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LAVENDER, A NATURAL ADDITION TO FISH DIET, ENHANCEMENTS IN GROWTH AND IMMUNE SYSTEM

Simona Cristina NIȚESCU, Daniel COCAN, Aurelia COROIAN

University of Agricultural Sciences and Veterinary Medicine of Cluj-Napoca,
3-5Calea Mănăștur Street, 400372, Cluj-Napoca, Romania

Corresponding author email: daniel.cocan@usamvcluj.ro

Abstract

Lavender, widely recognized for its medicinal properties, has gained attention for its potential to enhance fish health in aquaculture. This paper resumes current knowledge on the effects of lavender extracts, highlighting their antioxidant properties and immune-enhancing capabilities on fish. Evidence from recent studies indicates that lavender extracts efficiently reduce oxidative stress and improve immune responses in fish. These findings suggest that incorporating lavender extracts into aquaculture practices could reduce reliance on synthetic additives and antibiotics, supporting more sustainable and environmentally friendly approaches. Overall, lavender emerges as a promising natural alternative for promoting fish health and promoting eco- friendly aquaculture practices.

***Key words**: antioxidant effects, essential oil, fish health, lavender extracts, medicinal plants.*

INTRODUCTION

Aquaculture is one of the fastest-growing sectors within global food production, driven largely by the rising demand for aquatic products. This rapid expansion has brought about significant environmental and health-related challenges due to extensive reliance on synthetic chemicals such as antibiotics and pharmaceuticals, primarily used for disease control and enhancing fish health (Boaru et al., 2022; FAO, 2022). However, the detrimental ecological impacts, including antibiotic resistance, accumulation of toxic residues in animal tissues, and disruptions to ecological balance, have heightened public awareness and increased scrutiny from regulatory bodies, accelerating the search for sustainable, natural alternatives (Filep et al., 2016; Boaru et al., 2022; De la Cruz et al., 2020).

Intensification of aquaculture practices demands optimal water quality management and robust fish health maintenance. Synthetic chemical agents frequently utilized for disease prevention, stress mitigation, and growth improvement, particularly during transport or juvenile stages, pose significant ecological risks through environmental persistence and bioaccumulation (De la Cruz et al., 2018). Despite initial efficacy, these synthetic chemicals often result in oxidative stress, tissue damage, and pathological lesions in aquatic species, negatively affecting productivity and incurring substantial economic losses (De la Cruz et al., 2020; Morteza et al., 2020). Consequently, adopting eco-friendly alternatives is essential for sustainable aquaculture management.

Currently, there is increasing consumer demand globally, especially in markets such as the United States, Asia, and the European Union, for natural and organic aquaculture products. This trend is driven by heightened consumer preferences for healthier food options produced in environmentally sustainable ways (Ndakalimwe, 2019). Medicinal plants offer significant promise as alternative solutions due to their wide-ranging beneficial effects, including improved growth performance, enhanced immune responses, antimicrobial activities, and better overall health in farmed aquatic species (Antache et al., 2014; Farag et al., 2021).

Plants belonging to the Lamiaceae family have gained considerable attention within aquaculture research due to their diverse biological properties. These include antioxidant, anti-inflammatory, immunostimulant, antiviral, antiparasitic, and antihelminthic effects, which collectively contribute to enhanced fish health, improved disease resistance, and greater feed conversion efficiency (Bahaciu et al., 2018; Antache et al., 2014; Farag et al., 2021). Utilization of these plant-based solutions aligns closely with environmental conservation and public health concerns, providing aquaculture with sustainable management strategies.

Among medicinal plants suitable for aquaculture applications, lavender (*Lavandula angustifolia* Mill.) stands out due to its rich content of bioactive compounds and extensive historical use in traditional medicine (Muntean, 2016). Lavender is indigenous to Mediterranean regions and North Africa and has been recognized and utilized therapeutically since ancient times across various civilizations (Muntean, 2016). Despite its historical medicinal significance, its application in aquaculture is relatively novel but promising.

Lavender extracts exhibit strong antimicrobial properties, effectively inhibiting pathogenic bacteria and other microorganisms commonly encountered in aquaculture systems (Wimalasena et al., 2018). The antimicrobial activity of lavender essential oils primarily derives from constituents such as linalool and linalyl acetate, which effectively combat a broad spectrum of pathogens, including bacteria and parasites significant to aquaculture health management (Wimalasena et al., 2018; Perez et al., 2017; Bahmani et al., 2014; Bahaciu et al., 2021).

In addition to antimicrobial effects, lavender has demonstrated antihelminthic capabilities, significantly aiding in controlling parasitic infestations prevalent in aquaculture. Parasitic infections negatively impact fish growth, survival rates, and overall productivity, thus representing a critical management challenge in fish farming operations (Perez et al., 2017; Bahmani et al., 2014). Utilizing lavender-based treatments could substantially reduce reliance on chemical antiparasitic agents, thereby minimizing ecological risks and avoiding residual chemical accumulation in aquatic organisms (Bahmani et al., 2014).

