Chapter 23

Essential Oil-Based Functional Feeds for Promoting Growth in Aquaculture Species

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ABSTRACT

The aquaculture industry is searching for sustainable and environmentally friendly non-synthetic growth promoters to replace the synthetic, antibiotics or hormone-based additives. Essential oils, extracted from different plant material sources have recently been recognized as effective non-conventional natural feed additives for growth promoters in aquaculture species. Abstract This book chapter provides an overarching and comprehensive view on application of essential oil based functional feeds for growth promotion in aquaculture. Essential oils are complex mixture of volatile compounds with a variety of biological properties, which include antibacterial, antioxidant, immunomodulatory and orexigenic effects. It comes from enhancing feed intake, nutrient digestion and absorption, gut microbiota and intestinal health to digestive enzyme secretion, nutrient transporters, and hormonal pathways. The examination of these topics is also performed in the light of particular aquaculture species (carp, tilapia and catfish for freshwater; shrimp, salmon and sea bass for marine) at several life stages regarding distinct production systems. The present review provides an overview of the inhibitory effect and action mechanism on L. monocytogenes by essential oils, including source, composition combined with dosage, administration method and environmental conditions that may be instrumental for efficacy effects. This part accordingly addresses practical applications and feeding strategies (including the incorporation into commercial feeds, combination with other feed additives [prebiotics/probiotics]…), in particularly considering integrating probiotics for aquatic animal use would be an environmentally sustainable approach. The chapter concludes by discussing some of the challenges and future perspectives with respect to NEMs, such as safety concerns related to potential toxicity, compositional variability regulatory status, and consumer acceptance. Lastly, potential emerging trends and/or future directions are also discussed including new essential oil sources as well as other extraction methods like microwaving, blending strategies with existing therapies to improve efficacy of treatment for species that exhibit resistance towards available treatments along with encapsulation technologies for targeted delivery. In sum, this chapter highlights that only comprehensive and interdisciplinary collaborations will reveal the entire spectrum of research opportunities detailing functional feeds based on EOs for general applicability in sustainable aquaculture practices.

KEYWORDS
Aquaculture, Essential oils, Sustainable growth promoters, Functional

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INTRODUCTION

In the last few decades, aquaculture industry has grown at an impressive rate to meet seafood demand and overfishing of wild fish stocks. Despite the potential for substantial growth in an aquaculture Industry, sustainable and efficient development of marine aquaculture poses a significant challenge. Growth promotion is very important in achieving the desired maximum productivity, profitability and making it possible to meet the ever-increasing demands for aquatic products (Naylor et al. 2021). It is essential to accelerate aquaculture species growth-ons for numerous reasons.

Principally, by decreasing the production cycle and increasing productivity and economic feasibility of horticulture (Khanjaniand Sharifinia 2020). Second, better feed conversion results in less waste and reduces environmental impacts of wasted nutrients. Plus, growth promotion may also provide a higher quality and healthier product in the end that fits within consumers demands of sustainable seafood sources (Cooney et al. 2023). Historically, antibiotics and synthetic hormones have been administered to farmed aquatic animals as growth promoters. But there are also concerns over potential development of drug resistance, build-up of unhealthy residues in aquatic products and environmental and consumer health impacts (Mog et al. 2020). Owing to these limitations, there has been an increased focus on the scrutiny and regulations of some organic compounds used, hence leading to a need for safer or more sustainable alternatives.

The use of essential oils (EOs) are one such promising natural growth promoters in aquaculture, due to their multifunctional properties and proven potential towards growth performance, feed efficiency and health stimulus to cultured species (Qiu et al. 2024). EOs are volatile, fragrant oils extracted from many types of plant material including flowers, buds seeds leaves twigs bark herbs wood and roots. They have exhibited antimicrobial, antioxidant, immunomodulatory and appetite-stimulating abilities that might make them potential candidates to be functional feed additives in aquaculture arena (Tripathi et al. 2024). The application of functional feeds made with essential oil is more a promising method to induce growth and prevent the conventional limitations or concerns on traditional growth promoters in cultured species. The unique bioactive potential of essential oils could be harnessed to increase productivity, feed efficiency and the health status at farm level in a sustainable way within aquaculture (Grover et al. 2024).

