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Essential oils and essential oil compounds in animal production as antimicrobials and anthelmintics: an updated review

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Abstract

Several countries have shown an increased prevalence of drug resistance in animal production due to the indiscriminate use of antibiotics and antiparasitics in human and veterinary medicine. This article aims to review existing methods using naturally occurring essential oils (EOs) and their isolated compounds (EOCs) as alternatives to antimicrobials and antiparasitic compounds in animal production and, consequently, to avoid resistance. The most-reported mechanism of action of EOs and EOCs was cell membrane damage, which leads to the leakage of cytoplasmic content, increased membrane permeability, inhibition of metabolic and genetic pathways, morphologic changes, antibiofilm effects, and damage to the genetic material of infections. In parasites, anticoccidial effects, reduced motility, growth inhibition, and morphologic changes have been reported. Although these compounds regularly show a similar effect to those promoted by traditional drugs, the elucidation of their mechanisms of action is still scarce. The use of EOs and EOCs can also positively influence crucial parameters in animal production, such as body weight gain, feed conversion rate, and cholesterol reduction, which also positively impact meat quality. The application of EOs and EOCs is enhanced by their association with other natural compounds or even by the association with synthetic chemicals, which has been found to cause synergism in their antimicrobial effect. By reducing the effective therapeutical/prophylactic dose, the chances of off-flavors – the most common issue in EO and EOC application – is greatly mitigated. However, there is very little work on the combination of EOs and EOCs in large *in vivo* studies. In addition, research must apply the correct methodology to properly understand the observed effects; for example, the use of only high concentrations may mask potential results obtained at lower dosages. Such corrections will also allow the elucidation of finer mechanisms and promote better biotechnologic use of EOs and EOCs. This manuscript presents several information gaps to be filled before the use of EOs and EOCs are fully applicable in animal production.

Introduction

Bacterial resistance to antibiotics is increasingly widespread, with intensive antibiotic use in human and animal health as a primary factor of diffusion, representing a serious problem for the economy and public health (Corrêa *et al.*, 2019; Evangelista *et al.*, 2021). Such products are widely used in livestock, and it has been shown that soil in the vicinity of animal production contains microorganisms with a high prevalence of antibiotic-resistance genes (ARGs) (Duan *et al.*, 2019). This and other factors lead to the conclusion that the indiscriminate use of antibiotics in intensive animal production may be one of the leading causes of resistance among zoonotic microbial pathogens.

ARGs have been constantly found in Enteric commensal and pathogenic bacteria from production animals. *Escherichia coli* has been largely studied (Lanz *et al.*, 2003; Zhang *et al.*, 2017a, 2017b, 2020; Poirel *et al.*, 2018; Li *et al.*, 2019) and strains that cause diarrhea in pigs have been identified as resistant to several classes of antibiotics, including colistin, an antibiotic used to control multi-resistant microorganisms (Le Devendec *et al.*, 2018). Strains of *Salmonella* Typhimurium isolated from humans and animals in China have presented genes for resistance to a wide range of quinolones, aminoglycosides, and colistins (He *et al.*, 2020). Polymyxins, which belong to the colistin antimicrobial group, are still extensively used in animal production and have been found ineffective against many enterobacteria isolated from livestock (Giamarellou, 2016). Having ushered in a new era in medicine, the emerging ineffectiveness of antibiotics puts health at risk across the world. It is estimated that the United States spends $20 billion annually on treating antibiotic-resistant infectious diseases (Dadgostar, 2019).

In addition to antimicrobial resistance, antiparasitic resistance in animal production has also been an emerging problem due to the indiscriminate use of these compounds. Currently, the largest classes of drugs used to control intestinal parasites – imidothiazoles, tetrahydropyrimidines, benzimidazoles, and avermectins – have gradually lost effectiveness (Dey *et al*., 2020). Resistance to anthelmintics is increasing; among the farms tested, no antiparasitic activity of albendazole or fenbendazole was found against eggs of *Haemonchus contortus*, *Teladorsagia circumcincta,* and *Trichostrongylus* spp. (Claerebout *et al*., 2020). This also represents a serious problem, and it is estimated that the economic impact in Europe is about 38 million euros annually due to resistant parasites (Charlier *et al*., 2020). Another reason for the decreased effectiveness of these products is due to soil contamination by antiparasitic agents, as shown by de Oliveira Ferreira *et al*. (2019), who identified avermectins and moxidectin residues in Brazilian soils in concentrations close to 0.1 mg kg^{-1}.

As an alternative to the treatment of both bacteria and resistant parasites, the use of essential oils (EOs), which can also be later processed into purified compounds, has been evaluated (Shen *et al*., 2021; Zhang *et al*., 2021). For instance, *in vitro* tests using 1 mg ml^{-1} of *Ruta chalepensis* (fringed rue) flower EO showed positive effects (87.5% efficacy) leading to the death of *H. contortus* larvae, whilst 1 mg ml^{-1} albendazole had relatively lower beneficial effects (75% of efficacy) (Akkari *et al*., 2015). *Cuminum cyminum* oil (cumin) was responsible for 99% ovicidal activity in *Fasciola hepatica*, using a concentration of 0.03 mg ml^{-1} (Silva *et al*., 2020), which is a parasite that has been found resistant to albendazole (Ceballos *et al*., 2019). For bacteria, tested EOs also show good results against human and animal pathogens, such as *Melaleuca alternifolia* (tea tree) (Silva *et al*., 2019), *Syzygium aromaticum* (clove), *Cinnamomum cassia* (Chinese cinnamon) (Khaleque *et al*., 2016), *Cinnamomum zeylanicum* (true cinnamon tree), *Origanum vulgare* (oregano), *Thymus vulgaris* (thyme) (Mazzarrino *et al*., 2015), and *Brassica nigra* (black mustard) EO – composed mainly of allyl isothiocyanate, that has one of the greatest antimicrobial potentials among the essential oil compounds (EOCs) studied (Clemente *et al*., 2016; Reyes-Jurado *et al*., 2019).

To be able to consider their use in animals, there must be little or no interference in the beneficial animal microbiota (Ambrosio *et al*. (2017). Understanding of EO mechanisms of action is still lacking, but in general, some of the reported effects are the impairment of cell membrane integrity (e.g., cinnamaldehyde, present in cinnamon EO); the inhibition of protein synthesis (e.g., thyme EO); and the inhibition of genetic material repair (e.g., the effect observed in *E. coli* through phenolic compounds and terpenes, which can also affect the transfer of electrons in cellular respiration) (Ju *et al*., 2019).

This review aims to compile information about EO and EOC, covering their use as alternatives to antimicrobials and antiparasitics, evaluating their mechanisms of action, critically analyzing the information available about this topic, as well as to identify knowledge gaps in the available literature.

EO and EOC mechanisms of action as antiparasitic and antimicrobial agents

Mechanisms of action differ among EOs and EOCs (Table 1). In general, scientific studies found in the literature show that the main bactericidal activity occurs through plasmic membrane damage with extravasation of intracellular content, or an increase in its permeability (Lin *et al*., 2000; Bischoff *et al*., 2009; Hemaiswarya and Doble, 2009; Bassolé *et al*., 2010; Tyagi and Malik, 2012; Shen *et al*., 2015; Xu *et al*., 2016; Wang *et al*., 2017; Zhang *et al*., 2017a, 2017b; Bouyahya *et al*., 2019; Cui *et al*., 2019; Hu *et al*., 2019; Churklam *et al*., 2020; Liu *et al*., 2020, 2021). Other effects observed were the inhibition of metabolic and genetic pathways and damage to genetic material (Cui *et al*., 2019; Hu *et al*., 2019; Wang *et al*., 2020; Liu *et al*., 2021), morphological changes (Clemente *et al*., 2016), antibiofilm effects (Bouyahya *et al*., 2019; Liu *et al*., 2021), and anti-quorum sensing activity (Clemente *et al*., 2016). The accumulation of monoterpenes and phenylpropanoids (compounds present in many EOs) in the lipid part of the plasma membrane was responsible for destabilizing the structure of the phospholipid bilayer, depolarizing it, and increasing its permeability, compromising its proper functioning, and eventually causing cell death (Hammer and Heel, 2012).

Carvacrol, the major compound from oregano EO, caused the disruption of the cell membrane and increased transmembrane permeability (Cui *et al*., 2019). This is supported by the presence of free genetic material in the culture medium of treated groups and the increased concentration of carvacrol in the cytoplasm. Anti-quorum sensing activity and inhibition of peptidoglycan synthesis, which avoids repair and maintenance of the cell wall structure, were also reported (Bouyahya *et al*., 2019; Ni *et al*., 2021). Similar to carvacrol, *Zingiber officinale* (ginger) EO presented a membrane-related effect against *E. coli* and *Staphylococcus aureus*. The EO also caused metabolism disturbance, compromising the citric acid cycle, and inhibiting DNA repair and replication mechanisms (Wang *et al*., 2020).

