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MECHANISMS OF ACTION OF ESSENTIAL OILS IN PIGS AND THEIR IMPACT ON PORK QUALITY

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The growing demand for high-quality pork and consumers' preference for natural additives has sparked interest in using plant essential oils (EOs) as an alternative to synthetic preservatives, antibiotics and antioxidants in pig farming. This review summarises the current knowledge on the chemical composition, biological properties and mechanisms of action of EOs, and highlights their effects on gut microbiota, nutrient absorption, oxidative status, immune function and meat quality. Comparative studies suggest that EOs can match or complement conventional feed additives, enhancing growth performance, carcass characteristics and shelf life while providing additional advantages such as antimicrobial and antioxidant properties. EO efficacy depends on factors including plant source, purity, dosage, supplementation duration, pig genotype, age, diet composition, and potential interactions with other additives. Limitations include variability in EO composition, palatability issues at high inclusion levels, and potential toxicity. Future research directions include novel delivery systems (e.g. microencapsulation and nanoemulsions), combination strategies involving probiotics, prebiotics or enzymes, and omics-based approaches to elucidate the molecular mechanisms involved. Overall, EOs represent a promising natural tool for improving pork quality and sustainability in swine production. However, standardised application protocols and safety considerations are essential for their practical implementation.

Keywords: essential oils, pigs, meat quality, antioxidants, antimicrobials, gut health, phytogenic feed additives, oxidative status, swine nutrition, shelf life

МЕХАНІЗМИ ДІЇ ЕФІРНИХ ОЛІЙ ТА ЇХ ВПЛИВ НА ЯКІСТЬ СВИНИНИ

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Зростаючий попит на високоякісну свинину, поєднаний із зростанням зацікавленості споживачів у натуральних добавках, зумовив підвищений інтерес до використання рослинних ефірних олій (ЕО) як альтернативи синтетичним консервантам, антибіотикам та антиоксидантам у свинарстві. У цьому огляді узагальнено сучасні знання про хімічний склад, біологічні властивості та механізми дії ЕО, а також детально розглянуто їхній вплив на мікробіоту кишечника, засвоєння поживних речовин, окиснювальний статус, імунну функцію та якість м'яса. Результати порівняльних досліджень свідчать, що ЕО можуть не лише замінювати, а й доповнювати традиційні кормові добавки, підвищуючи продуктивність росту, покращуючи характеристики туші та подовжуючи термін зберігання продукції. При цьому вони забезпечують додаткові переваги, зокрема антимікробні та антиоксидантні властивості. Ефективність їх застосування залежить від багатьох факторів, серед яких джерело рослинної сировини, чистота та дозування олій, тривалість згодовування, генотип і вік свиней, склад раціону, а також можливі взаємодії з іншими кормовими добавками. Водночас існують певні обмеження, зокрема мінливість складу ЕО, зниження поїдання корму при високих рівнях їх включення та потенційна токсичність. У зв'язку з цим напрями майбутніх досліджень передбачають розробку нових систем доставки (наприклад, мікроінкапсуляції та наноемульсій), застосування комбінованих стратегій із пробіотиками, пребіотиками чи ферментами, а також використання омікс-підходів для глибшого розуміння молекулярних механізмів їх дії. Отже, ЕО є перспективним природним інструментом для підвищення якості свинини та забезпечення сталості свинарської галузі. Проте для їх широкого та безпечного впровадження необхідна розробка стандартизованих протоколів застосування та чітке дотримання вимог безпеки.

Ключові слова: ефірні олії, свині, якість м'яса, антиоксиданти, антимікробні засоби, здоров'я кишечника, фітогенні кормові добавки, окиснювальний статус, годівля свиней, термін зберігання.

Introduction. The quality of pork is critical to its market value and consumer acceptance. It encompasses sensory attributes such as colour, flavour, tenderness and juiciness, as well as nutritional composition and technological properties (Rodrigues S. S. Q. et al., 2024). In recent decades, consumer demand for 'clean-label' products, stricter food safety regulations, and growing concerns about antimicrobial resistance have put increasing pressure on the livestock industry to replace synthetic growth promoters and antimicrobial agents with natural, sustainable alternatives (Zhou Y. et al., 2025). Of the natural feed additives that have been investigated, plant essential oils (EOs) have attracted a great deal of attention thanks to their wide range of bioactive properties, including antimicrobial, antioxidant, anti-inflammatory and digestive-modulatory effects (Stevanović, Z. D. et al., 2018; Nehme R. et al., 2021).

EOs are complex mixtures of volatile secondary metabolites, primarily terpenes, terpenoids, and phenylpropanoids, derived from aromatic plants (Bassolé I. H. and Juliani H. R., 2012). Their inclusion in pig diets has been studied for various purposes, such as improving growth performance (Peng X. et al., 2021), modulating gut microbiota (Ruzauskas M. et al., 2020), enhancing immune responses (Su G. et al., 2018), and reducing oxidative stress (Tan C. et al., 2015; Peng X. et al., 2021). Importantly, these biological activities can translate into measurable improvements in meat quality, such as better oxidative stability, enhanced sensory properties, and a prolonged shelf life (Omonijo F. A. et al., 2018).

The mechanisms by which EOs influence meat quality are multifactorial. These mechanisms may involve the modulation of oxidative processes in muscle tissue, the alteration of lipid composition, the reduction of microbial spoilage and the effects on post-mortem proteolysis (Ojeda-Piedra S. A. et al., 2022). However, the extent of these effects depends on various factors, such as the type and chemical composition of the EO, the dosage, the duration of supplementation and interactions with other dietary components (Ji J. et al., 2023).

