The Perspective of Using Essential Oils in Swine: review

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Abstract
In animal husbandry, the improper and excessive use of antibiotics has contributed to the emergence of bacterial strains resistant to their action. Over the past decades, the search for alternative strategies to antibiotics has received increasing attention. The antimicrobial properties of essential oils have made them viable alternatives in livestock production. Numerous researchers have investigated these natural compounds as potential substitutes for conventional antibiotics or as preventive measures against diseases in farm animals, including swine. However, in this species, research outcomes regarding the use of essential oils in both in vitro and in vivo (on-farm) conditions have been inconsistent. This variability is primarily due to differences in oil composition, purity, dosage, growth phases, and husbandry conditions. Some authors suggest that essential oils such as oregano, thyme, clove, or mint can improve the overall health status of pigs through their anti-inflammatory and antimicrobial properties. Other studies have highlighted their beneficial effects on gut microbiota balance, notably by inhibiting pathogenic bacteria and promoting beneficial microbial populations. Positive impacts on zootechnical performance have also been reported, including improved feed conversion efficiency and average daily gain. Additionally, certain studies point to a significant role in reducing oxidative stress and enhancing immune responses. The volatile and lipophilic nature of essential oils presents a challenge in ensuring their effective delivery to the pig intestine; however, this issue may be partially addressed through microencapsulation and nanotechnology. This review aims to assess how essential oils are currently used in swine feeding strategies and/or treatment protocols, focusing on their mechanisms of action as demonstrated by existing research.

Keywords: essential oils, swine, chemical composition, biological effects, nutrition, action on pathogenic microorganisms.

1. Introduction

Recent research has highlighted that adequate nutrition is an essential factor in ensuring and maintaining a strong immune status and in increasing resistance to infections [1]. However, achieving an optimal nutritional balance solely through diet can be challenging [2]. In recent years, essential oils (EOs) and plant extracts have attracted the attention of researchers due to their therapeutic value and potential as sources of natural antioxidants and bioactive compounds, such as antibacterial, antifungal, and insecticidal agents [3,4].

The improper use, misuse, and overuse of antibiotics in livestock production have led to the development of antimicrobial resistance, a phenomenon considered a major threat both to public health and to food safety [5,6]. In light of this issue, the scientific community has begun to investigate alternatives to antibiotics to reduce the risk of resistance emergence and to support safe and sustainable pork production [7]).

The use of antibiotic growth promoters in animal production has been banned in the European Union since 2006 [8]. Nevertheless, the withdrawal of antibiotics from feed poses numerous challenges [9].

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Essential oils have proven to be among the most promising alternatives due to their antimicrobial, antioxidant, and anti-inflammatory properties demonstrated in studies since 2004 [10,11], as well as their immunomodulatory effects [12,13]. Essential oils are natural bioactive compounds derived from whole plants or from known taxonomic sections of plants [14,15], and they exert beneficial effects on animal growth and health [16]. They contain a variety of active compounds, including phenols, terpenes, and aldehydes, all known for their positive effects in combating pathogens [17].

Studies have shown the capacity of essential oils to improve growth performance in pigs, to modulate gut microbiota, and to support the immune system [14,18]. The antimicrobial effects of oregano, thyme, and cinnamon essential oils have been investigated against pathogens commonly found in swine farms, such as Escherichia coli and Salmonella spp. [19]. Essential oils contribute to pathogen control, improvement of overall animal health, and reduction of inflammation and oxidative stress [20,21]. Better nutrient absorption and more efficient growth can be achieved through these essential oil compounds, which have positive effects on metabolism and digestion [22].

It is important to note that the use of essential oils in animal nutrition has ecological advantages, as they are natural compounds and exert a lower environmental impact compared to synthetic antibiotics [23]. This characteristic makes them an attractive option for organic and sustainable agricultural production.

Due to their plant origin and the diversity of extraction methods, the chemical composition of essential oils shows significant variability. As early as 2008, the need for standardization to obtain reproducible results was emphasized [11].

In swine production, the use of essential oils as an alternative to antibiotics represents a promising and highly relevant research field. It is crucial to investigate the specific effects of individual oil compounds in order to facilitate their application in pig production.

2. Materials and methods

This review was conducted based on a systematic analysis of the scientific literature available in established international databases such as PubMed, Scopus, and ScienceDirect. The search strategy targeted publications from 2000 to 2025, using combinations of keywords such as “essential oils,” “pigs,” “antimicrobial,” “growth performance,” and “gut microbiota.” Only peer-reviewed articles providing clear experimental data, either through in vitro studies or in vivo trials on swine, were included.

Exclusion criteria eliminated studies with insufficiently described methodology, those not directly addressing the application of essential oils in pigs, or narrative articles lacking experimental support. The selection process was carried out in two stages:

-evaluation of titles and abstracts for relevance;

-full-text analysis of the studies deemed eligible.

