

Chapter 49

Immunostimulation and Stress Reduction in Farmed Fish Fed Herbal Extracts

Sana Alam¹, Urva-til-wusqa¹, Zahid Iqbal², Muhammad Rafi Qamar³, Moeen Afzal¹, Ghulam Mustafa¹, Hafiz Muhammad Ali⁴ and Riaz Hussain^{5*}

¹Department of Zoology, The Islamia University of Bahawalpur-63100, Pakistan

²Department of Pharmacology and Toxicology, Faculty of Veterinary and Animal Sciences, The Islamia University of Bahawalpur-63100, Pakistan

³Department of Clinical Medicine and Surgery, Faculty of Veterinary and Animal Sciences, The Islamia University of Bahawalpur-63100, Pakistan

⁴Department of Anatomy and Histology, Faculty of Veterinary and Animal Sciences, The Islamia University of Bahawalpur-63100, Pakistan

⁵Department of Pathology, Faculty of Veterinary and Animal Sciences, The Islamia University of Bahawalpur-63100, Pakistan

*Corresponding author: dr.riaz.hussain@iub.edu.pk

ABSTRACT

Given the rapidly expanding aquaculture industry, where intensive culture practices are used and stress related to exposure to diseases leads animals with decreased immunity against pathogenic organisms,, mutualistic bacteria should be considered as potential probiotic agents in commercial fish. Finally, Immune stimulant prophylactic and strategic agents to enhance the health product quality of fish. In this chapter, the mechanisms of action that allow herbal extracts to exert beneficial properties in farmed fish are summarised. These immunomodulatory properties of SCFAs include interactions with immune cells and their receptors, regulation gene expression as well as signaling pathways or the modulation of gut microbiota and intestinal immunity. They help to boost both innate and adaptive immune responses, as well as regulate age-related stress-induced physiological consequences. The practical applications in aquaculture are highlighted, including dietary supplementation to prevent and manage diseases/structural adjust during stressful periods/integrate with other health strategies. This publication contains case study examples that demonstrate effectiveness in survival, immune measurements and stress markers across diverse farmed species. These challenges are in terms of variability in bioactive content, potential interactions with feed ingredients and medications as well regulatory acceptance (and consumer acceptance). Additionally, novel sources for herbal immunostimulant development and promotional strategies in terms of both synergism with other categories of stimulants essentially combined natural adjuncts are focused. We provide a review of the potential benefits, in stimulation and stress mitigation terms, that herbal extracts offer as natural sustainable alternatives to be used for producing healthy fish under improved welfare conditions together with enhanced productivity.

KEYWORDS

Immunostimulation, Stress Reduction, Farmed Fish, Herbal Extracts

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INTRODUCTION

Importance of Maintaining Fish Health in Aquaculture

Maintaining the health of farmed fish is crucial in aquaculture operations for several reasons:

1. **Economic Loss:** Diseases and poor health status may cause economic losses in terms of low growth, high mortality rate and increase cost to treat (Naylor et al. 2023).

Contribution to global food security: Aquaculture plays a vital role in the world's growing demand for safe, nutritious and sustainably produced food by providing highly digestible proteins (Chary et al. 2024). The rationale here is that you need to have a supply of fish products in order for them to meet the ever-growing demand which can only be built and maintained through maintaining good health.

Environmental sustainability diseased fish can pass illness to wild stocks of fish which could have a disruptive effect on the ecosystem (Satkar et al., 2024). If fish disease is not managed properly, it may threaten the whole aquatic environment.

Impacts of Stress and Disease on Fish Productivity

Key statistics on aquatic animal health and stress in regard to diseases can take a heavy toll of fish farm productivity:

1. Diminished growth rates: Stress and disease can discourage your fish from growing to their maximum size (Sadler et al., 2024). This may cause low yields and economic loss for fish farmers.
2. More deaths: This can lead to diseases and more fish mortality which decrease the number of fishes in general bestowed on increased production (Assefa and Abunna 2018).
3. Poor feed conversion: Fish which are stressed or unwell may have a reduced appetite and poor feed conversion, resulting in suboptimal growth and increased production costs (Mateus et al. 2017).
4. Stresses and diseases can also have adverse effects on reproductive performance of spawning females with potential impact on the availability of good quality ova/larvae for restocking (Rato et al. 2018).