This review aims to summarise and critically analyse the current knowledge regarding the impact of plant-derived essential oils on pork quality, particularly in relation to their potential as natural dietary supplements for sustainable pork production. By integrating findings from animal nutrition, meat science, and food technology, this review provides an overview of the applicability, advantages, and limitations of using EOs to improve pork quality.

Chemical Composition and Biological Properties of Essential Oils

EOs are complex mixtures of volatile, aromatic, and bioactive secondary metabolites that give plants their characteristic aroma and flavour. Since ancient times, herbs and their EOs have been used to mask odours, enhance the sensory qualities of food, and in medicine, cosmetics, and perfumery (Bolouri P. et al., 2022). Due to their antioxidant, antimicrobial, and anti-inflammatory properties, EOs are widely used in the pharmaceutical, food, agriculture, cosmetics, and health industries.

EOs are produced by over 17,500 plant species, primarily within the *Lamiaceae*, *Rutaceae*, *Myrtaceae*, *Zingiberaceae*, and *Asteraceae* families, although only around 300 species are used commercially (Wińska K. et al., 2019). They mostly consist of lipophilic, volatile metabolites, including mono- and sesquiterpenes, phenolic compounds, aldehydes, ketones, and esters (Masyita A. et al., 2022). Major classes include:

- Terpenes (e.g. α-pinene, myrcene and limonene), which are hydrocarbons with antimicrobial activity through membrane disruption and the inhibition of protein and DNA synthesis (Álvarez-Martínez et al., 2021);
- Terpenoids are oxygenated derivatives of terpenes that play a role in plant defence and food preservation (Perricone M. et al., 2015).
- Phenylpropanoids are aromatic compounds with antioxidant activity via radical scavenging and metal chelation (Dai J. and Mumper R. J., 2010).

These compounds are synthesised via the malonic, mevalonic and MEP pathways, and are stored in glands, cavities or ducts. Typically, two to three dominant constituents (20–70%) are present alongside many minor components (Bergman M. E. et al., 2019).

Extraction strongly affects EO yield and composition. Conventional methods include hydrodistillation, steam distillation and cold pressing, while the Clevenger apparatus is used on a laboratory scale (Pandey V. K. et al., 2023). Modern techniques, such as microwave-assisted extraction and supercritical fluid extraction, improve efficiency and preserve thermolabile compounds (Sousa V. I. et al., 2022).

EO bioactivity arises from the synergistic interaction of its constituents. These constituents display broad antimicrobial effects against bacteria, fungi, viruses, parasites and insects (Bakkali et al., 2008), acting through mechanisms such as increasing membrane permeability and interfering with nutrient uptake (Gonelimali et al., 2018). Phenylpropanoids and terpenoids also act as antioxidants, stabilising free radicals and quenching singlet oxygen (Dai and Mumper, 2010).

The rising demand for natural preservatives in foodstuffs has led to increased use of EOs in the meat industry. Their antimicrobial and antioxidant properties enhance microbial safety, oxidative stability and shelf life, providing a natural alternative to synthetic additives (Bassolé and Juliani, 2012; Ojeda-Piedra et al., 2022). This dual preservative role is the focus of research into the effects of EOs on improving pork quality, which will be discussed later in this review.

Mechanisms of Action of Essential Oils in Pigs

Improving pork quality requires optimal genetic selection and husbandry practices, as well as targeted nutritional strategies to modulate pigs' physiological processes. One such strategy that has attracted considerable attention is the use of plant-derived EOs, which have antimicrobial, antioxidant and anti-inflammatory properties that can translate into measurable benefits for meat quality (Nhara R. B. et al., 2024).

Effects on gut microbiota and nutrient absorption. The gut microbiota plays a central role in the digestion and absorption of nutrients, as well as the overall health of pigs, thereby influencing their growth performance and meat quality (Szabó C. et al., 2023). EOs have been shown to modulate the composition and metabolic activity of intestinal microbiota, inhibiting pathogenic bacteria such as *Escherichia coli* and *Clostridium perfringens*, while promoting beneficial species such as *Lactobacillus* and *Bifidobacterium* (He Y. et al., 2022). These shifts in microbial balance can enhance nutrient digestibility, reduce intestinal inflammation and improve feed conversion efficiency (He Y. et al., 2022; Luise D. et al., 2023). The improved absorption of amino acids and fatty acids contributes to optimal muscle growth and reduced fat deposition, thereby supporting favourable carcass traits (Zhao B. C. et al., 2023) (Fig. 1).

Choi J. et al. (2020) demonstrated that the combination of microencapsulated organic acids and EOs enhanced the intestinal morphology of weaned piglets challenged with enterotoxigenic *E. coli* F4. This resulted in reduced diarrhoea, decreased gut permeability and increased villus height in the jejunum, thereby enhancing nutrient absorption. Similar effects were reported by Chen et al. (2023), who found that *Litsea cubeba* EO improved antioxidant status, nutrient digestibility and growth performance. Together, these findings highlight the potential of EOs, either alone or in combination with organic acids, as an alternative to antibiotic growth promoters, as they improve gut integrity, immunity, and nutrient utilisation.

