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IMMUNOSTIMULATORY PHYTOADDITIVES AND THEIR BENEFITS FOR FISH

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Abstract

Derived from plants, phytoadditives are emerging as a sustainable solution to enhance fish health and aquaculture practices. These compounds, including essential oils, herbal extracts, and polyphenols, improve immunity and reduce antibiotic use. Their antioxidant, antimicrobial, and immunomodulatory properties improve immune system and increase disease resistance on fish. The effectiveness of these additives depends on plant type, extraction methods, and dosage. Additional research is required to refine their use and evaluate the long-term effects on fish health and the sustainability of aquaculture.

***Key words**: fish welfare, herbal extracts, oxidative stress, phytoadditives, sustainable aquaculture.*

INTRODUCTION

Aquaculture is one of the most important sectors in global food production, playing a crucial role in meeting the increasing demand for fish protein (Ivan et al., 2024). It provides an important source of protein for human consumption (FAO, 2020). In recent decades, aquaculture production has grown rapidly, surpassing capture fisheries in terms of growth rate (FAO, 2022). However, the intensification of fish farming practices has introduced several challenges, with one major concern being the increased vulnerability of farmed fish to infectious diseases. This is further exacerbated by the excessive use of antibiotics, which disrupt aquatic ecosystems and environmental degradation (FAO, 2020; Cabello et al., 2013). These health risks are also amplified by stress factors such as overcrowding, handling, and environmental fluctuations (Li et al., 2004; Harikrishnan et al., 2011). Disease outbreaks in aquaculture significantly contribute to economic losses, with some regions experiencing production losses of up to 50% (Assefa & Abbuna, 2018).

The growing demand for eco-friendly and sustainable aquaculture practices has led to the exploration of alternative health management strategies, among which medicinal plants have gained significant attention due to their natural bioactive properties (Dawood et al., 2018). Plant-derived compounds, including essential oils, polyphenols, and herbal extracts, have been recognized for their ability to enhance fish immunity and overall welfare (Reverter et al., 2021).

The traditional reliance on antibiotics and synthetic drugs in aquaculture has raised concerns regarding the emergence of antibiotic-resistant pathogens, which pose a significant threat to both aquatic organisms and human health (Cabello et al., 2013). Moreover, the residual accumulation of these synthetic compounds in fish tissues and the surrounding environment has led regulatory agencies to impose strict limitations on their use (Van Boeckel et al., 2019). In this context, phytoadditives have emerged as promising natural alternatives due to their immunomodulatory, antimicrobial, and antioxidant properties (Adel et al., 2015). Unlike conventional drugs, phytogenic compounds offer a sustainable approach by stimulating innate and adaptive immune responses, thus enhancing disease resistance without inducing resistance in pathogens (Zhang et al., 2022).

These compounds exhibit antimicrobial, antioxidant, and immunostimulatory properties (Citarasu, 2010; Van Hai, 2015; Hoseinifar et al., 2020). Studies have shown that supplementing fish diets with plant extracts can improve growth performance, enhance disease resistance, and modulate immune responses in various fish species, including hybrid grouper (*Epinephelus lanceolatus* × *Epinephelus fuscoguttatus*) and rainbow trout (*Oncorhynchus mykiss*) (Sun et al., 2022; Adel et al., 2020).

The immunostimulatory properties of phytoadditives play a crucial role in strengthening fish against various pathogens, including bacteria, viruses, and parasites (Citarasu, 2010). Numerous studies have demonstrated that phytochemicals such as flavonoids, alkaloids, tannins, and terpenoids can modulate immune-related gene expression and enhance the activity of key immune enzymes, such as lysozymes, complement proteins, and superoxide dismutase (Chakrabarti et al., 2012). Furthermore, their ability to regulate oxidative stress and inflammatory responses provides additional health benefits, ensuring improved survival rates and better growth performance in aquaculture species (Dawood & Koshio, 2016).

A promising approach involves using natural products, particularly phytoadditives derived from medicinal plants, as dietary supplements in aquaculture (Gheisar & Kim, 2018).