The diversity of compounds present in EOs is extremely high. As an example, *Pinus* spp. (pine) EO was identified with 116 constituents, mostly belonging to the terpene class (Mitić *et al*., 2018). In the EO of some plants, the prevailing terpene is limonene, a compound that has anthelmintic activity on *H. contortus* and is bactericidal for *Salmonella* Paratyphi A and *Pseudomonas luteola*, with a moderate effect on *Enterococcus faecalis*. The mechanism of limonene is still not fully understood, but studies show that it can destroy cell integrity and cell wall structure of bacteria through an increase in conductivity and the leakage of intracellular biomacromolecules (nucleic acids and proteins) (Squires *et al*., 2010; Han *et al*., 2019; Yazgan *et al*., 2019).

The action of EO depends on different mechanisms inherent to each compound present or the association of mechanisms from the distinctive compounds, making it difficult to elucidate the exact pathways in which these complex solutions work. The resolution of this knowledge gap is of utmost importance, due to the growing need for alternatives to antimicrobial compounds. Another aggravating factor is the lack of adequate methodologies for identifying mechanisms of antimicrobial activity. Many studies use minimal inhibitory concentrations (MICs) and neglect effects that may not even have been documented because they appeared before the MIC was reached and the occurrence of morphologic alterations occurred in a way in which metabolic dysfunctions and genomic alterations become less noticeable.

EOs and EOCs are also used to control parasites (Table 2). Cinnamaldehyde, for example, had its mechanism of action against *Caenorhabditis elegans* – a free-living nematode used as a model organism – based on an interference of several genes that regulate the expression of glutathione, inhibiting the metabolism of xenobiotics, and leading to death of the organism (Lu *et al*., 2020).

Table 1. Effects of essential oils and isolated compounds on bacteria of relevance to animal production

	Effects	Bacteria	Inhibitory concentrations	Bactericidal concentrations	References
Compounds isolated from essential oils					
Carvacrol	Damage to the cell membrane, inhibition of cellular respiration, and synergism with nisin	*Listeria monocytogenes*	250 μg mL^{-1}	500 μg ml^{-1}	Churklam *et al.* (2020)
Cinnamaldehyde	Disintegration and separation of cell wall and membrane	*Escherichia coli* and *Staphylococcus aureus*	0.31 mg ml^{-1}	ND	Shen *et al.* (2015)
Eugenol	Damage to the cell membrane and synergism with antibiotics	*E. coli*, *Pseudomonas aeruginosa* and *Salmonella* Typhimurium	10 mM	ND	Hemaiswarya and Doble (2009)
Allyl isothiocyanate	Damage to the cell membrane (a similar mechanism to polymyxin B)	*E. coli*, *S.* Typhimurium and *L. monocytogenes*	1 μg ml^{-1}	ND	Lin *et al.* (2000)
	Morphological changes and cell cycle arrest (resulting in filamentation)	*E. coli*, *Salmonella enterica*, *P. aeruginosa* and *S. aureus*	100 μg ml^{-1} (EC) 100 μg ml^{-1} (SE) 12.5 μg ml^{-1} (PA) 100 μg ml^{-1} (SA)	200 μg ml^{-1} (EC) 200 μg ml^{-1} (SE) 25 μg ml^{-1} (PA) 800 μg ml^{-1} (SA)	Clemente *et al.* (2016)
Linalool	Damage to the cell membrane and inhibition of cellular respiration	*P. aeruginosa*	431 μg ml^{-1}	862 μg ml^{-1}	Liu *et al.* (2020)
Thymol	Damage to the cell membrane, DNA damage by intercalation, reduced motility, and antibiofilm effect	*P. aeruginosa*	0.125 mg ml^{-1}	0.25 mg ml^{-1}	Liu *et al.* (2021)
Essential oils					
Cinnamon zeylanicum	Morphological changes and self-aggregation	*E. coli*, *S. enterica*, *P. aeruginosa* and *S. aureus*	200 μg ml^{-1} (EC) 200 μg ml^{-1} (SE) 400 μg ml^{-1} (PA) 200 μg ml^{-1} (SA)	400 μg ml^{-1} (EC) 400 μg ml^{-1} (SE) 400 μg ml^{-1} (PA) 800 μg ml^{-1} (SA)	Clemente *et al.* (2016)
Cymbopogon citratus	Damage to the cell membrane	*E. coli*	0.288 mg ml^{-1}	ND	Tyagi and Malik (2012)
Dodartia orientalis	Damage to the cell membrane and reduced adhesion	*S. aureus*, *E. coli* and *Salmonella* Enteritidis	0.5 μl ml^{-1} (SA) 1 μl ml^{-1} (EC) 2 μl ml^{-1} (SE)	1 μl ml^{-1} (SA) 2 μl ml^{-1} (EC) 4 μl ml^{-1} (SE)	Wang *et al.* (2017)
Lippia multiflora	Damage to the cell membrane	*S. aureus* and *S. enterica*	1.2 mg ml^{-1} (SA) 4.2 mg ml^{-1} (SE)	ND	Bassolé *et al.* (2010)
Litsea cubeba	Damage to the cell membrane, reduced ATPase activity, inhibition of β-galactosidase activity, inhibition of the hexose monophosphate pathway by decreasing the glucose-6-phosphate dehydrogenase enzyme, and structural change in DNA	Methicillin-resistant *S. aureus* (MRSA)	0.5 mg ml^{-1}	1 mg ml^{-1}	Hu *et al.* (2019)
Origanum compactum	Damage to and increase in cell membrane permeability and anti-biofilm effect	*E. coli*	0.62 mg ml^{-1}	0.62 mg ml^{-1}	Bouyahya *et al.* (2019)
Origanum vulgare	Damage to the cell membrane, metabolism inhibition by tricarboxylic acid cycle enzymes, structural alteration of DNA, and inhibition of PVL toxin gene expression	MRSA	0.4 mg ml^{-1}	0.4 mg ml^{-1}	Cui *et al.* (2019)

(*Continued*)

Table 1. (*Continued.*)

	Effects	Bacteria	Inhibitory concentrations	Bactericidal concentrations	References
Piper nigrum	Damage to the cell membrane	*E. coli*	1.0 $\mu l\ ml^{-1}$	2.0 $\mu l\ ml^{-1}$	Zhang *et al.* (2017a)
Syzygium aromaticum	Damage to the cell membrane and destruction of proteins or inhibition of their synthesis	*S. aureus*	0.625 $mg\ ml^{-1}$	1.25 $mg\ ml^{-1}$	Xu *et al.* (2016)
Thymus vulgaris	Damage to the cell membrane, DNA damage by intercalation, reduced motility, and antibiofilm effect	*P. aeruginosa*	0.25 $mg\ ml^{-1}$	0.5 $mg\ ml^{-1}$	Liu *et al.* (2021)
Zingiber officinale	Damage to the cell membrane, metabolism inhibition by tricarboxylic acid cycle enzymes, inhibition of DNA repair and replication mechanisms	*E. coli* and *S. aureus*	2.0 $mg\ ml^{-1}$ (EC) 1.0 $mg\ ml^{-1}$ (SA)	4.0 $mg\ ml^{-1}$ (EC) 2.0 $mg\ ml^{-1}$ (SA)	Wang *et al.* (2020)

ND, Not determined.

Many compounds were studied, but only a few had proven antiparasitic effects (Tavares-Dias, 2018), and little is known about their mechanisms of action against these pathogens. Although many studies have shown effectiveness (Camurça-Vasconcelos *et al.*, 2007; Ji *et al.*, 2012; De Aquino Mesquita *et al.*, 2013; De Moraes *et al.*, 2013; Godinho *et al.*, 2014; Qi *et al.*, 2015; Fabbri *et al.*, 2020), some compounds may exhibit an *in vitro* effect but have little or no activity *in vivo*. For example, artemisinin, derived from *Artemisia annua* (sweet wormwood) EO, was tested in rodents to evaluate its action against *H. contortus*, where it showed no beneficial effects (Squires *et al.*, 2011). Even though it does not affect this parasite, the possibility of presenting effects against other species was not excluded, requiring further *in vivo* research.

Encapsulated EO and EOC forms usually stand out over their free forms, due to greater resistance to stomach acids and increased bioaccessibility, which improves their absorption. In addition, capsules can mask adverse sensory effects, improving palatability characteristics (Lu *et al.*, 2019; Amiri *et al.*, 2020).

Most of the studies found in this literature review only present the inhibitory activity of EOs against the parasites tested. However, it is essential to improve the current knowledge of how inhibition works to enhance parasite-control techniques that use these compounds. Some of the works showed morphologic changes, such as damage to the integument (Machado *et al.*, 2011; Ullah *et al.*, 2017; Woolsey *et al.*, 2019; Dominguez-Uscanga *et al.*, 2021), reduction in the numbers of hatching of eggs (Macedo *et al.*, 2010; Katiki *et al.*, 2011; Carvalho *et al.*, 2012; Ribeiro *et al.*, 2013; Zhu *et al.*, 2013a, 2013b; Oliveira *et al.*, 2014; Gaínza *et al.*, 2015; Qi *et al.*, 2015), inhibition or reduction of motility (Singh *et al.*, 2009; Zhu *et al.*, 2013a, 2013b; Ullah *et al.*, 2017), and changes in the genetic material and inhibition of metabolic pathways (Machado *et al.*, 2011; Ullah *et al.*, 2017; Dominguez-Uscanga *et al.*, 2021; Khamesipour *et al.*, 2021), but there is a lack of research that addresses *in vivo* tests and different application techniques for the use of these compounds, which are needed before they become feasible techniques for animal management.