Garavito-Duarte et al. (2025) demonstrated that both herb-based (HP) and EO-based phytobiotics mitigated the effects of *E. coli* F18+ in nursery pigs. Both treatments reduced faecal scores, supported jejunal enterocyte maturation and modulated mucosa-associated microbiota with antimicrobial-like effects. HP also exhibited antioxidant properties. These results are consistent with those of Choi J. et al. (2020) and confirm that phytogenic additives enhance gut barrier function, reduce diarrhoea and increase resilience to enteric pathogens. This supports their potential as an alternative to antibiotics.

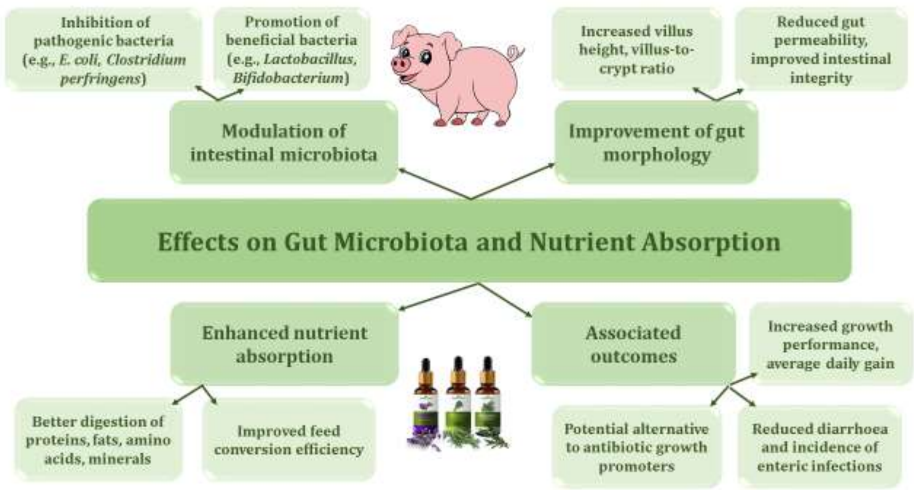

Fig. 1. **The effects of essential oils on gut microbiota and nutrient absorption in pigs**

Building on these findings, Zhao B. C. et al. (2023) discovered that dietary supplementation with cinnamaldehyde and carvacrol enhanced piglet growth, appetite, and intestinal health. EOs increased body weight and average daily gain (ADG), reduced diarrhoea, improved intestinal morphology, up-regulated tight junction proteins and digestive enzymes, and enhanced microbial diversity, promoting the growth of beneficial bacteria. These changes supported better feed utilisation and appetite regulation. Taken together, these studies confirm that phytogenic additives, particularly EOs, can enhance gut integrity, balance the microbiota, and improve growth performance, offering a viable alternative to antibiotics in nursery pigs.

Modulation of oxidative status and immune function. Oxidative stress is a key factor affecting pork quality, particularly under intensive farming conditions when animals are exposed to stressors such as high stocking density, transportation, and pre-slaughter handling (Hao Y. et al., 2021). Excessive reactive oxygen species (ROS) can accelerate the oxidation of lipids and proteins in muscle tissue, resulting in undesirable changes to colour, flavour, tenderness and shelf life (Domínguez R. et al., 2019). Essential oils rich in phenolic compounds, such as thymol, carvacrol and eugenol, possess strong antioxidant properties. They can neutralise ROS and stimulate the production of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx) (Frankič T. et al., 2010). Furthermore, EOs can modulate immune responses by reducing pro-inflammatory cytokine production and enhancing humoral immunity. This lowers the risk of disease outbreaks and associated carcass downgrading (Grazul M. et al., 2023) (Fig. 2).

Forte et al. (2017) reported that oregano EO improved growth and oxidative stability in outdoor-reared pigs, but not in those reared indoors. The greater benefits outdoors were attributed to higher levels of oxidative and physiological stress, in which the phenolic compounds carvacrol and thymol exhibit stronger antioxidant and antimicrobial properties. These results highlight the potential of oregano EO to counteract performance losses in challenging environments.

Similar findings have been observed with other essential oils. For example, Chen F. et al. (2023) demonstrated that *Litsea cubeba* oil (LCO) increased antioxidant capacity, improved nutrient digestibility and enhanced growth performance in fattening pigs while also modulating faecal microbiota. A 500 mg/kg dose increased serum catalase activity, while lower doses improved the digestibility of protein, ash, calcium and fat. LCO also reduced specific bacterial taxa (e.g. SMB53 and L7A_E11), suggesting that improvements in nutrient utilisation and antioxidant status are mediated by the microbiota. Notably, measurable physiological benefits were observed at a dose of just 250 mg/kg, supporting the use of LCO as an alternative to antibiotics.

