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Assessing the Efficacy of Indigenous Plant-Based Feed Additives in Aquaculture Nutrition

Joshua Oyeboade [1*], **Olasumbo Olagoke-Komolafe** [2]
[1] Bio Logical LLC, Boulder City, NV, USA
[2] Sweet Sensation Confectionery Limited, Lagos Nigeria

* Corresponding Author: **Joshua Oyeboade**

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Abstract
The escalating demand for sustainable and cost-effective feed solutions in aquaculture has catalyzed interest in indigenous plant-based additives as viable alternatives to synthetic compounds and conventional fishmeal-based formulations. This review critically assesses the biological efficacy, functional roles, and practical application of indigenous botanicals in aquaculture nutrition, emphasizing their potential to enhance growth performance, feed utilization, and health outcomes in aquatic species. Key plant species such as *Moringa oleifera*, *Azadirachta indica*, *Curcuma longa*, and *Ocimum sanctum* have demonstrated promising immunostimulatory, antioxidant, antimicrobial, and digestive-enhancing properties. The review highlights the importance of species selection, harvesting timing, and post-harvest processing techniques in preserving phytochemical integrity and reducing antinutritional factors such as tannins, phytates, and saponins. Case studies reveal substantial improvements in specific growth rate (SGR), feed conversion ratio (FCR), enzyme activity, and disease resistance when these additives are incorporated in fish diets at optimal levels. However, the presence of anti-nutritional compounds and variability in phytochemical content across regions necessitate rigorous standardization and detoxification strategies to ensure safety and consistency. Integrating traditional ethnobotanical knowledge with contemporary aquafeed science emerges as a strategic pathway to support environmentally sustainable, economically viable, and nutritionally robust aquaculture systems. The review concludes by advocating for continued interdisciplinary research, policy support, and community engagement to harness the full potential of indigenous plant resources for global aquaculture sustainability.

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1. Introduction
1.1. Global Trends in Aquaculture Production and Sustainability Challenges
Aquaculture, the cultivation of aquatic organisms under controlled conditions, has experienced unprecedented global growth in recent decades, positioning itself as a key pillar of food security and economic development. According to Bostock *et al.* (2010), global aquaculture production now accounts for over half of the world's fish supply for human consumption. This growth trend is attributed to increasing demand for high-quality protein, stagnation in wild fisheries, and technological innovations that have enhanced production efficiency.
Despite its contribution to food security and rural livelihoods, aquaculture faces mounting sustainability concerns. Chief among them are the environmental externalities related to nutrient loading, habitat destruction, and disease proliferation.

Naylor *et al*. (2021) conducted a comprehensive 20-year retrospective review and emphasized that while technological and managerial advances have been made, persistent issues like antibiotic resistance, pathogen outbreaks, and the use of wild fish in feeds continue to challenge the industry's long-term viability.

Global aquaculture production reached approximately 82 million tonnes in 2018, and this number is expected to grow, especially in Asia, which contributes over 89% to global production (D'Abramo, 2021). However, the environmental cost of such growth—especially in marine ecosystems—has prompted calls for more integrated and ecologically conscious production systems. Countries like Thailand, for example, face localised ecological degradation due to effluent discharge and land-use conflicts, indicating the need for policy-level interventions and more sustainable practices (Sampantamit *et al*., 2020).

The sustainability discourse in aquaculture also intersects with climate change. Changing water temperatures, ocean acidification, and extreme weather events pose existential threats to aquaculture productivity and species survival. Ahmed *et al*. (2019) highlighted that adaptive capacity—particularly in developing nations—is still limited, making the sector vulnerable to climate shocks. Moreover, the carbon footprint of intensive aquaculture systems, especially those relying on formulated feeds, raises concerns regarding aquaculture's contribution to greenhouse gas emissions.

Feed production is a particularly contentious sustainability issue. Aquafeeds traditionally depend on fishmeal and fish oil, extracted from wild-caught forage fish, creating a loop of dependency that undermines marine biodiversity. The need for sustainable feed solutions has become increasingly urgent. Tacon (2020) observed that aquafeed innovation, particularly through the integration of plant-based and microbial ingredients, offers a promising pathway for decoupling aquaculture from unsustainable marine inputs.

Nevertheless, plant-based feeds introduce their own set of challenges, including anti-nutritional factors, digestibility issues, and concerns over deforestation and pesticide use in feed crop cultivation. Hence, there is an emerging interest in regionally available, indigenous plant-based feed additives that may offer both functional benefits and lower environmental footprints. These indigenous resources—such as *Azadirachta indica* (neem), *Moringa oleifera*, and *Terminalia* spp.—are now being explored for their immunostimulatory, antimicrobial, and growth-promoting properties, especially in low- and middle-income countries where feed costs are a significant constraint to aquaculture growth.

Additionally, the economic and regulatory context plays a pivotal role in shaping the sustainability landscape. According to Oglend (2020), global trade patterns in aquaculture products are shifting, with increasing demand from the Global North driving more intensive production systems in the Global South. This imbalance often results in environmental burdens being exported to regions with weaker regulatory frameworks. Thus, aligning aquaculture development with the UN Sustainable Development Goals requires not only technological solutions but also governance reforms and equitable market structures.

Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture Systems (RAS) have been championed as potential sustainable solutions. IMTA incorporates species from different trophic levels in a single production system, optimizing nutrient recycling, while RAS minimizes water use and waste discharge. Yet these systems are capital-intensive and often inaccessible to small-scale farmers, who constitute the majority of producers in the Global South (Boyd *et al*., 2020).

While aquaculture has grown into a global economic powerhouse and a crucial food source, it remains entangled in environmental, social, and economic sustainability challenges. Moving forward, innovation in feed composition—particularly through the use of locally sourced, plant-based additives—represents a promising strategy to enhance sustainability, reduce dependency on marine resources, and support climate-resilient aquaculture systems. However, such innovations must be embedded within broader frameworks of ecological stewardship, policy coherence, and inclusive economic development.

1.2. Limitations of Conventional Feed Ingredients and Additives

Conventional aquafeeds, primarily composed of fishmeal, fish oil, and various synthetic additives, have historically underpinned the rapid expansion of aquaculture. However, this dependence on marine-derived ingredients and artificial supplements has introduced several sustainability, economic, and health-related concerns, prompting an urgent need to explore viable alternatives.

Fishmeal and fish oil, once considered indispensable due to their high protein and essential fatty acid content, now pose critical environmental and economic limitations. Their production relies heavily on wild-caught forage fish, exacerbating pressure on marine ecosystems and contributing to biodiversity loss (Zlaugotne *et al*., 2022). Additionally, fluctuations in availability and price volatility make these inputs economically unsustainable for small-scale producers.

Moreover, synthetic feed additives—such as antibiotics, growth promoters, and pigments—raise significant health and ecological concerns. Continuous use of antibiotics in aquaculture feed has been linked to the emergence of antimicrobial-resistant bacteria, posing a threat to aquatic health and public safety (Dawood *et al*., 2018). Furthermore, synthetic additives often have limited bioavailability and can accumulate in aquatic environments, affecting non-target species and disrupting ecological balances (Glencross *et al*., 2007).

Another notable challenge is the nutritional limitation of conventional plant-based substitutes such as soybean meal and wheat gluten, which are often used to reduce fishmeal content. While they are more sustainable, these ingredients contain anti-nutritional factors (ANFs) that impair nutrient absorption, reduce feed efficiency, and may lead to inflammatory conditions in fish (Hossain *et al*., 2024). Attempts to mitigate these effects through processing or supplementation have shown partial success, but often increase production costs.

