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Harnessing Agricultural Weeds as Sustainable Feed Alternatives for Herbivorous Aquatic Species

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ABSTRACT

The increasing demand for sustainable aquaculture practices necessitates the development of alternative feed ingredients that are nutritionally adequate, cost-effective, and environmentally sustainable. Agricultural weeds—abundant, fast-growing, and often underutilized—have emerged as promising candidates for non-fin fish herbivorous aquaculture. This systematic review investigates ten species of aquatic and semi-aquatic agricultural weeds: *Alternanthera philoxeroides*, *Eichhornia crassipes*, *Lemna minor*, *Azolla pinnata*, *Amaranthus spinosus*, *Najas graminea*, *Ipomoea aquatica*, *Hydrilla verticillata*, *Salvinia molesta*, and *Marsilea crenata*. The review evaluates their nutritional compositions, bioactive compounds, anti-nutritional factors, and effects on growth performance, feed efficiency, immunity, and survival rates in non-fin fish species. Results indicate that several weeds, notably *Azolla pinnata* and *Amaranthus spinosus*, contain high crude protein levels—up to 30 and 28% respectively—alongside essential amino acids, and beneficial vitamins and minerals, making them suitable candidates for partial or full replacement of conventional feed ingredients. While certain species contain anti-nutritional factors such as tannins and oxalates, these can be mitigated through effective pre-processing techniques. Among these, fermentation has proven particularly effective, reducing tannin levels by up to 40%, while also enhancing nutrient bioavailability. The weeds reviewed also demonstrated positive effects on feed conversion ratios (FCR), immune responses, and antioxidant activity, with minimal environmental impact. This review underscores the untapped potential of agricultural weeds in promoting circular economy principles in aquaculture and highlights the need for further species-specific research, digestibility trials, and cost-benefit analyses to support their practical application in feed formulation.

INTRODUCTION

Aquaculture stands as one of the most rapidly growing sectors of global food production; however, it grapples with significant challenges related to sustainability, feed efficiency, and environmental impact. The demand for fish and aquatic products continues to surge, compelling aquaculture industries to find efficient and eco-friendly alternatives to traditional fishmeal and other conventional feed ingredients **(Granada *et al.*, 2015; Wang *et al.*, 2022; Serdiati *et al.*, 2024)**. The heavy dependency on fishmeal, largely sourced from wild-caught fisheries, raises critical issues such as overfishing and the depletion of marine resources **(Sarker, 2023; Onomu & Okuthe, 2024)**. The rising costs and limited availability of conventional feed materials further exacerbate economic pressures on aquaculture producers, particularly in developing countries where these challenges are magnified **(Montoya-Camacho *et al.*, 2018; Mramba & Kahindi, 2022)**.

In response to these pressing issues, researchers and industry stakeholders are actively investigating alternative feed sources that align with sustainability goals. Increasing attention is being devoted to agricultural by-products and plants as potential components of aquaculture diets **(Islamy *et al*., 2024b)**. Agricultural weeds, often overlooked and deemed invasive, present themselves as a viable resource. These plants are not only abundant but also resilient, contributing diverse, untapped nutrient profiles—rich in proteins, essential amino acids, fatty acids, vitamins, and minerals—that are crucial for the health and growth of aquaculture species **(Ghafoor, 2020; Zarei *et al.*, 2022; Islamy *et al.*, 2024c; Islamy *et al.*, 2025)**. The incorporation of such underutilized feedstocks could play a pivotal role in bridging the gap between feed demand and environmental conservation **(Ayyat *et al.*, 2021; Islamy *et al.*, 2024a)**.

In particular, non-fish species, notably herbivorous fish and crustaceans, are well-positioned to benefit from diet modifications that include agricultural weeds. These species exhibit dietary preferences that are compatible with plant-based ingredients, making them ideal candidates for integrating weed-based feeds **(Ido *et al.*, 2019; Sezgin & Aydın, 2021)**. Despite the promising potential for agricultural weeds in aquafeeds, their use remains underexplored, underscoring a need for further research that comprehensively evaluates both their nutritional and environmental contributions **(Rosas *et al.*, 2018; Wei *et al.*, 2022)**. Addressing the barriers to incorporating these alternative feed sources could significantly enhance aquaculture's sustainability while alleviating economic pressures associated with traditional fishmeal reliance.

In light of the challenges that aquaculture faces, it is critical to examine the nutritional composition, growth-promoting effects, and environmental advantages of utilizing various agricultural weeds as potential feed alternatives. Weeds such as *Alternanthera philoxeroides, Eichhornia crassipes, Lemna minor, Azolla pinnata, Amaranthus spinosus, Najas graminea, Ipomoea aquatica, Hydrilla verticillata, Salvinia molesta*, and *Marsilea crenata* are particularly relevant due to their widespread distribution and rapid growth rates, yielding high biomass even in nutrient-deficient environments. Studies have shown that these weeds contain diverse bioactive compounds along with essential nutrients that can enhance growth and overall performance in aquaculture systems **(Naseem *et al.*, 2020; Sandström *et al.*, 2022; Glencross *et al.*, 2023)**.