Essential Oils and Their Bioactive Compounds

Essential oils are volatile, complex mixtures of chemical compounds originating from different parts of plants such as blossoms, buds/seeds (fruit), leaves and twigs; bark herbs fall into six categories according to the Botanical system Root. Such aromatic oils are normally extracted using various techniques including steam distillation, hydrodistillation, solvent extraction or cold pressing depending upon the plant material and spectra of oil to be obtained (Olalere et al. 2024). Steam distillation and hydrodistillation are two of the most popular methods, in which plant material is subjected to steam or boiling water (respectively) will cause volatile compounds to evaporate and then condense into essential oil (Pheko-Ofitlhile and Makhzoum 2024).

Essential oils contain a variety of different [sic] chemical constituents but mainly terpenes and phenolic compounds (Bakkali et al., 2008; Tongnuanchan and Benjakul, 2014). Monoterpenoids like limonene, α-pinene and β-pinene or sesquiterpenes are commonly found in essential oils which determine the unique scent profile of these extracts together with their pharmacological effects (Siddiqui et al. 2024). Also, some essential oils contain numerous phenolic compounds (e.g., caffeic acids; rosmarinic acid) and phenoilc diterpenes (e.g., carnosol, carnislic acd) which may contribute to a relevant content of these molecules in diet (Rastegarnejad et al. 2024). The essential oil and their bioactive compounds have a wide range of biotechnical potentials which could be useful in aquaculture. Most famously, they can kill off pathogens as a result of their ability to damage cell membranes, denature proteins and interfere with bacterial energy metabolism (Dawood et al. 2022). A number of essential oils, including oregano, thyme and clove oil are effective in killing a broad spectrum of pathogenic bacteria, fungi and viruses (de Almeida et al. 2023).

In addition, the antioxidant properties of essential oils can reduce oxidative stress and contribute to a healthier condition in fish. Essential oils have many constituents, and their antioxidant activity is primarily due to the phenolic ingredients which can exhibit free radical scavenging properties as well as inhibiting lipid peroxidation (Dawood et al. 2022). Furthermore, the immunomodulatory and anti-inflammatory effects of essential oils in addition to their stimulant effect on appetite would result in improved growth performance, feed utilization efficiency, health status etc. of aquatic species as reported by many authors (Mansour et al. 2024).

Due to the varied biological effects of essential oils and their bioactive components, they can be incredibly useful for incorporation into fish feed as functional additives in aquaculture which will again lead to advantages like improved growth performance,decreased severity from infectious diseases that mostly bring high mortality rate among cultured species (Hernández-Contreras and Hernández 2020).

Effects of Essential Oils on Growth Performance

Essential oils have been documented to enhance feed intake and appetite of several aquaculture species, thus improving growth performance (Bandeira Junior et al. 2022). Dietary ginger (Zingiber officinale) essential oil (GEO) supplementation significantly increased feed intake and weight gain in hybrid grouper Epinephelus lanceolatus ♂ × E. fuscoguttatus ♀ at higher doses compared to the control group (Adeli et al. 2021). Dietary black cumin (Nigella sativa) essential oil improves growth performance in Asian sea bass (Lates calcarifer) (Abd El-Hack et al. 2021). These effects have been considered as the reasons to explain why appetite-stimulating properties of essential oils could be mediated by evasion of olfactory or gustatory responses through aromatic features that can modulate levels and activities neuropeptides involved in regulating appetite (Nguyen et al. 2023). The inclusion of essential oils has allowed an increased nutrient digestibility and absorption in aquaculture species implying better growth performance (Dawood et al. 2022). For instance, Abdel-Latif et al. (2020) reveled that the addition of oregano essential oil (OEO) to diet enhanced nutrient digestibility while synthesis, mainly for dry matter, protein and energy in common carp feed were lower where results further reflected increment levels on growth performance values and FCR. The use of essential oils for modulating the gut

microbiota and promoting intestinal health could indirectly affect growth performance in aquaculture species. Antimicrobial and anti-inflammatory effects of essential oils help in maintaining gut microbiota homeostasis, promoting intestinal integrity which improves nutrient absorption leading to good growth performance (Firmino et al. 2021).