Lavender's immunomodulatory effects further amplify its potential in aquaculture by enhancing fish immune responses and resistance to diseases and stressors. The plant's extracts mitigate inflammation and oxidative stress, strengthening physiological resilience and reducing vulnerability to environmental and physiological stressors, crucial during fish transport, handling, or exposure to suboptimal water quality (Saeed et al., 2022; Fathem et al., 2020).

The anti-inflammatory properties of lavender contribute significantly to managing stress-induced health conditions commonly experienced in intensive aquaculture systems. Stress mitigation through lavender supplementation aids in maintaining physiological balance, improving overall fish welfare and productivity, and reducing economic losses associated with stress-induced disease outbreaks (Saeed et al., 2022).

Therefore, incorporating lavender extracts as dietary supplements in aquaculture represents a promising strategy for sustainable fish farming practices. Lavender's integration as a phytoadditive can considerably reduce dependency on synthetic antibiotics and chemicals, promoting safer and more environmentally friendly aquaculture operations. Additionally, the adoption of lavender aligns well with global initiatives aimed at promoting sustainable and responsible food production, potentially enhancing consumer acceptance, reducing environmental impacts, and improving animal welfare standards.

This study aims to synthesize existing scientific data concerning lavender's potential applications in aquaculture, specifically focusing on its antimicrobial and immunomodulatory properties. By examining key areas such as disease prevention, immune enhancement, and improved growth performance, this review underlines practical applications and benefits of lavender supplementation in aquaculture feeds, ultimately contributing to sustainable, eco-friendly, and economically viable aquaculture systems.

MATERIALS AND METHODS

Online databases such as Web of Science, Google Scholar, Researchgate and ScienceDirect, were used to collect published data regarding medicinal plants especially

lavender. Its effects, in the context of aquaculture and fish farming was prior. The reference list of each retrieved article was examined for other relevant studies related to this topic.
Articles published in english were selected, focusing on studies involving the use of lavender as a feed additive, but also including its application as an anaesthetic, water additive, or for other uses in aquaculture.
Both research articles and review papers were included in this study.

RESULTS AND DISCUSSIONS

PHYTOCHEMICAL COMPOSITION AND BIOACTIVE PROPERTIES OF LAVENDER

Lavender is rich in bioactive compounds that contribute to its medicinal and therapeutic properties. Its essential oil (LEO) comprises a diverse range of phytochemicals, with linalool, linalyl acetate, 1,8-cineole (cineole), camphor, borneol, and rosmarinic acid being the predominant constituents, each exhibiting significant biological activity (Habán et al., 2023; Prusinowska et al., 2014; Lis-Balchin, 2002). Among these, linalool and linalyl acetate stand out due to their potent antimicrobial, anxiolytic, and immunomodulatory effects, making lavender an attractive natural additive for aquafeeds (Alam et al., 2024; Yousefi et al., 2020).
Gas chromatography-mass spectrometry (GC-MS) analysis has consistently identified linalool as the most abundant compound in lavender essential oil, comprising approximately 25-45% of the total oil content, followed by linalyl acetate at 25-30% (Abdel-Rahim et al., 2024). These compounds enhance fish immunity, promoting growth, and mitigating oxidative stress (Boaru et al., 2022; Peana et al., 2002). Other bioactive components, such as geraniol, have demonstrated antimicrobial and anti-inflammatory properties, further supporting fish health and resilience against pathogens (Paray et al., 2020).
Lavender's phytochemical profile consists of a complex blend of essential oils, polyphenols, and flavonoids, contributing to its antimicrobial, anti-inflammatory, and immunostimulatory effects (Prusinowska et al., 2014; Habán et al., 2023). The primary bioactive compounds identified through GC-MS and their respective biological roles are summarized in the table below (Table 1).

Table 1. Primary bioactive compounds of lavender and their biological roles

Compound	Percentage in Essential Oil	Key Biological Effects	References
Linalool	25-45%	Antimicrobial, antioxidant, immunomodulatory	Abdel-Rahim et al., 2024; Boaru et al., 2022; Peana et al., 2002
Linalyl acetate	25-30%	Stress-reducing, anti-inflammatory	Abdel-Rahim et al., 2024; Yousefi et al., 2020
Cineole (1,8-cineole)	5-10%	Respiratory health, immune-enhancing	Habán et al., 2023
Camphor	2-7%	Antibacterial, antifungal, analgesic	Prusinowska et al., 2014; Habán et al., 2023
Borneol	1-5%	Wound healing, sedative properties	Prusinowska et al., 2014; Habán et al., 2023
Rosmarinic acid	1-4%	Antioxidant, anti-inflammatory, antiviral	Paray et al., 2020

Linalool and linalyl acetate, the two dominant constituents, are particularly responsible for lavender's antimicrobial efficacy and stress-mitigating properties(Abdel-Rahim et al., 2024). These compounds enhance immune function by modulating cytokine activity and improving phagocytic responses in fish, making lavender a promising phytoadditive in aquaculture (Boaru et al., 2022; Peana et al., 2002).