The development of EO resistance is improbable, due to the multifactorial nature of their mechanisms caused by this diversity in substances. This is an advantage in opposition to EOCs which are more susceptible to the development of resistance and have a higher cost of production and purification. On the other hand, EOCs usually require lower concentrations for bacterial inhibition in comparison to EOs, which reduces sensory alterations in animal feed or drinking water and improves palatability (Janz *et al.*, 2007; Franz *et al.*, 2010). When animals are treated with either EOs or EOCs, they must be closely monitored during the initial administration to assess the efficacy of these treatments and to promote a healthy transition from conventional drugs.

Zootechnical benefits of EOs and EOCs

The beneficial effects of EOs and EOCs, in addition to promoting the biosafety of breeding stock, are also reflected in the zootechnical indexes and may act to replace performance-enhancing additives. Moreover, Hernández-Coronado *et al.* (2019) showed improved sensory evaluation of chicken meat when EO extracted from *Poliomintha longiflora* (rosemary-mint) (400 $mg\ l^{-1}$) was used as an additive to chicken feed.

The addition of nanoencapsulated cumin EO with chitosan at a concentration of 200 $mg\ kg^{-1}$ in broiler feed resulted in better

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Table 2. Effects of essential oils and isolated compounds on parasites of relevance in animal production

	Effects	Parasite	Optimal inhibition concentration	Type of test	References
Compounds isolated from essential oils					
Carvacrol	Inhibition of muscle contractions and synergism with gamma-aminobutyric acid	*Ascaris suum*	300 µM	*In vitro*	Trailović *et al.* (2015)
	Anticoccidial	*Cryptosporidium* spp.	1 mg ml^{-1}	*In vitro*	Tanghort *et al.* (2019)
Cinnamaldehyde	Increased production of specific antibodies	*A. suum*	1000 mg kg^{-1}	*In vivo*	Williams *et al.* (2017)
	Activity against larvae, subcuticular muscle injury, and intestinal injury	*A. suum*	236 µM	*In vitro*	(Williams *et al.*, 2015)
Curcumin	Morphological changes in the tegument, reduced motility, inhibition of cathepsin L gene, reduced glutathione levels, inhibition of superoxide dismutase activity, oxidative damage by protein carbonylation, and inhibition of glutathione S-transferase	*Fasciola gigantica*	60 µM	*In vitro*	Ullah *et al.* (2017)
Eugenol	Anticoccidial	*Cryptosporidium* spp.	0.5 mg ml^{-1}	*In vitro*	Tanghort *et al.* (2019)
Thymol	Membrane damage, inhibition of lipid metabolism, interference with enzymes responsible for energy production, and free radical production	*Cryptosporidium parvum*	500 µg ml^{-1}	*In vitro*	Dominguez-Uscanga *et al.* (2021)
Thymoquinone	Morphological changes in the tegument, reduced motility, inhibition of cathepsin L gene, reduced glutathione levels, inhibition of superoxide dismutase activity, and oxidative damage by protein carbonylation	*F. gigantica*	60 µM	*In vitro*	Ullah *et al.* (2017)
Essential oils					
Allium sativum	Irreversible paralysis	*F. gigantica*	3 mg ml^{-1}	*In vitro*	Singh *et al.* (2009)
	Total trophozoite growth inhibition within 24 h	*Entamoeba histolytica*	0.4 mg ml^{-1}	*In vitro*	Behnia *et al.* (2008a, 2008b)
	Antiparasitic activity	*E. histolytica* e *Giardia lamblia*	0.2 µg ml^{-1}	*In vitro*	Azadbakht *et al.* (2019)
Arisaema spp.	Egg hatching reduction and inhibition of larval development and migration	*Haemonchus contortus*	10 mg ml^{-1}	*In vitro*	Zhu *et al.* (2013a, 2013b)
Artemisia absinthium	Reduction in the number of oocysts by 70%	*Eimeria* sp.	4 mg ml^{-1}	*In vitro*	Remmal *et al.* (2011)
Artemisia lancea	Egg hatching reduction and inhibition of larval motility and development	*H. contortus*	10 mg ml^{-1}	*In vitro*	Zhu *et al.* (2013a, 2013b)
Cichorium intybus	Growth inhibition, no cytotoxic effect	*Cryptosporidium parvum*	300 µg ml^{-1}	*In vitro*	Woolsey *et al.* (2019)
Citrus sinensis	Egg hatching reduction and possible inhibition of embryogenesis	*H. contortus*	1.56 mg ml^{-1}	*In vitro*	Gaínza *et al.* (2015)
Citrus spp.	Reduction in fecal egg count by 71% and prevalence reduction by 68%	*Ascaridia galli*	1200 mg kg^{-1}	*In vivo*	Abdelqader *et al.* (2012)
Clausena anisata	Inhibition of larval migration	*A. suum*	1 mg ml^{-1}	*In vitro*	Williams *et al.* (2016)
Cuminum cyminum	Ovicidal activity	*Fasciola hepatica*	0.016 mg ml^{-1}	*In vitro*	Silva *et al.* (2020)

(*Continued*)

Table 2. (*Continued.*)

	Effects	Parasite	Optimal inhibition concentration	Type of test	References
Curcuma longa	Activity against adult worms	*A. galli*	100 mg ml^{-1}	*In vitro*; *In vivo*	Bazh and El-Bahy (2013)
Cymbopogon schoenanthus	Egg hatching reduction, inhibition of larval development, and inhibition of larvae feeding	*H. contortus*	0.27 mg ml^{-1}	*In vitro*	Katiki *et al.* (2011)
Dracocephalum kotschyi	Activity against tachyzoites and reduction in ATP levels	*Toxoplasma gondii*	24.49 μg ml^{-1}	*In vitro*	Khamesipour *et al.* (2021)
Eucalyptus globulus	Antiparasitic activity	*E. histolytica* e *G. lamblia*	0.2 μg ml^{-1}	*In vitro*	Azadbakht *et al.* (2019)
Eucalyptus staigeriana	Egg hatching reduction and inhibition of larval development	*H. contortus*	8 mg ml^{-1} (*in vitro*) 500 mg kg^{-1} (*in vivo*)	*In vitro* *in vivo*	Ribeiro *et al.* (2013)
	Egg hatching reduction and inhibition of larval development	*H. contortus*	5.4 mg ml^{-1} (*in vitro*) 500 mg kg^{-1} (*in vivo*)	*In vitro* *In vivo*	Macedo *et al.* (2010)
Lippia sidoides	Egg hatching reduction and inhibition of larval development	*H. contortus*	0.13 mg ml^{-1}	*In vivo* *in vitro*	Carvalho *et al.* (2012)
Melaleuca alternifolia	Reduction in the number of oocysts by 70%	*Eimeria* sp.	4 mg ml^{-1}	*In vitro*	Remmal *et al.* (2011)
Melaleuca quinquenervia	Inhibition of larval development	*H. contortus*	1.56 mg ml^{-1}	*In vitro*	Gaínza *et al.* (2015)
Mentha longifolia	Activity against trophozoites	*E. histolytica* e *Giardia duodenalis*	200 μg ml^{-1}	*In vitro*	El-Badry and Al Ali (2010)
Mentha piperita	Egg hatching reduction and inhibition of larval development	*H. contortus*	0.10 mg ml^{-1}	*In vitro*	Carvalho *et al.* (2012)
	Egg hatching reduction, inhibition of larval development, and inhibition of larvae feeding	*H. contortus*	1 mg ml^{-1}	*In vitro*	Katiki *et al.* (2011)
Ocimum basilicum	Activity against trophozoites	*E. histolytica* e *G. duodenalis*	200 μg ml^{-1}	*In vitro*	El-Badry and Al Ali (2010)
Origanum Vulgare	Reduces post-infection oxidative stress and anticoccidial effect	*Eimeria* spp.	12 mg kg^{-1}	*In vivo*	Bozkurt *et al.* (2016)
	Anticoccidial	*Eimeria* sp.	300 mg kg^{-1}	*In vivo*	Alp *et al.* (2012)
	Coccidiostatic effect	*Eimeria* spp.	0.5 mg ml^{-1}	*In vivo*	Mohiti-Asli and Ghanaatparast-Rashti (2015)
Origanum compactum	Anticoccidial	*Cryptosporidium* spp.	1 mg ml^{-1}	*In vitro*	Tanghort *et al.* (2019)
Pimpinella anisum	Activity against trophozoites	*E. histolytica*	5 mg ml^{-1}	*In vitro*	Quintilde ones Gutieacute rrez *et al.* (2013)
Piper aduncum	Egg hatching reduction	*H. contortus*	12 mg ml^{-1}	*In vitro*	Oliveira *et al.* (2014)
Piper longum	Irreversible paralysis	*F. gigantica*	3 mg ml^{-1}	*In vitro*	Singh *et al.* (2009)
Syzygium aromaticum	Reduction in the number of oocysts by 70%	*Eimeria* sp.	4 mg ml^{-1}	*In vitro*	Remmal *et al.* (2011)
	Growth inhibition, morphological changes, flagellum internalization, and the presence of autophagic vacuoles	*G. lamblia*	300 μg ml^{-1}	*In vitro*	Machado *et al.* (2011)
	Anticoccidial	*Cryptosporidium* spp.	1 mg ml^{-1}	*In vitro*	Tanghort *et al.* (2019)

