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The Role of Medicinal Plants in Aquaculture: Enhancing Fish Health, Physiology, and Resistance to Infections

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Abstract

Aquaculture has emerged as a pivotal component of global food production, addressing the increasing demand for aquatic protein. However, the intensification of aquaculture practices has introduced challenges including disease outbreaks, environmental degradation, and the excessive use of antibiotics, contributing to antimicrobial resistance and residual contamination. In this context, the integration of medicinal plants into aquaculture has garnered attention as a sustainable and eco-friendly approach to enhance fish health, improve physiological performance, and bolster disease resistance. This review presents a comprehensive synthesis of current knowledge on the application of medicinal plants in aquaculture, highlighting their diverse roles in enhancing fish growth performance, modulating immune responses, and improving physiological and hematological parameters. Moreover, the review explores their antioxidant, antimicrobial (antibacterial, antifungal, and anti-parasitic), and stress-mitigating properties, along with their potential to improve water quality and overall fish health. Collectively, these insights underscore the potential of plant-derived bioactives to support more sustainable, resilient, and health-oriented aquaculture practices.

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1. Introduction

The global aquaculture industry has witnessed remarkable growth in recent decades, becoming a key contributor to food security by meeting the rising demand for aquatic protein. However, this expansion has not come without challenges. Infectious diseases caused by bacterial, viral, fungal, and parasitic agents are particularly common in high-density farming systems and under suboptimal environmental conditions. At the same time, environmental stressors such as fluctuating water temperatures, poor water quality, hypoxia, and pollution further compromise fish immunity and increase vulnerability to disease. Conventional strategies to address these issues, primarily relying on antibiotics and chemotherapeutics, are proving increasingly unsustainable. The overuse of antibiotics, in particular, has contributed to the development of antimicrobial resistance, accumulation of chemical residues in the environment, and potential risks to public health and aquatic ecosystems **(Abu-Zahra *et al.,* 2024a, b).**

As a result, there is an urgent need for effective, natural, and eco-friendly alternatives that can enhance fish health while minimizing environmental impact. One promising solution lies in the use of medicinal plants, which are rich in diverse bioactive compounds including alkaloids, flavonoids, saponins, tannins, and essential oils. These phytochemicals possess a broad spectrum of biological activities such as antimicrobial, antioxidant, immunostimulatory, antiparasitic, and anti-inflammatory properties **(Citarasu, 2010; Reverter *et al.,* 2014).** The application of medicinal plants, known as phytotherapy, has thus gained momentum as a sustainable strategy for improving fish resilience, promoting growth, and enhancing overall aquaculture performance.

Aims and objectives of this review (Fig. 1):

1. Critically examine the current challenges in aquaculture, with an emphasis on:
   - Disease control
   - Limitations of antibiotic use
   - Impact of environmental stress
2. Explore the potential of medicinal plants as effective alternatives by evaluating their:
   - Effects on fish growth
   - Influence on hematological parameters
   - Modulation of immune responses
   - Enhancement of antioxidant defense mechanisms
   - Contribution to stress tolerance
3. Discuss the antimicrobial (antibacterial, antifungal, and antiviral) and antiparasitic properties of various plant species and their role in improving water quality in aquaculture systems
4. Identify research gaps and propose future directions for the successful integration of phytotherapy into sustainable aquaculture practices.

2. Medicinal Plants in Aquaculture

Medicinal plants encompass a diverse array of herbs, shrubs, and trees known for their therapeutic properties. In aquaculture, various parts of these plants, including leaves, roots, seeds, and fruits, are utilized either in their natural form or as extracts. Commonly employed medicinal plants include garlic (*Allium sativum*), neem (*Azadirachta indica*), turmeric (*Curcuma longa*), aloe vera (*Aloe barbadensis*), peppermint (*Mentha piperita*), south Africa geranium (*Pelargonium Sidoides*), and moringa (*Moringa oleifera*). These plants are rich in bioactive constituents such as alkaloids, flavonoids, saponins, and tannins, which confer a range of health benefits to aquatic organisms **(Tadese *et al.,* 2021).** Medicinal plants used in aquaculture can be classified into several categories based on their origin and growth habits.

2.1. Classification of Medicinal Plants

Medicinal plants can be scientifically categorized based on their morphological characteristics, growth habits, and bioactive properties **(Okon *et al.,* 2024).** This classification helps guide their selection and application in aquaculture and other biomedical fields.

- **Herbs**: Small, non-woody plants used for their leaves, stems, or flowers. Example: *Basil* (*Ocimum basilicum*), *Thyme* (*Thymus vulgaris*).
- **Shrubs**: Woody or semi-woody perennials. Example: *Neem* (*Azadirachta indica*).
- **Spices and Condiments**: Aromatic plant parts with antimicrobial and antioxidant activities. Examples: *Garlic* (*Allium sativum*), *Turmeric* (*Curcuma longa*), *Ginger*

(*Zingiber officinale*).
- **Succulents**: Water-storing plants like *Aloe vera*, widely known for its healing and anti-inflammatory effects.
- **Marine Plants**: Seaweeds and algae such as *Ulva* and *Sargassum*, valued for their polysaccharides and immunostimulants.