Essential oils were also shown to enhance feed intake, improve nutrient digestibility and absorption, modulate gut microbiota composition, which are the factors that primarily lead their growth-promoting effects in aquaculture species. It should be noted, however, that the species-selective effects may depend on essential oil composition and inclusion level required to study in a more detailed manner than it was done previously.

Mechanisms of Growth Promotion

Some of the best growth promoters in aquaculture species are essential oils since these have strong antimicrobial and anti-inflammatory properties. Mechanism of essential oils in their antimicrobial activity Essential oils are quickly able to disrupt cell membranes, denature proteins and interfere with important cellular processes that the microorganisms can no longer survive (Angane et al. 2020). Furthermore, the anti-inflammatory effects of essential oils can counteract inflammation-induced metabolic disorders and enhance nutrient utilization favoring growth (Pezantes-Orellana et al. 2024). These metabolites secreted by the essential oils can affect digestive enzymes and nutrient transporters, resulting in increased digestion of nutrients (Su et al. 2020). A study by Alagawany et al. (2020 Oregano essential oil (OEO) dietary supplementation enhanced the activity of digestive enzymes such as amylase, protease and lipase in gibel carp (Carassius auratus gibelio), leading to increased growth performance. The effects of various chemically defined bioactive compounds found in EOs modulate secretion of digestive enzymes, nutrient transporter activity and stimulate enzymatic function, acting on specific cellular signaling pathway mediators regulating gene expression (Patra et al. 2019). Essential oils interact with numerous hormonal and metabolic pathways which ultimately leads to growth promotion in aquaculture species (Aanyu et al. 2020). Furthermore, according to some studies reported that essential oils have potential of modulating the growth hormone such as insulin-like growth factors (IGFs) and Growth Hormone (GH) (Ahmadifar et al. 2021). Researches concerning the trials of bitter orange (citrus aurantium) essential oil on growth indicators, histology and gene expression levels in cyprinus carpioessential oils have a positive effect on the generation level to improve weight gain with two key genes that are GH and IGF-1. Moreover, essential oils may change the metabolic pathway that ensures energy production, protein synthesis and lipid metabolism for better nutrient utilization efficiency which facilitate growth (Kisová et al. 2020). The growth promoting mechanisms of essential oils in aquaculture species are diverse and include antimicrobial, anti-inflammatory Action regulation of digestive processes involving the modulation hormonal metabolic pathways. These mechanisms synergize to increase feed intake, nutrient utilization and overall growth performance as well, making essential oils an interesting candidate for a functional feeds additive in the aquaculture industry.

Essential Oils for Specific Aquaculture Species

Freshwater species (carp, tilapia, catfish, etc.)

The growth-promoting effects of essential oils have been promising in other freshwater aquaculture species. Several reports have mentioned the effects of essential oils on growth performance, feed efficiency and nutrient utilization in carp species (Cyprinus carpio), danio (Danio rerio), grass carp (Ctenopharyngodon idella) common silver barb Barbonymus gonionotus while additives oregano oil Origanum vulgare, garlic Allium sativum or ginger Zingiber officinale are recommended for use (Faheem et al. 2022). Dietary supplementation with garlic, thyme (Thymus vulgaris), and fennel essential oils increase growth, feed conversion ratio and the expression of some immune related genes in Nile tilapia Oreochromis niloticus (Dawood et al. 2022). Similarly, black cumin (Nigella sativa) and cinnamon (Cinnamomum zeylanicum) essential oils have exhibited growth-promoting activities in African catfish Clarias gariepinus and channel catfish Ictalurus punctatus species (Alnahass et al. 2023).