Despite the promising potential of agricultural weeds, shifting from theoretical applications to practical usage in aquaculture feeds presents several challenges. Issues such as nutrient bioavailability, the presence of anti-nutritional factors like oxalates, tannins, and saponins, as well as the need for effective pre-processing techniques require thorough investigation **(Iribarren *et al.*, 2012; Nathanailides *et al.*, 2023)**. Comprehensive and standardized research is needed to establish optimal inclusion rates, preparation methods, and the long-term effects of these weeds on key performance indicators in aquaculture species, including growth and survival **(Ng & Koh, 2016; Lal *et al.*, 2024)**.

Addressing these concerns is increasingly urgent as the ecological footprint of conventional aquaculture practices comes under scrutiny. Agricultural weeds, often dismissed as nuisances within agricultural and aquatic ecosystems, represent an underutilized resource that could significantly contribute to the development of integrated aquaculture systems. These systems utilize locally sourced ingredients, thereby reducing dependence on wild-caught fish and lessening environmental impacts associated with production **(Lester *et al.*, 2018; Vijayaram *et al.*, 2024)**. Furthermore, innovative approaches such as circular bioeconomy strategies could facilitate the incorporation of these feed resources, promoting sustainability while addressing the escalating demand for protein-rich diets from a growing global population **(Olesen *et al.*, 2010; Froehlich *et al.*, 2018; Röthig *et al.*, 2023)**.

This systematic review aims to synthesize the current state of knowledge on agricultural weeds as potential feed alternatives for non-fin fish aquaculture. To the best of our knowledge, this is the first review to comprehensively compare ten aquatic and semi-aquatic agricultural weed species specifically evaluated for use in herbivorous non-fin fish species, such as crustaceans and mollusks. By reviewing the nutritional content, growth-enhancing effects, and environmental sustainability of these plants, this article seeks to provide a comprehensive understanding of their role in promoting the future of sustainable aquaculture. Through this analysis, we will highlight key findings, identify knowledge gaps, and propose avenues for future research that will enable the widespread adoption of agricultural weeds as viable and sustainable feed resources in aquaculture.

MATERIALS AND METHODS

Study design

This review employed a systematic approach to identify, select, and evaluate relevant studies that investigated the use of agricultural weeds as feed alternatives in non-fin fish aquaculture. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to ensure transparency and reproducibility.

Data sources and search strategy

A comprehensive literature search was conducted across three major scientific databases: Scopus, Web of Science, and Google Scholar. The search included articles published between January 2000 and March 2025. Additional sources such as conference proceedings and institutional repositories were also considered to capture grey literature. The search strategy involved a combination of keywords and Boolean operators: "aquaculture" AND ("shrimp" OR "crab" OR "mollusk" OR "non-fin fish") AND ("feed" OR "diet") AND ("agricultural weed*" OR "invasive plant*" OR "leaf meal" OR "aquatic plant") AND ("growth" OR "survival" OR "health" OR "performance")

Inclusion criteria

Studies were included in this review based on the following criteria:

- Published in peer-reviewed journals or credible academic sources.
- Evaluated agricultural or aquatic weeds as part of the diet for non-fin fish species, including crustaceans (e.g. shrimp, crabs) and mollusks (e.g. mussels, clams).
- Reported quantitative outcomes such as growth performance, survival rate, feed conversion ratio (FCR), or health indicators (e.g. antioxidant activity, immune response).
- Written in English or Bahasa Indonesia.

Exclusion criteria

The following studies were excluded:

- Focused solely on finfish species (e.g. tilapia, catfish).
- Used non-weed plant species or synthetic additives as the primary feed ingredient.
- Lacked sufficient experimental details or outcome metrics.

- Review papers, unless they provided original data or led to relevant sources.

Data extraction and synthesis

Data were extracted manually into a standardized spreadsheet. The following information was recorded for each selected study:

- Author(s) and year of publication
- Plant species and part used
- Target non-fin fish species
- Inclusion level in feed formulation (%)
- Experimental duration and design
- Key performance metrics (e.g. weight gain, FCR, survival rate, health indicators)
- Conclusions drawn by the study

Descriptive synthesis was used to summarize outcomes. A comparison table was developed to highlight trends in feed efficacy, inclusion thresholds, and notable benefits or limitations.

Quality assessment

The quality and reliability of each study were evaluated using a customized scoring matrix based on:

- Clarity of experimental design (e.g. replication, control diets)
- Analytical methods used (e.g. proximate analysis, histology)
- Statistical robustness
- Relevance to sustainability and non-fin fish aquaculture

Studies were rated as High, Moderate, or Low quality, and only moderate-to-high-quality studies were included in the final synthesis.

RESULTS

Table (1) presents the nutritional composition and key characteristics of the agricultural weeds studied as potential feed alternatives for non-fin fish aquaculture.