2.2. Commonly Used Medicinal Plants and Their Benefits

Medicinal plants have gained increasing attention in aquaculture due to their natural bioactive compounds that can enhance fish growth, immunity, and disease resistance while supporting sustainable farming practices. Table 1 summarizes widely used medicinal plants, their scientific names, and their major reported effects based on current literature.

Table (1). Reported Effects of Selected Medicinal Plants in Aquaculture

English Common Name	Scientific Botanical Name	Reported Effects in Aquaculture
Garlic	*Allium sativum*	Antibacterial, growth-promoting, immune-enhancing **(Nya & Austin, 2009)**
Neem	*Azadirachta indica*	Antiparasitic, antifungal, immunomodulatory **(Chakraborty & Hancz, 2011)**
Turmeric	*Curcuma longa*	Antioxidant, anti-inflammatory, hepatoprotective **(Dawood & Koshio, 2020; Arif et al., 2020; El-Gammal *et al.* 2025)**
Aloe vera	*Aloe barbadensis*	Enhances growth, boosts immunity, wound healing **(Sánchez *et al.,* 2020)**
Ginger	*Zingiber officinale*	Improves appetite, immunity, and stress resistance **(Ergena *et al.,* 2023)**
Basil	*Ocimum basilicum*	Antioxidant, antimicrobial, promotes survival and growth **(Talpur & Ikhwanuddin, 2013)**
Moringa	*Moringa oleifera*	Antibacterial, antioxidant, enhances feed efficiency **(Choudhary *et al.,* 2024)**
Peppermint	*Mentha piperita*	Enhances the biological responses, growth performance, disease resistance, and survival **(Abu-Zahra *et al.,* 2024c)**
South African Geranium	*Pelargonium Sidoides*	enhances antioxidant activity and immune responses, better hematological profiles, histological protection, and enhanced disease resistance **(Abu-Zahra *et al.,* 2025)**

This table compiles commonly used medicinal plants in aquaculture, highlighting their documented biological effects and health benefits in various fish species. The reported properties include immune enhancement, antioxidant activity, disease resistance, and improved growth performance, based on experimental studies in peer-reviewed literature

2.3. Active Phytochemical Constituents

Medicinal plants owe their bioactivity to a rich array of secondary metabolites, which include:

- **Flavonoids**: Potent antioxidants and anti-inflammatory agents that protect against oxidative damage and boost immune responses.
- **Alkaloids**: Possess antimicrobial, antiparasitic, and immune-regulating properties.
- **Terpenoids**: Contribute to antimicrobial activity and cellular protection mechanisms.
- **Saponins**: Known to modulate immune function and serve as natural growth promoters.
- **Phenolic compounds**: Exhibit antimicrobial, antioxidant, and hepatoprotective actions.
- **Tannins**: Inhibit pathogen growth and enhance gut health.

These compounds function synergistically to improve fish health and resistance, making medicinal plants a valuable component in functional feeds and aquaculture therapeutics.

3. Effect on Fish Growth

3.1 Growth Performance and Feed Efficiency

Medicinal plants have been widely reported to enhance fish growth performance by improving feed utilization, stimulating appetite, and boosting digestive enzyme activity. Dietary supplementation with species such as peppermint (*Mentha piperita*), south Africa geranium (*pelargonium sidoidis*), neem (*Azadirachta indica*), garlic (*Allium sativum*), turmeric (*Curcuma longa*), and moringa (*Moringa oleifera*) has led to significant improvements in weight gain (WG), specific growth rate (SGR), and feed conversion ratio (FCR) across various fish species **(Abu-Zahra *et al.,* 2025, Abu-Zahra *et al.,* 2024c, El-Gammal *et al.* 2025, Harikrishnan *et al.,* 2021; Arif *et al.,* 2020; Dawood & Koshio, 2020).** These benefits are further supported by the positive effects of plant compounds on liver function and metabolic regulation, contributing to enhanced overall fish health and growth efficiency.

3.2 Appetite Stimulation and Gut Morphology

Medicinal plants contain phytochemicals such as essential oils, terpenoids, and alkaloids, which act as natural appetite stimulants. These compounds improve feed intake and nutrient absorption by enhancing gut morphology- specifically, increased villus height, crypt depth, and mucosal surface area, as observed in studies with herbal feed additives like thyme (*Thymus vulgaris*) and basil (*Ocimum basilicum*) **(Talpur *et al.,* 2012)** and peppermint (*Mentha piperita*) **(Abu-Zahra *et al.,* 2024c).** Improved gut integrity and enzyme secretion lead to more efficient digestion and assimilation of nutrients, thereby supporting faster growth and improved condition factors in fish.