A key factor influencing the effectiveness of phytoadditives is the extraction method and the plant source utilized. Various extraction techniques, including solvent extraction, supercritical fluid extraction, and ultrasonic-assisted extraction, influence the concentration and bioavailability of active compounds in fish feed (Hernández et al., 2022). Additionally, factors such as dosage, administration route, and fish species specificity play a critical role in determining their efficacy (Abdel-Tawwab et al., 2021). While several studies highlight the beneficial impact of phytoadditives on immune function and disease resistance, further research is necessary to establish standardized formulations and evaluate their long-term effects on fish health and aquaculture sustainability (Van Hai, 2015).

Plants from the *Thymus* genus have demonstrated potential in disease prevention, immune system enhancement, and improving production performance in various fish species (Wunderlich et al., 2017; Honcharenko et al., 2018; Yassen et al., 2017; Hoseini & Yousefi, 2018; Nieto, 2020). Research has also explored their role in water quality management, particularly in the development of natural water filters. Studies investigating the effects of lavender and thyme, both individually and in combination, on water quality, fish growth, and overall health, have further emphasized the multiple benefits of medicinal and aromatic plants in sustainable aquaculture (Filep et al., 2016; Boaru et al., 2022).

According to recent FAO statistics (2022), the use of medicinal plants in aquaculture has increased by 35% over the past decade, reflecting the growing demand for sustainable fish health management strategies. Notable examples include studies on *Ocimum basilicum*, which has shown significant enhancement of immune responses in Nile tilapia (*Oreochromis niloticus*) by increasing lysozyme activity and phagocytic index (García-Beltrán et al., 2021). Extracts from *Withania somnifera* have demonstrated strong immunostimulatory effects in common carp (*Cyprinus carpio*), reducing mortality rates caused by bacterial infections (Singh et al., 2022).

Given the increasing interest in phytogenic feed additives, this review will explore the potential benefits of immunostimulatory phytoadditives in aquaculture. It will examine the mechanisms through which these bioactive compounds enhance immune function, their antimicrobial and antioxidant effects, and their role in reducing oxidative stress. Furthermore, it will discuss the current applications of phytoadditives in aquaculture, their potential limitations, and future directions for their integration into sustainable fish farming practices. By synthesizing the latest research, this review aims to provide a clear vision of the potential of phytobiotics as natural agents in promoting health in aquaculture.

MATERIALS AND METHODS

Published data on phytoadditives, were collected, using online scientific databases like Web of Science, Research Gate, Science Direct and Google Scholar. Priority was given to studies addressing the application of medicinal plants in aquaculture and fish farming. The

reference lists of all retrieved articles were also screened to identify additional relevant sources. Only articles published in English were considered, emphasizing those investigating the use of phytoadditives as a dietary supplement, as well as it`s roles as an antioxidant, antimicrobial, or for other purposes within aquaculture systems.
Both original research articles and review papers were included in the present analysis.

RESULTS AND DISCUSSIONS

PHYTOBIOTICS IN AQUACULTURE: DEFINITION AND THERAPEUTIC POTENTIAL

The application of phytobiotics in aquaculture is gaining substantial recognition due to their natural, sustainable, and therapeutic properties. Phytobiotics, which are plant-derived bioactive compounds, have been shown to provide various beneficial effects on fish health, including immunomodulation, disease resistance, and enhanced growth performance. This review explores the definition, classification, and therapeutic properties of phytobiotics in the context of aquaculture and fish health. Emphasis is placed on key bioactive compounds such as essential oils, polyphenols, flavonoids, and alkaloids, which have demonstrated promising potential for improving the health and welfare of farmed fish (Zhang et al., 2020).
Phytobiotics refer to bioactive compounds extracted from plants that exhibit therapeutic properties beneficial for fish health and growth. These compounds are increasingly being used as alternative or supplementary additives to synthetic chemicals and antibiotics, offering an eco-friendly solution to disease prevention and growth enhancement in fish (Surmeli et al., 2019; Zhang et al., 2020). The bioactive compounds found in phytobiotics are responsible for the therapeutic effects that promote fish health and well-being. These compounds exhibit a range of biological activities, including antimicrobial, antioxidant, immunomodulatory, and anti-inflammatory effects. Phytobiotics can be classified into several groups, including essential oils, polyphenols, flavonoids, and alkaloids, based on their chemical structure and biological activities.
For instance, a study by Nguyen et al. (2022) demonstrated that plant-based products, such as thyme essential oil, have significant antimicrobial effects against pathogens affecting farmed fish, which suggests that phytobiotics can be an alternative to synthetic antibiotics in aquaculture. Additionally, Sharma et al. (2020) reported that polyphenols extracted from green tea exhibited antioxidant and anti-inflammatory properties that enhanced the immune responses of fish, reducing the incidence of disease outbreaks.