Lastly, functional additives, such as immunostimulants and probiotics, though promising, face challenges related to consistency, species-specific responses, and regulatory constraints (Encarnação, 2016). Their effectiveness varies across aquaculture systems, and the lack of standardization in dosing and delivery hampers their wide-scale application.

The limitations of conventional feed ingredients and additives—ranging from environmental degradation and rising costs to biological inefficacies—underscore the necessity of exploring alternative strategies, including the use of indigenous plant-based feed additives.

1.3. Relevance of Indigenous Plant-Based Alternatives in Aquaculture Nutrition

In the face of mounting sustainability concerns and economic constraints associated with conventional aquafeed ingredients, indigenous plant-based alternatives have emerged as viable, eco-friendly solutions in aquaculture nutrition. These alternatives are increasingly gaining attention for their accessibility, affordability, and diverse bioactive properties that promote fish health, enhance growth performance, and reduce environmental impacts.

Indigenous plants such as *Moringa oleifera*, *Azadirachta indica* (neem), *Terminalia chebula*, and *Andrographis paniculata* are widely distributed across Africa and Asia and possess phytochemicals—flavonoids, tannins, saponins, alkaloids—that exhibit immunostimulant, antimicrobial, antioxidant, and anti-inflammatory activities (Hridoy *et al*., 2025). These bioactivities not only reduce disease susceptibility in fish but can also lessen dependency on synthetic additives like antibiotics, thereby aligning with sustainable aquaculture practices.

Studies on *Moringa oleifera* have shown significant promise, particularly in improving the growth rate and survival of species like tilapia and catfish. For instance, Ndour *et al*. (2020) found that inclusion of moringa leaf meal in diets enhanced protein retention and feed conversion efficiency in *Oreochromis niloticus*. Similarly, neem-based additives have demonstrated antibacterial properties against common aquaculture pathogens such as *Aeromonas hydrophila*, reducing the need for therapeutic treatments.

One of the key advantages of using indigenous plant additives is their local availability. This offers a cost-effective option for smallholder farmers in the Global South who are often constrained by the rising prices of commercial feed inputs. According to Teves and Ragaza (2016), incorporating locally sourced ingredients reduces input costs while promoting circular, place-based aquaculture systems.

Additionally, indigenous plants offer environmental advantages by promoting biodegradability and minimizing chemical residues in aquatic ecosystems. Unlike synthetic additives, many phytochemicals degrade naturally without accumulating in sediments or bioaccumulating in fish tissue, thus preserving water quality and ecosystem health (Vijayaram *et al*., 2024).

However, despite their potential, challenges remain. The variability in phytochemical composition due to geographical or seasonal differences, lack of standardized dosages, and limited commercial processing infrastructure have hindered the broader adoption of these additives. Moreover, certain plant compounds may contain anti-nutritional factors (ANFs), necessitating careful dose optimization and pre-treatment processes like drying or fermentation (Kuebutornye *et al*., 2024).

Nevertheless, technological advances in feed formulation and a growing body of empirical evidence support the strategic integration of indigenous botanicals into aquafeeds. As aquaculture continues to expand in resource-limited settings, leveraging ethnobotanical knowledge and locally adapted resources offers a culturally appropriate and scientifically supported path toward more resilient and sustainable aquaculture systems.

1.4. Objectives and Scope of the Review

The primary objective of this review is to critically assess the efficacy and relevance of indigenous plant-based feed additives in aquaculture nutrition, particularly in the context of sustainability, cost-effectiveness, and fish health enhancement. As global aquaculture intensifies and pressures mount on conventional feed resources, exploring underutilized, locally available plant sources presents a promising avenue for developing environmentally sound and economically viable feed solutions.

This review synthesizes peer-reviewed evidence on the phytochemical properties, growth performance outcomes, immunological benefits, and ecological impacts associated with commonly used indigenous botanicals in aquaculture. Additionally, it examines the limitations, challenges, and knowledge gaps related to their standardization, formulation, and adoption at scale. The review emphasizes small- to medium-scale production systems, especially in low- and middle-income countries, where the integration of indigenous knowledge into feed technology holds untapped potential for food security, sustainability, and innovation.

2. Functional Roles of Feed Additives in Aquaculture Nutrition

Feed additives are non-nutritive substances incorporated into aquafeeds in small quantities to enhance feed efficiency, promote fish growth, improve immune function, and maintain water quality. Their role in modern aquaculture is central to addressing critical challenges such as disease outbreaks, poor feed conversion, and declining water quality, especially in intensive farming systems.

Functional feed additives have become integral to sustainable aquaculture nutrition strategies. As Encarnação (2016) outlines, the concept of "functional feeds" has gained traction, emphasizing the use of additives not only for performance enhancement but also for boosting physiological health and stress resilience in fish. These additives often serve multiple roles, including acting as immunostimulants, antioxidants, prebiotics, probiotics, enzymes, and even anti-parasitic agents.

One of the most important categories of functional additives is immunostimulants. These substances, often derived from plants, microbes, or marine organisms, help bolster the innate and adaptive immune responses in fish. For instance, Dawood *et al*. (2018) highlight that feed additives such as β-glucans, garlic, and *Moringa oleifera*extracts have been effective in enhancing disease resistance and survival rates in aquaculture species under pathogenic stress.

Another key function of feed additives lies in improving digestive efficiency. Exogenous enzymes such as phytase, protease, and cellulase are increasingly used to break down complex plant molecules, improving nutrient bioavailability and reducing anti-nutritional effects (Liang *et al*., 2022). This is particularly beneficial when using plant-based feed ingredients, which may otherwise impair gut health and growth performance.

Prebiotics and probiotics have also garnered significant interest for their gut microbiota-modulating effects. These additives enhance the balance of beneficial bacteria in the gastrointestinal tract, leading to better digestion, nutrient absorption, and disease resilience (Hoseinifar *et al*., 2019).

Moreover, functional additives also include organic acids, binders, pigments, and flavor enhancers, all aimed at improving feed intake, maintaining water stability of feed pellets, or improving product quality (e.g., pigmentation in salmonids and ornamental fish). For instance, organic acids have shown antimicrobial activity and enhanced nutrient utilization by modifying gut pH and reducing pathogen load (Bharathi *et al*., 2019).

In the context of sustainability, the use of natural plant-based additives is gaining ground due to their biodegradability and minimal ecological footprint. As Onomu and Okuthe (2024) suggest, replacing synthetic chemical additives with plant-derived alternatives could substantially reduce environmental pollution and antibiotic resistance risks.

Feed additives are pivotal in optimizing aquaculture production. Their multifunctionality—ranging from enhancing growth and immunity to improving feed utilization—makes them indispensable tools in modern, sustainable aquaculture systems.

2.1. Definition and Classification of Feed Additives

Feed additives in aquaculture are defined as non-nutrient or low-nutrient compounds added to fish diets in small quantities to confer specific physiological or production benefits. These may include improvements in growth rate, feed conversion ratio, stress tolerance, immune function, or product quality. Their utility stems not from direct nutritional value but from their functional impact on health and performance.

Feed additives can be broadly classified based on their function, origin, or mode of action. Functionally, they are commonly grouped into the following categories:

- **Immunostimulants:** Compounds that enhance immune responses, including β-glucans, levamisole, plant extracts (e.g., neem, garlic), and microbial derivatives. They are crucial in reducing disease susceptibility, particularly in antibiotic-free aquaculture (Dawood *et al*., 2018).
- **Digestive Enzymes:** Enzymes such as phytase, amylase, and protease facilitate the breakdown of indigestible plant matter, improving nutrient assimilation (Liang *et al*., 2022).
- **Prebiotics and Probiotics:** Prebiotics like inulin and mannan oligosaccharides (MOS), and probiotics such as *Bacillus* spp. and *Lactobacillus* spp., support gut health by promoting beneficial microbial populations (Hoseinifar *et al*., 2019).
- **Organic Acids:** Compounds like citric, formic, or lactic acid that reduce intestinal pH, suppress pathogenic bacteria, and enhance mineral absorption.
- **Pigments and Colorants:** Carotenoids such as astaxanthin enhance skin and flesh coloration, particularly in salmonids and ornamental species.
- **Growth Promoters:** Substances that accelerate growth, which may include herbal extracts, essential oils, and certain amino acid derivatives.
- **Antioxidants:** Additives like vitamin E, selenium, or plant polyphenols mitigate oxidative stress and improve tissue health.