Antioxidant properties of lavender

Lavender essential oil (LEO) is well-documented for its potent antioxidant properties, which play a crucial role in mitigating oxidative stress in aquatic organisms (Habán et al., 2023; Hajirezaee et al., 2022). Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the efficiency of the antioxidant defense system in neutralizing these harmful molecules (Hoseini & Yousefi, 2019). ROS, including superoxide anions, hydrogen peroxide, and hydroxyl radicals, can cause severe cellular damage by oxidizing proteins, lipids, and DNA, leading to compromised physiological functions, immune suppression, and reduced growth performance in fish (Yousefi et al., 2019; Abdel-Rahim et al., 2024).

Numerous studies have demonstrated that lavender possesses strong free radical scavenging activity, which contributes to its ability to protect fish against oxidative damage (Yousefi et al., 2020). The bioactive compounds in lavender, particularly linalool, linalyl acetate, and rosmarinic acid, exhibit significant antioxidant potential by neutralizing ROS and enhancing the endogenous antioxidant defense system in aquatic species (Paray et al., 2020; Hajirezaee et al., 2022). These phytochemicals have been shown to upregulate the expression and activity of key enzymatic antioxidants, including catalase (CAT), superoxide dismutase (SOD), and glutathione peroxidase (GPx), which play essential roles in detoxifying ROS and maintaining cellular homeostasis (Hoseini & Yousefi, 2019; Yousefi et al., 2019).

Dietary inclusion of lavender in fish feed has been linked to increased levels of CAT, SOD, and GPx, indicating enhanced oxidative defense mechanisms (Abdel-Rahim et al., 2024). These enzymes work synergistically to decompose ROS; SOD catalyzes the conversion of superoxide radicals into hydrogen peroxide, which is then broken down by CAT and GPx into water and oxygen, thereby preventing oxidative damage to cellular components (Yousefi et al., 2019). Additionally, fish supplemented with lavender-based diets exhibit a significant reduction in malondialdehyde (MDA) levels, a widely recognized biomarker of lipid peroxidation, confirming its protective role against oxidative stress-induced cellular deterioration (Paray et al., 2020).

The antioxidative effects of lavender are particularly beneficial in aquaculture, where environmental stressors such as high stocking densities, poor water quality, and transport-induced stress can elevate ROS production and increase disease susceptibility (Hajirezaee et al., 2022; Yousefi et al., 2020). By reducing oxidative stress, lavender supplementation not only improves fish health and immune function but also enhances overall growth performance and feed efficiency, supporting the sustainability of aquaculture practices (Hoseini & Yousefi, 2019; Boaru et al., 2022).

Immunomodulatory effects of lavender

Lavender (*Lavandula angustifolia*) has gained attention in aquaculture for its immunostimulatory properties, primarily attributed to its bioactive compounds, including linalool, linalyl acetate, and 1,8-cineole (Hajirezaee et al., 2022; Hoseini & Yousefi, 2019). These compounds have been shown to enhance both innate and adaptive immune responses in fish, thereby improving disease resistance and overall health (Abdel-Rahim et al., 2024).

Dietary supplementation with lavender essential oil (LEO) has been found to significantly elevate key immune parameters in various fish species. For example, in European seabass (*Dicentrarchus labrax*), fish fed lavender-enriched diets exhibited increased levels of total immunoglobulin (IgM), respiratory burst activity (RBA), lysozyme activity, and complement component C3, all of which are critical in pathogen defense and immune system regulation (Abdel-Rahim et al., 2024; Ahmadi et al., 2014). Lysozyme is an essential enzyme involved in the innate immune response, directly targeting bacterial cell walls and enhancing phagocytosis, while complement proteins, such as C3, contribute to immune signaling and the destruction of pathogens (Banaee et al., 2011; Hoseini & Yousefi, 2019).

Lavender supplementation has been shown to modulate immune-related gene expression in fish. Studies have demonstrated that fish receiving lavender-based diets exhibit upregulated expression of inducible nitric oxide synthase (iNOS) and complement factor C3, both of which play key roles in immune defense mechanisms (Hajirezaee et al., 2022). iNOS is involved in the production of nitric oxide (NO), a crucial molecule in immune responses that enhances macrophage activity and antimicrobial defense (Paray et al., 2020). The upregulation of C3 further supports fish immunity by promoting the activation of the complement system, a fundamental component of innate immune protection (Ahmadi et al., 2014).

The immunostimulatory effects of lavender are likely due to the synergistic actions of its active compounds, particularly linalool and cineole, which have been shown to enhance immune cell function and reduce inflammation in aquatic organisms (Hoseini & Yousefi, 2019; Abdel-Rahim et al., 2024). Linalool is known for its anti-inflammatory and immunomodulatory properties, contributing to reduced oxidative stress and enhanced leukocyte activity (Dawood et al., 2022). Meanwhile, cineole has been reported to increase cytokine production and improve fish resistance to bacterial and parasitic infections (Yousefi et al., 2020).

Lavender supplementation has been found to reduce stress, a common challenge in aquaculture, particularly in intensive farming conditions where fish are exposed to high stocking densities, handling stress, and environmental fluctuations (Hajirezaee et al., 2022; Yousefi et al., 2019). Chronic stress suppresses immune function by elevating cortisol levels, which negatively impact leukocyte activity and reduce disease resistance in fish (Banaee et al., 2011).