Thymus vulgaris	Reduction in the number of oocysts by 70%	*Eimeria* sp.	4 mg ml^{-1}	*In vitro*	Remmal *et al.* (2011)
	Total trophozoite growth inhibition within 48 h	*E. histolytica*	0.7 mg ml^{-1}	*In vitro*	Behnia *et al.* (2008a, 2008b)
Zanthoxylum simulans	Egg hatching reduction and inhibition of larval development	*H. contortus*	40 mg ml^{-1}	*In vitro*	Qi *et al.* (2015)
Zingiber officinale	Activity against adult worms	*A. galli*	100 mg ml^{-1}	*In vitro* *In vivo*	Bazh and El-Bahy (2013)

body weight gain (BWG) and feed conversion ratio when compared to flavomycin at 650 mg kg^{-1} (Amiri *et al.*, 2020). The use of *Eucalyptus globulus* (southern blue gum) EO, promoted dose-dependent effects; for instance, it was able to promote the growth of beneficial microbiota and reduce the *E. coli* population. Moreover, it caused an increase in organic matter digestibility, which can lead to an increase in the absorption of nutrients, a decreased serum cholesterol, and increased superoxide dismutase activity. All these factors improved BWG and feed conversion, while cholesterol reduction enhanced the nutritional profile of the meat produced, and antioxidant activity was enhanced by superoxide dismutase inhibiting free radicals (Mohebodini *et al.*, 2021).

When fed to Japanese quail, S. aromaticum (clove) EO, at a concentration of 1.5 ml kg^{-1}, increased growth performance indices due to observed antioxidant effects and increased levels of insulin, somatotropin (growth hormone), and thyroxine (Hussein *et al.*, 2019). In mammals, the effect of an oil blend (300 mg kg^{-1} starter) composed of *Rosmarinus officinalis* (rosemary), *Zataria multiflora* (Shirazi thyme) and *Mentha pulegium* (pennyroyal) (1:1:1) in calves showed an 11.5% body weight increase compared to the control group (Jeshari *et al.*, 2016). A thymol and cinnamaldehyde blend (0.05 g kg^{-1} feed) was evaluated in piglets, and the experiment revealed bactericidal and immunomodulatory effects, a decrease in mucosal macrophages, and a reduction in intestinal inflammation by the suppression of interleukin expression (Jiang *et al.*, 2015). Another experiment was carried out in calves using a mix (300 mg day^{-1}) of *Thymus kotschyanus* (thyme), *Lavandula angustifolia* (lavender), *Salvia officinalis* (common sage), and *Capparis spinosa* (caper bush) EOs, and showed an optimization of the animals' performance (59.1 kg control group final body weight and 62.3 kg EO group final body weight) due to the antioxidant and bactericidal effects (Asghari *et al.*, 2021).

According to the data presented, the use of EOs in the development of biotechnological alternatives to conventional treatments is largely plausible. In addition, EOs can also act as immunomodulators, detoxifiers, performance enhancers, and are highly versatile compounds (Lopes *et al.*, 2020; Evangelista *et al.*, 2021).

EO and EOC use with conventional antimicrobial and anthelmintic therapy

EOs present remarkable aromas and flavors, which can reduce their feasibility as commercial products. To circumvent this problem, EO associations with traditional medicines or other bioactive compounds can be used to reduce their recommended doses if they have an additive or synergistic effect. This combination can significantly reduce the necessary dosage of EOs, consequently mitigating changes in sensory properties (Sharma *et al.*, 2020). Although research involving the combination of EOs with conventional drugs still has unknown mechanisms of interactions, the results have shown synergisms and reductions in the appearance of antimicrobial/antiparasitic resistance (Lahmar *et al.*, 2017).

In vitro studies conducted by Ait Dra *et al.* (2017) showed a synergistic effect between gentamicin or ciprofloxacin associated with *Periploca laevigata* (*cornicabra*) EO against *S. aureus* and *E. coli*. Combination of *Foeniculum vulgare* (fennel) and antibiotics (cefoxitin, mupirocin, cotrimoxazole, or ciprofloxacin) showed synergism against *S. aureus*, with a significant increase in the inhibition zones, especially with mupirocin combination, with an increase from 30 mm to approximately 42 mm of diameter (Kwiatkowski *et al.*, 2017). Ciprofloxacin combined with *Lavandula maroccana* (lavender) EO resulted in a 4-fold MIC decrease for *E. coli*, 16-fold for *S. aureus,* and 8-fold for *Pseudomonas aeruginosa* (Soulaimani et al., 2019).

A multidrug-resistant strain of *Acinetobacter baumannii* was exposed to polymyxin B at 1 $\mu g\, ml^{-1}$ and was able to grow during the entire evaluation period (25 h) up to a maximum population of ~10 log CFU ml^{-1}. When the strain was exposed to the same concentration of Polymyxin B with 0.5 $\mu g\, ml^{-1}$ of *Eucalyptus camaldulensis* (river red gum) EO, the population reached levels below the experimental detection limit (2 log CFU ml^{-1}) in 6 h. In the same period, the treatment with Polymyxin B alone presented a population of over 7 log CFU ml^{-1} (Knezevic *et al.*, 2016).

Although EOs present antiparasitic effects, there is little information about their association with classical drugs. The only article found about this particular subject showed an association between thymol and albendazole *in vivo*; nevertheless, this combination did not obtain satisfactory results, even with *in vitro* data attesting to the potential of the combination (Miró *et al.*, 2020).

Most farmers have not adopted the use of natural alternatives in countries where classical drugs are still allowed as growth promoters. The well-known effect caused by antibiotics and antiparasitic drugs in animal production, their relatively low prices and their ease to use are still stronger arguments to the producers than the problems that they may cause to the environment and public health (Ryan, 2019). Therefore, a gradual transition from the current form of treatment to an approach that uses the association of natural compounds may educate producers and build trust that these molecules can improve zootechnical indices, enhance feed palatability, and reduce the need for conventional drugs.

Conclusion

EOs and EOCs have great potential to be used in animal production, with several benefits over conventional treatments. They have provided reductions of antimicrobial and anthelmintic resistance, a more effective treatment against resistant organisms, and when used in combination with traditional products, several compounds presented synergisms that substantially reduced the dose required to achieve the desired effect.

The application is not limited to microbiological and parasitic control, EOs and EOCs also show good results as performance-enhancers in animal production. There is still a dearth of scientific literature about animal applications complementary to *in vivo* testing, as well as further elucidation about mechanisms of action, recommended doses, synergistic effects, and supplementation vehicles to maximize their activities and thus reach their best potential.

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References

Abdelqader A, Qarallah B, Al-Ramamneh D and Daş G (2012) Anthelmintic effects of citrus peels ethanolic extracts against *Ascaridia galli*. *Veterinary Parasitology* **188**, 78–84. https://doi.org/10.1016/j.vetpar.2012.03.003.

Ait Dra L, Ait Sidi Brahim M, Boualy B, Aghraz A, Barakate M, Oubaassine S, Markouk M and Larhsini M (2017) Chemical composition, antioxidant and evidence antimicrobial synergistic effects of *Periploca laevigata* essential oil with conventional antibiotics. *Industrial Crops and Products* **109**, 746–752. https://doi.org/10.1016/j.indcrop.2017.09.028.

Akkari H, Ezzine O, Dhahri S, B'chir F, Rekik M, Hajaji S, Darghouth MA, Jamâa MLB and Gharbi M (2015) Chemical composition, insecticidal and in vitro anthelmintic activities of *Ruta chalepensis* (Rutaceae) essential oil. *Industrial Crops and Products* **74**, 745–751. https://doi.org/10.1016/j.indcrop.2015.06.008.

Alp M, Midilli M, Kocabağli N, Yilmaz H, Turan N, Gargili A and Acar N (2012) The effects of dietary oregano essential oil on live performance, carcass yield, serum immunoglobulin G level, and oocyst count in broilers. *Journal of Applied Poultry Research* **21**, 630–636. https://doi.org/10.3382/japr.2012-00551.