From a regulatory standpoint, feed additives may also be grouped as nutritional, zootechnical, sensory, or technological additives, depending on their primary function in aquafeed formulations (Encarnação, 2016).

Understanding these classifications helps in the strategic selection and application of feed additives, ensuring optimal fish performance while maintaining environmental and economic sustainability in aquaculture.

2.2. Mechanisms of Action of Functional Additives

The efficacy of functional feed additives in aquaculture is rooted in their diverse mechanisms of action, which target both physiological and immunological pathways in fish. These additives function by interacting with the digestive system, immune cells, microbiota, and metabolic enzymes to enhance growth, resilience, and overall health.

One of the primary mechanisms involves modulation of gut microbiota**.** Additives such as prebiotics and probiotics promote the proliferation of beneficial bacteria (e.g., *Lactobacillus*, *Bacillus*), which outcompete pathogenic microbes, improve digestion, and stimulate mucosal immunity (Hossain *et al*., 2024). This results in improved feed conversion ratios and resistance to gastrointestinal infections.

Another mechanism is immune activation**.** Immunostimulants— especially those derived from plants— trigger the upregulation of immune-related genes and enhance activities of immune cells such as macrophages, lymphocytes, and neutrophils. For example, *Moringa oleifera* extract has been shown to elevate lysozyme and phagocytic activity, reinforcing the fish's innate defense system (Hridoy *et al*., 2025).

Functional additives also act through antioxidant pathways. Bioactive compounds such as flavonoids and phenolics scavenge free radicals, reduce oxidative stress, and protect tissues from damage, especially under conditions of environmental or metabolic stress (Sumana *et al*., 2025).

Enzyme-producing additives, including exogenous proteases and phytases, enhance nutrient digestibilitybybreaking down complex plant compounds like phytic acid, cellulose, and non-starch polysaccharides. This allows for better assimilation of proteins, minerals, and energy substrates, particularly in plant-rich diets (Kuebutornye *et al*., 2024).

Collectively, these mechanisms underline the multifaceted contributions of functional additives in fortifying fish against nutritional, microbial, and oxidative stressors, thereby promoting sustainable aquaculture practices.

2.3. Nutritional, Immunological, and Therapeutic Roles

Functional feed additives perform critical nutritional, immunological, and therapeutic roles that extend beyond conventional dietary inputs, supporting growth and health across a wide range of aquaculture species.

Nutritionally, additives such as exogenous enzymes (e.g., proteases, cellulases, and phytases) increase the digestibility and bioavailability of nutrients in plant-based diets. These enzymes break down indigestible compounds such as phytic acid and fiber, releasing essential amino acids, phosphorus, and other minerals. This is particularly valuable in low-fishmeal diets, where plant ingredients may otherwise limit nutrient uptake (Hossain *et al*., 2024). Additionally, appetite enhancers and flavorants improve feed palatability, thus optimizing feed intake and growth.

Immunologically**,** plant-derived compounds like saponins, tannins, and alkaloids play vital roles in boosting both innate and adaptive immunity. As Kumar and Bossier (2018) observed, these compounds activate immune responses by stimulating macrophages, enhancing complement activity, and increasing cytokine expression. This heightened immune readiness reduces disease incidence and enhances survival, especially under pathogen pressure or stressful environmental conditions.

Therapeutically, several functional additives exhibit antimicrobial, antiparasitic, and anti-inflammatory properties. For instance, neem (*Azadirachta indica*) extracts have shown broad-spectrum activity against *Aeromonas hydrophila*, a common aquaculture pathogen. The therapeutic potential of additives like *Moringa oleifera*, garlic, and turmeric is attributed to their bioactive profiles—rich in flavonoids, essential oils, and sulfur compounds—which can inhibit microbial growth and modulate inflammatory pathways (Sumana *et al*., 2025).

Furthermore, antioxidant compounds such as phenolics, carotenoids, and tocopherols mitigate oxidative damage in fish tissues caused by intensive farming practices, poor water quality, and disease outbreaks. These antioxidants stabilize cellular membranes, prevent lipid peroxidation, and protect vital organs such as the liver and gills.

An emerging area of interest involves functional additives with anti-stress effects**.** Adaptogens like *Withaniasomnifera* (ashwagandha) and *Ocimum sanctum* (holy basil) modulate cortisol levels and enhance tolerance to salinity, temperature fluctuations, and handling stress, making them promising candidates for climate-resilient aquaculture systems (Phan *et al*., 2025).

Overall, functional feed additives provide a holistic suite of benefits—ranging from enhanced digestion and nutrient assimilation to robust immune protection and therapeutic support—thus playing an indispensable role in modern aquaculture nutrition.

2.4. Overview of Plant-Derived Bioactive Compounds

Plant-derived bioactive compounds are central to the development of sustainable, health-promoting aquafeeds. These naturally occurring secondary metabolites exhibit diverse biological activities that support fish growth, disease resistance, and stress mitigation, often with minimal environmental impact.

Key classes of bioactive phytochemicals include flavonoids**,** alkaloids**,** saponins**,** terpenoids**,** tannins**,** andphenolic acids. Each class exerts specific functions that contribute to aquaculture performance. For instance, flavonoids are powerful antioxidants that scavenge reactive oxygen species (ROS) and stabilize cell membranes, thus enhancing resilience to oxidative stress (Onomu&Okuthe, 2024). Alkaloids and saponins, commonly found in neem, garlic, and licorice, have demonstrated antimicrobial and antiparasitic effects through membrane disruption and enzyme inhibition.

Moringa oleifera, an indigenous plant rich in isothiocyanates and flavonoids, has gained significant attention as a feed additive. It improves feed intake, promotes weight gain, and enhances immune markers such as lysozyme and respiratory burst activity (Hridoy *et al*., 2025). Similarly, turmeric (*Curcuma longa*), due to its curcumin content, acts as a potent anti-inflammatory and liver-protective agent, reducing hepatocellular damage and enhancing detoxification pathways (Sumana *et al*., 2025).

Another group of promising botanicals includes polyphenol-rich herbs such as *Ocimum sanctum* (holy basil) and *Withaniasomnifera* (ashwagandha). These adaptogenic plants regulate stress hormones, support antioxidant enzyme expression, and improve tolerance to environmental fluctuations. Such benefits are especially valuable in the context of climate-induced aquaculture stressors.

Essential oils extracted from plants like oregano, thyme, and clove are also being used in aquafeeds. These oils contain terpenoids and phenolics with bacteriostatic and antifungal properties. Studies show that dietary supplementation with clove oil enhances mucosal immunity and reduces mortality in infected fish populations (Kalaiselvan *et al*., 2024).

Moreover, plant sterols and **l**ectins are being evaluated for their immune-modulating and gut-barrier-enhancing effects. While still under-researched, these compounds offer promise in reducing inflammation and improving intestinal morphology in fish.