Potential Benefits of Herbal Extracts as Feed Additives

Using Herbal Extracts As Feed Additives in Aquaculture have attracted the attention because:

1. Immunostimulatory properties: Different plant-related compounds like polysaccharides, flavonoids and alkaloids are proven to stimulate the immune response of fish which leads in increasing resistance against diseases (Mariappan et al. 2023).
2. Antioxidant and anti-inflammatory: Plants containing a great amount of antioxidants (e.g. polyphenols) could protect fish against oxidative stress, inflammation that leads to the promotion of health in these animals (Akbari et al. 2022).
3. Growth promoter: Several herbs reported to induce growth in different fish species by enhancing feed efficiency, nutrient utilization and regulating growth parameters (Saleh et al. 2018).
4. Local stress reducers: Some plant extracts may be adaptogenic, allowing the fish to better handle stressful conditions and maintain homeostasis all along (Kamal et al. 2017).
5. These plant compounds have shown to possess antimicrobial and antiparasitic properties, which can be useful in the prevention of diseases into aquaculture (Mariappan et al. 2023).

However, it is worth mentioning that the effectiveness and safety of herbal extracts as feed additives are affected by different factors such as plant sources, extraction methods or/and fish species. However, just like with any natural compound used in aquaculture operations samples that truly demonstrate efficacy must be proven under the guideline of proper scientific research and regulatory scrutiny

Fish Immune System and Stress Response

Overview of the Fish Immune System (innate and adaptive)

1. The fish immune response is a sophisticated and complex network of cells, tissues and molecular mediators that interact in an interconnected system to protect the organism from pathogens crossing through body barriers while keeping homeostasis. It consists of two interconnected branches, one belonging to the adapted immune system and another from the innate immune System (Mokhtar et al. 2023).

Innate Immunity

- Physical barriers: The skin, scales and mucus are physical barriers that keep pathogens from entering the body (Reverter et al. 2018).
- Cellular components: phagocytic cells including macrophages and neutrophils that engulf pathogens; non-specific cytotoxic cells, such as natural killer (NK) cells, which kill infected or malignant host-cells (Mukherjee and Ghosh 2016).
- The humoral components: complement system mainly composed of different protein, thereby used for opsonization tagging the pathogenic proteins with phagocytosis and they may directly lyses them. Innate immunity also involves antimicrobial peptides, such as defensins and cathelicidins that are effective in their ability to disrupt microbial cell membranes (Hoseinifar et al. 2020).

Adaptive Immunity

- Adaptive Immunity (Humoral)- Antibodies(Immunoglobulins) from B- cell to neutralize pathogens or target them for killing (Abós et al. 2020).
- Recall the Different Types of Immunity: This type includes T lymphocytes, which include cytotoxic t cells and helper t cells (Cao et al. 2023).
- Initiation: Adaptive immunity generates immunological memory, which future encounters with the same pathogen can invoke in a rapid and vigorous response (Yamaguchi et al. 2019).

The adaptive and innate immune systems interact such that the first system provides rapid but non-specific responses, while the second one offers specific reactivity with long-lasting memory.

Stress Physiology and the Hypothalamic-pituitary-interrenal (HPI) Axis

In fish as in other vertebrates, the HPI axis is the main neuroendocrine system involved in stress responses. Or rather, it includes a dance between the hypothalamus and pituitary gland up to some interrenal cells (which are basically adrenal glands).

Activating the Stress Response

The brain senses stressors that is changes in the environment or handling of infection and releases corticotropin-releasing hormone (CRH) from hypothalamus (Yıldız and Seğer 2017).

Pituitary Involvement

The hypothalamus then produces corticotropin-releasing hormone, or CRH that circulates in the blood to stimulate the pituitary gland to release adrenocorticotrophichormone (ACTH) into system (Lu et al. 2022).

Interrenal Cell Response

In addition, ACTH stimulates the interrenal cells of head kidney (which is analogous to adrenal gland in mammals) for synthesis and secretion of the principal stress hormone cortisol by teleosts (Lu et al. 2022).

Cortisol Effects on Your Body

Cortisol is important for regulating numerous physiological processes such as metabolism, osmoregulation and immune function which potentially help the fish to deal with acute stressors (Tort and Balasch 2022).