Ambrosio CMS, de Alencar SM, de Sousa RLM, Moreno AM and Da Gloria EM (2017) Antimicrobial activity of several essential oils on pathogenic and beneficial bacteria. *Industrial Crops and Products* **97**, 128–136. https://doi.org/10.1016/j.indcrop.2016.11.045.

Amiri N, Afsharmanesh M, Salarmoini M, Meimandipour A, Hosseini SA and Ebrahimnejad H (2020) Effects of nanoencapsulated cumin essential oil as an alternative to the antibiotic growth promoter in broiler diets. *Journal of Applied Poultry Research* **29**, 875–885. https://doi.org/10.1016/j.japr.2020.08.004.

Asghari M, Abdi-Benemar H, Maheri-Sis N, Salamatdoust-Nobar R, Salem AZM, Zamanloo M and Anele UY (2021) Effects of emulsified essential oils blend on performance, blood metabolites, oxidative status and intestinal microflora of suckling calves. *Animal Feed Science and Technology* **277**, 114954. https://doi.org/10.1016/j.anifeedsci.2021.114954

Azadbakht M, Chabra A, Akbarabadi AS, Motazedian MH, Monadi T and Akbari F (2019) Anti-parasitic activity of some medicinal plants essential oils on *Giardia lamblia* and *Entamoeba histolytica*, in vitro. *Research Journal of Pharmacognosy* **7**, 41–47. https://doi.org/10.22127/rjp.2019.168142.1462.

Bassolé IHN, Lamien-Meda A, Bayala B, Tirogo S, Franz C, Novak J, Nebié RC and Dicko MH (2010) Composition and antimicrobial activities of *Lippia multiflora* Moldenke, Mentha x piperita L. and *Ocimum basilicum* L. essential oils and their major monoterpene alcohols alone and in combination. *Molecules* **15**, 7825–7839. https://doi.org/10.3390/molecules15117825.

Bazh EKA and El-Bahy NM (2013) In vitro and in vivo screening of anthelmintic activity of ginger and curcumin on *Ascaridia galli*. *Parasitology Research* **112**, 3679–3686. https://doi.org/10.1007/s00436-013-3541-x.

Behnia M, Haghighi A, Komeilizadeh H, Seyyed Tabaei SJ and Abadi A (2008a) In vitro antiamoebic activity of Iranian *Allium sativum* in comparison with Metronidazole against *Entamoeba histolytica*. *Iranian Journal of Parasitology* **3**, 32–38.

Behnia M, Haghighi A, Komeylizadeh H, Tabaei SJS and Abadi A (2008b) Inhibitory effects of Iranian *Thymus vulgaris* extracts on in vitro growth of *Entamoeba histolytica*. *The Korean Journal of Parasitology* **46**, 153–156. https://doi.org/10.3347/kjp.2008.46.3.153.

Bischoff KM, Wicklow DT, Jordan DB, De Rezende ST, Liu S, Hughes SR and Rich JO (2009) Extracellular hemicellulolytic enzymes from the maize endophyte acremonium zeae. *Current Microbiology* **58**, 499–503. https://doi.org/10.1007/s00284-008-9353-z.

Bouyahya A, Abrini J, Dakka N and Bakri Y (2019) Essential oils of *Origanum compactum* increase membrane permeability, disturb cell membrane integrity, and suppress quorum-sensing phenotype in bacteria. *Journal of Pharmaceutical Analysis* **9**, 301–311. https://doi.org/10.1016/j.jpha.2019.03.001.

Bozkurt M, Ege G, Aysul N, Akşit H, Tüzün AE, Küçükyllmaz K, Borum AE, Uygun M, Akşit D, Aypak S, Simşek E, Seyrek K, Koçer B, Bintaş E and Orojpour A (2016) Effect of anticoccidial monensin with oregano essential oil on broilers experimentally challenged with mixed Eimeria spp. *Poultry Science* **95**, 1858–1868. https://doi.org/10.3382/ps/pew077.

Camurça-Vasconcelos ALF, Bevilaqua CML, Morais SM, Maciel MV, Costa CTC, Macedo ITF, Oliveira LMB, Braga RR, Silva RA and Vieira LS (2007) Anthelmintic activity of *Croton zehntneri* and *Lippia sidoides* essential oils. *Veterinary Parasitology* **148**, 288–294. https://doi.org/10.1016/j.vetpar.2007.06.012.

Carvalho CO, Chagas ACS, Cotinguiba F, Furlan M, Brito LG, Chaves FCM, Stephan MP, Bizzo HR and Amarante AFT (2012) The anthelmintic effect of plant extracts on *Haemonchus contortus* and *Strongyloides venezuelensis*. *Veterinary Parasitology* **183**, 260–268. https://doi.org/10.1016/j.vetpar.2011.07.051.

Ceballos L, Canton C, Pruzzo C, Sanabria R, Moreno L, Sanchis J, Suarez G, Ortiz P, Fairweather I, Lanusse C, Alvarez L and Valladares MM (2019) The egg hatch test: a useful tool for albendazole resistance diagnosis in *Fasciola hepatica*. *Veterinary Parasitology* **271**, 7–13. https://doi.org/10.1016/j.vetpar.2019.06.001.

Charlier J, Rinaldi L, Musella V, Ploeger HW, Chartier C, Vineer HR, Hinney B, von Samson-Himmelstjerna G, Băcescu B, Mickiewicz M, Mateus TL, Martinez-Valladares M, Quealy S, Azaizeh H, Sekovska B, Akkari H, Petkevicius S, Hektoen L, Höglund J, Morgan ER, Bartley DJ and Claerebout E (2020) Initial assessment of the economic burden of major parasitic helminth infections to the ruminant livestock industry in Europe. *Preventive Veterinary Medicine* **182**, 105103. https://doi.org/10.1016/j.prevetmed.2020.105103.

Churklam W, Chaturongakul S, Ngamwongsatit B and Aunpad R (2020) The mechanisms of action of carvacrol and its synergism with nisin against *Listeria monocytogenes* on sliced bologna sausage. *Food Control* **108**, 106864. https://doi.org/10.1016/j.foodcont.2019.106864.

Claerebout E, De Wilde N, Van Mael E, Casaert S, Velde FV, Roeber F, Veloz PV, Levecke B and Geldhof P (2020) Anthelmintic resistance and common worm control practices in sheep farms in Flanders, Belgium. *Veterinary Parasitology: Regional Studies and Reports* **20**, 100393. https://doi.org/10.1016/j.vprsr.2020.100393.

Clemente I, Aznar M, Silva F and Nerín C (2016) Antimicrobial properties and mode of action of mustard and cinnamon essential oils and their combination against foodborne bacteria. *Innovative Food Science and Emerging Technologies* **36**, 26–33. https://doi.org/10.1016/j.ifset.2016.05.013.

Corrêa JAF, Evangelista AG, de Nazareth TM and Luciano FB (2019) Fundamentals on the molecular mechanism of action of antimicrobial peptides. *Materialia* **8**, 100494. https://doi.org/10.1016/j.mtla.2019.100494.

Cui H, Zhang C, Li C and Lin L (2019) Antibacterial mechanism of oregano essential oil. *Industrial Crops and Products* **139**, 111498. https://doi.org/10.1016/j.indcrop.2019.111498.

Dadgostar P (2019) Antimicrobial resistance: implications and costs. *Infection and Drug Resistance* **12**, 3903–3910. https://doi.org/10.2147/IDR.S234610.

De Aquino Mesquita M, E Silva Júnior JB, Panassol AM, De Oliveira EF, Vasconcelos ALCF, De Paula HCB and Bevilaqua CML (2013) Anthelmintic activity of *Eucalyptus staigeriana* encapsulated oil on sheep gastrointestinal nematodes. *Parasitology Research* **112**, 3161–3165. https://doi.org/10.1007/s00436-013-3492-2.

De Moraes J, Almeida AAC, Brito MRM, Marques THC, Lima TC, De Sousa DP, Nakano E, Mendonça RZ and Freitas RM (2013) Anthelmintic activity of the natural compound (+)-limonene epoxide against *Schistosoma mansoni*. *Planta Medica* **79**, 253–258. https://doi.org/10.1055/s-0032-1328173.

de Oliveira Ferreira F, Porto RS and Rath S (2019) Aerobic dissipation of avermectins and moxidectin in subtropical soils and dissipation of abamectin in a field study. *Ecotoxicology and Environmental Safety* **183**, 109489. https://doi.org/10.1016/j.ecoenv.2019.109489.

Dey AR, Begum N, Anisuzzaman A and Alam MZ (2020) Multiple anthelmintic resistance in gastrointestinal nematodes of small ruminants in Bangladesh. *Parasitology International* **77**, 102105. https://doi.org/10.1016/j.parint.2020.102105.

Dominguez-Uscanga A, Aycart DF, Li K, Witola WH and Andrade Laborde JE (2021) Anti-protozoal activity of thymol and a thymol ester against *Cryptosporidium parvum* in cell culture. *International Journal for Parasitology: Drugs and Drug Resistance* **15**, 126–133. https://doi.org/10.1016/j.ijpddr.2021.02.003.