4. Hematological Effects

Hematological parameters are essential biomarkers for assessing the physiological and immunological status of fish. Medicinal plants have demonstrated significant potential in modulating these parameters, reflecting enhanced health, stress resilience, and immune competence. Notably, improvements in red blood cell (RBC) count, hemoglobin (Hb) concentration, hematocrit (Hct), and white blood cell (WBC) count have been consistently observed following dietary inclusion of various plant-based additives.

For instance, the dietary administration of moringa (*Moringa oleifera*) and ginger (*Zingiber officinale*) were significantly improved the hematological profiles of *Oreochromis niloticus*, indicating enhanced oxygen transport capacity and immune readiness **(Aly *et al.,* 2023).** Likewise, curcumin (*Curcuma longa*) supplementation demonstrated potent immunomodulatory and antioxidant properties in *Oreochromis niloticus* (*O. niloticus*) challenged with *Aeromonas hydrophila (A. hydrophila*), resulting in elevated white blood cell counts, enhanced antioxidant defenses, and greater resistance to infection **(El-Gammal *et al.,* 2025).**

These findings underscore the role of curcumin in supporting hematopoietic and immune function under bacterial stress. In another study, dietary inclusion of peppermint (*Mentha piperita*) powder enhanced the biological responses and hematological parameters of *O. niloticus* infected with *Vibrio alginolyticus* (*V. alginolyticus*) **(Abu-Zahra *et al.,* 2024c).** Treated fish exhibited elevated RBCs, Hb, and leukocyte counts, which contributed to improved growth performance, immune protection, and survival rates. This illustrates the synergistic effect of plant-derived compounds on both metabolic and immune-related blood parameters.

Moreover, dietary supplementation with south Africa geranium (*Pelargonium sidoides*) extract significantly mitigated the adverse hematological impacts of thermal stress in *O. niloticus* **(Abu-Zahra *et al.,* 2025).** Fish exposed to elevated temperatures while receiving the extract displayed stabilized hematocrit levels, preserved erythrocyte integrity, and enhanced leukocyte responses, highlighting the plant's adaptogenic and immunoprotective capabilities under environmental stress conditions.

Together, these findings support the application of medicinal plants as effective modulators of hematological health in aquaculture. By improving both the oxygen-carrying capacity and immune surveillance functions, plant-based additives play a vital role in enhancing fish resilience to pathogens and environmental stressors.

5. Immunostimulatory Effects

Medicinal plants play a pivotal role in enhancing the immune system of fish, owing to their rich content of bioactive compounds such as flavonoids, alkaloids, terpenoids, and phenolics. These compounds are known to stimulate both innate and adaptive immune responses, thereby improving disease resistance and overall health in aquaculture species. Plant-derived immunostimulants have been shown to increase phagocytic activity, lysozyme levels, immunoglobulin production, and cytokine expression, critical components of the fish immune defense. The immune-related effects of common medicinal plants used in aquaculture are summarized in Table 2.

Dietary supplementation with turmeric (*Curcuma longa*) has demonstrated potent immunomodulatory and antioxidative effects in *O. niloticus* challenged with *A. hydrophila*. Curcumin enhanced non-specific immune parameters such as phagocytic activity and index and lysozyme activity. These responses contributed to improved pathogen resistance and reduced oxidative damage, showcasing curcumin's dual role in immunity and cellular protection **(El-Gammal *et al.,* 2025).** Similarly, peppermint (*Mentha piperita*) powder has been shown to enhance the biological and immune responses of *O. niloticus* infected with *V. alginolyticus* **(Abu-Zahra *et al.,* 2024c).** Fish fed peppermint (*Mentha piperita*)-supplemented diets exhibited significantly increased levels of immunological markers, including lysozyme, phagocytic activity, and immunoglobulins, resulting in higher disease resistance and survival rates. These findings highlight the immunopotentiating properties of peppermint (*Mentha piperita*) and its potential application in disease management.

In addition, dietary inclusion of south Africa geranium (*Pelargonium sidoides*) extract was found to mitigate thermal stress while enhancing immune responses in *O. niloticus* **(Abu-Zahra *et al.,* 2025).** Fish exposed to elevated temperatures showed upregulated immune responses and increased activity of key immune enzymes when fed the extract. These effects contributed not only to improved thermal tolerance but also to a strengthened defense against opportunistic infections, indicating the adaptogenic and immunoprotective roles of this plant. Moreover, other plants such as purple coneflower (*Echinacea purpurea*), astragalus (*Astragalus membranaceus*), and holy basil (*Ocimum sanctum*) have been reported to boost immunoglobulin production and innate immune activities **(Reverter *et al.,* 2014; Dadras *et al.,* 2023),** underscoring the broad spectrum of immunostimulatory effects offered by botanical compounds.