Lavender-based phytoadditives in aquaculture diets represents a promising strategy for enhancing fish health while reducing reliance on synthetic immunostimulants and antibiotics (Abdel-Rahim et al., 2024; Ahmadi et al., 2014). By modulating innate immune responses and gene expression, lavender offers a natural and effective approach to strengthening fish immunity, minimizing disease outbreaks, and promoting sustainable aquaculture practices (Hajirezaee et al., 2022; Hoseini & Yousefi, 2019).

Antimicrobial and antiparasitic activity

Lavender essential oil (LEO) possesses potent antimicrobial and antiparasitic properties, making it a promising natural alternative to conventional antibiotics and chemical treatments in aquaculture (Wimalasena et al., 2018; Hoseini & Yousefi, 2019). The bioactive compounds in lavender, particularly linalool, linalyl acetate, and 1,8-cineole, have been shown to exert strong antimicrobial effects against a range of Gram-positive and Gram-negative bacterial pathogens commonly affecting fish species (Paray et al., 2020).

Numerous studies have demonstrated the efficacy of lavender oil in inhibiting the growth of key fish pathogens, including *Aeromonas hydrophila*, *Streptococcus iniae*, *Vibrio anguillarum*, and *Edwardsiella tarda*, bacteria responsible for severe infections such as hemorrhagic septicemia, vibriosis, and streptococcosis in aquaculture systems (Baba et al., 2016; Abdel-Tawwab, 2012; Rattanachai-kunsopon & Phumkhachorn, 2010; Hajirezaee et al., 2022).

The antimicrobial mechanism of lavender oil is primarily linked to its ability to disrupt bacterial cell membranes, leading to increased permeability and leakage of intracellular contents, ultimately resulting in bacterial cell lysis (Wimalasena et al., 2018; Yousefi et al., 2020).

Lavender has also been recognized for its antiparasitic potential, particularly against ectoparasites and endoparasites affecting fish health (Rattanachaikunsopon & Phumkhachorn, 2010; Abdel-Rahim et al., 2024). Studies indicate that lavender oil effectively reduces parasite load in fish infected with *Ichthyophthirius multifiliis* (commonly known as ich), *Gyrodactylus* spp., and *Dactylogyrus* spp., which are major contributors to high mortality rates in aquaculture (Hajirezaee et al., 2022). The anti-parasitic effects of lavender are linked to its bioactive compounds, which interfere with parasite metabolism and disrupt their life cycle, thereby reducing infestation rates and improving fish survival (Moon et al., 2006; Abdel-Tawwab, 2012).

In addition to its direct antimicrobial and antiparasitic effects, lavender supplementation has been shown to enhance fish immune defenses, further contributing to pathogen resistance (Yousefi et al., 2020). By stimulating immune parameters such as lysozyme activity, respiratory burst activity, and complement system activation, lavender strengthens fish resilience against infections and improves overall aquaculture productivity (Baba et al., 2016; Abdel-Rahim et al., 2024).

Given the increasing concerns about antibiotic resistance and chemical residues in aquaculture, lavender essential oil represents a viable and eco-friendly alternative for managing bacterial, fungal, and parasitic

infections. Its broad-spectrum antimicrobial action, combined with its immunostimulatory effects, highlights its potential for sustainable disease management in fish farming (Hoseini & Yousefi, 2019; Hajirezaee et al., 2022).
Beyond its antibacterial properties, lavender also exhibits antifungal effects against common aquaculture-related fungal pathogens, such as *Saprolegnia* spp. and *Aspergillus* spp., which are responsible for skin and gill infections in fish (Hoseini et al., 2020; Yousefi et al., 2019). The antifungal activity of lavender is attributed to its capacity to inhibit fungal spore germination and mycelial growth, preventing the spread of infections within aquaculture systems (Paray et al., 2020).

Effects of lavender on growth performance and feed utilization

Several studies have reported improvements in growth performance, feed utilization, and intestinal morphology in fish supplemented with lavender oil (Abdel-Rahim et al., 2024). Lavender's ability to enhance digestive enzyme activity (amylase, protease, lipase), improve feed conversion ratio (FCR), and increase specific growth rate (SGR) makes it a viable natural growth promoter in aquaculture (Hedayati et al., 2019).

Growth performance enhancement

Fish growth performance is commonly assessed through parameters such as weight gain (WG), specific growth rate (SGR), and condition factor (CF) (Rahimnejad et al., 2021). Studies have reported that dietary supplementation with lavender can positively influence these parameters in various fish species.

Weight gain and specific growth rate

Lavender has been shown to enhance weight gain and specific growth rate in different fish species. In a study by Hassanalizadeh et al. (2020), *Oncorhynchus mykiss* fed diets containing LEON at concentrations of 0, 100, 150, and 200 ml/kg over a 60 days. The results demonstrated that fish receiving 150 ml/kg of LEON exhibited the highest weight gain percentage (WG%) and specific growth rate (SGR), with WG% reaching 252.16%. Similar findings were reported by Al-Derawi et al. (2021), where *Oreochromis niloticus* supplemented with 2% lavender extract demonstrated significant growth improvements due to enhanced protein synthesis and metabolic regulation.
The mechanisms underlying these improvements are attributed to the bioactive compounds in lavender, particularly linalool and rosmarinic acid, which modulate digestive enzyme activity and gut microbiota composition (Mahmoud et al., 2022). This, in turn, facilitates better nutrient absorption and utilization, contributing to enhanced growth performance (Soltani et al., 2021).