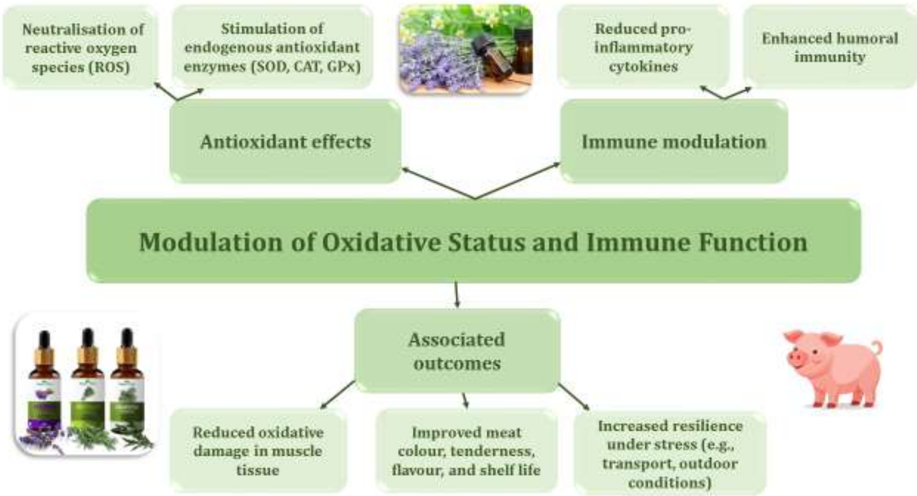

Fig. 2. **Essential oils and modulation of oxidative status and immune function in pigs**

Chen et al. (2024) found that *Alpinia oxyphylla* oil (AEO) improved immune and antioxidant functions, as well as altering the gut microbiota of pigs, though it had no effect on growth performance. AEO increased serum IgG, glutathione (GSH) activity, and the digestibility of ash and calcium in a dose-dependent manner. It also promoted beneficial bacteria such as *Blautia*, *Butyricicoccus* and *Lactobacillus*, while reducing *Clostridium* and *Turicibacter*. The strongest benefits were observed at a dose of 1,000 mg/kg, suggesting that higher doses may be required to achieve significant effects and offering an alternative to conventional antibiotics such as CTC.

Taken together, the studies by Forte (2017) and Chen (2023, 2024) demonstrate that EOs can enhance oxidative stability, immunity, nutrient utilisation and gut microbiota composition in pigs. While growth responses vary depending on the conditions and type of oil, phytogenic additives offer a promising approach to reducing antibiotic use, particularly in situations of stress or immune challenges.

Influence on metabolism relevant to muscle and meat quality. Nutritional modulation through EOs can influence metabolic pathways related to muscle fibre composition, energy utilisation and fat deposition in pigs (Yan E. et al., 2023). Certain EOs have been reported to promote lean muscle growth by increasing protein synthesis and reducing intramuscular fat accumulation (Janz J. A. et al., 2007). This is particularly important for achieving the desired pH value and colour stability of meat after slaughter, since the energy status at slaughter determines the rate at which glycogen is depleted and the pH value declines during rigor mortis (Towers L., 2016). Furthermore, EOs may help to maintain the integrity of muscle cell membranes, thereby reducing drip loss and improving water-holding capacity – critical parameters for consumer acceptance and processing yield (Omonijo F. A. et al., 2018).

Cheng C. et al. (2017) found that supplementing a low-protein, amino acid-balanced diet with oregano EO and benzoic acid improved the oxidative stability and antioxidant enzyme activity of pig muscle, but reduced its intramuscular fat (IMF) content, which could affect its flavour. This highlights the trade-off between extending shelf life and maintaining sensory quality, and emphasises the importance of balancing feed strategies.

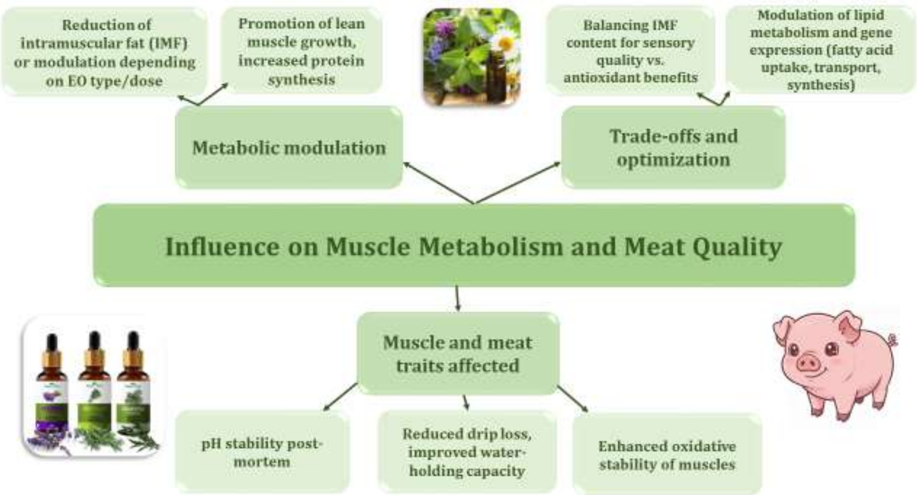

Fig. 3. **The influence of essential oils on muscle metabolism and meat quality**

Huang C. et al. (2022) reported that administering 200 mg/kg of plant essential oils to finishing pigs improved growth, nutrient digestibility, antioxidant capacity and IMF content while reducing shear force. By modulating lipid metabolism and oxidative balance, EOs can enhance both efficiency and meat quality, thus aligning with consumer demand for premium, functional products.

EOs may also mitigate the effects of acute stress. Zou Y. et al. (2017) demonstrated that 25 mg/kg of oregano EO reduced transport stress in pigs more effectively than vitamin E, resulting in higher post-mortem muscle pH, reduced drip loss, lower serum cortisol and creatine kinase levels, and improved intestinal morphology in supplemented pigs. EO also down-regulated stress-related heat shock proteins, suggesting enhanced resilience and meat quality under stress.

