cost concerns, and feed interactions, ongoing advancements in standardization, nanoencapsulation, precision dosing, and novel plant combinations are addressing these limitations. With robust market growth and increasing regulatory support, EOs are poised to play a pivotal role in sustainable, eco-friendly livestock farming improving animal health, environmental impact, and food safety in a One Health framework.

REFERENCES

- Abdelli, N., Pérez, J.F. and Vilarrasa, E. 2021. Phytogetic feed additives in poultry nutrition: A review on their effects on gut microbiota, immunity, and growth performance. *Animals*, **11**(8): 1–21.
- Acosta, A. *et al.* 2025. Global trends in antimicrobial use in food-producing animals and implications for antimicrobial resistance. *Lancet Planet. Health*, **9**(1): e45–e56.
- Bach, A. *et al.* 2023. Effects of phytogetic compounds on nutrient digestibility and intestinal morphology in livestock. *J. Anim. Sci. Biotechnol.*, **14**: 98.
- Bao, H. *et al.* 2023. Encapsulated essential oils as alternatives to antibiotics in broiler production. *Poult. Sci.*, **102**(4): 102456.
- Benchaar, C. 2023. Essential oils and plant extracts as feed additives in ruminant nutrition: Effects on rumen fermentation, methane emissions, and performance. *Anim. Feed Sci. Technol.*, **297**: 115548.
- Casewell, M., Friis, C., Marco, E., McMullin, P. and Phillips, I. 2003. The European ban on growth-promoting antibiotics and emerging consequences. *J. Antimicrob. Chemother.*, **52**(2): 159–161.
- Dhifi, W., Bellili, S., Jazi, S., Bahloul, N. and Mnif, W. 2016. Essential oils' chemical characterization and investigation of some biological activities: A critical review. *Medicines*, **3**(4): 25.
- Elbaz, A.M. *et al.* 2022. Dietary essential oils mitigate heat stress effects and improve broiler performance. *Animals*, **12**(15): 1978.
- Erfan, A.M. and Marouf, S. 2019. Efficacy of essential oils against respiratory pathogens in poultry. *Avian Pathol.*, **48**(6): 505–514.
- Franz, C., Baser, K.H.C. and Windisch, W. 2010. Essential oils and aromatic plants in animal feeding – A European perspective. *Flavour Fragr. J.*, **25**(5): 327–340.
- Gadde, U., Kim, W.H., Oh, S.T. and Lillehoj, H.S. 2017. Alternatives to antibiotics for maximizing growth performance and feed efficiency in poultry. *Anim. Health Res. Rev.*, **18**(1): 26–45.
- Government of India (GOI). 2025. National Action Plan on Antimicrobial Resistance (NAP-AMR) 2025–2030. *Ministry of Health and Family Welfare, New Delhi*.
- Hunt, A. 2024. Use of essential oils in mastitis management: An alternative approach. *J. Dairy Res.*, **91**(2): 123–130.
- Jerkovic-Mujkic, A. *et al.* 2024. Antimicrobial activity of ginger and clove essential oils against *Clostridioides difficile*. *J. Appl. Microbiol.*, **136**(1): e13952.
- Kholif, A.E. *et al.* 2023. Essential oils as rumen modifiers: Effects on fermentation, methane mitigation, and animal performance. *Anim. Feed Sci. Technol.*, **295**: 115482.
- Khurana, R. *et al.* 2023. Phytogetic feed additives in livestock: Meta-analysis of performance and methane mitigation. *Front. Vet. Sci.*, **10**: 1189452.
- Lans, C. 2012. Ethnoveterinary medicines used for livestock in traditional cultures. *J. Ethnobiol. Ethnomed.*, **8**: 33.
- Luise, D. *et al.* 2023. Microencapsulated essential oils in swine nutrition: Gut health and performance effects. *Animals*, **13**(6): 1021.
- Meenu, M. *et al.* 2023. Antimicrobial activity of plant essential oils against foodborne pathogens. *Food Control*, **148**: 109657.
- Nasir, M. *et al.* 2025. Synergistic essential oil blends for methane reduction in ruminants. *Animal*, **19**(2): 100911.
- Nazzaro, F., Fratianni, F., De Martino, L., Coppola, R. and De Feo, V. 2013. Effect of essential oils on pathogenic bacteria. *Pharmaceuticals*, **6**(12): 1451–1474.
- Nehme, R. *et al.* 2021. Essential oils in livestock health: Antioxidant, anti-inflammatory, and stress-reducing effects. *Antioxidants*, **10**(2): 256.
- Omonijo, F.A. *et al.* 2018. Essential oils as alternatives to antibiotics in swine production. *Anim. Nutr.*, **4**(2): 126–136.
- Patra, A.K. 2016. Recent advances in phytogetic feed additives for ruminants. *Anim. Prod. Sci.*, **56**(4): 1–15.
- Panda, S.K. 2022. Antiparasitic activity of essential oils in livestock and aquaculture. *Vet. Parasitol.*, **305**: 109696.
- Permata, D.A. *et al.* 2023. Effects of menthol-based essential oils on nutrient digestibility in pigs. *Livest. Sci.*, **266**: 105075.

- Pires, J.R. *et al.* 2024. Nanoencapsulated essential oils against *Campylobacter jejuni*. *Food Microbiol.*, **116**: 104357.
- Putra, R.P. *et al.* 2024. Meta-analysis of essential oil supplementation on broiler performance and gut health. *Poult. Sci.*, **103**(1): 102344.
- Rodrigues, H.L. de S. *et al.* 2025. Essential oils as feed additives in antibiotic-free poultry production. *Animals*, **15**(3): 412.
- Sitowski, M. *et al.* 2025. Antibacterial activity of clove essential oil against *Salmonella* and *E. coli*. *J. Essent. Oil Res.*, **37**(1): 45–53.
- Stevanović, Z.D. *et al.* 2024. Phytogetic feed additives in livestock nutrition: Mechanisms and applications. *Anim. Nutr.*, **13**: 1–14.
- Tongnuanchan, P. and Benjakul, S. 2014. Essential oils: Extraction, bioactivities, and applications in food and agriculture. *J. Food Sci.*, **79**(7): R1231–R1249.
- Wells, C.W. 2023. Role of peppermint and aromatic plants in mitigating heat stress in livestock. *J. Therm. Biol.*, **115**: 103564.
- WHO. 2017. Guidelines on use of medically important antimicrobials in food-producing animals. *World Health Organization, Geneva*.
- Yang, C., Chowdhury, M.A., Huo, Y. and Gong, J. 2015. Phytogetic compounds as alternatives to antibiotic growth promoters in poultry. *World's Poult. Sci. J.*, **71**(1): 97–114.