In summary, the strategic use of medicinal plants in aquaculture diets effectively enhances fish immunity through multiple mechanisms (Table 2). These natural immunostimulants contribute to reduced disease outbreaks, improved survivability, and a more sustainable approach to fish health management.

Table (2). Immunomodulatory Effects of Selected Medicinal Plants Used in Aquaculture

Medicinal Plant	Immune Responses	Hematological Effects	Cytokine/ Immune Gene Modulation	Key Benefits/ Applications	References
Garlic (*Allium sativum*)	Enhances lysozyme activity, phagocytosis, respiratory burst; boosts resistance against pathogens like *Aeromonas hydrophila* and *Streptococcus iniae*.	No significant hematological data reported.	N/A	Boosts innate immunity, especially in fish like *Oreochromis niloticus* and *Labeo rohita*.	**Nya & Austin (2009); Awad & Awaad (2017)**
Neem (*Azadirachta indica*)	Offers antibacterial protection, enhances phagocytic activity.	Increases RBC count, WBC count, and hemoglobin levels.	N/A	Strengthens immune surveillance; enhances resistance to infections.	**Aly *et al.* (2008); Harikrishnan *et al.* (2011); Zahran & Risha (2014)**
Turmeric (*Curcuma longa*)	Anti-inflammatory, antioxidant properties aid in immune balance.	May improve general health but lacks specific hematological data.	N/A	Supports immune balance, reduces inflammation, and enhances stress tolerance.	**Zahran & Risha (2014)**
Moringa (*Moringa oleifera*)	Stimulates genes involved in innate and adaptive immunity, enhances resistance to bacterial and parasitic infections.	No direct hematological effects noted.	Upregulates immune-related genes, pro-inflammatory cytokines like IL-1β, TNF-α.	Promotes immune system activation, enhances disease resistance.	**Giri *et al.* (2018); Chakraborty & Hancz (2011); (Choudhary *et al.*, 2024)**
Ginger (*Zingiber officinale*)	Modulates immune responses and cytokine expression, especially pro-inflammatory cytokines.	No direct effects on hematological parameters reported.	Modulates cytokine profiles, stimulates genes involved in immunity.	Enhances immune responses and helps combat infections.	**Harikrishnan *et al.* (2012)**

This table summarizes the immune-related effects of common medicinal plants used in aquaculture. Data were extracted from peer-reviewed studies focusing on immune responses, hematological effects, cytokine/gene modulation, and practical benefits for disease resistance and health enhancement in farmed fish species. NA: Not Available.

6. Antioxidant Capacity

Oxidative stress, resulting from the excessive production of reactive oxygen species (ROS), poses a significant threat to fish health by damaging cellular components and impairing physiological processes. Medicinal plants rich in antioxidants have emerged as effective agents for mitigating this stress in aquaculture. These plants enhance the activity of key antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), which were collectively worked to neutralize ROS and restore cellular homeostasis. For instance, dietary supplementation with *Camellia sinensis* (green tea) and *Withania somnifera* (ashwagandha) has been reported to significantly improve antioxidant defenses in fish. Studies have indicated that these plants were not only boost the activities of SOD, CAT, and GPx but also reduce lipid peroxidation and other markers of oxidative damage. This enhancement of antioxidant capacity is crucial for maintaining tissue integrity, supporting immune function, and promoting overall physiological resilience in fish under intensive farming conditions **(Dawood *et al.,* 2021; Dadras**

***et al.,* 2023).**

By incorporating these antioxidant-rich medicinal plants into aquaculture practices, producers can help counteract the harmful effects of oxidative stress, thereby contributing to improved fish growth, survival, and quality of aquaculture products.

6.1. Reduction of Oxidative Stress

Oxidative stress arises when ROS production exceeded the capacity of antioxidant defenses, leading to cellular and molecular damage. Environmental stressors such as poor water quality, handling, crowding, or exposure to contaminants can exacerbate oxidative stress in aquaculture systems, resulting in tissue injury, immune suppression, and increased disease susceptibility.

Several medicinal plants are known to counteract oxidative stress through their rich composition of antioxidant phytochemicals. For example:

- **Turmeric (*Curcuma longa*)** contains curcumin, a potent antioxidant that scavenges free radicals and reduces lipid peroxidation.
- **Garlic (*Allium sativum*)** contains allicin, which has strong antioxidant and immunostimulant effects.
- **Moringa (*Moringa oleifera*)** is rich in polyphenols and flavonoids with ROS-scavenging activity.

Biomarkers such as thiobarbituric acid reactive substances (TBARS) and malondialdehyde (MDA) are commonly used to evaluate oxidative stress in fish. Several studies have reported that dietary inclusion of these medicinal plants significantly lowers TBARS and MDA levels in the liver, gills, and blood, confirming their protective effects against oxidative damage.