The long-term effects were examined by Hofmann H. H. et al. (2022), who found that high doses of omega-3 fatty acids caused minimal changes in carcass traits, but modulated the expression of genes related to the gut barrier and immune system (e.g. tight junction proteins and interferons). These findings suggest that the benefits may be more evident at the molecular level than in performance traits.

Nannoni E. et al. (2023) explored the effects of inhaling lavender EO. While it had little impact on carcass traits or meat quality, once-daily inhalation reduced tail lesions, whereas twice-daily inhalation increased body lesions. No residues were detected in edible tissues, indicating its suitability for Parma ham production. However, the welfare benefits remain inconclusive and require optimisation of the dosage.

In summary, EOs influence pigs at multiple physiological levels, enhancing antioxidant defences, modulating the microbiota and supporting immune resilience and improving meat quality traits. Their multifunctional effects make them a promising natural alternative to synthetic additives and meet the demand for cleaner, more sustainable pork production.

The effects of plant essential oils on pig meat quality

The spoilage of pork is primarily driven by microbial growth, lipid oxidation and enzymatic autolysis (Zhu et al., 2024). The lipid oxidation of minced pork depends on the fatty acid composition, the presence of radicals, oxygen levels, the balance of antioxidants and pro-oxidants, additives such as spices and herbs, processing methods such as irradiation, cooking, grinding and cutting, packaging methods such as vacuum packing and modified or active atmospheres, and storage conditions (Huang X. and Ahn D.U., 2019). Microbial contamination also plays a significant role, with pork acting as a reservoir for *E. coli*, *Staphylococcus aureus*, *Salmonella* spp. and *Listeria* spp. (Zhu Y. et al., 2022).

The quality of pork – defined by tenderness, juiciness, flavour, colour and shelf life – is influenced by the animal's diet, metabolism and well-being (Lebret and Čandek-Potokar, 2022a, b). EOs can enhance these characteristics through their antioxidant and antimicrobial properties, improving flavour by modulating fatty acid composition and oxidative stability, reducing the microbial load and extending the shelf life. Their natural origin also meets consumer demand for alternatives to synthetic preservatives (Zhai H. et al., 2018). Meat quality can be improved by either dietary EO supplementation, which alters fatty acid profiles and stability, or by direct application to meat products (Wenk, 2003). However, at high concentrations, some EOs can act as pro-oxidants with cytotoxic effects, damaging DNA and proteins (Bakkali F. et al., 2008).

Meat quality. Plant-derived compounds such as EOs and oleoresins are attracting increasing interest in the meat industry due to their ability to enhance animal performance and meat quality, as well as extending shelf life through natural preservation. These bioactive substances are typically obtained from herbs such as oregano, rosemary, thyme, garlic, and ginger, and exhibit antimicrobial, antioxidant, and flavour-modulating properties. Incorporating them into diets, marinades, or surface applications therefore represents a promising strategy for meeting consumer demand for clean-label, minimally processed meat products.

Janz J. A. et al. (2007) provided an example of dietary supplementation, testing a low inclusion level (0.05%) of rosemary, garlic, oregano, and ginger extracts in finishing pigs. The study showed that garlic supplementation increased feed intake and daily weight gain, while oregano supplementation reduced lipid oxidation. However, carcass traits and sensory quality were not significantly affected, suggesting that higher doses or longer supplementation periods may be required to achieve measurable improvements.

As dietary inclusion produced only modest effects, further research shifted towards marination as a direct method of improving pork quality. Siroli L. et al. (2020) demonstrated that marination using a mixture of oil, beer and lemon enriched with oregano, rosemary and juniper EOs improved both tenderness and water-holding capacity, as well as enhancing sensory scores. Notably, microbiological analyses revealed reduced spoilage organisms and complete inhibition of major pathogens, suggesting that combining marination with essential oils can improve technological, sensory, and safety attributes simultaneously.

Similar findings were reported by Boskovic M. et al. (2019), who investigated the impact of thyme and oregano EOs on minced pork stored in vacuum or modified atmosphere packaging (MAP). Both EOs reduced lipid oxidation and lipolysis in a dose-dependent manner, with oregano EO demonstrating superior antioxidant properties. Furthermore, vacuum packaging was found to enhance stability even more, highlighting the potential for essential oils and packaging technologies to work together to extend pork shelf life.

Building on this, Zduńczyk W. et al. (2023) explored the effect of applying oregano EO superficially to pork loins stored in MAP. While a 1.0% dose modified the colour and imparted a distinct herbal aroma, the antimicrobial activity was marginal and only observed at later stages of storage. At 0.5%, the effects were negligible, suggesting that surface treatment may be better suited to creating value-added products with unique sensory attributes than to extending shelf life.

Taken together, these studies emphasise that the effectiveness of EOs and oleoresins depends largely on the mode of application. While low dietary levels primarily affect feed preference and growth, strategies involving marination and packaging provide more substantial enhancements to sensory appeal, microbial safety, and oxidative stability. Overall, integrating EOs into pork production emerges as a versatile, natural approach to improving product quality, extending shelf life and meeting consumer expectations for safe, minimally processed foods.

Microbiological analysis. Due to its susceptibility to microbial and oxidative spoilage, preserving fresh pork is a major challenge for the meat industry (Zhu Y. et al., 2022). *Pseudomonas* spp. predominate under aerobic storage conditions, while lactic acid bacteria (*Lactobacillus*, *Leuconostoc* and *Carnobacterium* spp.) and *Brochothrix thermosphacta* dominate under anaerobic conditions. Spoilage manifests as off-flavours, discolouration, and acidification (Zhao F. et al., 2015). Microbiological quality is routinely assessed using mesophilic and psychrotrophic counts, with an upper acceptability limit of 7.0 log CFU/g (Ercolini D. et al., 2009).