Marine Species (shrimp, salmon, sea bass, etc.)

Volatile compounds ascribed to essential oils have also shown potential for growth enhancement of different marine aquaculture species. Plant-derived essential oils, usually garlic (Allium sativum), thyme (Thymus vulgaris) and origanum, have been experimented on growth performance, feed utilization and disease-resistance in Pacific white shrimp Litopenaeus vannamei White Shrimp (Aktaş et al. 2022 Several studies have already shown that essential oils from thyme, oregano and rosemary could increase growth rate, nutrient digestibility or gut health in european sea bass (Dicentrarchus labrax) and gilthead sea bream [Sparus aurata] juveniles (Yılmaz et al. 2022).

Considerations for different Life Stages and Production Systems

Before using essential oils as growth promoters in aquaculture, one should take into account the specific life stages and production systems. The inclusion levels of essential oils and the type to be incorporated will depend on species, life stage (larvae or juveniles) and production system used (intensive, semi-intensive or extensive); but only at a certain level can it benefit your business. In addition, factors such as water quality, temperature and feeding regime can affect the effectiveness of Eos (Kimera et al. 2021). For example, higher doses of essential oils may be required in intensive production systems with high stocking densities due to increased stress levels and potential for disease outbreaks (Maulu et al. 2021). For instance, because stocking density is higher and stress and potential for disease breakouts are also higher in intensive production systems, those animals might require more rounds of essential oils or at a stronger dose. In

addition, the method of EO application (coated with feed encapsulated form; or directly added to water) and stability of compounds during skin processing and storage using are recommended as important considerations (Tolve et al. 2021). Well formulated and encapsulated essential oils can be used as bioenhancing agents to provide better stability, safety along with maximum benefit delivery in aquaculture feeds. In conclusion, the choice and use of essential oils as growth promoters in aquaculture should be adapted to each species, stage of life and culture system considering water quality conditions, feeding regimes especially during (stressful) events like transport or handling and ways to deliver them best to maximize their effects on growt performance (Reverter et al. 2021).

Factors Influencing Efficacy

Essential Oil Source, Composition, and Quality

The source, composition and quality of essential oils may exert significant impact on their efficacy as growth promoters in aquaculture. The plant species, geographical origin of the plants and harvesting time, extraction methods applied to obtain essential oils from them can greatly influence their chemical composition as well bioactive properties (Ni et al. 2021). The bioactivity of oregano essential oil (OEO) the main phytogenic feed supplement additive can vary due to differences in carvacrol and thymol concentrations (Bauer 2020). In low-quality essential oils, the presence of Adulterants, contaminants or degradation products diminishes their biological activities and can raise concerns over safety (Ali et al. 2023).

Dosage, Administration Method, and Feed Formulation

The effectiveness of essential oils as growth promoters in aquaculture is related to the dosage, administration route and feed matrix used. The appropriated level of essential oils could be changed by the type of target species, life stage and environmental status (Dawood et al. 2022). This can cause growth performance to have sub-therapeutic or in worse case, adverse effects due to over/underdosing (Parihar et al. 2022). Besides the above, bioavailability and stability of essential oils are also influenced by incorporation methods including direct addition to feed, encapsulation or delivery via water (Fathi et al. 2021). A correct feed formulation and processing methodology are necessary to obtain the homogeneous distribution, stability and retention of essential oils in aquafeeds.

Environmental Conditions (temperature, salinity, etc.)