Influence on digestive enzyme activity

One of the primary mechanisms through which lavender enhances feed utilization is by modulating digestive enzyme activity. Ashraf et al. (2023) demonstrated that dietary lavender oil supplementation significantly increased the activities of digestive enzymes such as amylase, lipase, and protease in European seabass, leading to improved digestion and nutrient absorption.

Amylase, protease, and lipase activity

Research conducted by Soltani et al. (2021) demonstrated that *Salmo salar* supplemented with lavender essential oil exhibited a 20% increase in amylase and protease activity, facilitating more efficient carbohydrate and protein breakdown. Similarly, Mahmoud et al. (2022) observed a significant upregulation of lipase activity in *Clarias gariepinus*, enhancing lipid metabolism and energy utilization.
These findings align with those of Al-Derawi et al. (2021), who suggested that the phenolic compounds in lavender interact with gut microbiota, promoting the secretion of digestive enzymes. Consequently, fish can extract more energy from their feed, translating into improved growth performance and feed efficiency (Raslan et al., 2025).

Impact on gut microbiota and nutrient absorption

The gut microbiome plays a crucial role in nutrient digestion, immune function, and overall fish health. Recent studies indicate that lavender supplementation can positively modulate gut microbiota composition, improving nutrient absorption and feed efficiency (Sutili et al., 2018).

Modulation of gut microbiota

In a study by Torrecillas et al. (2021), *Sparus aurata* fed essential oil-supplemented diets exhibited an increase in beneficial bacteria, such as *Lactobacillus* and *Bifidobacterium*, while pathogenic bacteria like *Aeromonas* and *Pseudomonas* were significantly reduced. This shift in microbial composition enhances gut health and improves the bioavailability of nutrients, leading to better growth performance (Paritova et al., 2024; Ashraf et al., 2023).

Lavender's antimicrobial properties help maintain gut integrity, reducing inflammation and improving nutrient assimilation (Rahimnejad et al., 2021).

COMPARATIVE ANALYSIS OF LAVENDER WITH OTHER LAMIACEAE MEDICINAL PLANTS IN AQUACULTURE

The use of phytogenic additives in aquaculture has gained significant attention due to their ability to enhance fish growth, feed efficiency, immune response, and overall health. Among these, medicinal plants from the Lamiaceae family, including lavender (*Lavandula angustifolia*), thyme (*Thymus* spp.), oregano (*Origanum vulgare*), basil (*Ocimum basilicum*), and rosemary (*Rosmarinus officinalis*), have been extensively studied for their bioactive properties. While lavender has demonstrated substantial efficacy in promoting fish growth and feed utilization, a comparative evaluation with other *Lamiaceae* species is essential to understand its relative benefits.

Lavender vs. Thyme (*Thymus vulgaris*)

Thyme, known for its antimicrobial, antioxidant, and digestive enzyme-enhancing properties, primarily due to its high content of thymol and carvacrol (Rahimnejad et al., 2021; Fathi et al., 2022). Studies have demonstrated its efficacy in improving feed conversion ratio (FCR) and specific growth rate (SGR) in several fish species. For instance, dietary thyme supplementation in *Oncorhynchus mykiss* improved weight gain (WG) by 14%, but a similar concentration of lavender resulted in slightly higher protein efficiency ratio (PER) and better lipid metabolism, suggesting superior nutrient utilization (Yousefi et al., 2022). Thyme has also been found to enhance intestinal microbiota by increasing *Lactobacillus* populations, though lavender has demonstrated a more potent influence on gut health and digestion (Akbari et al., 2023).

Lavender vs. Oregano (*Origanum vulgare*)

Oregano is another widely used phytogenic additive due to its high concentration of polyphenols and essential oils with antimicrobial and digestive-enhancing properties (Leyva-López et al., 2017). Studies on *Sparus aurata* have shown that dietary oregano can improve gut health and increase digestive enzyme secretion (Magouz et al., 2022). However, comparative studies indicate that lavender supplementation yields slightly better nutrient assimilation and antioxidant enzyme activity, possibly due to its higher rosmarinic acid content, which aids in oxidative stress reduction and metabolic balance (Georgiev et al., 2009). Furthermore, oregano has shown notable antibacterial effects against *Aeromonas hydrophila*, but lavender appears to provide broader antimicrobial protection, covering a wider range of pathogens (Alam et al., 2022).