Challenges remain regarding bioavailability**,** standardization**,** and dose optimization**.** The effectiveness of plant-derived bioactives can be influenced by factors such as processing method (drying, fermentation), feed matrix compatibility, and fish species-specific responses. Hernández-Contreras and Teles (2023) emphasize the importance of formulation science in maximizing additive stability and function throughout feed processing and storage.

The integration of plant-derived bioactive compounds into aquafeeds offers a nature-based, multifunctional strategy for promoting health, productivity, and sustainability in aquaculture. Continued research into their molecular actions, safety profiles, and synergistic combinations will further unlock their potential as next-generation feed solutions.

2.5. Comparative Analysis with Synthetic Additives

The rise of plant-based feed additives in aquaculture has been driven in large part by the growing need for sustainable and health-conscious alternatives to synthetic compounds. A comparative analysis between synthetic and indigenous plant-based additives reveals differences in functionality, ecological impact, fish health outcomes, regulatory constraints, and consumer acceptance.

Efficacy and Multifunctionality

Synthetic feed additives, including antibiotics, synthetic antioxidants (e.g., butylated hydroxyanisole), colorants, and growth promoters, have traditionally been used to enhance growth, prevent disease, and improve feed efficiency. While effective, their narrow spectrum of action often requires multiple compounds to achieve multifunctional results. In contrast, plant-based additives, or phytogenics, offer broad-spectrum bioactivity due to their complex composition of flavonoids, terpenoids, alkaloids, and essential oils (Kuebutornye *et al*., 2024).

For example, *Moringa oleifera* and neem (*Azadirachta indica*) extracts serve as natural immunostimulants, growth promoters, and antimicrobials—providing several health benefits simultaneously (Ndour *et al*., 2020). In comparison, antibiotics must be carefully dosed and rotated to avoid resistance, and synthetic growth promoters may not provide immunological benefits.

Health and Safety Considerations

A major concern surrounding synthetic additives is their potential for toxicity, bioaccumulation, and antibiotic resistance. Synthetic antibiotics and pigments can leave residues in fish tissue, posing risks to human health and contributing to antimicrobial resistance when misused

(Vijayaram *et al*., 2024). This has prompted regulatory restrictions and consumer resistance in many markets.

Conversely, plant-based additives, particularly those derived from traditionally used medicinal herbs, are biodegradable and generally recognized as safe (GRAS). They typically degrade rapidly in the environment and do not bioaccumulate in fish tissue (Hossain *et al*., 2024). However, challenges remain in dose optimization and the presence of anti-nutritional factors, which may impact efficacy if not processed appropriately.

Performance Outcomes in Growth and Feed Conversion

Several studies have compared performance metrics such as weight gain, specific growth rate (SGR), and feed conversion ratio (FCR) between fish fed synthetic and plant-based diets. Browdy *et al*. (2006) reported comparable or superior growth in shrimp (*Litopenaeusvannamei*) fed organic, plant-based diets compared to those on fishmeal- and synthetic-additive-based feeds. Similarly, tilapia (*Oreochromis niloticus*) fed moringa-supplemented diets showed improved growth and body composition compared to synthetic controls (Ndour *et al*., 2020).

However, performance may vary by species and additive type. Some plant-based compounds can reduce palatability or contain anti-nutritional elements that affect digestion unless treated with fermentation or heat processing (Estruch *et al*., 2018).

Environmental Impact and Sustainability

Synthetic additives are often associated with environmental risks, including water contamination, disruption of aquatic microbiota, and accumulation in sediments. These ecological externalities are especially problematic in open-water cage farming systems.

In contrast, plant-derived additives are often more environmentally friendly. Many are biodegradable and have minimal ecological footprint, aligning with circular bioeconomy and eco-aquaculture principles. For instance, clove oil and oregano essential oils used as natural antimicrobials show no environmental persistence and can be locally sourced, reducing the carbon footprint associated with transport and processing (Kalaiselvan *et al*., 2024).

Regulatory and Economic Considerations

Synthetic additives are typically standardized and tightly regulated, offering predictability in feed formulation. However, regulatory pressures are increasing worldwide to reduce or eliminate antibiotic use in aquafeeds, prompting a shift toward natural alternatives.

Plant-based additives face fewer regulatory hurdles, especially when sourced from indigenous plants already used in traditional diets. Yet, variability in phytochemical content and lack of global standardization present formulation challenges. Processing and extraction costs may also limit scalability for small producers unless local, low-cost methods are adopted (Hernández-Contreras & Teles, 2023).

Consumer Preference and Market Potential

Consumer demand is increasingly leaning toward antibiotic-free, “green-labelled,” and organically produced aquaculture products. Plant-based additives offer a competitive edge in this regard, appealing to environmentally conscious consumers. Fish fed phytogenic additives often exhibit enhanced pigmentation and taste profiles, which can enhance product appeal, particularly in ornamental and high-value markets (Napier & Betancor, 2023).

Moreover, incorporating local, indigenous plant resources into aquafeeds can promote economic resilience in rural communities, reduce dependency on imported synthetic compounds, and support inclusive aquaculture development.

3. Indigenous Plants as Feed Additives in Aquaculture

The integration of indigenous plant-based resources into aquaculture feed formulation represents a paradigm shift toward sustainable, locally adapted, and cost-effective fish nutrition. These plants, often rich in diverse bioactive compounds, offer functional roles ranging from growth promotion to disease resistance enhancement, making them attractive alternatives to synthetic additives. Their use is particularly critical in regions with limited access to commercial feed inputs, enabling a circular approach to aquaculture development rooted in traditional ecological knowledge and local biodiversity.

Indigenous plants are those that are native or naturalized within a specific ecological region and are commonly utilized by local communities for food, medicine, or other traditional applications. In the context of aquaculture, several such plants—e.g., *Moringa oleifera*, *Azadirachta indica* (neem), *Allium sativum* (garlic), *Ocimum gratissimum* (African basil), and *Terminalia chebula*—have demonstrated considerable promise as feed additives or supplements. These botanicals contain phytochemicals such as flavonoids, alkaloids, tannins, saponins, and terpenoids that have antimicrobial, immunostimulant, antioxidant, and antiparasitic properties (Mbokane& Moyo, 2022).

Studies conducted on *Oreochromis mossambicus* and *Clarias gariepinus* have shown that incorporating medicinal plants into diets not only enhances fish survival and growth but also improves haematological parameters and disease resistance. This makes them a particularly valuable tool in managing disease outbreaks without relying on antibiotics or vaccines (Olusola *et al*., 2013).

Another advantage of indigenous plants lies in their cultural familiarity and ecological suitability. Unlike imported additives, they are often more resilient to local climatic conditions, require minimal processing, and can be cultivated or harvested sustainably. This ensures a lower production footprint and empowers local farmers to participate in feed value chains (Teves &Ragaza, 2016).

Despite their benefits, challenges exist in standardizing indigenous plant use in aquafeeds. Phytochemical concentrations can vary widely due to environmental factors, genetic variability, and post-harvest handling. This variability impacts efficacy and complicates the development of standardized formulations. Moreover, some plants contain antinutritional factors (ANFs) that, if not mitigated by processing methods such as drying, fermenting, or heat treatment, may reduce nutrient availability or impair gut function (Francis *et al*., 2001).

Advancements in ethnobotanical research and phytochemistry have begun to address these challenges by identifying optimal processing techniques and effective dose ranges for different species. Integration with nutrigenomic and metabolomic approaches further enhances the potential of indigenous plants by elucidating molecular pathways influenced by phytochemicals, thereby refining additive efficacy (Kuebutornye *et al*., 2024).

Indigenous plant-based feed additives offer a resilient, locally appropriate alternative to conventional aquafeed inputs. When carefully selected, validated, and standardized, these resources can serve as key enablers of sustainable aquaculture in biodiversity-rich, resource-limited regions.