To address these issues, plant-derived bioactive compounds, especially EOs and extracts, are being explored increasingly as natural preservatives. When applied through marination, coatings or packaging, these compounds offer clean-label alternatives to synthetic additives (Aguiar Campolina G. et al., 2023). Siroli L. et al. (2020) demonstrated that marination, particularly with EOs, can suppress the growth of *Pseudomonas* spp., coliforms, *Listeria monocytogenes* and *Salmonella enteritidis*, thereby improving microbial safety. The addition of organic acids, ethanol and sodium chloride further enhances preservation (Friedman M. et al., 2007).

Building on this, Mantzourani I. et al. (2023) tested the effect of wine-based marinades containing pomegranate extract and thyme/oregano EOs on pork fillets. These treatments were highly effective in inhibiting *Enterobacteriaceae*, *Staphylococcus* spp., lactic acid bacteria, and yeasts/moulds, thereby extending the shelf life of the pork fillets by up to four days. Importantly, tenderness, colour and flavour were also preserved. Similar results were obtained with cranberry and pomegranate extracts in pork meatballs, where the strong antimicrobial effects were attributed to the presence of phenolic acids, terpenes and organic acids (Mantzourani I. et al., 2022).

Other EO-based strategies have also shown promise. For example, Hernández-Hernández E. et al. (2017) demonstrated that oregano EO, particularly when used in microencapsulated coatings, can effectively inhibit spoilage bacteria, slow down lipid oxidation, and preserve colour for up to 15 days. Similarly, Zhang J. et al. (2016) found that black pepper EO reduced lipid oxidation and microbial growth in pork while improving its appearance.

Further innovation comes from combining natural antimicrobials with advanced technologies. Xu Y. et al. (2022) reported that cinnamon EO nanoemulsions containing ε-polylysine effectively suppressed spoilage and pathogens in pork during storage and radio frequency cooking, thereby maintaining freshness and improving textural attributes.

Overall, these findings emphasise that plant-derived extracts and EOs, when applied through marination, coatings, or nanoemulsion systems, can inhibit the growth of spoilage and pathogenic microorganisms, delay oxidation, and preserve sensory qualities. Novel approaches, such as micro- and nanoencapsulation or their combination with compounds like ε-polylysine, can further enhance efficacy. Overall, these natural strategies demonstrate significant potential for extending the shelf life of pork while meeting consumer expectations for safe, high-quality, minimally processed meat.

An approach to improving pig health. The voluntary feed intake of pigs is strongly influenced by the characteristics of their diet. EOs, with their intense aroma, can increase consumption by 3–19% compared to control diets (Kiarie E. G. and Mills A., 2019; Peng X. et al., 2021). Their flavour and odour enhance palatability, and their antioxidant properties preserve feed quality, ensuring it remains attractive to animals (Moyo P. et al., 2019; Nhara R. B. et al., 2024).

Beyond influencing feed intake, EOs improve nutrient utilisation. Supplementation enhances the apparent digestibility of crude protein and dry matter by modulating gene expression in the ileum and stimulating digestive secretions (Moyo P. et al., 2019; Hofmann H. H. et al., 2022). Morphological benefits have also been observed, including increased jejunal villus height, a higher villus-to-crypt ratio, fewer intraepithelial lymphocytes and improved intestinal integrity. These effects are closely linked to favourable modulation of the gut microbiota, which decreases pathogens while promoting lactobacilli and other beneficial microbes (Liu Y. et al., 2018; Tariq S. et al., 2019).

In parallel, EOs contribute to immune modulation and the control of oxidative stress. Extracts containing carvacrol, capsicum oleoresin and cinnamaldehyde have been shown to reduce DNA damage in lymphocytes, thus demonstrating their antioxidant and immunoprotective properties (Frankič T. et al., 2010). Similarly, preferred EO flavours were found to increase voluntary feed intake, resulting in higher average daily gain without compromising carcass quality (Janz J. A. et al., 2007).

Taken together, these findings suggest that EOs can enhance pig nutrition and performance through various mechanisms. They do this by improving palatability and feed quality, supporting nutrient digestibility, optimising gut morphology and microbiota, and protecting against oxidative damage. Consequently, they contribute to better growth rates, feed efficiency, and potentially improved meat quality. This highlights their value as functional feed additives with broad benefits for animal health and production outcomes.

Comparative studies: Essential Oils vs. Conventional Additives

The growing demand for natural alternatives in pig farming has prompted research into using EOs instead of conventional feed additives, such as antibiotics and synthetic antioxidants. Although antibiotics promote growth and prevent disease and antioxidants such as BHT and BHA limit lipid oxidation in meat, there are concerns about antimicrobial resistance, chemical residues and potential health risks (Oswell N. J. et al., 2018).

EOs offer multifunctional benefits: they act as antimicrobials against pathogens such as Escherichia coli, Salmonella spp., Listeria monocytogenes and Staphylococcus aureus, and they also serve as natural antioxidants, preventing lipid and protein oxidation in pork (Bakkali F. et al., 2008; Siroli L. et al., 2020). They can also modulate gut microbiota, enhance nutrient digestibility and support immune function — effects that synthetic antioxidants alone cannot provide (Moyo P. et al., 2019; Hofmann H. H. et al., 2022; Nhara R. B. et al., 2024).