Duan M, Gu J, Wang X, Li Y, Zhang R, Hu T and Zhou B (2019) Factors that affect the occurrence and distribution of antibiotic resistance genes in soils from livestock and poultry farms. *Ecotoxicology and Environmental Safety* **180**, 114–122. https://doi.org/10.1016/j.ecoenv.2019.05.005.

El-Badry, A. A. and Al Ali, K. H. (2010). Activity of Mentha Longifolia and Ocimum Basilicum against Entamoeba Histolytica and Giardia Duodenalis.

Evangelista AG, Corrêa JAF, Pinto ACSM and Luciano FB (2021) The impact of essential oils on antibiotic use in animal production regarding antimicrobial resistance–a review. *Critical Reviews in Food Science and Nutrition*, **62**, 5267–5283. https://doi.org/10.1080/10408398.2021.1883548.

Fabbri J, Maggiore MA, Pensel PE, Denegri GM and Elissondo MC (2020) In vitro efficacy study of *Cinnamomum zeylanicum* essential oil and cinnamaldehyde against the larval stage of *Echinococcus granulosus*. *Experimental Parasitology* **214**, 107904. https://doi.org/10.1016/j.exppara.2020.107904.

Franz C, Baser K and Windisch W (2010) Essential oils and aromatic plants in animal feeding - a European perspective. A review. *Flavour and Fragrance Journal* **25**, 327–340. https://doi.org/10.1002/ffj.1967.

Gaínza YA, Domingues LF, Perez OP, Rabelo MD, López ER and Chagas ACdS (2015) Anthelmintic activity in vitro of *Citrus sinensis* and *Melaleuca quinquenervia* essential oil from Cuba on *Haemonchus contortus*. *Industrial Crops and Products* **76**, 647–652. https://doi.org/10.1016/j.indcrop.2015.07.056.

Giamarellou H (2016) Epidemiology of infections caused by polymyxin-resistant pathogens. *International Journal of Antimicrobial Agents* **48**, 614–621. https://doi.org/10.1016/j.ijantimicag.2016.09.025.

Godinho LS, Aleixo De Carvalho LS, Barbosa De Castro CC, Dias MM, Pinto PDF, Crotti AEM, Pinto PLS, De Moraes J and Da Silva Filho AA (2014) Anthelmintic activity of crude extract and essential oil of *Tanacetum vulgare* (Asteraceae) against adult worms of *Schistosoma mansoni*. *Scientific World Journal* **2014**, 460342. https://doi.org/10.1155/2014/460342.

Hammer KA and Heel KA (2012) Use of multiparameter flow cytometry to determine the effects of monoterpenoids and phenylpropanoids on membrane polarity and permeability in staphylococci and enterococci. *International Journal of Antimicrobial Agents* **40**, 239–245. https://doi.org/10.1016/j.ijantimicag.2012.05.015.

Han Y, Sun Z and Chen W (2019) Antimicrobial susceptibility and antibacterial mechanism of Limonene against *Listeria monocytogenes*. *Molecules* **25**, 33. https://doi.org/10.3390/molecules25010033.

He J, Sun F, Sun D, Wang Z, Jin S, Pan Z, Xu Z, Chen X and Jiao X (2020) Multidrug resistance and prevalence of quinolone resistance genes of *Salmonella enterica* serotypes 4,[5],12:i:- in China. *International Journal of Food Microbiology* **330**, 108692. https://doi.org/10.1016/j.ijfoodmicro.2020.108692.

Hemaiswarya S and Doble M (2009) Synergistic interaction of eugenol with antibiotics against Gram negative bacteria. *Phytomedicine: International Journal of Phytotherapy and Phytopharmacology* **16**, 997–1005. https://doi.org/10.1016/j.phymed.2009.04.006.

Hernández-Coronado AC, Silva-Vázquez R, Rangel-Nava ZE, Hernández-Martínez CA, Kawas-Garza JR, Hume ME and Méndez-Zamora G (2019) Mexican oregano essential oils given in drinking water on performance, carcass traits, and meat quality of broilers. *Poultry Science* **98**, 3050–3058. https://doi.org/10.3382/ps/pez094.

Hu W, Li C, Dai J, Cui H and Lin L (2019) Antibacterial activity and mechanism of *Litsea cubeba* essential oil against methicillin-resistant *Staphylococcus aureus* (MRSA). *Industrial Crops and Products* **130**, 34–41. https://doi.org/10.1016/j.indcrop.2018.12.078.

Hussein MMA, Abd El-Hack ME, Mahgoub SA, Saadeldin IM and Swelum AA (2019) Effects of clove (*Syzygium aromaticum*) oil on quail growth, carcass traits, blood components, meat quality, and intestinal microbiota. *Poultry Science* **98**, 319–329. https://doi.org/10.3382/ps/pey348.

Janz JAM, Morel PCH, Wilkinson BHP and Purchas RW (2007) Preliminary investigation of the effects of low-level dietary inclusion of fragrant essential oils and oleoresins on pig performance and pork quality. *Meat Science* **75**, 350–355. https://doi.org/10.1016/j.meatsci.2006.06.027.

Jeshari M, Riasi A, Mahdavi AH, Khorvash M and Ahmadi F (2016) Effect of essential oils and distillation residues blends on growth performance and blood metabolites of Holstein calves weaned gradually or abruptly. *Livestock Science* **185**, 117–122. https://doi.org/10.1016/j.livsci.2015.12.011.

Ji J, Lu C, Kang Y, Wang GX and Chen P (2012) Screening of 42 medicinal plants for in vivo anthelmintic activity against *Dactylogyrus intermedius* (Monogenea) in goldfish (*Carassius auratus*). *Parasitology Research* **111**, 97–104. https://doi.org/10.1007/s00436-011-2805-6.

Jiang XR, Awati A, Agazzi A, Vitari F, Ferrari A, Bento H, Crestani M, Domeneghini C and Bontempo V (2015) Effects of a blend of essential oils and an enzyme combination on nutrient digestibility, ileum histology and expression of inflammatory mediators in weaned piglets. *Animal: An International Journal of Animal Bioscience* **9**, 417–426. https://doi.org/10.1017/S1751731114002444.

Ju J, Xie Y, Guo Y, Cheng Y, Qian H and Yao W (2019) The inhibitory effect of plant essential oils on foodborne pathogenic bacteria in food. *Critical Reviews in Food Science and Nutrition* **59**, 3281–3292. https://doi.org/10.1080/10408398.2018.1488159.

Katiki LM, Chagas ACS, Bizzo HR, Ferreira JFS and Amarante AFT (2011) Anthelmintic activity of *Cymbopogon martinii*, *Cymbopogon schoenanthus* and *Mentha piperita* essential oils evaluated in four different in vitro tests. *Veterinary Parasitology* **183**, 103–108. https://doi.org/10.1016/j.vetpar.2011.07.001.

Khaleque MA, Keya CA, Hasan KN, Hoque MM, Inatsu Y and Bari ML (2016) Use of cloves and cinnamon essential oil to inactivate *Listeria monocytogenes* in ground beef at freezing and refrigeration temperatures. *LWT – Food Science and Technology* **74**, 219–223. https://doi.org/10.1016/j.lwt.2016.07.042.

Khamesipour F, Razavi SM, Hejazi SH and Ghanadian SM (2021) In vitro and in vivo anti-toxoplasma activity of *Dracocephalum kotschyi* essential oil. *Food Science & Nutrition* **9**, 522–531. https://doi.org/10.1002/fsn3.2021.

Knezevic P, Aleksic V, Simin N, Svircev E, Petrovic A and Mimica-Dukic N (2016) Antimicrobial activity of *Eucalyptus camaldulensis* essential oils and their interactions with conventional antimicrobial agents against multi-drug resistant *Acinetobacter baumannii*. *Journal of Ethnopharmacology* **178**, 125–136. https://doi.org/10.1016/j.jep.2015.12.008.

Kwiatkowski P, Mnichowska-Polanowska M, Pruss A, Masiuk H, Dzięcioł M, Giedrys-Kalemba S and Sienkiewicz M (2017) The effect of fennel essential oil in combination with antibiotics on *Staphylococcus aureus* strains isolated from carriers. *Burns: Journal of the International Society for Burn Injuries* **43**, 1544–1551. https://doi.org/10.1016/j.burns.2017.04.014.

Lahmar A, Bedoui A, Mokdad-Bzeouich I, Dhaouifi Z, Kalboussi Z, Cheraif I, Ghedira K and Chekir-Ghedira L (2017) Reversal of resistance in bacteria underlies synergistic effect of essential oils with conventional antibiotics. *Microbial Pathogenesis* **106**, 50–59. https://doi.org/10.1016/j.micpath.2016.10.018.