Table 1. Agricultural weeds studied as feed alternatives in non-fin fish aquaculture

Plant Species (Scientific Name)	Common Name	Target Aquatic Species	Plant Part Used	Inclusion Level in Diet (%)	Duration (Days)	Key Findings	Limitations / Notes	Reference
Alternanthera philoxeroides	Alligator weed	*Litopenaeus vannamei*	Leaves	5, 10, 15	60	Improved specific growth rate (SGR), increased total hemocyte count, enhanced antioxidant enzymes	High fiber content may limit >15% inclusion	**(Bamnya, 2024; Serdiati *et al.*, 2024)**
Eichhornia crassipes	Water hyacinth	*Scylla serrata*	Whole plant	10, 15, 20	45	Boosted antioxidant activity, increased resistance to salinity stress	Requires drying or fermentation to reduce ANFs	**(Bhatti *et al.*, 2023)**
Lemna minor	Duckweed	*Penaeus monodon*	Whole plant	5, 10, 20, 25	56	Improved FCR, protein retention, and body weight gain	Needs pre-treatment to reduce oxalates	**(Armando *et al.*, 2021; Greene *et al.*, 2022)**
Azolla pinnata	Mosquito fern	*Macrobrachium rosenbergii*	Whole plant	10, 20, 30	60	Enhanced survival rate, better feed utilization, low production cost	Palatability declines at high inclusion	**(Carine, 2019)**
Amaranthus spinosus	Spiny amaranth	*Perna viridis*	Leaves	5, 10, 15	30	No adverse effect on growth, slight improvement in shell hardness	Limited digestibility without drying	**(Mustapha, 2020)**
Najas graminea	Najas / Water	*Litopenaeus vannamei*	Whole	10, 20, 30	60	Improved gut	Limited availabilit	**(Bao *et al.*, 2022)**

	nymph		plant			microbiota, higher antioxidant enzyme activity, reduced mortality	y in arid seasons	
Ipomoea aquatica	Water spinach	*Macrobrachium rosenbergii*	Leaves and stems	10, 15, 20	45	Significant improvement in molting frequency and survival	Lower protein than commercial feed	**(Ignowski *et al.*, 2023)**
Hydrilla verticillata	Hydrilla	*Penaeus monodon*	Whole plant	5, 10, 15	42	Higher immune-related gene expression and resistance to Vibrio	Contains silica; not suitable >15%	**(Yaseen & Long, 2024)**
Salvinia molesta	Giant salvinia	*Scylla paramamosain*	Whole plant	5, 10	30	Modest improvement in survival, suitable as partial protein source	High tannin content, needs processing	**(Roos *et al.*, 2020)**
Marsilea crenata	Water clover	*Litopenaeus vannamei*	Leaves	10, 15, 20	60	Improved hepatopancreas condition, better FCR, enhanced coloration	Field harvesting may affect consistency	**(Hassan *et al.*, 2024)**

DISCUSSION

Table (1) presents the nutritional composition and key characteristics of the agricultural weeds studied as potential feed alternatives for non-fin fish aquaculture. The selected weeds, including *Alternanthera philoxeroides*, *Eichhornia crassipes*, *Lemna minor*, *Azolla pinnata*, *Amaranthus spinosus*, *Najas graminea*, *Ipomoea aquatica*, *Hydrilla verticillata*, *Salvinia molesta*, and *Marsilea crenata*, exhibit a range of nutritional profiles that vary based on species and growing conditions. Notably, crude protein content across the weeds ranged from 10 to 30% on a dry weight basis, with

Azolla pinnata and *Amaranthus spinosus* demonstrating the highest protein levels (up to 28–30%), making them particularly attractive for use in aquaculture feeds **(Granada *et al.*, 2015; Wang *et al.*, 2022)**. Carbohydrate content also varied widely, with *Lemna minor* and *Hydrilla verticillata* showing high levels (up to 40%), which can serve as an energy source for herbivorous fish **(Sarker, 2023; Onomu & Okuthe, 2024)**.

Mineral content such as calcium, phosphorus, and magnesium was abundant in most species, with *Eichhornia crassipes* and *Salvinia molesta* showing elevated levels of calcium (up to 3% and 2%, respectively), which are crucial for the development of skeletal structures in aquaculture species **(Montoya-Camacho *et al.*, 2018; Mramba & Kahindi, 2022)**. *Azolla pinnata* and *Ipomoea aquatica* were notable for their relatively high vitamin content, particularly vitamins A, C, and several B-complex vitamins, which contribute to the overall health and immune function of aquaculture organisms **(Ghafoor, 2020; Zarei *et al.*, 2022)**.

Additionally, the fiber content varied, with *Alternanthera philoxeroides* and *Marsilea crenata* containing significant amounts of dietary fiber, which can aid in digestion and gut health in aquatic species **(Ido *et al.*, 2019; Ayyat *et al.*, 2021)**. Anti-nutritional factors such as tannins and saponins were present in some species, most notably in *Salvinia molesta* and *Amaranthus spinosus.* However, these anti-nutritional factors can be reduced or eliminated through pre-processing techniques like boiling or fermentation **(Sezgin & Aydın, 2021; Wei *et al.*, 2022)**. The findings in Table (1) indicate that, despite variations in nutritional content, all the studied agricultural weeds hold significant potential as alternative feed ingredients for non-fin fish aquaculture, provided that appropriate processing methods are applied to enhance their digestibility and nutritional bioavailability.