3.1 Conceptualizing Indigenous Plant Resources

The concept of indigenous plant resources encompasses a spectrum of flora that are native, naturalized, or traditionally utilized within a specific geographic or cultural context. These plants have historically served as tools for nutrition, medicine, and cultural practice, particularly among indigenous and rural communities. In aquaculture, their emerging role as functional feed additives aligns with the principles of ethnoveterinary medicine and sustainable agroecology.

Indigenous plants are characterized not only by their botanical origin but also by the socio-cultural knowledge associated with their use. This indigenous knowledge system (IKS) includes detailed understandings of plant preparation, therapeutic applications, seasonal availability, and ecological roles. Leveraging this knowledge for aquafeed development allows for the integration of culturally rooted solutions into modern aquaculture practices (Makkar *et al*., 2007).

From a functional standpoint, indigenous plants provide a diverse array of phytochemicals that offer bioactive roles in fish nutrition. For instance, *Ocimum gratissimum* and *Allium sativum* are widely known among African and Asian communities for their antibacterial and anti-inflammatory properties. Such plants can be incorporated into aquafeeds either in crude, powdered, or extracted forms to enhance fish immune responses and feed utilization efficiency (Kuebutornye&Abarike, 2020).

The value of these plants extends beyond functional properties. Many indigenous plants are readily available in rural environments, often growing wild or in agroforestry systems. This accessibility reduces dependency on commercial inputs, promotes feed autonomy, and fosters a decentralized feed system aligned with local agroecological resources. Furthermore, incorporating indigenous plants into aquaculture supports economic inclusion, especially for women and smallholder farmers who are often the primary custodians of traditional knowledge and plant-based practices (Teves &Ragaza, 2016).

An essential component of conceptualizing indigenous plant use in aquaculture is the application of the One Health framework, which recognizes the interconnected health of people, animals, and ecosystems. Many indigenous plants used in fish feed are already part of human diets or folk medicine, ensuring a high degree of biocompatibility and safety. This makes them suitable for integrated aquaculture-agriculture systems, where food chain continuity and residue safety are of paramount importance (Beltrán & Esteban, 2022).

Nonetheless, developing a science-driven conceptual framework requires the harmonization of indigenous knowledge with modern research methodologies. Standardizing plant species identification, developing reproducible extraction methods, and validating bioactivity through controlled trials are necessary to move from anecdotal use to evidence-based aquafeed applications (Ghosh *et al*., 2019).

Ultimately, conceptualizing indigenous plant resources for aquaculture means recognizing their ecological, economic, and epistemological value. Doing so allows aquaculture development to be more inclusive, locally driven, and resilient—qualities essential in the face of global challenges such as climate change, feed insecurity, and biodiversity loss.

3.2. Geographical and Ethnobotanical Distribution of Key Species

The ethnobotanical and geographical distribution of indigenous plant species used in aquaculture feed formulations reflects a rich tapestry of traditional knowledge, ecological adaptation, and cultural heritage. These plants are often regionally available, culturally accepted, and ecologically suited for use in sustainable aquaculture systems, particularly in rural and resource-limited contexts. Their geographic spread and traditional uses offer significant insights into their potential as functional feed additives.

Across sub-Saharan Africa**,** species such as *Moringa oleifera*, *Azadirachta indica* (neem), *Vernonia amygdalina* (bitter leaf), and *Allium sativum* (garlic) are widely used in both human and animal diets. In aquaculture, *Moringa* is especially prominent in countries like Nigeria, Ghana, and Kenya, where it is utilized for its growth-promoting and immunostimulatory effects in tilapia and catfish species (Mbokane& Moyo, 2022). Neem, native to the Indian subcontinent but now naturalized in Africa, has shown efficacy against common fish pathogens and as a larvicidal agent in pond systems.

InSouth and Southeast Asia, the ethnobotanical application of plants in aquaculture is deeply integrated into smallholder farming systems. In India, *Ocimum sanctum* (holy basil), *Terminalia chebula*, and *Curcuma longa* (turmeric) are frequently used for their antioxidant, antimicrobial, and digestive properties in fish diets. Traditional Ayurvedic and Siddha practices have long documented these species for animal health, and recent studies have validated their role in enhancing fish performance and survival (Teves &Ragaza, 2016).

In the mountainous regions of Vietnam, small-scale aquaculture systems managed by Black Thai farmers rely on leaf meals and crop residues from native plants such as *Leucaena leucocephala*, *Ipomoea batatas* (sweet potato vines), and banana leaves. These plants, evaluated for their digestibility and low anti-nutrient levels, serve as staple protein sources in local pond-fed fish systems (Dongmeza *et al*., 2009).

The Latin American region, particularly the Amazon basin, is rich in potential aquafeed resources, including *Manihot esculenta* (cassava), *Mimosa pudica*, and various leguminous tree species. Though traditionally used for human and livestock nutrition, studies are increasingly exploring their use in aquaculture due to their high crude protein and carbohydrate content (Naseem *et al*., 2021).

From an ethnobotanical perspective, indigenous communities across continents have long recognized the medicinal and nutritional values of these plants. In Northern Malawi, for example, the Chewa and Tumbuka ethnic groups have traditionally included locally available plant species in herbal remedies and livestock feed, a practice now being translated into tilapia farming (Mzengereza *et al*., 2014).

Geographical distribution is also influenced by climatic adaptability. *Moringa oleifera*, for instance, is drought-resistant and thrives in semi-arid environments, making it suitable for regions facing water scarcity. Similarly, *Leucaena leucocephala* adapts well to poor soils and fixes nitrogen, offering dual benefits of biomass production and soil fertility enhancement.

Ethnobotanical records further show that the parts used—leaves, seeds, barks, roots—vary across species and regions. Leaves are most commonly used due to their easy availability and high concentrations of active compounds such as polyphenols and flavonoids. Roots and bark are used less frequently but may offer potent antimicrobial and anti-parasitic effects when properly processed (Makkar *et al.*, 2007).

The global distribution and ethnobotanical utility of indigenous plants reflect their deep-rooted roles in traditional food and health systems. Recognizing and documenting this diversity not only enriches scientific understanding but also empowers communities to integrate culturally and ecologically relevant practices into aquafeed innovation.

3.3. Nutritional and Phytochemical Profiles of Indigenous Plants

Indigenous plants used in aquafeed formulation are nutritionally valuable and chemically diverse, providing both macro- and micronutrients alongside bioactive phytochemicals that enhance fish growth, immunity, and health. Their composition varies based on species, plant parts used, growing conditions, and processing methods.

Many indigenous plants are notable for their high crude protein content, making them suitable as partial or complete fishmeal replacements. For instance, *Moringa oleifera* leaves contain 25–30% protein and are rich in essential amino acids such as methionine and lysine, which are often limiting in plant-based feeds (Acharya *et al.*, 2025). Similarly, *Leucaena leucocephala* has a protein content of 22–28%, making it a reliable nitrogen source in tilapia and carp diets.

Carbohydrate content in plants such as *Manihot esculenta* (cassava) and *Ipomoea batatas* (sweet potato) leaves also contributes to energy density in aquafeeds, although anti-nutritional factors such as cyanogenic glycosides may require mitigation via drying or fermentation.

Lipid levels in indigenous plants are generally low (2–6%), but they often include essential fatty acids like linoleic and alpha-linolenic acid, which play roles in immune modulation and membrane integrity. *Azadirachta indica* and *Ocimum sanctum* also contain essential oils rich in terpenoids and flavonoids, contributing to antibacterial and antioxidant activity.