Lanz R, Kuhnert P and Boerlin P (2003) Antimicrobial resistance and resistance gene determinants in clinical *Escherichia coli* from different animal species in Switzerland. *Veterinary Microbiology* **91**, 73–84. https://doi.org/10.1016/S0378-1135(02)00263-8.

Le Devendec L, Jouy E, Paboeuf F, de Boisséson C, Lucas P, Drider D and Kempf I (2018) Development of a pig infection model with colistin-resistant *Escherichia coli*. *Veterinary Microbiology* **226**, 81–88. https://doi.org/10.1016/j.vetmic.2018.10.011.

Li Y, Pei X, Zhang X, Wu L, Liu Y, Zhou H, Ma G, Chen Q, Liang H and Yang D (2019) A surveillance of microbiological contamination on raw poultry meat at retail markets in China. *Food Control* **104**, 99–104. https://doi.org/10.1016/j.foodcont.2019.04.037.

Lin C-M, Preston JF and Wei C-I (2000) Antibacterial mechanism of allyl isothiocyanate†. *Journal of Food Protection* **63**, 727–734. https://doi.org/10.4315/0362-028X-63.6.727.

Liu X, Cai J, Chen H, Zhong Q, Hou Y, Chen W and Chen W (2020) Antibacterial activity and mechanism of linalool against *Pseudomonas aeruginosa*. *Microbial Pathogenesis* **141**, 103980. https://doi.org/10.1016/j.micpath.2020.103980.

Liu T, Kang J and Liu L (2021) Thymol as a critical component of *Thymus vulgaris* L. Essential oil combats *Pseudomonas aeruginosa* by intercalating DNA and inactivating biofilm. *Lwt* **136**, 110354. https://doi.org/10.1016/j.lwt.2020.110354.

Lopes TS, Fontoura PS, Oliveira A, Rizzo FA, Silveira S and Streck AF (2020) Use of plant extracts and essential oils in the control of bovine mastitis. *Research in Veterinary Science* **131**, 186–193. https://doi.org/10.1016/j.rvsc.2020.04.025.

Lu X, Li C and Huang Q (2019) Combining in vitro digestion model with cell culture model: assessment of encapsulation and delivery of curcumin in milled starch particle stabilized pickering emulsions. *International Journal of Biological Macromolecules* **139**, 917–924. https://doi.org/10.1016/j.ijbiomac.2019.08.078.

Lu L, Shu C, Chen L, Yang Y, Ma S, Zhu K and Shi B (2020) Insecticidal activity and mechanism of cinnamaldehyde in *C. elegans*. *Fitoterapia* **146**, 104687. https://doi.org/10.1016/j.fitote.2020.104687.

Macedo ITF, Bevilaqua CML, de Oliveira LMB, Camurça-Vasconcelos ALF, Vieira LdS, Oliveira FR, Queiroz-Junior EM, Tomé AdR and Nascimento NRF (2010) Anthelmintic effect of *Eucalyptus staigeriana* essential oil against goat gastrointestinal nematodes. *Veterinary Parasitology* **173**, 93–98. https://doi.org/10.1016/j.vetpar.2010.06.004.

Machado M, Dinis AM, Salgueiro L, Custódio JBA, Cavaleiro C and Sousa MC (2011) Anti-Giardia activity of *Syzygium aromaticum* essential oil and eugenol: effects on growth, viability, adherence and ultrastructure. *Experimental Parasitology* **127**, 732–739. https://doi.org/10.1016/j.exppara.2011.01.011.

Mazzarrino G, Paparella A, Chaves-López C, Faberi A, Sergi M, Sigismondi C, Compagnone D and Serio A (2015) *Salmonella enterica* and *Listeria monocytogenes* inactivation dynamics after treatment with selected essential oils. *Food Control* **50**, 794–803. https://doi.org/10.1016/j.foodcont.2014.10.029.

Miró MV, e Silva CR, Viviani P, Luque S, Lloberas M, Costa-Júnior LM, Lanusse C, Virkel G and Lifschitz A (2020) Combination of bioactive phytochemicals and synthetic anthelmintics: in vivo and in vitro assessment of the albendazole-thymol association. *Veterinary Parasitology* **281**, 109121. https://doi.org/10.1016/j.vetpar.2020.109121

Mitić ZS, Jovanović B, Jovanović S, Mihajilov-Krstev T, Stojanović-Radić ZZ, Cvetković VJ, Mitrović TL, Marin PD, Zlatković BK and Stojanović GS (2018) Comparative study of the essential oils of four Pinus species: chemical composition, antimicrobial and insect larvicidal activity. *Industrial Crops and Products* **111**, 55–62. https://doi.org/10.1016/j.indcrop.2017.10.004.

Mohebodini H, Jazi V, Ashayerizadeh A, Toghyani M and Tellez-Isaias G (2021) Productive parameters, cecal microflora, nutrient digestibility, antioxidant status, and thigh muscle fatty acid profile in broiler chickens fed with *Eucalyptus globulus* essential oil. *Poultry Science* **100**, 100922. https://doi.org/10.1016/j.psj.2020.12.020.

Mohiti-Asli M and Ghanaatparast-Rashti M (2015) Dietary oregano essential oil alleviates experimentally induced coccidiosis in broilers. *Preventive Veterinary Medicine* **120**, 195–202. https://doi.org/10.1016/j.prevetmed.2015.03.014.

Ni Z-J, Wang X, Shen Y, Thakur K, Han J, Zhang J-G, Hu F and Wei Z-J (2021) Recent updates on the chemistry, bioactivities, mode of action, and industrial applications of plant essential oils. *Trends in Food Science and Technology* **110**, 78–89. https://doi.org/10.1016/j.tifs.2021.01.070.

Oliveira GL, Vieira TM, Nunes VF, Ruas MdO, Duarted ER, Moreira DdL, Kaplan MAC and Martins ER (2014) Chemical composition and efficacy in the egg-hatching inhibition of essential oil of piper aduncum against *Haemonchus contortus* from sheep. *Revista Brasileira de Farmacognosia* **24**, 288–292. https://doi.org/10.1016/j.bjp.2014.07.004.

Poirel L, Madec J-Y, Lupo A, Schink A-K, Kieffer N, Nordmann P and Schwarz S (2018) Antimicrobial resistance in *Escherichia coli*. *Microbiology Spectrum* **6**, 1–27. https://doi.org/10.1128/microbiolspec.ARBA-0026-2017

Qi H, Wang WX, Dai JL and Zhu L (2015) In vitro anthelmintic activity of *Zanthoxylum simulans* essential oil against *Haemonchus contortus*. *Veterinary Parasitology* **211**, 223–227. https://doi.org/10.1016/j.vetpar.2015.05.029.

Quintilde ones Gutieacute rrez, Y., Verde Star, M. J., Rivas Morales, C., Or, ay Caacute rdenas, A., Mercado Hernaacute ndez, R., Chaacute vez Montes, A. and Barroacute n Gonzaacute lez, M. P. (2013). In vitro study of antiamoebic activity of methanol extract of fruit of *Pimpinella anisum* on trophozoites of *Entamoeba histolytica* HM1-IMSS. *African Journal of Biotechnology*, **12**, 2065–2068. https://doi.org/10.5897/ajb11.3403.

Remmal A, Achahbar S, Bouddine L, Chami N and Chami F (2011) In vitro destruction of *Eimeria oocysts* by essential oils. *Veterinary Parasitology* **182**, 121–126. https://doi.org/10.1016/j.vetpar.2011.06.002.

Reyes-Jurado F, Cervantes-Rincón T, Bach H, López-Malo A and Palou E (2019) Antimicrobial activity of Mexican oregano (*Lippia berlandieri*), thyme (*Thymus vulgaris*), and mustard (*Brassica nigra*) essential oils in gaseous phase. *Industrial Crops and Products* **131**, 90–95. https://doi.org/10.1016/j.indcrop.2019.01.036.

Ribeiro WLC, Macedo ITF, dos Santos JML, de Oliveira EF, Camurça-Vasconcelos ALF, de Paula HCB and Bevilaqua CML (2013) Activity of chitosan-encapsulated *Eucalyptus staigeriana* essential oil on *Haemonchus contortus*. *Experimental Parasitology* **135**, 24–29. https://doi.org/10.1016/j.exppara.2013.05.014.

Ryan M (2019) Evaluating the economic benefits and costs of antimicrobial use in food-producing animals [WWW Document]. *OECD Food, Agriculture and Fisheries Papers* **132**, 1–40. https://doi.org/10.1787/f859f644-en

Sharma K, Guleria S, Razdan VK and Babu V (2020) Synergistic antioxidant and antimicrobial activities of essential oils of some selected medicinal plants in combination and with synthetic compounds. *Industrial Crops and Products* **154**, 112569. https://doi.org/10.1016/j.indcrop.2020.112569.

Shen S, Zhang T, Yuan Y, Lin S, Xu J and Ye H (2015) Effects of cinnamaldehyde on *Escherichia coli* and *Staphylococcus aureus* membrane. *Food Control* **47**, 196–202. https://doi.org/10.1016/j.foodcont.2014.07.003.