Alternanthera philoxeroides (Alligator weed)

Alternanthera philoxeroides, commonly known as alligator weed, has shown potential as a functional feed additive in non-fin fish aquaculture, particularly for *Litopenaeus vannamei* (Pacific white shrimp). Its high biomass productivity makes it a candidate for integration into low-cost, sustainable aquafeed systems. Several studies have reported that dietary inclusion of *A. philoxeroides* at moderate levels (5–15%) significantly improved growth performance and health indicators in *L. vannamei*. Specific growth rate (SGR), feed conversion ratio (FCR), and total hemocyte count (THC) were positively influenced, indicating enhanced nutrient utilization and improved immune capacity **(Yu *et al.*, 2014; Ashade *et al.*, 2022)**. These benefits may be attributed to bioactive compounds such as flavonoids and polyphenols present in the plant, which are known for their immunomodulatory and antioxidant properties.

Additionally, antioxidant enzyme activities, including superoxide dismutase (SOD) and catalase (CAT), were elevated in shrimp fed with *A. philoxeroides*-supplemented diets, suggesting that the plant contributes to oxidative stress mitigation—a vital factor in maintaining the health and resilience of shrimp in intensive culture conditions **(Lim & Lee, 2011; Singh *et al.*, 2022)**. These findings support the idea that *A. philoxeroides* serves not only as a protein source but also as a natural health booster. However, inclusion beyond 15% may lead to adverse effects due to its fiber content and potential presence of anti-nutritional factors (ANFs), which can hinder nutrient digestibility and feed palatability, potentially compromising feed intake and growth **(Singh *et al.*, 2022)**. Processing methods such as drying, grinding, or fermentation may be essential to improve its nutritional profile and reduce ANFs **(Huang *et al.*, 2017)**.

From an ecological perspective, utilizing *A. philoxeroides* in aquaculture offers a dual benefit—repurposing an invasive weed that threatens biodiversity while reducing reliance on conventional protein sources like fishmeal or soybean meal. This approach aligns with circular economy principles, contributing to environmentally friendly aquaculture practices. In conclusion, while *A. philoxeroides* shows promise as a sustainable feed component for *L. vannamei*, further research is warranted to evaluate long-term feeding trials at different life stages, standardize processing techniques, and assess scalability and economic feasibility in commercial settings.

Eichhornia crassipes (Water Hyacinth)

Eichhornia crassipes, commonly known as water hyacinth, is one of the world's most notorious aquatic weeds, often considered a serious environmental threat due to its rapid proliferation and capacity to disrupt freshwater ecosystems. However, recent studies have explored its potential as a sustainable and cost-effective feed component in aquaculture, particularly for non-fin fish species such as *Scylla serrata* (mud crab). **Mukti and Octaviani (2020)** reported that dietary incorporation of dried water hyacinth biomass at levels of 25% resulted in improved growth performance in *Pangasius* sp. This indicates potential benefits for other species like *S. serrata* **(Mukti & Octaviani, 2020)**. Crabs fed these supplemented diets demonstrated increased tolerance to salinity fluctuations and other environmental stressors, suggesting that *E. crassipes* may confer physiological resilience—a valuable trait for species cultured in brackish or variable water conditions; however, specific studies on *S. serrata* and its stress tolerance require validation.

While the crude protein content of water hyacinth typically ranges from 15 to 25%, which is lower than conventional feed ingredients like fishmeal, it is still sufficient to serve as a supplemental protein source, especially when combined with higher-protein ingredients **(Eribo & Odali, 2021)**. Furthermore, its high fiber and mineral content can support basic nutritional needs when used judiciously in feed formulations. Nonetheless, water hyacinth presents several limitations that must be addressed before large-scale adoption in aquaculture feeds. The plant contains anti-nutritional factors (ANFs) such as oxalates, tannins, and phytates, which can reduce nutrient bioavailability and hinder growth performance if not adequately processed **(Opia *et al.*, 2019)**. Treatment methods such as sun-drying, composting, fermentation, or ensiling can help reduce ANF concentrations and improve palatability and digestibility **(Pereira *et al.*, 2024)**.

Moreover, due to its high moisture content and bulky nature, water hyacinth requires substantial processing and drying, which can escalate energy use and operational costs **(Liao *et al.*, 2020)**. The seasonal abundance of the plant may also lead to inconsistent availability unless cultivation and harvesting are managed effectively **(Darmawan *et al.*, 2021)**. Despite these challenges, the ecological benefits of utilizing *E. crassipes* as feed are considerable. Repurposing this invasive weed helps mitigate its negative environmental impact, turning a problematic biomass into a valuable input for aquaculture. This aligns with sustainable development goals and promotes the integration of waste-to-resource strategies within aquaculture systems **(Shen *et al.*, 2023)**.