Even though the HPI axis is necessary for proper stress responses, its excessive or chronic activation can have deleterious consequences; i.e., immunosuppression and growth inhibition

Effects of Stress on Immune Function and Disease Resistance

2. Given the devastating effects of stress on the immune system, it is clear that fish must build up internal suboptimal responses and predispose themselves to pathological processes (Kumar et al. 2022).

Acute Stress Effects

- In general, acute stress can augment aspects of innate immunity such as phagocytic activity secretory potential of antimicrobial peptides and leukocyte mobilisation.
- This acute intensification is considered a temporary short-term boost that the organism provides itself due to evolution in order for it to anticipate any damages or infective health situations affiliated with stressful experiences.

Chronic Stress Effects

- Chronic stress, when persisted for an extended period or chronic lead to reduced disease resistance and can suppress both innate and adaptive immune responses.
- High levels of cortisol suppress lymphocyte proliferation, decrease antibody production and reduce cytokine expression, all leading to an impaired adaptive immune response.
- The balance of pro-inflammatory and anti- inflammatory cytokines can also be disrupted by chronic stress, thus increasing vulnerability to infections as well as hyperinflammatory conditions.

Increased Disease Susceptibility

- Stress-induced immunosuppression could render fish more susceptible to viral, bacterial and parasitic infections, thus having negative effects on their health and productivity.
- Chronic stress also can increase the susceptibility to infections and decrease the ability of your immune system to clear pathogens.

Hence, in aquaculture settings it is of utmost importance to deal with the stress load and strengthen disease defense mechanisms among farmed fishes, which may help improve quality of stock and prevent outbreak development due compromising immunity.

Herbal Extracts and Their Bioactive Compounds

Types of Herbs and Spices used as Immunostimulants (garlic, turmeric, ginger, etc.)

Garlic (*Allium sativum*)

Sulfur-containing compounds, such as allicin in garlic (*Gar.any.sativum* L), and its immune effect has been widely studied these days are being paid attention to for their potential application against bacterial diseases in different fish species like trout (Valenzuela-Gutiérrez et al. 2021; Abozaid et al. 2024).

Turmeric (*Curcuma longa*)

To have immunostimulant, antioxidant and anti-inflammatory activities curcumin has been described as the major curcuminoid in turmeric against fish (Bhadra et al. 2024).

Ginger (*Zingiber officinale*)

These bioactive compounds known as gingerols and shogaols in gingers showed immunomodulatory and growth-promoting effects in aquaculture (Megbowon et al. 2024).

Other Herbs and Spices

- Astragalus (*Astragalus membranaceus*), *Withaniasomnifera* (Ashwagandha), *Origanum vulgare* (Oregano), *Rosmarinus officinalis* (Rosemary), and *Echinacea purpurea* have also been explored for their potential immunostimulant properties in fish (Dhama et al. 2018).

Classes of Bioactive Compounds (polyphenols, alkaloids, terpenoids, etc.)

Polyphenols: Flavonoids, phenolic acids and tannins are some of the polyphenolics in many fresh herbs and spices (Elumalai et al. 2020). These compounds exhibit antioxidant, anti-inflammatory and immunomodulatory properties that may improve immunity in aquaculture species.

Alkaloids: Alkaloids, such as berberine, piperine, and capsaicin, are nitrogen-containing compounds found in plants like goldenseal, black pepper, and chili peppers. Some alkaloids have demonstrated antimicrobial, immunostimulant, and growth-promoting properties in fish (Almarri et al. 2023).

Terpenoids: Terpenes, are present in a variety of herbs and spices like thyme, oregano, licorice as monoterpenes, diterpenes, and triterpenes. These compounds have been found to exhibit antimicrobial, antioxidant and immunomodulatory activities rendering them as potential candidates for use in aquaculture (Elumalai et al. 2020).

Further compounds: Other bioactive compounds are also found in spices and herbs such as; saponins, lectins, polysaccharides which may influence the immune system of fish due to their immunostimulant effect on other animals (Vijayaram et al. 2022).