Essential Oils

Essential oils are volatile, aromatic compounds derived from plant materials through methods like distillation or cold pressing. These oils contain various organic compounds, including terpenoids and phenylpropanoids, which exhibit antimicrobial, anti-inflammatory, and antioxidant properties that can benefit fish health (Bakkali et al., 2008). Notably, essential oils from plants such as oregano, thyme, and garlic are especially recognized for their potent antimicrobial effects, making them valuable for preventing infections in aquaculture settings. For instance, research by Cimino et al. (2021) demonstrated that oregano oil significantly mitigated bacterial infections in farmed tilapia, leading to improved overall health. The active compounds such as allicin (garlic) and carvacrol (oregano), which have been shown to effectively inhibit the growth of pathogenic bacteria and fungi in fish farms (Cimino et al., 2021). In addition to their antimicrobial properties, other essential oils like eucalyptus and peppermint have been found to reduce stress in fish, promoting their overall well-being (Bakkali et al., 2008). For example, a study by Wang et al. (2021) emphasized the antimicrobial activity of garlic oil, showing that it effectively decreased bacterial infections in farmed trout. These findings underscore the therapeutic potential of essential oils in enhancing fish health and preventing disease outbreaks in aquaculture.

Polyphenols

Polyphenols are secondary metabolites found in plants, known for their potent antioxidant properties. These compounds play a crucial role in neutralizing free radicals and reducing oxidative stress within cells. In the context of aquaculture, polyphenols are utilized to boost fish immunity, enhance disease resistance, and promote overall health (Milanović et al., 2020). For example, research by Iqbal et al. (2021) on polyphenol enriched extracts from rosemary and turmeric demonstrated significant improvements in the immune responses of rainbow trout, leading to enhanced disease resistance.

Polyphenols such as ellagic acid and resveratrol, present in various fruits and herbs, have also shown considerable health benefits in fish, including reduced inflammation and strengthened immune responses (Baur & Sinclair, 2006). These compounds are among the most extensively studied bioactive components in phytobiotics for aquaculture. The strong antioxidant activity of polyphenols helps protect fish from oxidative damage caused by environmental stressors. Resveratrol, found in grapes, for instance, has been shown to improve immune responses in fish, thus enhancing their resistance to infections and diseases (Baur & Sinclair, 2006).

Furthermore, polyphenols such as tannins, present in plants like oak and tea, exhibit antimicrobial and anti-inflammatory properties, contributing to better overall health in fish (Milanović et al., 2020). In line with these findings, Zhang et al. (2020) observed that polyphenolic extracts from green tea enhanced immune function in freshwater fish, thereby reducing the incidence of bacterial infections. These studies highlight the significant role of polyphenols as therapeutic agents in aquaculture, promoting fish health and disease resistance.

Flavonoids

Flavonoids, a subclass of polyphenols, are widely recognized for their potent antioxidant, anti-inflammatory, and anticancer properties. In aquaculture, flavonoids such as quercetin and catechins have demonstrated significant benefits, including enhanced immune responses, reduced oxidative stress, and improved disease resistance in fish (Nijveldt et al., 2001). For example, a study by Li et al. (2021) revealed that dietary supplementation with quercetin in common carp significantly increased resistance against *Aeromonas hydrophila*, a prevalent aquatic pathogen. These bioactive compounds, commonly found in plant sources such as citrus fruits, onions, and green tea, have been extensively studied for their immunomodulatory effects and their potential to enhance growth performance in farmed fish (Li et al., 2021).

Flavonoids have gained increasing attention in aquaculture due to their ability to regulate immune function and strengthen disease resistance. Quercetin, a flavonoid abundant in onions and apples, has exhibited strong anti-inflammatory and antioxidant properties, shielding fish from oxidative damage and mitigating the impact of inflammatory diseases (Nijveldt et al., 2001). Additionally, catechins, another group of flavonoids primarily found in green tea, have been shown to upregulate immune-related gene expression, thereby improving the ability of fish to combat infections (Li et al., 2021). Supporting this, Zarei et al. (2019) conducted a study on shrimp and found that catechins extracted from green tea enhanced disease resistance by modulating immune responses. These findings highlight the promising role of flavonoids as natural immunostimulants in aquaculture, offering a sustainable approach to improving fish health and resilience against diseases.