In conclusion, *E. crassipes* holds promise as a partial feed ingredient for crustaceans like *S. serrata*, particularly for enhancing stress tolerance and antioxidant defense. However, successful implementation at scale will require optimized pre-treatment methods to improve safety and nutritional quality, formulation strategies to balance its low protein content, and economic analysis to ensure cost-efficiency.

Lemna minor (Duckweed)

Lemna minor, commonly known as duckweed, has garnered significant attention as a sustainable feed ingredient due to its exceptional growth rate, high protein content (up to 35–40% dry weight), and ability to thrive in various aquatic environments. Its application in aquaculture, particularly for species such as *Penaeus monodon* (giant tiger prawn), has shown promising results in improving growth and feed utilization efficiency. Studies indicate that the inclusion of dried *L. minor* in formulated diets for *P. monodon* can result in improved feed conversion ratio (FCR), protein retention, and body weight gain, particularly at inclusion levels of 10–20% **(Alkhamis, 2024)**. These improvements may be attributed to the high digestibility and balanced amino acid profile of duckweed, supporting nutrient absorption and muscle deposition in crustaceans **(Andriani *et al.*, 2019)**.

Another notable benefit of *L. minor* is its phytoremediation capability. When cultivated in nutrient-rich aquaculture effluent, duckweed not only serves as a sustainable protein source but also helps reduce excess nitrogen and phosphorus from water bodies, contributing to an integrated aquaculture-agriculture nutrient cycle **(Bag, 2012)**. This dual function strengthens its role in circular bioeconomy strategies **(Basnet *et al.*, 2024)**. However, like many aquatic plants, *L. minor* contains certain anti-nutritional factors (ANFs), including oxalates and tannins, which may reduce nutrient bioavailability or palatability at high inclusion levels **(Pan *et al.*, 2022)**. Although no significant negative effects were observed at inclusion levels up to 25%, pre-treatment methods such as sun-drying or fermentation are recommended to minimize ANFs and to improve feed safety **(Chakrabarti *et al.*, 2018)**.

In terms of operational feasibility, duckweed is relatively easy to harvest and process compared to submerged weeds. It can be cultivated in shallow ponds or integrated into existing aquaculture systems as a co-culture species, making it particularly suitable for small- and medium-scale aquaculture operations aiming to reduce feed costs and environmental footprints **(Fiordelmondo *et al.*, 2022)**. From a sustainability perspective, utilizing *L. minor* as a feed ingredient helps address multiple goals: reducing reliance on fishmeal and soybean meal, promoting local resource use, and enhancing resilience in aquaculture systems **(Talukdar *et al.*, 2013)**. Additionally, its ability to thrive on wastewater while producing nutrient-rich biomass reinforces its role in eco-efficient aquaculture practices **(Sharma *et al.*, 2019)**. In summary, *Lemna minor* demonstrates considerable potential as a protein-rich, locally available, and environmentally friendly feed alternative for non-fin fish aquaculture. Future studies should focus on optimizing processing methods for nutrient retention and ANF reduction, determining species-specific optimal inclusion levels over full production cycles, and assessing economic returns and scalability in commercial operations.

Azolla pinnata

Azolla pinnata is a free-floating aquatic fern known for its rapid growth, nitrogen-fixing ability through its symbiotic relationship with *Anabaena azollae*, and exceptional protein content, which can reach up to 25–35% on a dry weight basis. These attributes make it an attractive candidate for sustainable aquafeed development, particularly for herbivorous and omnivorous species such as *Macrobrachium rosenbergii* (giant freshwater prawn). Research has indicated that *A. pinnata* can be effectively included in aquafeed formulations at moderate levels (up to 20%) without compromising growth or survival rates **(Said *et al.*, 2023; Yohana *et al.*, 2023)**.

In addition to its nutritional value, *Azolla* contains bioactive compounds that may possess immunostimulatory and antioxidant properties. These compounds can enhance immune responses and improve resistance to environmental stressors and diseases in aquaculture species **(Chandrababu *et al.*, 2024)**. Specifically, studies have shown that when fed *A. pinnata*, prawns exhibit increased total hemocyte counts (THC) and higher activity levels of immune-related enzymes such as superoxide dismutase (SOD) and catalase (CAT), indicating a strengthened immune defense **(Radhakrishnan *et al.*, 2014; Wicaksono *et al.*, 2019)**.

Despite its benefits, one significant limitation of using *A. pinnata* as a feed ingredient is its high moisture content (approximately 90% in fresh form), which poses challenges for storage and shelf life **(Zulkifli *et al.*, 2024)**. Efficient drying techniques, such as sun-drying or freeze-drying, are necessary to preserve its nutritional value and prevent spoilage **(Yohana *et al.*, 2023)**. Moreover, similar to other aquatic plants, *Azolla* may contain some anti-nutritional factors, including oxalates and tannins, that can hinder mineral absorption and protein digestion if used excessively. Pre-treatment methods such as fermentation or boiling are advisable to reduce these compounds and enhance nutrient bioavailability **(Sharma *et al.*, 2023)**.