Lavender vs. Basil (*Ocimum basilicum*)

Basil is known for its immunomodulatory and digestive enzyme-stimulating properties, attributed to its high content of flavonoids and essential oils such as eugenol and linalool (El-Bahr et al., 2020). Research by Sharifian et al. (2023) indicated that dietary supplementation with basil significantly enhanced amylase and protease activity in *Oncorhynchus mykiss*, leading to better carbohydrate and protein digestion. However, a comparison with lavender showed that while both plants significantly improved feed utilization, lavender had a greater impact on lipid metabolism and gut microbiota modulation, suggesting superior energy utilization (Karami et al., 2023).

Lavender vs. Rosemary (*Rosmarinus officinalis*)

Rosemary is widely recognized for its potent antioxidant properties, primarily due to its high levels of rosmarinic acid and carnosic acid

(Loussouarn et al., 2017; Naiel et al., 2020). Studies have shown that dietary rosemary enhances fish immunity, reduces oxidative stress, and improves feed utilization in species such as *Cyprinus carpio* and *Salmo salar* (Chelemal et al., 2022). In a study on tilapia, rosemary supplementation improved FCR by 16%,while lavender exhibited comparable effects with additional benefits on gut microbiota composition, reducing pathogenic bacterial loads and increasing beneficial microbial populations (Yilmaz et al., 2019). These findings suggest that lavender not only improves antioxidant capacity but also enhances digestive function and nutrient absorption to a greater extent than rosemary (Sivamaruthi et al., 2024).

Mechanisms responsible for the efficacy of lavender compared to other *Lamiaceae* plants

The superior effects of lavender on fish growth and feed efficiency may be attributed to its unique combination of bioactive compounds, including linalool, rosmarinic acid, and flavonoids (Abdel-Rahim et al., 2024). These compounds not only enhance digestive enzyme activity but also improve gut health by promoting beneficial bacteria while reducing pathogenic microbes (Sutili et al., 2018). Compared to other *Lamiaceae* species, lavender has been shown to exert stronger antimicrobial effects on gut microbiota, leading to better nutrient assimilation and reduced inflammation (Rahimnejad et al., 2021).

Furthermore, lavender's ability to mitigate oxidative stress through its antioxidant properties allows for more efficient energy allocation towards growth rather than stress responses (Fathi et al., 2022). This is particularly evident when compared to rosemary, which, despite its strong antioxidant activity, does not exhibit the same level of enhancement in digestive enzyme activity and gut microbiota modulation (Sharifian et al., 2023).

WAYS OF INTRODUCING LAVENDER INTO FISH DIETS

The incorporation of lavender into fish diets has been widely studied due to its potential health benefits, particularly its immunostimulatory and antimicrobial properties. Different forms of lavender can be used as dietary supplements in aquaculture, including lavender essential oil, dried lavender flowers, aqueous or ethanolic extracts, and nanoemulsions. Each method has distinct advantages in terms of bioavailability, effectiveness, and ease of application (Hajirezaee et al., 2022; Fazio et al., 2017).

Lavender essential oil (LEO)

Lavender essential oil (LEO) is a volatile oil extracted through steam distillation, primarily composed of linalool, linalyl acetate, and camphor, which contribute to its antioxidant and antimicrobial properties (Bajpai et al., 2020). Essential oils have been successfully incorporated into fish diets to enhance immune responses and growth performance (Elumalai et al., 2022).

Studies indicate that adding LEO at optimized concentrations improves fish health. For example, ElHady et al. (2024) found that dietary supplementation of 1% LEO enhanced growth performance, increased antioxidant enzyme activity, and reduced oxidative stress in Nile tilapia (*Oreochromis niloticus*). Similarly, Kuebutornye et al. (2024) reported improved immune function in common carp (*Cyprinus carpio*) when fed diets containing LEO at concentrations of 0.5-1.5%.

Essential oils, including lavender, exhibit antimicrobial activity against various pathogens such as *Aeromonas hydrophila* and *Vibrio* spp. (Chouhan et al., 2017). Dietary incorporation of LEO at 2% significantly reduced bacterial infections in rainbow trout (*Oncorhynchus mykiss*), according to a study by Mirzaei et al. (2023). However, excessive concentrations may cause toxicity and negatively impact fish metabolism (Hosseini et al., 2020), indicating the necessity for dose optimization.

Dried lavender flowers

Dried lavender flowers can be used as a natural supplement in formulated aquafeeds. This method provides a more sustainable and cost-effective alternative to essential oils while still delivering bioactive compounds such as polyphenols, flavonoids, and tannins (Caser et al., 2023). Unlike essential oils, which may lose volatile components over time, dried lavender ensures a gradual release of bioactive compounds during digestion. Baloochi et al. (2021) reported that feeding dried lavender to rainbow trout enhanced gut microbiota diversity and increased resistance to parasitic infections.

The use of dried lavender also contributes to the sustainable management of aquaculture by utilizing whole plant material, thereby reducing waste. However, proper standardization of drying and processing techniques is essential to maintain bioactive compound integrity (Caser et al., 2023).

Lavender extracts (aqueous and ethanolic)

Lavender extracts, obtained through aqueous or ethanolic extraction, provide highly concentrated bioactive compounds with enhanced bioavailability. Ethanolic extracts, in particular, contain a higher concentration of polyphenols and flavonoids compared to aqueous extracts (Torras-Claveria et al., 2007). These compounds have been linked to immunostimulatory and anti-inflammatory properties in fish (Dobros et al., 2022).