6.2. Effects on Cortisol and Glucose Levels

Cortisol is the primary stress hormone in fish, released in response to various physical and environmental stressors. Elevated cortisol levels were typically lead to hyperglycemia, as part of the stress-induced metabolic response. Chronic elevation of cortisol and glucose can impair immune function, suppress growth, and increase mortality.

Certain medicinal plants have been shown to modulate the stress response by regulating cortisol and glucose levels:

- **South Africa geranium (*Pelargonium sidoides*)** has demonstrated cortisol-lowering effects in fish subjected to stress, while also contributing to blood glucose stabilization **(Abu-Zahra *et al.,* 2025).**
- **Moringa (*Moringa oleifera*)** has been reported to normalize glucose levels in stressed fish, likely through modulation of insulin sensitivity and antioxidant action.

By stabilizing cortisol and glucose levels, these plants will alleviate the physiological burden of stress, support homeostasis, and improve the overall health and performance of fish in aquaculture systems. Incorporating antioxidant-rich medicinal plants into aquafeeds will offer a practical strategy to reduce oxidative stress and its associated impacts on fish health. Their ability to enhance endogenous antioxidant enzymes, reduce lipid peroxidation, and regulate stress markers such as cortisol and glucose further underscores their potential in promoting resilience and sustainability in aquaculture.

Table 3 highlights the multifaceted roles of medicinal plants in aquaculture, emphasizing their antioxidant, adaptogenic, and stress-mitigating effects. While most plants show strong potential in improving fish health and stress resilience, select species like moringa and neem also contribute to water quality through phytoremediation, offering a holistic approach to sustainable aquaculture.

Table (3). Multifunctional Roles of Selected Medicinal Plants in Aquaculture Health Management

Medicinal Plant	Adaptogenic Properties	Reduction of Oxidative Stress	Effect on Cortisol and Glucose Levels	Phytoremediation Potential	References
Ashwagandha (*Withania somnifera*)	Enhances stress adaptation, regulates HPI axis, reduces handling stress	Reduces oxidative stress by increasing antioxidant enzyme activity	Reduces cortisol levels and stabilizes glucose levels during stress	No significant studies on phytoremediation in aquaculture, mainly adaptogenic and antioxidant effects	**Wankhede *et al.* (2015); Rathi *et al.* (2019)**
Garlic (*Allium sativum*)	Reduces stress response, enhances immune resilience	Reduces TBARS and MDA levels, enhances antioxidant capacity	Modulates cortisol and glucose levels in stressed fish	Limited phytoremediation, mainly known for antioxidant effects in aquaculture systems	**Nya & Austin (2009); Awad & Awaad (2017)**
Turmeric (*Curcuma longa*)	Adaptogenic effects via curcumin, reduces environmental and handling stress	Reduces TBARS and MDA, potent antioxidant effects	Modulates cortisol levels during acute stress	No significant phytoremediation, more focus on antioxidant properties for fish health	**Zahran & Risha (2014)**
Moringa (*Moringa oleifera*)	Enhances stress tolerance and immune response under environmental stress	Reduces oxidative stress, decreases MDA and TBARS	Reduces cortisol levels and normalizes glucose levels in stressed fish	Phytoremediation potential in removing ammonia, nitrates, and heavy metals from aquaculture water	**Giri *et al.* (2018); Chakraborty & Hancz (2011); Moyo *et al.* (2015)**
Neem (*Azadirachta indica*)	Adaptogenic properties help fish cope with various stressors	Reduces oxidative stress by increasing antioxidant levels	Modulates cortisol and glucose levels during stressful conditions	Potential for water purification, removes excess nutrients and heavy metals from aquaculture systems	**Aly *et al.* (2008); Harikrishnan *et al.* (2011); Zahran & Risha (2014)**
Ginger (*Zingiber officinale*)	Reduces physiological stress and enhances adaptive responses	Reduces oxidative stress and TBARS levels	Reduces cortisol and glucose levels in stressed fish	No significant phytoremediation research, mainly known for antioxidant and stress-reducing effects	**Harikrishnan *et al.* (2012); Rathi *et al.* (2019)**

Adaptogenic properties refer to the ability of plants to help organisms adapt to stress by modulating the hypothalamic-pituitary-interrenal (HPI) axis, reducing stress-induced physiological disruptions.

7. Antimicrobial, Antiparasitic Properties and Resistance to Infections

Medicinal plants offer a promising natural alternative to synthetic antimicrobials in aquaculture due to their broad-spectrum antibacterial, antifungal, antiviral, and antiparasitic activities. Bioactive compounds such as allicin (in *Allium sativum*), curcumin (in *Curcuma longa*), and andrographolide (in *Andrographis paniculata*) exert antimicrobial effects by disrupting microbial membranes, inhibiting replication, and suppressing virulence factors, ultimately reducing pathogen loads and disease severity.