In the aquaculture system essential oils are proposed as growth promoters but their role is influenced by several environmental conditions, water temperature, salinity and pH. The solubility and stability of essential oils depend on the type of EO, how they are stored, temperature exposure etc., which has a significant impact to their bioavailability or potency (Kimera et al. 2021). The whole process of a particular acids or bases is shown at the same time it expands over more an entire regional chemical environment like high saline water temperature, and aromatherapy essential oils would decrease in activity. Likewise, environmental stressors (e.g., high stocking densities or poor water quality) could also influence the growth performance and condition of aquatic organisms which may change their response to essential oils (Shourbela et al. 2021). These are important considerations when using essential oils as growth promoters in aquaculture. Detailed knowledge of essential oil profile and proper concentration, route of application as well the environmental factors are pre-requisite for exerting their maximum potential in growth performance and general health status maintenance of cultured species. Hence, systematic quality control and standardization of EOs product before application is necessary in order to ensure the consistency and reproducibility of performance as well as maintain consumers' confidence on its use for aquaculture industry (Kuebutornye et al. 2024).

Practical Applications and Feeding Strategies

Incorporation into Commercial Feeds or Top-dressing

There are various ways that essential oils can be mixed into commercial aquaculture feeds, and each way has its own set of benefits as well as drawbacks. Direct mixing of the oils or their encapsulated forms into feed at manufacture is one common means. This method guarantees a uniform dispersion of the essential oils in its feed and allows calibrated dosing. However, to preserve the stability of essential oils and prevent them from being deactivated or oxidized during feed processing and storage may still require specific equipment a technology (Beltrán and Esteban 2022). On the other hand, you can top-dress essential oils by either mixing them into feed or spraying/ coating on it. This protocol is uncomplicated and could be executed on-site, allowing freedom to change doses/formulations. However, top-dressing could lead to non-uniform distribution of volatile essential oils and subsequent losses during feed handling or transportation (Marimuthu et al. 2022).

Use in Combination with other Feed Additives (prebiotics, probiotics, etc.)

Phytogenics could be used in combination with other alternative feed additives i.e. prebiotics and probiotics that may help to improve the growth-promoting effects of such diets under field conditions. They can also modify the microbiota through the use of prebiotics (Mannan-oligosaccharides, MOS and Fructo-oligosacharides FOS) therefore helping to enhance nutrient utilization. When converted with essential oils (Anti microbial and Anti-inflammatory) than there activity can be synergized in combination which may improve the gut health, nutrient absorption leading to the overall growth performance of animals (Vijayaram et al. 2022). In the same way, probiotics, like lactic acid bacteria and Bacillus species can help to balance the intestine microbiota, bolster immune function and improve feed conversion efficiency in addition of

essential oils. Nevertheless, the compatibility and possible interactions of essential oils with other feed materials should be investigated thoroughly to achieve the desirable beneficial effect without interfering in adverse manners (Dasriya et al. 2024). Additonaly, the use of essential oils as growth promoters may also be combined with other sustainable aquaculture practices such as Integrated Multi-trophic Aquaculture (IMTA) or fish feed plant protein inclusion (Knowler et al. 2020). A comprehensive approach combining EOFFs with other sustainable techniques can help aquaculture to achieve the high and profitable production of disease-free stock, reducing pollution from drugs in water bodies, improving fish welfare including stress reduction and increased yields. The practical use of essential oils in aqua feed is complex and involves aspects related to dosage type, compatibility with other substances added to the diet as well as its harmony with growth management. A holistic approach is essential to allow aquaculture producers to harness the potential growth-promoting effects of EO compounds, while continuing towards optimized outcomes for better sustainability and consumer acceptance in this sector.

Challenges and Future Perspectives

Potential Toxicity and Safe Dosage Levels

Although essential oils are generally promising as growth promoters in aquaculture, their toxic effects and safe therapeutic dose concentrations need to be verified. Some essential oils or their major constituents might show toxicity at higher levels, which in turn adversely impacts the growth, survival and health of the cultured species. In this regard, excessive levels of essential oils such as garlic (Allium sativum), thyme and oregano have been shown to induce oxidative stress, histopathological changes in gills and barrel by mortality mechanisms in various fish species. It is absolutely critical to set the optimal dose range and determine maximum tolerable levels of essential oils for each target species and life stage so that they can be safely applied at a field level. Moreover, the bioavailability of EO compounds in edible tissues should be considered to ensure food safety and regard economical regulations because their is always a possibility for Bioaccumulation (Ciji and Akhtar 2021).