Research by Yousefi et al. (2020) indicated that supplementing fish diets with 2% lavender ethanolic extract significantly enhanced the antioxidant defense system in common carp. Similarly, El-Sayed et al. (2022) found that a combination of lavender aqueous extract and vitamin C improved stress resistance in Asian seabass (*Lates calcarifer*) during transportation. However, the efficacy of lavender extracts depends on their stability and solubility. Encapsulation techniques have been suggested to protect bioactive compounds from degradation during feed processing (Azizi et al., 2021).

Lavender nanoemulsions

Nanoemulsions are emerging as a novel delivery system for lavender bioactive compounds, offering increased absorption and targeted physiological effects. Nanoemulsified lavender essential oil (NE-LEO) enhances bioavailability by improving solubility and protecting active compounds from oxidation (Miastkowska et al., 2023).

Several studies have highlighted the benefits of nanoemulsions in aquaculture. For instance, Rahimi et al. (2023) reported that feeding NE-LEO at 0.3% significantly improved growth rates, gut health, and immune responses in juvenile sturgeon (*Acipenser persicus*). Additionally, nanoemulsions have been shown to reduce stress-induced cortisol levels, as observed in a study on European sea bass (*Dicentrarchus labrax*) by Abdel-Rahim et al. (2024).

Despite their promising applications, the high cost of nanoemulsion technology remains a limiting factor for large-scale implementation. Future research should focus on cost-effective nanoencapsulation techniques and optimizing carrier systems to enhance the stability of lavender-based formulations in aquafeeds (Sheikh et al., 2024).

OPTIMIZING DOSAGE AND ADMINISTRATION METHODS

The efficacy of *Lavandula angustifolia* in fish diets largely depends on the optimal dosage and the form of administration, which influence its bioavailability and physiological effects (Hajirezaee et al., 2022). Various studies have demonstrated that different lavender-derived products, such as essential oils, aqueous or ethanolic extracts, and dried plant material, can positively impact fish health, growth, and immune responses. However, the appropriate dosage varies based on species, life stage, and environmental conditions. Ensuring the correct concentration is crucial to maximizing benefits while preventing potential toxicity, particularly with highly concentrated forms like essential oils (Mirzaei et al., 2023).

Recent research suggests that lavender supplementation improves growth performance, immune response, gut microbiota composition, and oxidative stress resistance across multiple fish species (Dawood et al., 2022). However, the most effective form and dosage depend on species-specific physiological responses and metabolism. The following table summarizes optimal dosages and observed benefits in various fish species (Table 2).

Table 2. Optimal dosages of lavender on different fish species

Fish Species	Optimal Dosage	Observed Benefits	References
Nile Tilapia (*Oreochromis niloticus*)	1-2% extract	Enhanced immunity, improved growth	Al-Deraw et al., 2021
Rainbow Trout (*Oncorhynchus mykiss*)	0.5-1.5% essential oil	Reduced oxidative stress, enhanced antioxidant enzyme activity	Mirzaei et al., 2023
Common Carp (*Cyprinus carpio*)	1-1.5% extract	Improved gut microbiota, increased disease resistance	Rahmanet al., 2021
European Seabass (*Dicentrarchus labrax*)	0.5-1% extract	Enhanced growth performance, reduced lipid peroxidation	Abdel-Rahim et al., 2024
Catfish (*Clarias gariepinus*)	1-2% dried leaves	Improved hematological parameters, reduced stress biomarkers	Ebrahimi et al., 2023
Zebrafish (*Danio rerio*)	0.3-0.7% essential oil	Enhanced antioxidant defense, neuroprotective effects	Sharma et al., 2022
Japanese Flounder (*Paralichthys olivaceus*)	0.8-1.5% extract	Increased survival rates, improved immune gene expression	Liu et al., 2023

Despite these promising findings, further research is needed to standardize optimal dosage recommendations and investigate potential interactions with other phytogenics. Additionally, long-term studies should assess the safety and efficacy of continuous lavender supplementation, ensuring that its benefits persist over time without adverse effects (Sousa et al., 2023).

Potential risks and limitations of lavender supplementation in aquaculture

Lavender (*Lavandula angustifolia* Mill.) has shown promise as a phytoadditive in aquaculture due to its antimicrobial, immunostimulatory, and growth-promoting properties (Smith et al., 2021; Zhao et al., 2022). However, despite these benefits, several limitations and potential risks must be addressed before its widespread implementation in aquafeeds. Excessive doses may result in mild toxicity, metabolic disruptions, alterations in gut microbiota, and challenges related to standardization and quality control (Patel et al., 2021). A thorough evaluation of these factors is essential to optimize the application of lavender in fish nutrition.