Extraction Methods and Standardization

Water, ethanol, methanol and other types of solvents as well maceration and decoction are the most used systems regarding these herbal recipes. This has led researchers to investigate more advanced techniques, such as supercritical fluid extraction (SFE), ultrasound-assisted extraction and microwave-assisted extraction. Herbal extracts must be standardized to guarantee that they convey comparative quality assurance, safety and effectiveness. High-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GCMS) and nuclear magnetic resonance (NMR) are used to detect the phytochemical profile of extracts. Standardization parameter can be the concentration of particular markers, total phenolic content or antioxidant activity et cetera. The bioactive constitution, and consequently the probable effects of a herbal extract are subject to considerable variations in relation with e.g. plant source; cultivation conditions; extraction methods or standardization processes applied. Robust characterization and rigorous quality control is required in order to ensure that herbal extracts can be incorporated reproducibly and safely into aquaculture feed formulations (Tangendjaja 2022).

Immunostimulatory Effects of Herbal Extracts

Modulation of Innate Immune Parameters (phagocytic activity, respiratory burst, etc.)

For instance in several fish species, many herbal extracts like garlic, ginger and turmeric have shown to stimulate phagocytic activity of macrophages as well blood neutrophils. In addition, the high phagocytic activity facilitates pathogen and cellular debris clearance associated with improved immune defense. Some herbal extracts are capable of triggering the respiratory burst activity in phagocytic cells to generate killing reactive oxygen species (ROS) and nitrogen species (RNS), which can eliminate pathogens that have penetrated into tissue. *Astragalus membranaceus* and *Withania somnifera* extracts were shown, for instance, to boost respiratory burst levels of fish cells. For example, some herbal extracts may lead to the induction of antimicrobial peptides such as defensins and cathelicidins which are important human immune response molecules acting against bacteria, viruses or fungi. For example, extracts from garlic (*Allium sativum*), ginger (*Zingiber officinale*) and oregano have been observed to stimulate the expression of certain AMP genes in fish (Kumar et al 2022).

Regulation of Cytokine Production and Inflammatory Responses

Cytokines are important small molecule intermediates that allow the immune system to produce and express itself more widely, but herbal extracts can tune various cytokine productions through their elaborated work. In the case methods have been robust in that extracts were able to stimulate pro-inflammatory cytokines, including interleukin-1 β (IL-1 β) and tumor necrosis factor- α (TNF α), what can include the additionally enhance entity inflammatory response recruiting immune cells necessary for conducting infection. More extracts can be anti-inflammatory through the control of inflammation mediators like prostaglandins and leukotrienes. Herbal extracts often possess high levels of polyphenolic components that serve as powerful antioxidants and anti-inflammatory agents, capable to counteract oxidative damage and excessive inflammation taking place in fish (Dziewulska et al. These effects, in turn, can promote immune homeostasis and protect tissues from damage by the chronic inflammatory responses that are common with age (Mokhtar et al. 2023).

Enhancement of Specific Antibody Production and Cellular Immunity

Certain herbal extracts have been documented to improve the production of certain antibodies (immunoglobulins) in fish, which suggests their ability to trigger humoral adaptive immune response. Extracts from *Withaniasomnifera* and *Astragalus membranaceus* have for example been found to enhance antibody titers in a number of fish species. A number

of herbal extracts have shown the ability to modulate proliferation and activity of lymphocytes particularly T cells and B cells, integral components responsible for cellular immune adaptive responses. Plant derived extracts such as curcumin and gingerol induced T-cell proliferation, cytokine production improving cell mediated immunity in fish. Due to several factors such as plant source, extraction techniques used or whether the extracts were tested in vitro or in vivo; different fish species might show varied immunostimulatory actions of herbal usage. Moreover, the pathways responsible for these effects are likely modulated through extensive interactions between various bioactive compounds in extracts with an array of immunological components. More in vivo and in vitro studies are needed to reveal exactly how different herbal extracts modulate the immune activities of cultured aquaculture species (Zhang et al. 2020).

Stress-Mitigating Effects of Herbal Extracts **Antioxidant Properties and Reduction of Oxidative Stress**

Most of herbal extracts are rich in antioxidant compounds, including polyphenols (e.g., flavonoids and phenolic acids), carotenoids and vitamins C and E which can scavenge free radicals and reactive oxygen species (ROS) thus alleviating oxidative stress in fish. Environmental stressors, pathogens or metabolic disturbances can cause oxidative stress inducing cellular damage and therefore compromising the immune function resulting in an increased risk of diseases. Efficacy of the Antioxidants in Herbal Extracts Several recent studies have demonstrated that herbal extracts with antioxidant potential such as turmeric, ginger and green tea reduce oxidative stress markers while enhancing activities/expressions of various antioxidant enzymes systems in fish (Hoseinifar et al. 2020).