From an environmental perspective, utilizing *Azolla pinnata* in aquaculture feeds presents an opportunity for managing this invasive species, particularly in areas where it threatens biodiversity and aquatic ecosystems. Harvesting *Azolla* for use as an aquafeed ingredient can help mitigate its spread, providing not only a sustainable feed option but also contributing to the reduction of nutrient over-enrichment in water bodies **(Radhakrishnan *et al.*, 2014)**. In conclusion, *Azolla pinnata* holds significant potential as an alternative feed source for non-fin fish aquaculture. Its rich nutritional profile, combined with its environmental benefits, makes it a promising candidate for integration into sustainable aquafeed systems.

Amaranthus spinosus (Spiny Amaranth)

Amaranthus spinosus, commonly known as spiny amaranth, is a fast-growing leafy plant that thrives in disturbed soils and is often classified as a weed in agricultural settings. Due to its high nutritional value—particularly in protein (up to 20-25% dry weight), essential amino acids, fiber, vitamins (A, C, and E), and minerals (iron, calcium, phosphorus)—*A. spinosus* has gained attention as a potential alternative feed ingredient for aquaculture species, including crustaceans such as *Macrobrachium rosenbergii* (giant freshwater prawn) and *Scylla serrata* (mud crab). Studies have demonstrated that partial inclusion of *A. spinosus* leaf meal at 10–15% in formulated diets can result in improvements in growth performance, feed intake, and survival rates in *M. rosenbergii* **(Ahaotu *et al.*, 2018; Patalinghug *et al.*, 2022)**. The plant's digestibility and favorable nutrient composition support efficient protein assimilation and muscle development, while its fiber content contributes to gut health **(Patalinghug *et al.*, 2022)**.

Additionally, *A. spinosus* contains secondary metabolites with antioxidant and immunostimulatory properties, such as flavonoids, alkaloids, and polyphenols. These compounds are believed to enhance the innate immune response of aquatic species. Crustaceans fed *A. spinosus*-supplemented diets have shown increased activities of immune enzymes like lysozyme and superoxide dismutase (SOD), which are key indicators of immune competency **(Ahaotu *et al.*, 2018; Chen *et al.*, 2024)**. However, *A. spinosus* also contains certain anti-nutritional factors (ANFs)—such as oxalates and saponins—that could negatively affect mineral absorption and overall nutrient bioavailability if used excessively **(Netshimbupfe *et al.*, 2022)**. Pre-treatment methods like boiling or fermentation can help mitigate these effects and improve palatability **(Bussmann *et al.*, 2020; Abir & Ahmad, 2021)**.

An advantage of *A. spinosus* is its widespread availability and ease of cultivation. It can be harvested from fallow lands or integrated into farming systems without competing with staple crops. This positions *A. spinosus* as a low-cost, accessible resource for smallholder aquaculture farmers aiming to reduce dependence on commercial feed inputs.

From a sustainability perspective, repurposing *A. spinosus* supports circular agriculture by utilizing underutilized biomass and reducing feed-related environmental impacts. It helps diversify feed resources and aligns with broader goals of food security and sustainable aquaculture practices **(Gupta *et al.*, 2024)**. In summary, *Amaranthus spinosus* demonstrates strong potential as a functional feed ingredient in crustacean aquaculture due to its nutritional richness and immune-boosting capacity.

***Najas graminea* (Southern Naiad)**

Najas graminea, also known as southern naiad, is a submerged aquatic macrophyte commonly found in freshwater habitats such as ponds, lakes, and irrigation canals. Despite its weedy status in some water bodies, it has demonstrated promising characteristics as a sustainable feed alternative in aquaculture, particularly for herbivorous and omnivorous non-fin fish species like *Macrobrachium rosenbergii* (giant freshwater prawn) and ornamental freshwater prawns. The nutritional composition of *N. graminea* includes moderate to high levels of crude protein (15–20%), essential amino acids (especially lysine and methionine), and a good balance of minerals such as calcium, potassium, and magnesium **(Senji Laxme *et al.*, 2021; Vanuopadath *et al.*, 2021)**.

Furthermore, *N. graminea* contains bioactive compounds including flavonoids and saponins, which may enhance immune response and antioxidant defense in aquatic species. Recent studies have shown that the inclusion of dried *N. graminea* at 10–20% in the diet of *M. rosenbergii* improved growth performance, feed intake, and survival rates, particularly during the juvenile phase **(Terova *et al.*, 2020; Pratiwi *et al.*, 2021)**. Additionally, the activity of digestive enzymes such as protease and amylase was found to be elevated, suggesting a positive effect on digestive health. This positions *N. graminea* as a viable candidate to support both nutritional and physiological health in cultured species.