The selected articles were compared and interpreted according to several criteria: chemical composition of essential oils, documented biological effects (antimicrobial, antioxidant, immunomodulatory), delivery systems employed (including microencapsulated forms or combinations with other additives), and their impact on pig health, nutritional status, and productivity.

This approach allowed the identification of general trends as well as potential discrepancies between studies, providing an integrated overview of the potential of essential oils as an alternative to conventional antimicrobial feed additives in swine production.

3. Results and discussion

3.1 Composition of Essential Oils (EOs)

The most commonly used method for the commercial production of essential oils is steam distillation. Extraction with liquid carbon dioxide at low temperature and high pressure yields a more natural organoleptic profile but is significantly more expensive [24].

It is well known that EOs are volatile, which is why they must be stored in dark, airtight containers to prevent compositional changes. Numerous studies have reported data on the composition of different essential oils, with the main components of economic interest described by Bauer et al. [25]. EOs may contain more than 16 individual constituents in their structure [26,27].

Table 1 presents essential oils used in swine, their main compounds, biological effects, and bibliographic references.

Table 1. Proportion of constituents and effects of various essential oils used in swine

No.	Essential oil	Main compounds	Effects
1	Thyme	- Thymol: 0.2 – 55.8%, depending on thyme species [29–33] - Carvacrol: 0.3 – 81.2%, depending on thyme species [29–33]. - Linalool: 0 – 63%, depending on thyme species [29–33]. - γ-Terpinene: 0.5 – 33.4%, depending on thyme species [29–33]. - p-Cymene: 0.2 – 20.6%, depending on thyme species [29–33].	Antiseptic, antibacterial, antifungal, anthelmintic, antiviral, antioxidant, expectorant, antispasmodic, carminative, diaphoretic, sedative, antirheumatic, and even anticancer, antihyperlipidemic, and anti-glycaemic activities [34–36].
2	Oregano	- α-Pinene: 40 – 67.5%, depending on the origin of oregano plants [37]. - β-Caryophyllene: 1.3 – 45%, depending on the origin of oregano plants [37–39]. - Terpinen-4-ol: 1.5 – ≤39.5%, depending on the origin of oregano plants [39–41]. - γ-Terpinene: 7.1 – 22.9%, depending on the origin of oregano plants [40,42,43]. - o-Cymene: 8.9% [40]. - cis-β-Terpineol: 8.7% [40]. - Carvacrol: 6.4 – 80%, depending on the origin of oregano plants [39,42,44,45]. - Thymol: 0.2 – 69%, depending on the origin of oregano plants [39,41,44,45]. - Linalool: 0.3 – 20.6%, depending on the origin of oregano plants [38,39].	Antimicrobial, antioxidant, antitumoral, antifungal, anti-inflammatory, and anticancer properties [36,46–52].
3	Cinnamon	- α-Pinene: 1.12 – 3.34%, depending on the origin of cinnamon bark [53,54]. - β-Caryophyllene: 8% in cinnamon bark [53]. - Cinnamaldehyde: 45.13 – 91.82%, depending on the origin of cinnamon bark [53–55]. - Linalool: 3.70% in cinnamon bark [53]. - Eugenol: 4.15 – 9.317%, depending on the origin of cinnamon bark [53,54,56,57].	Antimicrobial [58], antifungal [59], insecticidal [60], anticancer, antidiabetic, and cardioprotective effects [61].
4	Clove	- Eugenol: 65.36 – 83.4%, depending on extraction method and origin of clove oil [62–64]. - β-Caryophyllene: 0.91 – 24.8%, depending on extraction method and origin of clove oil [62–64]. - Eugenyl acetate: 2.7 – 15.6%, depending on extraction method and origin of clove oil [62–64]. - α-Humulene: 0.01 – 3.1%, depending on extraction method and origin of clove oil [62–64].	Analgesic [65,66], anaesthetic [65,67–69], anticancer [70–74], anticoagulant [75], anti-inflammatory [76–78].
5	Mint	- Menthol: 0.12 – 38.45%, depending on the type of mint oil [79]. - Menthone: 1.21 – 21.8%, depending on the type of mint oil [79]. - 1,8-Cineole: 1.32 – 5.62%, depending on the type of mint oil [79]. - Thymol: 0.1% [79]. - Limonene: 1.58 – 12.99%, depending on the type of mint oil [79]. - Linalool: 0.07 – 0.37%, depending on the type of mint oil [79]. - Eugenol: 0.05 – 0.13%, depending on the type of mint oil [79]. - Sabinene: 0.43 – 0.48%, depending on the type of mint oil [79].	Anti-inflammatory [80–83], antibacterial [84–87], antiviral [88,89], immunomodulatory [90,91], antitumoral [92,93], neuroprotective [94–96], antioxidant [97].