Numerous plant extracts have demonstrated efficacy against major aquaculture pathogens, including *A. hydrophila* **(Abu-Zahra *et al.,* 2025; El-Gammal *et al.,* 2025),** Vibrio spp. **(Abu-Zahra *et al.,* 2024c),** and *Streptococcus iniae*, as well as parasitic infestations such as *Ichthyophthirius multifiliis*. For instance, extracts from *P. sidoides*, *M. piperita*, *C. longa*, *A. sativum*, *Nigella sativa*, and *Azadirachta indica* have exhibited strong antimicrobial activities. Moreover, *Andrographis paniculata* has been effective in significantly reducing bacterial infections in fish.

In addition to their direct antimicrobial actions, many of these plants enhance both innate and adaptive immune responses, thereby improving resistance to infections. Fish receiving herbal supplements frequently show improved survival rates and heightened immune responses when challenged with bacterial, viral, or parasitic agents **(Yilmaz *et al.,* 2020; Pandey, 2022).** These results highlight the potential of phytotherapy as a sustainable and eco-friendly alternative to reduce antibiotic dependence and enhance health resilience in aquaculture systems.

7. 1. Mechanisms of Action

Medicinal plants exert their antimicrobial (antibacterial, antifungal, and antiviral) and antiparasitic effects through multiple mechanisms, often targeting essential biological pathways of pathogens:

7.1.1. Disruption of Microbial Membranes: Compounds such as saponins, alkaloids, and phenolic acids disrupt microbial membranes, increasing permeability and causing leakage of intracellular contents. This leads to cell lysis and pathogen death. For instance, saponins from *Quillaja saponaria* have been shown to damage bacterial and fungal cell membranes, reducing their viability **(Li *et al.,* 2024).**

7.1.2. Inhibition of Replication: Plant-derived compounds interfere with microbial DNA and protein synthesis by targeting key enzymes like DNA gyrase and RNA polymerase. Flavonoids and tannins are particularly effective in halting microbial replication and preventing the spread of infection **(Li *et al.,* 2024).**

7.1.3. Immunomodulation: Many medicinal plants stimulate immune responses by activating macrophages, enhancing antimicrobial peptide production, and increasing phagocytic activity. This immunomodulatory effect contributes to the host's ability to combat infections more effectively **(Abu-Zahra *et al.,* 2025; El-Gammal *et al.,* 2025; Abu-Zahra *et al.,* 2024c).**

7.2. Antimicrobial Evidence

Numerous medicinal plants have demonstrated broad-spectrum antimicrobial activity in both in vitro and in vivo studies:

- **Antibacterial Properties:** garlic (*Allium sativum*), neem (*Azadirachta indica*), and turmeric (*Curcuma longa*) have shown potent antibacterial effects against *A. hydrophila*, *S. iniae*, and Vibrio spp. Garlic, for example, enhances immune function and disrupts bacterial membranes, effectively controlling these infections.
- **Antifungal Properties:** Neem (*Azadirachta indica*) and thyme (*Thymus vulgaris*) inhibit fungal pathogens such as *Saprolegnia* spp., primarily due to active compounds like azadirachtin and thymol, which compromise fungal cell wall integrity.
- **Antiparasitic Properties:** garlic (*Allium sativum*), ginger (*Zingiber officinale*), and Moringa *(Moringa oleifera)* have demonstrated activity against protozoan parasites such as *Ichthyophthirius multifiliis* and *Trichodina* spp., likely through a combination of direct toxicity and immune system enhancement.
- **Antiviral and Antibiotic Alternatives**
  Emerging evidence supports the use of certain medicinal plants as natural antivirals and alternatives to antibiotics. For example:
  Echinacea (*Echinacea purpurea*) exhibits antiviral activity by enhancing interferon production and macrophage activation **(Medina-Beltrán *et al.,* 2012).**
  Licorice (*Glycyrrhiza glabra*) contains glycyrrhizin, known to inhibit viral replication, including in fish viruses **(Wahab *et al.,* 2021).**
  Such plant-derived compounds offer sustainable, resistance-free alternatives to synthetic antibiotics and antivirals, supporting fish health while minimizing ecological risks.

7.3. Comparative Effectiveness with Synthetic Drugs

Studies suggest that medicinal plants may offer efficacy comparable to, or even exceeding, that of synthetic antimicrobials:

- **Garlic vs. Antibiotics:** Garlic (*Allium sativum*) extract can significantly reduce *A. hydrophila* loads, rivaling the efficacy of oxytetracycline, without inducing antibiotic resistance. It also provides long-term immune benefits.

- **Neem vs. Synthetic Antiparasitics**: Neem extract effectively controls *I. multifiliis*, performing similarly to formalin but with the added advantages of being biodegradable and non-toxic to aquatic ecosystems.
- **Turmeric vs. Antifungals**: Turmeric demonstrates antifungal efficacy comparable to synthetic treatments against *Saprolegnia* infections, with additional anti-inflammatory and immunostimulatory effects.