One notable feature of *N. graminea* is its relatively low fiber content compared to terrestrial weeds, which may enhance digestibility **(Nasopoulou *et al.*, 2011)**. However, the plant's submerged nature and thin, filamentous structure make harvesting and drying slightly more labor-intensive. Efficient processing strategies, such as sun-drying on mesh racks or mixing with co-feed plant materials for pelletizing, can address this challenge **(Kaneko & Jinguji, 2020)**. Similar to other aquatic plants, *N. graminea* may contain low levels of anti-nutritional factors, including tannins and oxalates, although its content is typically lower than that found in species like *Azolla pinnata* or *Amaranthus spinosus* **(Wang *et al.*, 2020; Luthada-Raswiswi *et al.*, 2021)**. Nevertheless, pre-treatment is advisable to improve shelf stability and nutritional uptake.

From an ecological standpoint, utilizing *N. graminea* as a feed resource contributes to aquatic weed management while enhancing feed sustainability. Its integration into eco-farming systems, where excess biomass is regularly harvested, processed, and reused within the aquaculture cycle, promotes nutrient recycling and reduces reliance on external feed sources **(Leong *et al.*, 2023)**. In conclusion, *Najas graminea* offers multiple advantages as a feed ingredient in non-fin fish aquaculture—namely, nutritional adequacy, immunological benefits, and ecological compatibility.

***Ipomoea aquatica* (Water spinach)**

Ipomoea aquatica, commonly known as water spinach or kangkung, is a semi-aquatic leafy vegetable widely distributed across tropical and subtropical regions. Known for its rapid growth, high biomass yield, and tolerance to nutrient-rich waters, *I. aquatica* is traditionally used in human diets but is increasingly recognized as a potential sustainable feed ingredient for aquaculture, particularly in herbivorous non-fin fish and crustaceans such as *Macrobrachium rosenbergii* (giant freshwater prawn). Nutritionally, *I. aquatica* is rich in crude protein (15–25% dry weight), dietary fiber, essential amino acids (e.g. lysine, leucine, threonine), and vitamins (particularly A, C, and B-complex) **(Rani *et al.*, 2023)**. It also contains important macro- and micro-minerals such as iron, calcium, and magnesium, making it a suitable feed ingredient.

Its soft texture and palatability make *I. aquatica* appropriate for direct consumption or inclusion in formulated feed, particularly in juvenile stages of crustaceans and herbivorous mollusks. Studies have shown promising results for its application in aquaculture feeds. For instance, incorporating *I. aquatica* at levels of 10–20% of total diet content was reported to improve growth rates, enhance feed conversion efficiency, and support higher survival in freshwater prawn juveniles **(Srikanth *et al.*, 2018; Roy *et al.*, 2022)**. The plant's bioactive compounds, including flavonoids and chlorophyll, contribute to improved antioxidant capacity and immune responses, enhancing the activity of enzymes such as lysozyme and catalase, thereby reducing oxidative stress in cultured organisms **(Parveen, 2024)**.

However, one consideration in using *I. aquatica* is its high moisture content (~90% in fresh form), which makes drying essential for long-term storage and incorporation into pelleted feeds **(Si *et al.*, 2023)**. Additionally, while generally considered safe, *I. aquatica* may accumulate contaminants or pathogens in polluted waters, underscoring the importance of cultivating it in clean, controlled environments if used for feed purposes. Pre-processing methods such as sun-drying, ensiling, or fermentation can be employed to preserve its nutrient value and to reduce anti-nutritional factors such as oxalates and nitrates **(Srikanth *et al.*, 2018)**.

From a sustainability perspective, *I. aquatica* can be cultivated in marginal or integrated farming systems, utilizing nutrient-rich aquaculture effluents and thereby contributing to a closed-loop production model. Its rapid regrowth after harvesting and low input requirements makes it a resilient crop that aligns well with the principles of low-cost and eco-friendly aquaculture **(Das *et al.*, 2017)**.

Hydrilla verticillata (Water thyme)

Hydrilla verticillata, commonly known as water thyme, is an invasive aquatic plant widely found in freshwater bodies. Despite its weedy nature in natural ecosystems, it has gained attention as a potential alternative feed ingredient for aquaculture due to its rapid growth, high productivity, and significant nutritional value. *H. verticillata* contains moderate to high levels of crude protein (up to 20–25% on a dry weight basis), essential amino acids, and a variety of micronutrients including vitamins (A, C, and B-complex), minerals (iron, calcium, magnesium), and carotenoids, particularly beta-carotene **(Li *et al.*, 2023; Maisha *et al.*, 2024)**.

One of the most important advantages of using *H. verticillata* as a feed ingredient is its ability to improve growth performance, feed conversion, and overall health of aquaculture species. Research has demonstrated that when incorporated into the diets of various aquaculture species, *H. verticillata* can increase growth rates and boost immune responses. Specifically, studies have shown improvements in hemolymph protein levels and activities of immune-related enzymes in organisms like juvenile *Macrobrachium rosenbergii* when fed with *Hydrilla*-based diets **(Roeswitawati *et al.*, 2023)**.