Potential toxicity and metabolic disruptions

Lavender contains bioactive compounds such as linalool, linalyl acetate, and rosmarinic acid. However, excessive intake may induce toxic effects in fish species. High concentrations of essential oils and plant extracts have been shown to disrupt metabolic pathways, leading to hepatotoxicity, nephrotoxicity, or oxidative stress (Lis-Balkin et al., 2002; Li et al., 2022). For example, a study on Nile tilapia (*Oreochromis niloticus*) revealed that dietary inclusion of lavender oil above 1% increased hepatic enzyme activity, suggesting metabolic stress and potential hepatotoxic effects (Rodriguez et al., 2020). Similarly, excessive exposure to plant-derived essential oils can induce oxidative damage in fish tissues due to the generation of reactive oxygen species (ROS), impairing normal physiological functions (Hassan et al., 2023).

These findings highlight the necessity of dose optimization to prevent unintended metabolic disturbances while maximizing the benefits of lavender supplementation (Chakraborty et al., 2022).

Effects on gut microbiota and digestive processes

Another concern associated with lavender supplementation is its potential to alter gut microbiota composition in fish, which may affect nutrient absorption and immune function (Navarro et al., 2022). The gut microbiome plays a crucial role in fish health, aiding digestion, pathogen resistance, and immune modulation (Merrifield & Dimitroglou, 2021). However, excessive phytochemical intake may disrupt microbial equilibrium, favoring the proliferation of certain bacterial taxa while suppressing beneficial species (Wang et al., 2023).

Such imbalances may compromise gut integrity, leading to digestive inefficiencies and increased susceptibility to infections. Phytochemicals from lavender, particularly polyphenols, may exert antimicrobial effects that inadvertently suppress beneficial gut bacteria required for optimal digestion and immunity (Feng et al., 2021).

Digestive enzyme activity may also be affected by lavender supplementation. Research on Asian seabass (*Lates calcarifer*) indicated that lavender extract at high concentrations (above 4 g/kg) reduced amylase and protease enzyme activity, potentially interfering with nutrient assimilation (Das et al., 2020). While lavender provides immunostimulatory advantages, its impact on digestive physiology necessitates careful formulation strategies to avoid negative effects on gut health and nutrient utilization (Rahman et al., 2021).

CHALLENGES IN STANDARDIZATION AND QUALITY CONTROL

One significant challenge in utilizing lavender as an aquafeed additive is ensuring consistency in efficacy and safety across different batches of feed formulations. The bioactive composition of lavender extracts can vary considerably depending on plant cultivar, growth conditions, extraction methods, and storage conditions (Gupta et al., 2021). This variability poses a challenge in achieving standardized dosing, which is critical for maintaining predictable biological responses in fish (Karakaya et al., 2022).

For example, a comparative study on different lavender cultivars demonstrated substantial variation in linalool and rosmarinic acid content, with some extracts exhibiting significantly higher antioxidant activity than others (Silva et al., 2022). Such inconsistency raises concerns regarding the reproducibility of research findings and the effectiveness of lavender-based feed additives in commercial aquaculture settings (Pavlidis et al., 2023). Moreover, standardization issues may lead to fluctuating immune responses, as variations in phytochemical concentrations could result in either suboptimal or excessive immune stimulation, thereby affecting fish health outcomes (Castro et al., 2021).

Potential contamination with heavy metals, pesticides, or fungal toxins during lavender cultivation and processing poses another safety risk (Popescu et al., 2019; Ferreira et al., 2022). Quality control measures such as chromatographic fingerprinting and bioassays are essential to ensure that lavender-based additives meet required safety and efficacy standards (Gonzalez et al., 2021). Addressing these challenges will be crucial for the successful integration of lavender into sustainable aquafeed formulations.

Implications for commercial application

Given the potential risks associated with lavender supplementation, it is imperative to establish appropriate guidelines for its inclusion in aquaculture diets. Studies suggest that safe dosage levels vary among fish species, with most research indicating optimal effects at concentrations between 0.5% and 1.5% of total feed weight (Jiang et al., 2022). However, exceeding these thresholds may lead to adverse metabolic, microbial, or toxicological effects, underscoring the importance of species-specific trials and regulatory oversight (Martinez et al., 2023).

Furthermore, synergistic effects between lavender and other phytoadditives should be explored to optimize its benefits while reducing potential limitations. For example, combining lavender with prebiotics or probiotics may help maintain gut microbial balance, preventing dysbiosis while enhancing immune responses (Alvarez et al., 2022). Similarly, encapsulation technologies could improve the bioavailability and controlled release of lavender bioactives, reducing the risk of toxicity and metabolic disruptions (Oliveira et al., 2021).

CONCLUSIONS

Lavender is a promising phytoadditive in aquaculture, enhancing fish health, growth, and immunity through its bioactive compounds, particularly linalool and flavonoids, which improve nutrient absorption, gut microbiota, and oxidative stress resistance. Different administration methods, such as essential oils, dried flowers, and extracts, offer distinct benefits, with nanoemulsions enhancing bioavailability but requiring higher production costs. Future research should focus on optimizing dosage, evaluating long-term effects, and exploring synergies with other phytogenics across different fish species, life stages, and environmental conditions. Compared to other Lamiaceae plants, lavender demonstrates superior impacts on protein metabolism, gut microbiota, and oxidative stress reduction. Consideration of dosage and potential risks is necessary to ensure its safe and effective integration into sustainable aquaculture.

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