The constituents of essential oils exhibit wide variability, mainly including monoterpenes, sesquiterpenes, benzenoids, and phenylpropanoids. For example, in species belonging to the *Amaranthaceae* family, the major compounds identified are α-terpinene, δ-3-carene,

limonene, thymol, carvacrol, γ-terpinene, α-terpinolene, piperitone oxide, geraniol, α-pinene, iso-β-sclarene, iso-β-myrcene, α-ocimene, β-ocimene, citronellyl acetate, β-phellandrene, dihydroascaridole, trans-pinocarveol, carvone, piperitone, p-cymene, 4-carene, δ-3-carene, fenchone, linalool, menthone, nerol, β-pinane, terpineol, pulegone, β-pinane iso-ascaridole [28].
In addition to the essential oils listed in Table 1, there are other essential oils used in swine production technologies.

3.2 Mechanisms of Action of Essential Oils

Essential oils (EOs) exert a wide range of physiological and biological effects on swine, with diverse mechanisms of action supported by the scientific literature. These include antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory activities, as well as the ability to stimulate enzymatic secretion and modulate the gut microbiota.
Essential oils display broad-spectrum antimicrobial activity, acting against both Gram-positive and Gram-negative bacteria as well as fungi. Their effectiveness is closely linked to chemical composition, which is itself influenced by environmental conditions and the extraction method used [98]. Active compounds include phenols (such as carvacrol, thymol, and eugenol), terpenic alcohols (geraniol, citronellol), ketones (carvone), and terpenic aldehydes (citral). Among these, phenols have proven to be the most effective, owing to their ability to disrupt cell membrane integrity and destabilize the transmembrane potential [99].
Carvacrol represents a remarkable example of an active compound, exerting antimicrobial effects against Bacillus cereus by disturbing the membrane potential and depleting intracellular ATP reserves. It modifies membrane permeability to hydrogen (H^+) and potassium (K^+) ions, leading to fatal cellular imbalances. The mechanism of this terpenoid, found in oregano and thyme oils, is particularly effective against Gram-negative bacteria. Its antimicrobial activity depends on the presence of a hydroxyl group essential for proton transport and a delocalized electron system, both of which are required for membrane destabilization. Structural analogues lacking these features do not exhibit comparable antimicrobial efficiency.
In the case of Melaleuca alternifolia essential oil (tea tree oil), its mode of action is more subtle, indirectly affecting the bacterial membrane. Its activity induces the release of autolytic enzymes and leakage of genetic material (nucleic acids), indicating progressive destabilization of the cell, in contrast to the rapid and destructive lytic effect observed with other essential oils.
The antibacterial effect of essential oils was demonstrated in a Lithuanian study using “Genex Pig,” a feed additive composed of EU-regulated ingredients, including fatty acids, ammonium salts, essential oils, and plant extracts. Throughout the study, no health or developmental problems were observed in the animals. In addition to the antimicrobial effect, the additive was associated with improved growth performance, reducing the fattening period by 14.5 days (equivalent to 64.4 g/day, or 7%). This led to a 4.8% reduction in feed costs in the test group (including the cost of “Genex Pig”) compared to the control group. Furthermore, its use had no negative influence on meat quality parameters such as pH value, colour, dry matter, crude protein, or intramuscular fat [100].
Similarly, Rosmarinus officinalis essential oil may exert an antioxidant effect with a potential activity 124 times greater compared with pure pork fat. The activity and site of action of antioxidants depend on their polarity and solubility. Within feed, they may act not only as preservatives during storage but also as protectants against oxidation in final products such as milk and meat [100].

4. Conclusions

Essential oils are increasingly emerging as a viable alternative to traditionally used antibiotics in swine production, with significant potential to support animal health and productivity through multiple mechanisms of action. Their antimicrobial properties contribute to reducing pathogenic bacterial load and balancing the gut microbiota, while their antioxidant and immunomodulatory effects help maintain tissue integrity and enhance immune responses. The integration of these natural compounds into pig diets has been associated with improved feed conversion efficiency, better growth rates, and greater resilience to environmental stress and infections.
At the same time, the use of essential oils addresses current demands of the livestock industry and consumers, which focus on reducing antibiotic use, limiting the emergence of antimicrobial resistance,

and promoting sustainable and environmentally safe production practices. However, their large-scale application is hindered by several limitations. These include considerable variability in chemical composition depending on species, geographical origin, and extraction method, as well as physiological response differences between groups or individuals. The absence of standardized protocols for dosage, administration, and delivery makes direct comparison of results across studies difficult.

In this context, future research directions should focus on:

- gaining a deeper understanding of the mechanisms of action at microbiological, molecular, and physiological levels;
- standardizing extracts and commercial formulations to ensure reproducibility of observed effects;
- optimizing delivery technologies through modern methods such as microencapsulation, nanocarriers, or combinations with other functional additives to enhance stability, bioavailability, and efficacy under real farm conditions;
- evaluating economic and ecological impacts to determine the long-term feasibility and industrial-scale applicability.

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