7.4. Examples of Disease Control

Medicinal plants have proven effective against various aquaculture diseases caused by bacterial, fungal, viral, and parasitic pathogens:

- *A. hydrophila*: Garlic and neem reduce infection severity through both direct antimicrobial activity and immune enhancement.
- Streptococcus spp.: Garlic and neem significantly lower mortality rates in fish infected with *S. iniae*.

Ichthyophthirius multifiliis (Ich Disease): Ginger and garlic treatments reduce parasite burden through immunostimulation and potential direct toxicity.

Table 4 highlights the antibacterial, antifungal, antiviral, and antiparasitic effectiveness of key medicinal plants and their comparative efficacy with synthetic drugs. These plants not only match the performance of conventional treatments but also enhance immune function without promoting resistance or causing environmental harm, making them valuable tools for sustainable aquaculture health management.

Table (4). Comparative Antimicrobial and Antiparasitic Effects of Selected Medicinal Plants Used in Aquaculture

Medicinal Plant	Mechanisms of Action	Antibacterial Activity	Antifungal Activity	Antiparasitic Activity	Antiviral Activity	Comparison with Synthetic Drugs	References
Garlic (*Allium sativum*)	Disrupts microbial membranes, enhances immune response, inhibits replication	Effective against *A. hydrophila*, *S. iniae*, Vibrio spp.	Mild antifungal activity	Effective against *Ichthyophthirius multifiliis*, Trichodina spp.	Shown to inhibit viral replication; active against fish rhabdoviruses and nodaviruses	Comparable to antibiotics like oxytetracycline; enhances immune response without resistance issues	**Nya & Austin (2009); Awad & Awad (2017)**
Neem (*Azadirachta indica*)	Disrupts microbial membranes, inhibits protein synthesis, enhances immune response	Effective against *A. hydrophila*, Vibrio spp.	Effective against Saprolegnia spp.	Effective against *I. multifiliis*, Trichodina spp.	Exhibits antiviral effects against fish viruses; suppresses viral load and enhances immunity	Comparable to formalin in treating Ich; more environmentally friendly, no toxic effects	**Aly *et al.* (2008); Harikrishnan *et al.* (2011); Zahran & Risha (2014)**
Turmeric (*Curcuma longa*)	Anti-inflammatory, antioxidant, disrupts microbial membranes, inhibits replication	Effective against *S. iniae*, *A. hydrophila*	Effective against Saprolegnia spp.	Mild antiparasitic activity	Shown to inhibit replication of fish viruses via antioxidant-mediated pathways	Comparable to synthetic antifungals in controlling Saprolegnia infections; supports immune balance	**Zahran & Risha (2014)**
Moringa (*Moringa oleifera*)	Enhances immune response, modulates immune gene expression, disrupts microbial membranes	Effective against *A. hydrophila*, Vibrio spp.	No significant antifungal activity reported	Effective against *I. multifiliis*, Trichodina spp.	Enhances resistance to viral infections; modulates antiviral immune genes	No direct comparison with synthetic drugs, but supports immune response and disease resistance	**Giri *et al.* (2018); Chakraborty & Hancz (2011)**
Ginger (*Zingiber officinale*)	Modulates immune response, inhibits replication, disrupts microbial membranes	Effective against *A. hydrophila*, *S. iniae*	Mild antifungal activity	Effective against *I. multifiliis* (Ich disease)	Demonstrated antiviral activity against spring viremia of carp virus (SVCV) and others	Comparable to synthetic antibiotics; boosts immunity and helps in stress management	**Harikrishnan *et al.* (2012)**

This table summarizes the key antimicrobial mechanisms, spectrum of activity, and comparative efficacy of selected medicinal plants against common fish pathogens. The information is based on experimental data from peer-reviewed studies, highlighting their potential as natural alternatives to synthetic drugs in aquaculture.

8. Stress Mitigation and Water Quality Improvement

Medicinal plants play a significant role in mitigating stress and enhancing environmental conditions within aquaculture systems. Many herbs exhibit adaptogenic properties, helping fish cope with common stressors such as temperature fluctuations **(Abu-Zahra *et al.,* 2025),** crowding, hypoxia, and handling. These adaptogens can stabilize physiological functions, reduce the overproduction of stress hormones like cortisol, and regulate blood glucose levels, thereby promoting homeostasis and improving overall health and survival **(Abu-Zahra *et al.,* 2025).**

In addition to their physiological benefits, certain medicinal plants contribute to phytoremediation, a process where plants remove, neutralize, or stabilize environmental pollutants. In aquaculture, this capability is particularly valuable for improving water quality, a critical component of fish health. Plants such as Moringa (*Moringa oleifera*), neem (*Azadirachta indica*), and water hyacinth (*Eichhornia crassipes*) have been shown to absorb excess ammonia, nitrates, and even heavy metals from aquatic environments. This not only detoxifies the water but also reduces the reliance on synthetic chemicals, supporting more sustainable and eco-friendly farming practices.