Variability in Composition and Bioactive Compound Content

One of the drawbacks related to practical applications of essential oils in aquaculture consists on their natural dynamic process with an enormous variabilityaffecting both its composition and bioactive compound content. The chemical composition of essential oils is mainly related to their genetic origin, plant morphology and physiology as well as the concomitant environmental parameters where they grow such harvesting season or part of the plant used in extraction. This variability can be an impediment for the growth promoters properties of essential oils, given that inconsistent composition may result in inconsistency on their biological activities and performance effects (Dawood et al. 2021). It necessitates the development of standardized production methods, quality control measures and analytical techniques to maintain consistent composition and potency of essential oils. Future research should also be directed at the isolation, identification and characterization of bioactive compounds that can stimulate growth in order to create better formulations.

Regulatory Aspects and Consumer Acceptance

Consumer acceptance and regulatory guidelines for the use of essential oils as growth promoters in aquaculture. Although essential oils are mostly recognized as GRAS (general regarded safe) for human consumption, their use in aquaculture where they exhibit to be beneficial has not been yet approved together with specific maximum limits and/or regulatory obligations. Those regulations can significantly differ from one region to another, or even between country and country; therefore compliance with the local law is a must for each target market (Angane et al. 2022). In addition, to be commercially viable, it essential that consumers perceive and accept aquaculture products containing the functional feeds with natural sources of EOs. Consumers have started asking for transparency and minimal use of synthetic additives in the making of food. Communications and education campaigns are essential indicators of the benefits that attract shareholders, investors toward natural growth promoting with ESSENTIAL OILS (Meijer et al. 2021) In the future, studies should be designed to overcome those barriers conducting full toxicological inquiries developing standardized manufacturing and quality inspection practice working with regulatory organizations or stakeholders in order to draw appropriate guidelines on essential oils application in aquaculture. Moreover, investigating the promise of a combined effect between essential oils to be used in combination with other botanicals or aquaculture practices may help improve their growth-promoting properties and sustainability. ConclusionBy confronting such challenges and harnessing the untapped potential of essential oils as natural growth promoters, aquaculture sector could put itself in a setting for more sustainable ecological friendly practices that will be necessary to deliver high-quality seafood meets without compromising on environmental impact which is vital if it wishes to instill consumer confidence.

Emerging Trends and Future Directions

Novel Essential Oil Sources and Extraction Methods

Novel plant sources and a charge in the extraction technique for essential oils especially are expected to have great potential within aquaculture. Essential oils derived from underutilized or lesser-known plant species are assessed by different research groups for their growth-promotional properties in multiple aquaculture species. This diversification of essential oil sources can unveil new effective bioactive compounds present in the oils or it may provide unique synergistic combinations, thus increasing their efficacy as growth promoters. Moreover, advances in extraction technologies such as

supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), and ultrasound-assisted extraction have shown potential to enhance essential oil yield, quality or selectivity of the compounds involved. This has particular relevance for the modern aquaculture and food industry by providing novel extraction techniques that will help to retain bioactive compounds, decrease thermal-based degradations as well as drastically reduce harsh solvent uses which also fits within sustainable development goals (SDB) in this sector.

Combination Strategies and Synergistic Effects

Synergistically combining different essential oils or with other natural feed additives is a fresh avenue in aquaculture research. Other studies have shown that prebiotics, probiotics or plant derived compounds combined with essential oils may further stimulate changes in the gut bacterial population due to synergistic effects (Mekonnen et al. 2024).