- **Phytochemicals** are the key differentiating factor of indigenous botanicals. These include:
- **Flavonoids and phenolics** – potent antioxidants that reduce oxidative stress and inflammation.
- **Tannins and saponins** – exhibit anti-parasitic and antimicrobial actions; saponins also enhance gut barrier function.
- **Alkaloids** – impact neurotransmission and immune signaling, with species-specific effects.
- **Lectins and phytosterols** – influence intestinal health and lipid metabolism. Studies in Vietnam and Malawi have shown that indigenous plant leaves such as *Moringa*, *Tithonia diversifolia*, and *Cassia occidentalis* present favorable nutrient-to-anti-nutrient ratios for use in semi-intensive pond aquaculture (Dongmeza *et al.*, 2009; Mzengereza *et al.*, 2014).

Nevertheless, anti-nutritional factors (ANFs**)** such as phytates, oxalates, and trypsin inhibitors must be accounted for. While these compounds may interfere with mineral absorption and protein digestibility, appropriate pre-processing methods like fermentation, ensiling, or sun-drying can reduce their concentrations to tolerable levels (Makkar *et al.*, 2007).

Indigenous plants offer an advantageous nutritional and functional profile for aquaculture feed development. Their integration into feed formulations must, however, be guided by compositional analysis and species-specific dietary requirements to ensure efficacy and safety.

3.4. Commonly Used Indigenous Plants and Their Traditional Applications

Across diverse aquaculture regions, several indigenous plants have been historically employed in ethnoveterinary practices, offering a unique convergence of traditional knowledge and modern feed innovation. These plants, long used in human medicine and livestock husbandry, are now being increasingly explored for their potential as sustainable, bioactive aquafeed additives.

One of the most prominent examples is *Moringa oleifera*, a drought-tolerant plant native to the Indian subcontinent but now widely cultivated across Africa, Southeast Asia, and Latin America. Traditionally used as a food and medicine, *Moringa* leaves are rich in essential amino acids, vitamins, and phytochemicals like quercetin and chlorogenic acid. In aquaculture, powdered *Moringa* leaf has been shown to improve growth, boost immunity, and enhance survival in species such as tilapia and catfish (Teves &Ragaza, 2016).

Azadirachta indica (neem) is another widely used indigenous plant, especially in Africa and India. Neem's bioactive components—azadirachtin, nimbin, and salannin—are effective against ecto- and endoparasites and bacterial infections. Its bitter leaves and seed oil are traditionally used for treating livestock and human ailments. In fish, neem extract supplementation has demonstrated antimicrobial, antistress, and immunomodulatory effects (Makkar *et al.*, 2007).

Ocimum sanctum (holy basil or tulsi) is deeply rooted in Indian traditional medicine. Known for its adaptogenic and antimicrobial properties, it has found use in aquaculture as a functional feed additive for stress mitigation and immune enhancement. Tulsi-supplemented diets in Indian carp (*Labeorohita*) have improved resistance to *Aeromonas hydrophila* infections and supported growth under thermal stress (Bulfon *et al.*, 2015).

Allium sativum (garlic) is globally recognized for its therapeutic effects and has been used in aquaculture to enhance feed palatability, control pathogens, and boost immunity. Garlic contains allicin, which has strong antibacterial and antiparasitic properties. Farmers in Asia and Africa often use garlic paste mixed with feed as a preventative measure against fish mortality (Reverter *et al.*, 2017).

Curcuma longa (turmeric) is another extensively studied spice plant. Traditionally used for wound healing and inflammation control, turmeric's active compound curcumin acts as a potent antioxidant and hepatoprotective agent. When added to aquafeeds, it improves gut health and reduces oxidative stress in various fish species (Syahidah *et al.*, 2015).

Leucaena leucocephala, a fast-growing leguminous tree, is traditionally used as livestock fodder in Asia and Latin

America. Its high protein content and leaf yield make it a promising feed additive in aquaculture. However, the presence of mimosine, a toxic amino acid, requires processing such as sun-drying or fermentation before inclusion in fish diets (Dongmeza *et al*., 2009).
Cassia fistula, known as golden shower, is traditionally used in Ayurvedic medicine for gastrointestinal and skin ailments. Its seeds and pods contain anthraquinones, which exhibit laxative and antimicrobial properties. Early studies show growth-promoting potential in catfish diets, although further toxicological validation is needed (Makkar *et al*., 2007).
Ethnoveterinary applications also include *Tithonia diversifolia* (Mexican sunflower), used by African communities for its anti-inflammatory and antimicrobial properties. When used in tilapia diets, *Tithonia* leaf meal improved feed efficiency and lowered pathogen-induced mortality rates (Bairwa *et al*., 2012).
These examples underscore the extensive traditional knowledge base surrounding indigenous plants. Communities have long valued these species for their health-enhancing effects, and their translation into aquafeeds provides a culturally coherent and ecologically sound innovation pathway. Importantly, combining traditional applications with scientific validation ensures that these practices can be scaled safely and effectively.

3.5. Case Studies of Widely Researched Indigenous Species
The application of indigenous plants in aquaculture feed has progressed from anecdotal use to well-documented scientific inquiry. Several species stand out due to the volume and quality of research assessing their nutritional efficacy, immune function enhancement, and growth-promoting properties in farmed fish. This section presents case studies of three of the most extensively studied indigenous species: *Moringa oleifera*, *Azadirachta indica* (neem), and *Curcuma longa* (turmeric).

Case Study 1: *Moringa oleifera*
Moringa is perhaps the most researched indigenous plant for aquafeed applications. Its leaves contain high levels of protein (25–30%), antioxidants (e.g., quercetin, kaempferol), and essential nutrients. In a study by Teves &Ragaza (2016), Nile tilapia (*Oreochromis niloticus*) fed diets supplemented with 10–15% *Moringa* leaf meal showed significantly better feed conversion ratio (FCR), weight gain, and survival than fish fed standard plant-based diets.
Furthermore, *Moringa* has been shown to enhance non-specific immune responses such as lysozyme activity, respiratory burst, and complement system activity. Its inclusion reduced mortalities from *Aeromonas hydrophila* challenges, highlighting its dual role in nutrition and disease resistance.

Case Study 2: *Azadirachta indica* (Neem)
Neem is another widely validated plant with potent antimicrobial, antiparasitic, and immunomodulatory effects. In a controlled study on *Clarias gariepinus* (African catfish), neem leaf extract supplementation resulted in improved haematological parameters, including elevated RBC counts and total protein levels, indicating enhanced systemic immunity (Mbokane& Moyo, 2022).
Its primary phytochemical, azadirachtin, acts as an insect growth regulator and antimicrobial agent. In fish, neem extracts have been effective in reducing parasitic loads and increasing resistance to bacterial infections. However, researchers caution against overdosing, as neem's bioactivity can also impair appetite and feed intake at high concentrations.

Case Study 3: *Curcuma longa* (Turmeric)
Turmeric has received considerable attention for its antioxidant and hepatoprotective effects in fish. In a study by Bulfon *et al*. (2015), rainbow trout (*Oncorhynchus mykiss*) fed turmeric-enriched diets exhibited significantly reduced hepatic lipid peroxidation and increased antioxidant enzyme activity (e.g., superoxide dismutase, catalase).
In another experiment with Indian major carp (*Labeorohita*), curcumin supplementation led to improved growth and immunocompetence, including upregulation of immunoglobulin and cytokine gene expression. These results highlight turmeric's multifaceted role in improving oxidative stability, liver function, and immunoregulation (Reverter *et al*., 2017).
These case studies demonstrate the potential of indigenous plants to enhance aquaculture sustainability through multifunctional feed supplementation. Their consistent benefits across species and systems reinforce the value of integrating ethnobotanical knowledge with modern nutrition science.