Alkaloids

As compounds found in several plants, alkaloids contain nitrogen and they are known for their therapeutic properties. Nicotine, caffeine, and quinine have been explored for their pharmacological effects, including their ability to modulate fish physiology, enhance stress tolerance, and promote disease resistance (Wink, 2015). However, the use of alkaloids in aquaculture must be carefully managed due to their potential toxicity at high doses. An example of alkaloids in aquaculture includes the study by Silva et al. (2019), which investigated the use of caffeine to alleviate the effects of hypoxia on farmed tilapia, showing that caffeine supplementation could improve stress tolerance and growth performance in fish. Alkaloids, such as caffeine and nicotine, are known for their ability to modulate the physiological responses of fish. For example, nicotine has been shown to have anti-inflammatory effects, while caffeine has been linked to improved stress tolerance and enhanced immune function in fish (Wink, 2015). Alkaloids can also serve as stimulants, promoting increased feed intake and improved growth rates in fish under specific conditions. A study by Oliveira et al. (2020) showed that the administration of nicotine in fish diets promoted growth in farmed tilapia by enhancing appetite and metabolic rate, highlighting the role of alkaloids in fish production.

ROLE OF MEDICINAL PLANTS IN FISH HEALTH

Growth promotion

Medicinal plants have been extensively studied for their ability to enhance fish growth, primarily by improving feed utilization, digestive efficiency, and nutrient absorption (Palanikani et al., 2020). For example, *Andrographis paniculata* has demonstrated improvements in feed conversion efficiency in *Labeo rohita* (Palanikani et al., 2020). Similarly, *Ocimum basilicum* (basil) has been identified as an effective growth promoter by enhancing protein metabolism and stimulating enzymatic activity in fish (Behl et al., 2021). The mechanisms underlying these growth-promoting effects are largely attributed to the presence of active compounds that facilitate nutrient uptake and optimize metabolic processes (Fu et al., 2019).

Immunostimulatory Effects

Medicinal plants are widely recognized for their immunostimulatory properties, which enhance the fish immune system and increase resistance to pathogens (Liu et al., 2022). Active compounds such as flavonoids, alkaloids, and polysaccharides found in plants like *Sophora flavescens* and *Rosmarinus officinalis* (rosemary) stimulate both innate and acquired immune responses in fish (Shen et al., 2019; Alavinia et al., 2018). Studies have shown that *Sophora flavescens* extracts significantly enhance immune responses, providing better resistance against viral infections, while rosemary extracts improve antioxidant enzyme activity, boosting fish immunity (Alavinia et al., 2018; Liu et al., 2022). The immunomodulatory potential of medicinal plants offers a promising alternative to synthetic antibiotics, which are commonly used in aquaculture but contribute to the rise of antibiotic resistance (Shah et al., 2021).

Antihelminthic Properties

Many medicinal plants exhibit antihelminthic (anti-parasitic) effects, which are crucial for controlling parasitic infestations in aquaculture systems (Fu et al., 2019). For instance, extracts from *Dioscorea colletti* are highly effective against *Gyrodactylus kobayashii*, a parasitic species that infects goldfish (*Carassius auratus*) (Zhou et al., 2021). Similarly, plants such as *Thymus vulgaris* (thyme) and *Origanum vulgare* (oregano) have shown significant antiparasitic activity, disrupting parasite reproduction and reducing infection rates in fish populations (Fu et al., 2019). The use of medicinal plants as antihelminthic agents in aquaculture offers an environmentally friendly and cost-effective means of parasite control, contributing to sustainable fish farming practices (Zhou et al., 2021).

Antioxidant and Antimicrobial Properties

Oxidative stress, often induced by environmental stressors such as poor water quality and high stocking densities, is a major concern in aquaculture (Liu et al., 2020). Medicinal plants rich in antioxidants, such as *Illicium verum* (star anise), have been shown to reduce oxidative damage in fish, improving overall health and survival (Liu et al., 2020). Furthermore, the antimicrobial properties of essential oils from *Mentha piperita* (peppermint) and *Lavandula angustifolia* (lavender) effectively combat common aquatic pathogens like *Aeromonas hydrophila* and *Vibrio spp.*, reducing disease outbreaks in farmed fish (De Souza Silva et al., 2019). These plants not only contribute to fish health but also reduce the need for synthetic antimicrobial agents, which are often associated with the development of antibiotic-resistant strains (Li et al., 2022).