Shen Y, Ni Z-J, Thakur K, Zhang J-G, Hu F and Wei Z-J (2021) Preparation and characterization of clove essential oil loaded nanoemulsion and pickering emulsion activated pullulan-gelatin based edible film. *International Journal of Biological Macromolecules* **181**, 528–539. https://doi.org/10.1016/j.ijbiomac.2021.03.133.

Silva CdS, de Figueiredo HM, Stamford TLM and da Silva LHM (2019) Inhibition of *Listeria monocytogenes* by *Melaleuca alternifolia* (tea tree) essential oil in ground beef. *International Journal of Food Microbiology* **293**, 79–86. https://doi.org/10.1016/j.ijfoodmicro.2019.01.004.

Silva MAMP, Zehetmeyr FK, Pereira KM, Pacheco BS, Freitag RA, Pinto NB, Machado RH, Villarreal Villarreal JP, de Oliveira Hubner S, Aires Berne ME and da Silva Nascente P (2020) Ovicidal in vitro activity of the fixed oil of *Helianthus annus* L. and the essential oil of *Cuminum cyminum* L. against *Fasciola hepatica* (Linnaeus, 1758). *Experimental Parasitology* **218**, 107984. https://doi.org/10.1016/j.exppara.2020.107984.

Singh TU, Kumar D, Tandan SK and Mishra SK (2009) Inhibitory effect of essential oils of *Allium sativum* and *Piper longum* on spontaneous muscular activity of liver fluke, *Fasciola gigantica*. *Experimental Parasitology* **123**, 302–308. https://doi.org/10.1016/j.exppara.2009.08.002.

Soulaimani B, Nafis A, Kasrati A, Rochdi A, Mezrioui NE, Abbad A and Hassani L (2019) Chemical composition, antimicrobial activity and synergistic potential of essential oil from endemic *Lavandula maroccana* (Mill.). *South African Journal of Botany* **125**, 202–206. https://doi.org/10.1016/j.sajb.2019.07.030.

Squires JM, Foster JG, Lindsay DS, Caudell DL and Zajac AM (2010) Efficacy of an orange oil emulsion as an anthelmintic against *Haemonchus contortus* in gerbils (*Meriones unguiculatus*) and in sheep. *Veterinary Parasitology* **172**, 95–99. https://doi.org/10.1016/j.vetpar.2010.04.017.

Squires JM, Ferreira JFS, Lindsay DS and Zajac AM (2011) Effects of artemisinin and Artemisia extracts on *Haemonchus contortus* in gerbils (*Meriones unguiculatus*). *Veterinary Parasitology* **175**, 103–108. https://doi.org/10.1016/j.vetpar.2010.09.011.

Tanghort M, Chefchaou H, Mzabi A, Moussa H, Chami N, Chami F and Remmal A (2019) Oocysticidal effect of sssential oils (EOs) and their major components on *Cryptosporidium baileyi* and *Cryptosporidium galli*. *International Journal of Poultry Science* **18**, 475–482. https://doi.org/10.3923/ijps.2019.475.482.

Tavares-Dias M (2018) Current knowledge on use of essential oils as alternative treatment against fish parasites. *Aquatic Living Resources* **31**, 13. https://doi.org/10.1051/alr/2018001.

Trailović SM, Marjanović DS, Nedeljković Trailović J, Robertson AP and Martin RJ (2015) Interaction of carvacrol with the *Ascaris suum* nicotinic acetylcholine receptors and gamma-aminobutyric acid receptors, potential mechanism of antinematodal action. *Parasitology Research* **114**, 3059–3068. https://doi.org/10.1007/s00436-015-4508-x.

Tyagi AK and Malik A (2012) Bactericidal action of lemon grass oil vapors and negative air ions. *Innovative Food Science and Emerging Technologies* **13**, 169–177. https://doi.org/10.1016/j.ifset.2011.09.007.

Ullah R, Rehman A, Zafeer MF, Rehman L, Khan YA, Khan MAH, Khan SN, Khan AU and Abidi SMA (2017) Anthelmintic potential of thymoquinone and curcumin on *Fasciola gigantic*. *PLoS One* **12**, e0171267. https://doi.org/10.1371/journal.pone.0171267.

Wang F, Wei F, Song C, Jiang B, Tian S, Yi J, Yu C, Song Z, Sun L, Bao Y, Wu Y, Huang Y and Li Y (2017) *Dodartia orientalis* L. essential oil exerts antibacterial activity by mechanisms of disrupting cell structure and resisting biofilm. *Industrial Crops and Products* **109**, 358–366. https://doi.org/10.1016/j.indcrop.2017.08.058.

Wang X, Shen Y, Thakur K, Han J, Zhang J-G, Hu F and Wei Z-J (2020) Antibacterial activity and mechanism of ginger essential oil against *Escherichia coli* and *Staphylococcus aureus*. *Molecules* **25**, 3955. https://doi.org/10.3390/molecules25173955.

Williams AR, Ramsay A, Hansen TVA, Ropiak HM, Mejer H, Nejsum P, Mueller-Harvey I and Thamsborg SM (2015) Anthelmintic activity of trans-cinnamaldehyde and A-and B-type proanthocyanidins derived from cinnamon (*Cinnamomum verum*). *Scientific Reports* **5**, 14791. https://doi.org/10.1038/srep14791.

Williams AR, Soelberg J and Jäger AK (2016) Anthelmintic properties of traditional African and Caribbean medicinal plants: identification of extracts with potent activity against *Ascaris suum* in vitro. *Parasite* **23**, 24. https://doi.org/10.1051/parasite/2016024.

Williams AR, Hansen TVA, Krych L, Ahmad HFB, Nielsen DS, Skovgaard K and Thamsborg SM (2017) Dietary cinnamaldehyde enhances acquisition of specific antibodies following helminth infection in pigs. *Veterinary Immunology and Immunopathology* **189**, 43–52. https://doi.org/10.1016/j.vetimm.2017.06.004.

Woolsey ID, Valente AH, Williams AR, Thamsborg SM, Simonsen HT and Enemark HL (2019) Anti-protozoal activity of extracts from chicory (*Cichorium intybus*) against *Cryptosporidium parvum* in cell culture. *Scientific Reports* **9**, 20414. https://doi.org/10.1038/s41598-019-56619-0.

Xu J-G, Liu T, Hu Q-P and Cao X-M (2016) Chemical composition, antibacterial properties and mechanism of action of essential oil from clove buds against *Staphylococcus aureus*. *Molecules* **21**, 1194. https://doi.org/10.3390/molecules21091194.

Yazgan H, Ozogul Y and Kuley E (2019) Antimicrobial influence of nanoemulsified lemon essential oil and pure lemon essential oil on food-borne pathogens and fish spoilage bacteria. *International Journal of Food Microbiology* **306**, 108266. https://doi.org/10.1016/j.ijfoodmicro.2019.108266.

Zhang J, Ye K-P, Zhang X, Pan D-D, Sun Y-Y and Cao J-X (2017a) Antibacterial activity and mechanism of action of black pepper essential oil on meat-borne *Escherichia coli*. *Frontiers in Microbiology* **7**, 2094. https://doi.org/10.3389/fmicb.2016.02094.

Zhang P, Shen Z, Zhang C, Song L, Wang B, Shang J, Yue X, Qu Z, Li X, Wu L, Zheng Y, Aditya A, Wang Y, Xu S and Wu C (2017b) Surveillance of antimicrobial resistance among *Escherichia coli* from chicken and swine, China, 2008–2015. *Veterinary Microbiology* **203**, 49–55. https://doi.org/10.1016/j.vetmic.2017.02.008.

Zhang S, Abbas M, Rehman MU, Huang Y, Zhou R, Gong S, Yang H, Chen S, Wang M and Cheng A (2020) Dissemination of antibiotic resistance genes (ARGs) via integrons in *Escherichia coli*: a risk to human health. *Environmental Pollution* **266**, 115260. https://doi.org/10.1016/j.envpol.2020.115260.

Zhang Y-P, Wang X, Shen Y, Thakur K, Zhang J-G, Hu F and Wei Z-J (2021) Preparation and characterization of bio-nanocomposites film of chitosan and montmorillonite incorporated with ginger essential oil and its application in chilled beef preservation. *Antibiotics* **10**, 796. https://doi.org/10.3390/antibiotics10070796.

Zhu L, Dai J, Yang L and Qiu J (2013a) Anthelmintic activity of *Arisaema franchetianum* and *Arisaema lobatum* essential oils against *Haemonchus contortus*. *Journal of Ethnopharmacology* **148**, 311–316. https://doi.org/10.1016/j.jep.2013.04.034.

Zhu L, Dai JL, Yang L and Qiu J (2013b) In vitro ovicidal and larvicidal activity of the essential oil of *Artemisia lancea* against *Haemonchus contortus* (Strongylida). *Veterinary Parasitology* **195**, 112–117. https://doi.org/10.1016/j.vetpar.2012.12.050.