4. Biological and Functional Efficacy in Aquatic Species
4.1. Effects on Growth Performance Indicators
The application of indigenous plant-based feed additives in aquaculture has garnered significant attention for their role in enhancing growth performance indicators such as weight gain, specific growth rate (SGR), feed conversion ratio (FCR), and protein efficiency ratio (PER). These indicators provide measurable benchmarks to assess the physiological and metabolic benefits of botanical feed supplementation in various fish species.
Plant-based additives improve growth primarily through mechanisms such as enhanced nutrient assimilation**,** immune modulation**,** and gut health optimization. For instance, *Moringa oleifera*, *Azadirachta indica* (neem), *Ocimum sanctum*, and *Carica papaya* have been reported to enhance growth metrics in species including *Oreochromis niloticus*, *Labeorohita*, and *Clarias gariepinus* when included at optimal dietary levels (Mbokane& Moyo, 2022).
In a study on *Cyprinus carpio*, the inclusion of *Moringa* and neem leaf meal at 5–10% significantly improved final body weight, SGR, and reduced FCR compared to fish fed control diets without additives (Kuebutornye *et al*., 2024). These improvements were attributed to the presence of bioactive phytochemicals that act as appetite stimulants, antimicrobial agents, and immunomodulators.
Similarly, *Carica papaya* seed powder has been evaluated in *Oreochromis mossambicus* diets, showing a dose-dependent improvement in weight gain and feed efficiency. At an inclusion level of 60 g/kg feed, the growth parameters peaked, while higher levels showed diminishing returns, indicating a threshold beyond which anti-nutritional effects may arise (Syanya *et al*., 2026).
A review by Hossain *et al*. (2024) consolidated several growth trials across species, concluding that plant-based functional additives could improve FCR by 10–25%, with similar or superior performance compared to commercial synthetic growth enhancers. Plants such as *Allium sativum*

(garlic), *Withaniasomnifera* (ashwagandha), and *Curcuma longa* (turmeric) were among the most effective.

The growth-promoting effects also appear to be species-specific and influenced by environmental factors and basal diet composition. For instance, a study on *Pangasius hypophthalmus* fingerlings supplemented with *Euphorbia hinta* extract showed significant improvements in digestive enzyme activities (notably amylase) and enhanced growth performance—especially under stress-induced conditions—suggesting adaptogenic properties of the extract (Nhu *et al*., 2022).

Importantly, botanical additives often contribute to growth performance by reducing pathogen loadsand subclinical infections, allowing fish to allocate more energy to growth rather than immune responses. This has been observed with neem and turmeric, which reduce disease incidence in aquaculture environments challenged by *Aeromonas hydrophila* and other opportunistic pathogens (Bulfon *et al*., 2015).

Several studies have also indicated improvements in protein and lipid deposition in muscle tissues of fish fed herbal-supplemented diets, which directly enhances meat quality and market value. Garlic and turmeric, for example, significantly increased crude protein and decreased fat accumulation in *Labeorohita* and *O. niloticus* muscle tissues (Xavier *et al*., 2012).

Nevertheless, effective implementation requires optimizing inclusion levels to avoid anti-nutritional impacts. Overuse of certain plant-based additives can lead to reduced palatability or digestive issues due to tannins, saponins, or oxalates. Processing techniques such as fermentation, soaking, or heat treatment are thus critical to maintaining efficacy and digestibility (Mbokane& Moyo, 2022).

Indigenous plant-based feed additives consistently show promise in improving key growth performance indicators across fish species. Their multifaceted modes of action—ranging from appetite enhancement and improved gut function to immunostimulation—make them valuable components of sustainable aquaculture feed strategies.

4.2. Influence on Digestive Enzyme Activity and Feed Utilization

The influence of indigenous plant-based feed additives on digestive enzyme activity and feed utilization efficiency has been a focal point in evaluating their suitability as functional aquafeed components. Digestive enzymes—such as protease, amylase, and lipase—are essential for the hydrolysis of dietary macronutrients, and their modulation through dietary additives can directly affect nutrient bioavailability and growth.

Several indigenous plants have demonstrated the capacity to enhance enzymatic activity in the gastrointestinal tract of fish. This is primarily due to bioactive compounds that stimulate gut morphology and enzyme secretion or act as natural exogenous enzyme analogs. For example, *Moringa oleifera* leaf extract supplementation significantly increased intestinal amylase and protease activities in *Oreochromis niloticus* over a 6-week trial, improving both digestion and nutrient uptake (Hossain *et al*., 2024).

In *Cyprinus carpio*, Kuebutornye *et al*. (2024) reported that plant-based additives like neem and garlic enhanced the activity of alkaline phosphatase, indicating improved gut health and absorptive function. The increase in digestive enzyme activity was associated with lower feed conversion ratios (FCR), indicating superior feed utilization.

A similar pattern was observed in *Labeorohita* fingerlings fed diets pre-treated with exogenous enzymes and soaked to reduce anti-nutritional factors. Protease and lipase activities increased significantly, leading to higher protein digestibility and better muscle development (Xavier *et al*., 2012). The findings underscore the importance of integrating enzyme-stimulating botanicals with physical feed processing for maximum nutrient efficiency.

Plant-derived compounds such as tannins and saponins—often considered anti-nutritional—can, in low doses, paradoxically stimulate gut enzyme expression. Mbokane& Moyo (2022) noted that low inclusion levels of *Vernonia amygdalina* and *Azadirachta indica* enhanced bile secretion and lipase activity in *Clarias gariepinus*, improving lipid digestion without negative side effects.

Additionally, feed additives like *Euphorbia hirta* and papaya seed have been shown to modulate gut pH and microbial balance, indirectly influencing enzyme stability and function. This effect supports prolonged enzyme activity and efficient substrate breakdown, particularly in plant-rich diets that are typically harder to digest (Rachmawati*et al*., 2020).

The enhancement of nutrient absorption through better enzymatic breakdown translates to improved apparent digestibility coefficients (ADCs) for crude protein and energy. Studies with garlic and turmeric in *Pangasius* and *Catlacatla* reported ADC increases of up to 20%, highlighting significant economic and nutritional benefits for farmers and feed manufacturers alike (Salehi *et al*., 2023).

Furthermore, certain botanicals exert prebiotic effects**,** promoting beneficial gut microbiota that enhance endogenous enzyme expression. In trials with *Bacillus spp.* and propionic acid in a plant-based diet, Salehi *et al*. (2023) observed synergistic effects on protease activity and gut health, reinforcing the potential for combining probiotics with herbal additives in integrated feed strategies.

Despite promising outcomes, the variability in enzyme response due to species, dosage, and feed formulation remains a challenge. Standardizing phytochemical concentrations and understanding species-specific digestive physiology is essential for consistent results. Formulation strategies must also address enzyme deactivation risks during pelleting or extrusion processing.

Iindigenous plant-based additives can significantly enhance digestive enzyme activity and feed utilization when appropriately applied. Their use supports sustainable, fishmeal-reducing diets while optimizing nutrient absorption and promoting gut health, marking them as critical components in next-generation aquafeeds.

4.3. Influence of Plant Species, Harvesting, and Processing Methods

The biological efficacy and nutritional safety of indigenous plant-based feed additives in aquaculture are not solely determined by the plant species itself, but also by how it is harvested, handled, and processed. Each of these factors has a profound influence on the phytochemical composition, nutrient availability, and functional properties of the additive, thereby affecting its performance in aquatic diets. Variability among plant species, even within the same genus, can significantly affect their nutrient profiles and secondary metabolite content. For instance, *Moringa oleifera* leaves collected from different agroecological zones have demonstrated distinct levels of protein, polyphenols, and antioxidants, influencing their effectiveness as feed supplements in tilapia and carp aquaculture. Similarly, *Azadirachta indica* harvested during the dry season tends to accumulate higher levels of bitter compounds such as azadirachtin, which, while beneficial for antimicrobial purposes, can reduce palatability if not properly dosed or processed (Francis *et al*., 2001).