Comparative studies with other phytobiotics, such as plant extracts and oleoresins, further highlight the potential of EOs. Janz J.A. et al. (2007) found that EOs or oleoresins from rosemary, garlic, oregano or ginger improved feed intake and growth performance without adversely affecting carcass or meat quality. This multi-targeted action, which combines flavour enhancement, antioxidant protection and antimicrobial activity, could reduce the need for multiple additives.

The cost-effectiveness of EOs depends on concentration, formulation, and application. Despite their higher per-unit cost, their multifunctionality may reduce overall supplementation expenses by addressing several production challenges simultaneously (Wenk C., 2003; Zhai H. et al., 2018). Furthermore, consumer preference for natural and clean-label products can increase market acceptance and add economic value (Ojeda-Piedra S.A. et al., 2022).

However, variability in EO composition, influenced by plant species, harvest conditions and extraction methods, can affect efficacy and stability (Wińska K. et al., 2019). Careful selection of the type and dosage of EOs, as well as standardised extraction, is essential for achieving consistent benefits in terms of meat quality and animal health.

In summary, EOs represent a promising, multifunctional alternative to antibiotics, synthetic antioxidants, and other phytobiotics. Their ability to improve gut health, enhance meat quality and reduce oxidative and microbial spoilage makes them valuable for sustainable pig production, provided that practical considerations such as cost, dosage and variability are taken into account.

Factors Influencing the Efficacy of Essential Oils

The effectiveness of EOs in improving the health and growth performance of pigs, and the quality of their meat, is influenced by various factors. These include the oils' chemical composition and purity, the dosage and duration of supplementation, host-specific characteristics such as age, genetics and gut microbiota composition, and diet-related variables that may interact with EO bioactivity.

EO type and purity. The biological activity of EOs largely depends on the specific plant species, chemotype and extraction method. EOs are complex mixtures of terpenes, terpenoids, phenylpropanoids, aldehydes, and other minor compounds which can vary in concentration depending on harvest conditions, the part of the plant used and processing techniques (Wińska K. et al., 2019). High-purity EOs with consistent chemical profiles tend to be more effective, whereas variability in composition can result in inconsistent antioxidant, antimicrobial and immune-modulating activities (Bolouri P. et al., 2022; Masyita A. et al., 2022).

Dosage and duration of supplementation. The optimal effects of EOs depend on the concentration and duration of feeding. Low levels may be insufficient to elicit significant biological responses, whereas excessive doses can have cytotoxic effects, act as pro-oxidants, or reduce feed intake due to their strong odours and flavours (Bakkali F. et al., 2008; Janz J. A. et al., 2007). While long-term supplementation can enhance gut health and immune responses, intermittent or strategic administration may be more cost-effective in avoiding the development of tolerance in the gastrointestinal microbiota (Kiarie E. G. and Mills A., 2019; Peng X. et al., 2021).

The pig's genotype, age and diet composition. The efficacy of EOs can be modulated by the host animal's genetic background, developmental stage and nutritional composition of its diet. Different pig breeds or lines may exhibit variable sensitivity to phytogenic compounds, which influences feed intake, nutrient absorption, and metabolic responses (Lebret B. and Čandek-Potokar M., 2022a, b). Similarly, the age of pigs affects gut morphology and microbiota composition, thereby impacting the antimicrobial and digestive-stimulant properties of EOs (Liu Y. et al., 2018). The composition of the diet, including the type of basal feed, fibre content, and presence of other bioactive compounds, can interact with EOs, thereby enhancing or reducing their overall effectiveness (Nhara R. B. et al., 2024).

EOs can interact synergistically or antagonistically with other additives. The presence of multiple feed additives, such as organic acids, probiotics or vitamins, can affect the biological activity of EOs. Synergistic effects can improve antioxidant protection, gut health and meat quality, whereas antagonistic interactions may reduce bioavailability or interfere with microbial modulation (Bassolé I. H. and Juliani H. R., 2012; Siroli L. et al., 2020). Understanding these interactions is crucial for designing dietary strategies that maximise the benefits of EOs while minimising negative effects.

In conclusion, the efficacy of essential oils in enhancing pig nutrition and meat quality is not consistent and depends on a combination of essential oil-related, host-related, and dietary factors. Careful selection of the type of essential oil, standardised extraction procedures, optimal dosing strategies, consideration of the genotype and age of the pig, and evaluation of potential interactions with other feed additives are all essential for achieving consistent, beneficial outcomes in commercial pig production systems.

Potential limitations and safety considerations

EOs are increasingly recognised as multifunctional pig feed additives, with demonstrated effects on growth performance, gut health, immune modulation, mitigation of oxidative stress, and meat quality (Zhai H. et al., 2018; Ruzauskas M. et al., 2020; Luise D. et al., 2023). The bioactive compounds found in EOs, such as monoterpenes, phenolic acids, and aldehydes, contribute to their antioxidant, antimicrobial, and immunomodulatory activities (Su G. et al., 2018; Peng X. et al., 2021). This makes EOs an attractive alternative to synthetic additives (Liu Y. et al., 2018). However, despite these benefits, their practical application in pig diets requires careful consideration of potential limitations. Variability in EO composition, strong sensory characteristics and the risk of toxicity at high inclusion levels can affect both the response of the animals and the quality of the meat (Stevanović Z. D. et al., 2018). Therefore, understanding these limitations is crucial for optimising EOs in pig diets, ensuring safety, and achieving consistent and beneficial results.