Modulation of Cortisol and other Stress Hormone Levels

In fish, cortisol is the major interrenal stress hormone which could be synthesized and secreted into circulation from their respective organ in response to a range of osmoregulatory perturbations. Some herbal extracts have shown to highly regulate/cortisol in fish, whether by reduction or maintenance within normal levels. For instance, extracts from *Withaniasomnifera* (Ashwagandha) and *O.sanctum*(Tulsi) have been found to reduce cortisol levels in fish during stress (Nazeemashahul et al. 2024).

Besides cortisol, certain plant extracts have also been found to alter the levels of other stress-related hormones like catecholamines (epinephrine, norepinephrine) which play a role in fight-or-flight. In such a condition, herbal extracts by modulating hormones of stress response may help in the maintenance of physiological homeostasis and thwart disadvantageous consequences brought on chronic stress (Ciji and Akhtar 2021).

Influence on Metabolic and Behavioral Responses to Stress

Metabolic changes, such as shifts in energy metabolism, protein synthesis and immune function are common responses to stress-induced physiological trade-offs in fish. Herbal extracts, by influencing various metabolic parameters like glucose levels, lipid profile or enzyme activities had the capacity to counteract these changes induced due to stress as observed in one of our previous studies.

Under stressful conditions, fish exhibit abnormal or maladaptive behaviors including decreased feeding activity erratic swimming and increased aggression. The aforementioned properties could reduce stress-induced behavior changes in fish by improving their overall well-being and anxiolytic (anti-anxiety) effects, but more relevant investigation is needed. For instance, net anxiolytic effects on fish have been reported for various phytopharmaceuticals, including the extracts of *Valeriana officinalis* (Muniandy 2018; de Mendonça et al. 2022).

Note, herbal extracts from different plant sources as well the method of extraction in addition to dose and type NOS for fish species may cause differences in stress-mitigating properties. Furthermore, the actions of these extracts on stress-induced changes in neurochemistry might result from intricate interactions between a variety of bioactive compounds within them and numerous physiological systems implicated in mediating the effects triggered by stress. In vivo and in vitro studies need to be conducted based on proper experimental design which are essential to know the activities of particular herbal extract against stressors in aquaculture species. These immunomodulating properties likely stem from the polyphenols, flavonoids and terpenoids making up the bioactive compounds found in herbal extracts that may act directly on immune cells or receptors(nodes sensei). These interactions can vary the immune response fish (López et al. 2020).

Polyphenols can promote the growth and function of immune cells, such as lymphocytes (antibody producing B-cells), macrophages, and neutrophils. Cytokines Cytokines, signaling molecules that mediate the adaptive immune response, might be influenced by flavonoids. Phagocytic activity of immune cells, an essential step for purging pathogens, can also be regulated by terpenoids. Gene expression and signal pathway regulation: Herbal extracts may regulate gene expressions especially responsible for the immune response, also altered stress-related pathways in fish (Ahmadifar et al. 2021).

Various plant products are known to elicit effects on activation of transcription factors including nuclear factor- κ B (NF- κ B) and activator protein 1 (AP-1), leading to modulation in the expression of various genes associated with inflammatory pathways as well as immune responses. HTAs may therefore act on the hypothalamic-pituitary-adrenal (HPA) axis, which can dial down cortisol levels_loan repayment_cc by exacting psychological stress. Many of the herbal compounds are able to interfere with these enzymes and decrease oxidative stress, inflammation through inhibiting cyclooxygenase-2 (COX-2) [levels]or inducible nitric oxide synthase(NO), as a response you can see decreased levels in inflammatory mediators Nhu et al. 2020; Zheng et al. 2022).

The gut microbiota is key to the health of fish and their immune function. Herbal extracts have the ability to influence and shape intestinal immunity through changing the composition, function of gut microbiota. One of the mechanisms through which certain herbal compounds can affect enteric dysbiosis is selective stimulation of beneficial gut bacteria, like lactic acid microbiota for a high-production profile in antimicrobial compound and immunological modulation. Herbal extracts can enhance intestinal functions, maintain the balance and function of the gut barrier to prevent pathogen invasion and toxic translocation *in vivo*, which helps improve local inflammatory response in intestine tract so as it promotes active mucosal immunity. In addition, some herbal compounds can modulate the production of antimicrobial peptides (AMP) and cytokines in intestinal mucosa, so as to enhance local immune function (Zimmermann and Wagner 2021).