Antiviral Properties

Viral diseases are a significant threat to fish farming, causing severe losses in production (Shen et al., 2019). Several medicinal plants possess antiviral properties that help reduce the impact of viral infections in aquaculture. For

example, *Gardenia jasminoides* (gardenia) contains *geniposidic acid*, which has been shown to inhibit viral replication, offering protection against viral infections in farmed fish (Huang et al., 2019).
Similarly, extracts from *Lonicera japonica* (honeysuckle) and *Bupleurum falcatum* have demonstrated antiviral activity by preventing viral attachment and replication (Shen et al., 2019). By incorporating such plants into aquaculture systems, farmers can help mitigate the spread of viral diseases, reducing the need for costly vaccines and chemical treatments (Huang et al., 2019).

Anti-Stress Effects

Stress is a major factor that negatively impacts fish health in aquaculture systems (Qian & Zhu, 2019). Medicinal plants, such as *Citrus* species, have been shown to reduce cortisol levels and alleviate stress in fish (Qian & Zhu, 2019). Moreover, *Matricaria chamomilla* (chamomile) has been reported to have calming effects, reducing stress-induced oxidative stress markers and promoting relaxation in stressed fish (Lim et al., 2020). The use of such plants with anti-stress properties can improve fish welfare, increase growth rates, and reduce the negative effects of environmental stressors in intensive aquaculture systems (Lim et al., 2020).

Most Commonly Used Medicinal Plants in Aquaculture

The following table summarizes some of the most commonly used medicinal plants in aquaculture and their specific effects they have on fish (Table 1).

Table 1. Most Commonly Used Medicinal Plants in Aquaculture

Medicinal Plant	Latin Name	Effects on Fish	Reference
Ginger	*Zingiber officinale*	Antiparasitic, antimicrobial	Trasviña-Moreno et al., 2019
Licorice	*Glycyrrhiza uralensis*	Antiviral, antibacterial	Li et al., 2022
Star Anise	*Illicium verum*	Antioxidant, antiviral	Liu et al., 2020
Basil	*Ocimum basilicum*	Growth promoter	Behl et al., 2021
Thyme	*Thymus vulgaris*	Antibacterial, antihelminthic	Fu et al., 2019
Lavender	*Lavandula angustifolia*	Antimicrobial, stress reducer	De Souza Silva et al., 2019
Oregano	*Origanum vulgare*	Antimicrobial, antibacterial	Behl et al., 2021
Rosemary	*Rosmarinus officinalis*	Immunostimulant, antioxidant	Alavinia et al., 2018
Turmeric	*Curcuma longa*	Antioxidant, anti-inflammatory	Shahat et al., 2021
Echinacea	*Echinacea purpurea*	Immunostimulant, anti-inflammatory	Pandey, 2013
Aloe Vera	*Aloe barbadensis miller*	Antioxidant, wound healing	Ali et al., 2020
Clove	*Syzygium aromaticum*	Antibacterial, antifungal	Tamer et al., 2021
Mint	*Mentha* spp.	Antimicrobial, stress reducer	Liu et al., 2022
Sage	*Salvia officinalis*	Antioxidant, antimicrobial	Behl et al., 2021
Chamomile	*Matricaria chamomilla*	Stress reducer, antioxidant	Lim et al., 2020

EXTRACTION METHODS FOR PHYTOADDITIVES

The application of medicinal plants in aquaculture depends significantly on the efficiency of the extraction methods used to obtain bioactive compounds (Pandey, 2013). Traditional extraction techniques, such as solvent extraction, maceration, and decoction, are commonly employed due to their simplicity and low cost (Pandey, 2013). However, these methods may not always yield the highest purity or potency of active compounds, and they can lead to the degradation of heat-sensitive phytochemicals (Fu et al., 2019).

Conventional Extraction Methods

Solvent extraction, maceration, and decoction are the most widely used conventional methods for extracting bioactive compounds from plants (Pandey, 2013). Solvent extraction involves dissolving plant material in a solvent to extract desired compounds, while maceration and decoction utilize prolonged soaking and boiling, respectively, to extract plant constituents (Pandey, 2013). While these methods are cost-effective, they can lead to the degradation of certain compounds, especially those that are sensitive to heat or prolonged exposure to solvents (Fu et al., 2019).