Variability in EO composition and standardisation challenges. The chemical composition of EOs can vary depending on plant species, cultivar, harvest time, geographic origin and extraction method (Wińska K. et al., 2019; Masyita A. et al., 2022). This variability makes standardisation challenging and can lead to inconsistent effects on animal performance, gut health and meat quality. Therefore, establishing standardised profiles and quality control measures is essential for reproducible outcomes.

Risk of reduced feed intake due to strong odours or flavours. EOs have intense odours and flavours, which can negatively affect feed palatability at higher inclusion levels. Studies have shown that pigs may reduce their voluntary feed intake when their diets are supplemented with EOs at concentrations that exceed the optimal level, which could limit growth performance and nutrient utilisation (Janz J. A. et al., 2007; Kiarie E. G. and Mills A., 2019). Careful formulation and inclusion strategies are therefore necessary to balance bioactivity and palatability.

Toxicity at high doses. Certain EO components can be cytotoxic when administered at high concentrations. Excessive supplementation may induce oxidative stress, impair digestive or metabolic functions, or cause cellular damage (Bakkali F. et al., 2008). Therefore, adhering to established safe dosage ranges and monitoring animal health is critical when incorporating EOs into pig diets.

In conclusion, while essential oils have the potential to significantly improve pig nutrition and meat quality, their use must be carefully managed. Standardising EO composition and implementing quality control is essential to ensure consistent results. Optimising inclusion levels is key to balancing bioactivity with palatability and avoiding reductions in voluntary feed intake. Furthermore, adhering to safe dosage ranges is essential to prevent cytotoxic effects and maintain animal health. Addressing these considerations enables EOs to serve as effective, natural feed additives that can improve growth performance, gut integrity, immune function and meat quality, thereby supporting the development of sustainable, high-quality pork production.

Future perspectives and research directions. Future research on EOs in pig production should focus on improving their efficacy, safety and practical application in commercial settings. One key approach is the development of novel delivery systems, such as microencapsulation and nanoemulsions. These systems protect EO compounds from degradation during feed processing, enhance bioavailability and enable controlled release in the gastrointestinal tract (Stevanović Z. D. et al., 2018; Moyo P. et al., 2019; Sousa V. I. et al., 2022). These technologies can also mitigate the strong odours and flavours that can reduce feed palatability at higher inclusion levels.

Combining EOs with probiotics, prebiotics, or digestive enzymes is another promising strategy. Such synergistic approaches can support gut microbiota balance, enhance nutrient absorption, modulate immune responses and ultimately improve growth performance and meat quality (Nhara R. B. et al., 2024; Tariq S. et al., 2019). Investigating these interactions could help to identify the most effective supplementation regimes for optimal animal health and productivity.

Omics-based methods, including genomics, transcriptomics, metabolomics and microbiomics, offer valuable insights into the molecular mechanisms of EO action. These mechanisms include the effects of EOs on gut microbiota, metabolic pathways, oxidative stress and immune function (Frankič T. et al., 2010; Hofmann H. H. et al., 2022). Linking molecular changes to phenotypic outcomes can inform precision nutrition strategies and guide the tailored supplementation of EOs adapted to specific production goals, breeds, or environmental conditions.

Future studies should prioritise long-term feeding trials, dose-response assessments and evaluations under commercial farm conditions, in order to validate laboratory findings. Addressing these aspects will bridge the gap between experimental research and practical application, ensuring that EOs can be safely and effectively incorporated into pig diets to enhance performance, welfare, and meat quality.

Conclusions. Essential oils are increasingly recognised as a promising natural alternative to conventional feed additives in pig farming. They offer potential benefits for gut health, oxidative status, immune function and meat quality. Research has shown that essential oils can modulate lipid oxidation, inhibit the growth of spoilage and pathogenic microorganisms, and influence sensory attributes such as flavour, aroma, colour, tenderness and juiciness. This contributes to improved meat quality and an extended shelf life.

However, the efficacy of EOs depends on a number of factors. These include the chemical composition and bioactive profile of the oil; the dosage and duration of supplementation; host-specific factors, such as age, genetic line and gut microbiota composition; and interactions with other dietary components, including macronutrients, probiotics and prebiotics. Careful consideration of these factors is essential to achieve consistent and reproducible improvements in pig performance, health and product quality.

The practical application of essential oils also requires the consideration of safety and standardisation. Variability in the composition of EOs due to plant species, harvest conditions or extraction methods can affect the consistency and predictability of results. Additionally, the strong aroma and flavour of EOs can reduce the palatability of feed at high inclusion levels, and certain EO constituents can have cytotoxic effects if overdosed. Therefore, optimised formulations, dosing strategies and quality control measures are essential for the safe and effective use of EOs in commercial pig production.

Incorporating EOs into pig diets enables the swine industry to reduce its reliance on synthetic antioxidants and antibiotics, thereby aligning with consumer demand for natural, clean-label products while maintaining or enhancing pork quality. Future research should focus on developing standardised EO formulations and advanced delivery systems, such as microencapsulation or nanoemulsions. Other areas of research should include synergistic combinations with other feed additives and mechanistic studies employing omics technologies. These efforts will enable the design of optimised, evidence-based essential oil interventions that promote sustainable, safe and high-quality pork production.

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