Factors Influencing Efficacy

Factors affecting the potency of herbal extract in farmed fish as immunostimulants and stress-reducing agents are:

Fish Species and Life Stage

Fish are different and each responds differently to the same herbal extract, depending on its physiology, immune system and metabolism. This, in addition to the life stage of the fish also plays a role on how herbal extract effectively works. Example: Immunostimulatory effects of herbal extracts from *Phyllanthus amarus* and *Ocimum sanctum* in Asian sea bass (*Lates calcarifer*) against *Vibrio harveyi*. They found that the herbal extracts increased immune parameters, i.e., respiratory burst activity and complement activity--but variably between fish species (Subramani et al. 2023).

Dosage, Duration, and Administration Method

The effectiveness of herbal extracts can also be highly dosage and duration dependent. Taking too little or not taking it for long enough may have no consequence, but if you took too much of Benadryl Tablets and also had damage as a result further treatment is likely to be advised (Zhu 2020). To illustrate, effects of the herbal extract *Withaniasomnifera* in rohu (*Labeorohita*) on stress and immune responses were evaluated by feeding through diet. A dietary supplementation of *W. somnifera* extract was found to significantly elevate different immune parameters (e.g., respiratory burst activity, serum lysozyme, and antimicrobial complement), accompanied by reduced stress indicators as measured through cortisol levels (Gupta et al. 2021; Trivedi et al. 2024).

Environmental Conditions (temperature, salinity, etc.)

The effectiveness of the herbal extracts might be influenced by environmental factors, as temperature, salinity and water quality have effects on fish physiological state and their immune response. As an example, the effects of dietary supplementation containing herbal extract (*Andrographis paniculata*) on immune response and disease resistance of Asian seabass (*Lates calcarifer*) exposed to different salinity levels. They concluded that the herbal extract was able to improve immune parameters and enhance disease resistance against *Vibrio parahaemolyticus* infection in both freshwater reared fish but depending on a dose-dependent variation with brackish water condition (Susanto et al. 2024).

The performance of most herbal extracts as immunostimulant and stress reducers in farmed fish could be varied due to the reasons like type of herbs, species or life stages of fishes treated, dose rate administered and duration treatment made. These factors may influence the beneficial effects of herbal extracts in aquaculture practices which should be carefully taken into consideration.

Practical Applications and Case Studies

Research reports varying from *in vitro* to experimental studies have been reported which focus on dietary supplementation of herbal extracts for improved disease resistance and immune response, overall performance etc. in various farm raised fish species. Efficacy of dietary supplementation of herbal extracts *A.indica* and *O. sanctum* to protect goldfish (*Carassius auratus* Linnaeus, 1758) against *Aeromonas hydrophila* infection. The results showed that the addition of these plant extracts to fish diets significantly increased survival rates, hematological parameters and blood activities (serum lysozyme activity, antiprotease activity), superior metabolic and hematic responses including serum respiratory burst) compared to those fed with this basal mixture without plants (Semwal et al. 2023).

The potential of herbal extracts for fish stress reduction in handling, transport and other aquaculture practices have been explored. The impact of supplementation with the herbal extract, *Phyllanthus amarus* on stress and immune responses in grey mullet (*Mugil cephalus*) subjected to transportation injury. The study indicated that in fish receiving diets with *P. amarus* extract, lower cortisone and glucose levels but higher respiratory burst activity, lysozyme activity as well as complement activities were detected relative to the group control, indicating the stress reducing properties of this herbal supplement along with its immunomodulatory effects against a viral infection lehemomediated immunity (Viral Nervous Necrosis) (Mariappa et al. 2023).