Advanced Extraction Techniques

Recent advancements in extraction technologies, such as supercritical fluid extraction (SFE) and ultrasound-assisted extraction (UAE), have been developed to improve the yield and purity of bioactive compounds from medicinal plants (Fu et al., 2019). These methods are more efficient and help preserve the integrity of sensitive compounds, ensuring higher-quality extracts (Fu et al., 2019). These modern extraction techniques are gaining popularity in aquaculture due to their ability to maximize the bioavailability and therapeutic potential of plant-derived compounds (Fu et al., 2019).

INCORPORATION OF PHYTOADDITIVES INTO FISH FEED

Once medicinal plants are processed into extracts or powders, they can be incorporated into fish feed using various methods (Lim et al., 2020). Direct mixing, where plant powders or extracts are blended with feed ingredients, is the most straightforward method, but it can lead to the degradation of active compounds during processing (Lim et al., 2020). Alternatively, encapsulation techniques, in which plant compounds are enclosed in protective coatings, provide better stability and controlled release of bioactive compounds in the fish's digestive system (Fu et al., 2019). More recently, nano-formulations, which use nanoparticles to enhance the solubility and bioavailability of plant compounds, have been explored as a promising approach to improve the efficacy of phytoadditives in aquaculture feed (Lim et al., 2020).

POTENTIAL LIMITATIONS OF PHYTOADDITIVES IN AQUACULTURE

The integration of medicinal plants as phytoadditives in aquaculture has attracted substantial interest due to their promising effects on fish health, including growth promotion, immune enhancement, and parasitic control (Behl et al., 2021; Fu et al., 2019). However, despite their potential benefits, the widespread application of phytoadditives in aquaculture faces several limitations that need to be addressed for their effective and sustainable use.

A key limitation is the inherent variability in the concentration and composition of bioactive compounds in medicinal plants. Numerous factors, including plant species, cultivation conditions, harvest timing, and post-harvest processing, influence the levels of active ingredients (Liu et al., 2020; Tamer et al., 2021). This variability can result in inconsistent outcomes when medicinal plants are used as additives, complicating efforts to standardize their application across different aquaculture systems (Li et al., 2022). The lack of consistency in the quality of these plants can undermine their efficacy, making it essential to develop precise management and formulation strategies to optimize their use (Li et al., 2022).

Bioavailability of plant-derived compounds represents another critical challenge for their effective use in aquaculture. Active compounds such as flavonoids and alkaloids often exhibit poor absorption in the digestive systems of fish, limiting their therapeutic potential (Shahat et al., 2021). This suboptimal bioavailability restricts the overall efficacy of phytoadditives, particularly for compounds that require higher concentrations to exert their beneficial effects. To overcome this challenge, innovative delivery systems such as encapsulation and nano-formulation technologies have been developed to enhance the bioavailability and stability of these compounds (Fu et al., 2019).

However, these technologies often introduce added complexity and increased production costs, which could pose significant barriers to the large-scale adoption of phytoadditives in aquaculture (Shahat et al., 2021).

Furthermore, the long-term effects of using phytoadditives on fish health and ecosystem stability are not yet fully understood. While numerous studies demonstrate positive short-term impacts, the cumulative effects of prolonged exposure to plant-derived compounds remain underexplored (Behl et al., 2021). Continuous or excessive use of certain phytoadditives could alter the microbial composition within aquaculture systems or contribute to the development of resistance in fish parasites, which could compromise the long-term sustainability of their use (Ali et al.,

2020). These concerns highlight the necessity for long-term studies to assess the safety and ecological consequences of using medicinal plants in aquaculture (Ali et al., 2020).
Another significant limitation is the lack of standardized regulatory frameworks for the use of medicinal plants in aquaculture. Despite the widespread recognition of the health benefits of many plant species, there are currently no universally accepted guidelines or safety standards for their incorporation into aquaculture practices (Alavinia et al., 2018). The absence of such regulations can hinder the acceptance and consistent application of phytoadditives, particularly in regions where regulatory infrastructure is either underdeveloped or lacking entirely (Alavinia et al., 2018). The establishment of clear regulatory standards is crucial to ensuring the safe and effective use of phytoadditives in aquaculture.