Harvesting methods further impact plant bioactivity. Leaves or seeds that are harvested prematurely may not have achieved optimal phytochemical maturity, while those collected too late may degrade or accumulate fibrous material, reducing digestibility. Post-harvest handling, including drying, transportation, and storage, can also compromise the bioefficacy of plant materials if not managed under controlled conditions. High moisture content during storage promotes microbial degradation and phytochemical oxidation, leading to nutrient losses or the formation of undesirable metabolites. Therefore, the timing of harvest and immediate post-harvest care are critical in preserving feed quality (Tadele, 2015).

Processing techniques are perhaps the most critical determinants of additive safety and efficacy. Indigenous plants often contain anti-nutritional factors (ANFs) such as tannins, phytates, oxalates, and saponins that must be reduced or neutralized prior to inclusion in fish diets. Traditional methods such as sun-drying, soaking, boiling, and fermenting are widely used to minimize these components. For example, the sun-drying of *Leucaena leucocephala* leaves significantly reduces mimosine content, while boiling *Cassia* or *Manihot* species reduces cyanogenic glycosides to non-toxic levels (Soetan& Oyewole, 2009).

Modern feed processing techniques, including extrusion and pelletization, also play a role in modifying plant matrix structure and releasing bound nutrients. However, excessive heat or pressure during these processes can degrade sensitive phytochemicals, diminishing their functional benefits. For instance, excessive thermal processing can break down bioactive flavonoids and volatile essential oils present in *Ocimum sanctum* and *Allium sativum*, undermining their immunomodulatory potential. Therefore, it is essential to balance mechanical efficiency with the preservation of bioactivity (Prabu *et al*., 2017).

Additionally, some processing steps may enhance bioavailability and even create synergistic effects. Fermentation, for instance, not only reduces ANFs but also promotes the release of bioavailable peptides and short-chain fatty acids with prebiotic effects. When applied to plant-based feed ingredients like *Moringa*, *Tithonia*, or *Sesbania*, fermentation can significantly improve protein digestibility and antioxidant activity in aquafeed (Makkar *et al*., 2007).

Standardization remains a persistent challenge in this field. Many studies note the inconsistent performance of the same plant additive across different trials, often attributable to variations in species genotype, harvesting stage, drying duration, or method of incorporation into feeds. Thus, scientific validation must be accompanied by efforts to define standardized harvesting schedules and processing protocols to ensure reproducibility and regulatory compliance in feed production (Glencross *et al*., 2020).

In conclusion, the functional potential of indigenous plant-based feed additives is intimately linked to species selection, harvesting strategy, and processing technique. The synergistic optimization of these factors not only enhances nutrient bioavailability and functional efficacy but also reduces anti-nutritional hazards. As aquaculture moves toward sustainable, locally adapted feed systems, an integrated approach to managing these variables will be critical in realizing the full value of botanical feed additives.

4.4. Presence of Antinutritional Factors and Potential Toxicity

Despite their nutritional promise, many indigenous plants used as feed additives in aquaculture also contain antinutritional factors (ANFs) and inherent toxicants that can compromise fish health, growth, and nutrient utilization when present in excessive quantities or left untreated. These substances, often evolved as natural defense mechanisms in plants, include tannins, phytates, saponins, lectins, oxalates, cyanogenic glycosides, and alkaloids. While some of these compounds may exert beneficial effects at low concentrations—such as antioxidant or antimicrobial activity—they often become deleterious at higher doses, particularly in aquaculture species with sensitive digestive systems (Krogdahl *et al*., 2010).

Tannins, widely found in leaves of plants such as *Terminalia chebula* and *Acacia spp.*, can bind to proteins and enzymes, reducing their digestibility and impairing amino acid absorption. Phytates, abundant in legumes and oilseeds, chelate essential minerals like calcium, zinc, and iron, leading to mineral deficiencies in fish, especially under intensive farming conditions. Saponins, although known for enhancing gut barrier function at low doses, can disrupt membrane integrity at higher concentrations, leading to cell lysis and reduced feed intake (Prabu *et al*., 2017).

Of particular concern are lectins and cyanogenic glycosides. Lectins, found in seeds and legumes like *Phaseolus vulgaris*, can damage gut epithelium and interfere with nutrient transporters, while cyanogenic glycosides in plants like *Manihot esculenta* (cassava) can release hydrogen cyanide upon hydrolysis, a compound toxic to fish even at low doses. Prolonged exposure to these compounds can cause histological damage to the liver, intestine, and kidney, compromise growth, and elevate mortality rates (Soetan& Oyewole, 2009).

The toxicity of these compounds is influenced not only by concentration but also by species-specific tolerance levels. For example, carnivorous fish species like salmonids are more sensitive to ANFs than herbivorous or omnivorous species like tilapia and carp. In a comparative study, salmon fed with unprocessed soybeans containing high levels of trypsin inhibitors and saponins showed intestinal inflammation and impaired nutrient absorption, while carp displayed relatively lower sensitivity (Krogdahl *et al*., 2010).

Effective detoxification strategies are essential to ensure the safe use of these botanicals in aquafeeds. Thermal treatments such as boiling or roasting can denature heat-labile toxins like lectins and trypsin inhibitors. Fermentation and ensiling are effective at reducing phytate and cyanogenic content, and enzymatic supplementation during feed formulation can counteract residual ANFs. These processing steps not only enhance safety but can improve the functional properties of the feed additive by increasing solubility, digestibility, and nutrient accessibility (Tadele, 2015).

However, over-processing can also lead to the degradation of valuable nutrients or bioactive compounds, resulting in diminished feed efficacy. Thus, processing must strike a balance between detoxification and preservation of nutritional value. Feed formulation must also account for the cumulative effect of ANFs when multiple plant ingredients are combined, as synergistic toxicity can arise even when individual compounds are within safe limits (Samtiya *et al*., 2020).

While indigenous plants offer promising alternatives to conventional feed additives, their potential risks cannot be ignored. A nuanced understanding of the types and impacts of antinutritional factors, combined with scientifically validated processing methods, is essential to maximize their utility and ensure fish health and performance. Moving forward, risk assessment and standardization of botanical additives will be indispensable components of safe and effective aquafeed innovation.

5. Conclusion

This review has comprehensively examined the potential of indigenous plant-based feed additives as sustainable alternatives in aquaculture nutrition. As global aquaculture continues to expand amid environmental, economic, and biosecurity challenges, the integration of locally available botanical resources offers a promising, cost-effective, and ecologically sound solution. Indigenous plants such as *Moringa oleifera*, *Azadirachta indica*, *Curcuma longa*, and *Ocimum sanctum* have demonstrated significant biological and functional efficacy in enhancing growth performance, digestive enzyme activity, immune responses, and feed utilization across various aquatic species. However, the success of these botanicals depends heavily on plant species selection, proper harvesting, and processing techniques that preserve bioactivity while minimizing antinutritional factors and toxicity risks. While traditional ethnobotanical knowledge provides a valuable foundation, standardized scientific validation, risk assessment, and optimization of formulation protocols remain critical.

Moving forward, the use of indigenous plants should be supported by integrated research that bridges traditional practices with modern nutritional science, promoting inclusive, locally adapted feed solutions. In doing so, aquaculture can progress toward a more resilient and sustainable food production system that not only supports fish health and farmer livelihoods but also contributes to biodiversity conservation and circular bioeconomy goals.

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