The herbal extracts have immense practical applications and case studies that show herbals as effective immunostimulants and stress-reducing agents in aquaculture. Nevertheless, it has to be considered that the efficacy of herbal extracts depends on fish species as well as dosage level and influence significant differences due application method or environmental conditions. Hence, additional studies and optimization are needed to exploit the properties of

herbal extracts best in individual aquaculture scenarios. Bioactive compound content and standardization issues: Herbal extracts are mixtures of different complex bioactive compounds, they can vary greatly due to differences in plant species, geographical locations, agroclimatic conditions and extraction methods. Such variance can translate to differences in the extracts, which may be difficult for them to standardize as well as that they put on stringent quality control measures. In order to solve this issue, much work is being accomplished about identifying and quantifying the bioactive ingredients leading to health effects of herb extracts. Standardization protocols and analytical techniques such as high-performance liquid chromatography (HPLC) and mass spectrometry are discussed for herbal extracts to identify the gross chemical composition (Sarmiento et al. 2024).

In addition, scientists are trying to adopt modern biotechnological strategies using plant cell culture techniques and metabolic engineering that can help produce uniform as well as standardized herbal extracts with clear profiles of these bioactive compounds.

Consumers and regulations oversee the use of herbal extracts in aqua feeding. The use of herbal extracts as feed additives or therapeutic agents needs a lot long term safety and efficacy data which may be only satisfied by some regulatory agencies. One area of concern in some regions may be the possibility of contaminants or residues in herbal extracts, and the importance for that information to appear on labels among other disclosures. A final factor to consider is consumer acceptance; some consumers may be wary of the use plant-based additives in farming an animal product, whilst others may view them as naturally derived preferred to synthetics. Meeting these challenges requires a coordinated effort by researchers in public health, regulatory agencies and industry partners. It is necessary to conduct safety and efficacy trials, allow standardization methodologies as well use lap transparency for communication with consumers prior herbal extracts get approval from regulatory bodies especially in public perception (Throne-Holst 2023).

These emerging trends and future directions explore the diverse efforts to identify new sources of herbal extracts, design combination schemes for increased efficacy, and take benefit from advanced omics technologies in order to better comprehend the underlying mechanisms. These developments will be effective in the novel application of herbal extracts that can improve fish health, disease resistance and overall productivity in aquaculture.

Potential Applications in Sustainable Aquaculture

Utilization of herbal extracts in aquaculture supports sustainable and eco-friendly approach. Natural compounds represent an effective means of supplementing synthetic immunostimulants and antibiotics, reducing the likelihood(s) for promoting AMR (antimicrobial resistance), as well as environmental contamination. The inclusion of herbal extracts in aquafeed and health management practices can aid to overall industry sustainability by enhancing fish health, welfare coupled with reduced reliance on synthetic compound utilization.

Future Research Opportunities and Collaborations

Great strides have been made in comprehension of the role of plants extracts for aquaculture but some issue area is there to be solved. This will involve issues such as variation in bioactive compound content and the requirement for standardization, potential interactions with other feed ingredients or medications, and regulatory considerations along with consumer acceptance.

Future research should focus on:

1. Identifying the active principles accountable for herbal extracts therapeutic effects and devising the standardization protocols.
2. Examining interactions between herbal extracts and other feed inputs or medications in current use for aquaculture.
3. Diversifying clinical safety and efficacy studies to bolster regulatory clearances beyond proven food-safety with consumers.
4. Development of new herbal extracts and sources, combining with other immunostimulants as well health management options.
5. Unscrambling clinical pharmacology utilizing omics-centric strategies to define the molecular constituents mediated by herbs contributing to immunomodulatory/anti-stress effects.

To move this subsector of sustainable aquaculture forward, interdisciplinary collaborations between academics and industry stakeholders from private sectors as well regulatory agencies will also be essential for a broad scientific background of herbal extracts applications. These partnerships can enable the sharing of information to deal with relevant issues and make recommendations for proper usage of these natural compounds in boosting fish healthiness production.

Summary of Key Findings

Utilization of moderate plant extracts to boost the fish immune response and lower resistance in farmed-freshwater fishes has gained much attention because it is thought to help improve health conditions, production capacity. Studies have shown that herbal extracts can interact with immune cells and receptors, modulate gene expression and signaling pathway of cellular function or regulate gut microbiota alongside intestinal immunity. These are examples of the mechanisms by which herbal extracts provide a part of their immunomodulatory and stress mitigating effects. In a wider perspective, many are the investigations entailing practical applications of herbal extracts for dietary supplementation

within aquaculture to prevent and cope with diseases in addition to stressful situations (e.g., handling, transport) as well as their association with other health management strategies. Studies include case reports of enhanced survival from bacterial infections, improved immune parameters and reduced stress indicators.

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