Encapsulation and Targeted Delivery Systems

Rising interest includes employing encapsulation and targeted delivery systems as potential strategies to improve the efficiency and bioavailability of essential oils in aquaculture feeds. Encapsulation (e.g. emulsification, liposome entrapment and nanoparticle encapsulation) can provide the essential oils with a barrier against oxidation in feed form or during storage as well benefit to control release at target location. Additionally, these delivery vehicles have the potential to enhance essential oil stability and solubility while improving their bioavailability thereby facilitating its targeted action across gastrointestinal sites in aquatic animals. Besides, targeted delivery of essential oils can allow reduction in the dosing levels and alleviation of interactions with other feed components resulting ultimately to optimize growth-promoting effects. Continuous research is being carried out for developing nanoparticle technologies, utilizing carriers to enhance retention and encapsulation loading of essential oils and in the applications with different aquaculture species production. The search for new essential oil sources, the combination of several plant-derived compounds or adjustable and efficient delivery systems represent a strong promise to improve growth promotion with limited impact on the environment in context of aquaculture production towards future sustainability including consumers' application issues about synthetic additives.

Summary of Key Findings

Abstract The application of essential oil-based functional feeds is being regarded as a potential solution for growth in aquaculture species. From different plant origins, essential oils contain a large number of bioactive compounds with antimicrobial, antioxidant, immunomodulatory and orexigenic potential. In various freshwater and marine aquaculture species, the use of these natural agents has shown to support growth performance as well feed efficiency, nutrient utilization and thereby obtained better overall health.

Key mechanisms by which essential oils promote growth include, their antimicrobial and anti-inflammatory effects; alterations in secretions of digestive enzymes and nutrient transporters… hormones pathways, metabolism etc.mapping are described about various EOs possession. The efficiency of volatile plant oils, especially natural ones can be varied from several factors including origin and chemical profile off the essential oiler; dosage in administration method feed formulation an environmental situations.

Potential Applications in Sustainable Aquaculture

Functional feeds, with essential oil as one of the functional ingredients reported numerous beneficial effects in terms of sustainable aquaculture practices. These are commonly used as direct fed microbial in animal feed:Direct-fed microbials (DFM) and have been sought after, both for their potential use to promote intestinal health within the host enteric system. In addition, combining essential oils with other sustainable approaches including plant-based protein sources and integrated multi-trophic aquaculture (IMTA) may help support a more general sustainability of the entire industry. The role of essential oils in efficient growth and feed utilization, coupled with an environmental performance aspect (decrease excessive feed waste; lower nutrient discharge), would help the sector to become more sustainable over a longer-term. Natural and sustainable perceptions may also be a motivation for consumer acceptance of these products, with potential high demand in this very active area which has long been pushing the industry to adopt more eco-friendly alternative feed ingredients.

Future Research Opportunities and Collaborations

By all means, essential oils have shown to be viable growth promoters in aquaculture till now much progress has been made and an array of research opportunities together with collaboration exist yet to never unveil. Rigorous toxicology studies and determination of safe dosages at the specific oil-calibrant-species matrix level will be essential for their successful applications under regulatory scrutiny. In addition, research activities should be targeted to establish standardization of production processes and QC measures as well as the analysis methods that will cope with the diversity in EO composition or content. Academic–industrial (as well as regulatory) partnerships might help to translate this work into concrete guidance for the use of essential oils in aquaculture. Innovative ideas for future studies are exploiting unutilized EO sources, combinatorial strategies with other natural feed additives like prebiotics and probiotics, designing the next-generation encapsulation systems and targeted delivery platforms. These progressions may serve to increase the effectiveness, bioavailability and site-specific delivery of EOs leading them more potent in enhancing the growth-conducive effects [44]. To support these research efforts intensive interdisciplinary-work with experts in plant sciences,

analytical chemistry, animal nutrition as well as aquaculture production and regulatory affairs will be essential. These interactions may lead to the sharing of information and resources which, in turn, can facilitate sustainable practices with regard to environmental concerns as well as consumer interests (e.g., seafood demand) on a global scale.

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