FUTURE DIRECTIONS FOR PHYTOADDITIVES IN SUSTAINABLE FISH FARMING

The integration of phytoadditives in aquaculture presents a promising solution for improving fish health and supporting sustainable farming practices. However, several challenges need to be addressed to ensure their broad adoption and effectiveness (Behl et al., 2021; Palanikani et al., 2020).

Standardization of Phytoadditives

One significant issue is the variability in the bioactive compounds of medicinal plants, which can be influenced by factors such as species, growing conditions, and harvest timing (Tamer et al., 2021; Behl et al., 2021). This variability can result in inconsistent results across aquaculture systems, hindering the reliable use of phytoadditives (Palanikani et al., 2020). Therefore, establishing standardized extraction methods and certification processes will be essential for improving the consistency and effectiveness of phytoadditives (Shah et al., 2021).

Bioavailability and formulation

The bioavailability of bioactive compounds in medicinal plants is often low due to poor absorption in the digestive systems of fish (Shahat et al., 2021; Lim et al., 2020). This limitation restricts their therapeutic effects and reduces their efficacy in aquaculture settings (Ali et al., 2020). To address this challenge, research into optimizing extraction methods and developing advanced formulation techniques, such as encapsulation and nano-formulation, is needed to enhance bioavailability and stability (Shen et al., 2019). While these techniques offer potential, they also increase production costs, which could hinder their widespread adoption (Behl et al., 2021).

Long term safety and ecological impact

Although short-term studies demonstrate benefits, the long-term effects of phytoadditives on fish health and ecosystems remain largely unexplored (Ali et al., 2020). Continuous use of these additives could alter microbial populations or lead to resistance in fish parasites (Shah et al., 2021). Therefore, long-term studies are necessary to assess their cumulative effects and ensure their safe and sustainable use in aquaculture systems (Liu et al., 2020). Such research will also be crucial for understanding any potential negative ecological impacts (Behl et al., 2021).

Tailoring phytoadditives for different species and their specific needs

Different fish species may respond differently to phytoadditives due to variations in their physiological and immunological needs (Li et al., 2022; Fu et al., 2019). Tailoring plant-derived additives to suit specific species could enhance their therapeutic effects and minimize adverse impacts (Palanikani et al., 2020). Customizing formulations according to the unique requirements of each species is critical for maximizing the effectiveness of phytoadditives in aquaculture systems (Behl et al., 2021).

Integration with Other Sustainable Practices

For phytoadditives to significantly contribute to sustainable aquaculture, they must be integrated with other eco-friendly practices, such as organic farming and integrated pest management (Behl et al., 2021; Palanikani et al., 2020). Phytoadditives can reduce the reliance on synthetic chemicals, which decreases environmental pollution and promotes better fish health (Shen et al., 2019).

By incorporating phytoadditives into broader sustainable farming practices, aquaculture can achieve better ecological sustainability and fish welfare (Palanikani et al., 2020).

Regulatory framework development

A major obstacle to the widespread adoption of phytoadditives is the lack of regulatory frameworks governing their use in aquaculture (Alavinia et al., 2018; Liu et al., 2020). The absence of standardized guidelines on safety, dosage, and application methods hinders the safe incorporation of phytoadditives in fish feed (Li et al., 2022). Establishing safety standards and usage guidelines will ensure the effective and consistent use of these additives across various aquaculture systems (Shen et al., 2019).

Consumer acceptance

As consumers become more aware of the benefits of sustainable farming, the demand for fish raised with phytoadditives is expected to grow (Ali et al., 2020). Fish raised using phytoadditives are seen as healthier and more environmentally friendly, which appeals to an increasingly eco-conscious market (Shahat et al., 2021). Educating consumers about the advantages of these additives could drive their market adoption and increase the demand for sustainably farmed fish (Ali et al., 2020).

CONCLUSIONS

Medicinal plants offer a promising alternative to synthetic additives in aquaculture, promoting growth, immunity, and disease control. However, challenges such as variability in bioactive compound concentration and poor bioavailability limit their effectiveness. To address these issues, future research should focus on standardizing extraction methods, improving bioavailability through advanced formulations, and tailoring additives to specific fish species. Additionally, establishing regulatory frameworks for safe and effective use is essential. Overcoming these challenges will enable medicinal plants to play a key role in sustainable aquaculture practices.

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