For instance, the application of Moringa seed powder in aquaculture systems has been reported to significantly reduce ammonia and nitrate concentrations in the water, while also acting as an immunostimulant for cultured species. Likewise, duckweed (*Lemna minor*) has been recognized for its ability to absorb nutrients and maintain ecological balance in fish ponds.

Collectively, these properties make medicinal plants valuable tools not only for stress management in fish but also for maintaining optimal water quality, contributing to the resilience and sustainability of aquaculture ecosystems.

9. Application Strategies

Medicinal plants can be administered in aquaculture through several practical delivery methods, each offering distinct advantages depending on the target condition, fish species, and operational scale. The most common strategy is dietary supplementation, where plant powders, extracts, or essential oils are incorporated directly into feed. This method is convenient, cost-effective, and allows for long-term, systemic health benefits, including growth enhancement and disease prevention **(Abu-Zahra *et al.,* 2025, Abu-Zahra *et al.,* 2024c, El-Gammal *et al.* 2025, Harikrishnan *et al.,* 2021; Dawood & Koshio, 2020).**

Immersion baths represent another effective technique, particularly for delivering antimicrobial or antiparasitic agents to external tissues. This method ensures direct contact with pathogens on the skin, gills, or fins and is often used during short-term treatments. Injections, though less commonly used due to labor and stress concerns, offer a targeted approach for administering precise doses, especially during acute disease outbreaks.The form of medicinal plant preparation also plays a key role, ranging from crude powders and aqueous extracts to essential oils and encapsulated phytochemicals. These forms vary in stability, bioavailability, and potency.

Dosage and duration are critical factors for achieving efficacy without causing toxicity. Typical inclusion levels for dietary supplements range from 0.5% to 2% of the feed **(Abu -Zahra *et al.,* 2024c; El-Gammal *et al.* 2025),** though optimal concentrations vary depending on the plant species, active compounds, and fish physiology. Overdosage may lead to reduced feed intake or physiological stress, emphasizing the need for empirical validation and species-specific optimization **(Abu-Zahra *et al.,* 2024c, El-Gammal *et al.* 2025).**

Furthermore, standardization of plant material, consistent quality control, and understanding the pharmacokinetics of phytocompounds are essential for reproducible outcomes in commercial applications.

10. Challenges and Limitations

Despite the growing interest in the use of medicinal plants in aquaculture, several challenges limit their widespread adoption. One major issue is the variability in phytochemical composition, which can arise from differences in plant genotype, environmental conditions, harvesting time, and processing methods. This variability often results in inconsistent efficacy across studies and limits the reproducibility of

outcomes in practical applications.
Moreover, there is a lack of standardized protocols for the extraction, formulation, and administration of plant-based therapeutics. Without consistent quality control and dosage guidelines, it becomes difficult to compare results or ensure safety and efficacy. In many countries, regulatory frameworks governing the use of phytotherapeutic products in aquaculture remain underdeveloped, leading to uncertainty about approval processes, labeling, and safety evaluation. These gaps highlight the need for rigorous in vivo studies, toxicological assessments, and harmonized regulations to support the responsible integration of phytotherapy in aquaculture systems.

11. Future Prospects

The future of medicinal plant use in aquaculture will be promising, particularly with the integration of advanced technologies. Nanotechnology can offer new frontiers for improving the delivery, stability, and bioavailability of plant-derived compounds. Nanoformulations such as nanoemulsions and nanoparticles can enhance the therapeutic efficacy of phytochemicals at lower doses, minimizing potential toxicity.
Omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, can help unravel the molecular mechanisms underlying plant-fish interactions. These insights will facilitate the design of targeted dietary strategies and precision nutrition approaches. Furthermore, the development of eco -certified, functional feeds incorporating medicinal plants will align\ with the growing demand for sustainable and environmentally friendly aquaculture practices.
Sustainable cultivation and harvesting of medicinal plants, combined with good agricultural and manufacturing practices, will be crucial for ensuring a reliable supply of high-quality raw materials, supporting the scalability of phytotherapeutics in the aquaculture industry.

12. Conclusion

Medicinal plants represent a natural, sustainable, and effective alternative to conventional drugs in aquaculture. Their integration into fish diets and farming systems can enhance growth performance, immune responses, antioxidant capacity, and resistance to infections, while also contributing to stress mitigation and water quality improvement. These multi-functional benefits highlight their potential to promote holistic fish health and support the development of eco-friendly, resilient aquaculture systems. However, to fully realize this potential, there is a pressing need for standardization, toxicological assessments, and regulatory support, along with continued research on optimal dosages, delivery methods, and long-term impacts.
Collaborative efforts among researchers, industry stakeholders, and policymakers will be essential to overcome current limitations and drive the wider adoption of medicinal plants in modern aquaculture practices.

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