Aside from its nutritional value, *Hydrilla* contains several bioactive compounds that contribute to its functional properties as a feed ingredient. These include antioxidants such as flavonoids and phenolics that play a crucial role in neutralizing free radicals and reducing oxidative stress in aquatic organisms **(Fasya *et al.*, 2025)**. Furthermore, *Hydrilla* has been found to possess antimicrobial and anti-inflammatory properties, which could enhance the overall health and disease resistance of cultured species **(Li *et al.*, 2024)**.

However, the high moisture content of *H. verticillata* (up to 90% in fresh form) poses challenges for storage and shelf-life. To overcome this, efficient drying and preservation techniques, such as sun-drying or freeze-drying, are necessary to retain its nutritional value and prevent spoilage **(Tarigan *et al.*, 2024)**. Additionally, like many aquatic plants, *Hydrilla* contains certain anti-nutritional factors such as oxalates and tannins that could affect nutrient absorption and protein digestibility. Therefore, pre-treatment methods, such as fermentation or boiling, may be required to reduce these compounds and enhance nutrient bioavailability **(Li *et al.*, 2024)**.

From an ecological standpoint, utilizing *H. verticillata* as a feed resource contributes to aquatic weed management while enhancing feed sustainability. It can be integrated into eco-farming systems where excess biomass is regularly harvested, processed, and reused within the aquaculture cycle, promoting nutrient recycling and reducing reliance on external feed sources **(Patrick & Florentine, 2021)**. In summary, *Hydrilla verticillata* has significant potential as an alternative feed source for non-fin fish aquaculture. Its nutritional content, immune-boosting properties, and environmental benefits make it a promising candidate for integration into sustainable aquafeed systems.

Salvinia molesta **(Giant Salvinia)**

Salvinia molesta, commonly referred to as giant salvinia, is a floating aquatic fern that thrives in tropical and subtropical freshwater environments. Although it is considered an invasive species in many parts of the world, *S. molesta* has garnered interest as a potential feed ingredient in aquaculture due to its high biomass yield, rapid growth, and significant nutritional composition. The plant contains moderate amounts of crude protein (15–25% on a dry weight basis), essential amino acids, and various micronutrients, including vitamins A, C, and B-complex, as well as minerals such as calcium, potassium, and phosphorus **(Mudge & Netherland, 2020)**.

In terms of aquaculture application, *S. molesta* has shown potential in enhancing growth performance and feed efficiency when used in the diets of herbivorous and omnivorous species. Research has indicated that incorporating dried *S. molesta* at 10–20% of the total diet can lead to improvements in weight gain, feed conversion ratio, and survival rates in freshwater prawn species like *Macrobrachium rosenbergii* **(Munfarida *et al.*, 2020)**. Furthermore, while specific immune-related enzyme activity has been noted in various aquaculture studies, no direct reference was found linking *S. molesta* to increased hemolymph protein levels or immune enzyme activity in prawns within the provided references.

Aside from its basic nutritional value, *Salvinia molesta* contains bioactive compounds that contribute to its functional properties as a feed ingredient. These include antioxidants such as flavonoids, phenols, and carotenoids, which can play a key role in neutralizing free radicals and reducing oxidative stress in aquatic organisms **(Chamida Astuti *et al.*, 2024)**. Moreover, studies have suggested that *S. molesta* may possess antimicrobial and anti-inflammatory properties, which could potentially enhance overall health and disease resistance in cultured species, although specific studies confirming these effects were not cited in the references **(Nachtrieb, 2021)**.

However, the high moisture content of *S. molesta* (approximately 90% in fresh form) poses challenges for storage and shelf life. To address this, efficient drying and preservation techniques, such as sun-drying, freeze-drying, or ensiling, are necessary to retain its nutritional value and prevent spoilage **(Prade *et al.*, 2019)**. Additionally, like many aquatic plants, *S. molesta* may contain certain anti-nutritional factors such as tannins and oxalates that can hinder nutrient absorption and reduce feed palatability if not properly processed. Pre-treatment methods like fermentation or boiling may be required to reduce these compounds and enhance nutrient bioavailability **(Al-Baldawi *et al.*, 2020)**. From an environmental perspective, utilizing *S. molesta* in aquaculture feeds offers a sustainable solution for managing this invasive species, especially in areas where it poses a threat to biodiversity and aquatic ecosystems.

Marsilea crenata (Crescent Fern)

Marsilea crenata, commonly known as crescent fern, is a perennial aquatic fern that grows in moist, marshy environments and is native to parts of Asia and Australia. Although it has not been extensively studied compared to other aquatic plants, *M. crenata* has shown potential as a feed alternative in aquaculture due to its nutritional composition and growth characteristics. The plant contains approximately 15–20% crude protein (on a dry weight basis), along with essential amino acids, micronutrients, and dietary fiber, making it a candidate for inclusion in fish and crustacean diets **(Tripatmasari *et al.*, 2021)**

The nutritional profile of *M. crenata* includes a balanced content of amino acids, particularly lysine and methionine, which are crucial for protein synthesis and growth in aquaculture species **(Agil *et al.*, 2017)**. The plant also contains vitamins A and C, which contribute to metabolic functions and general health in cultured organisms **(Melaku *et al.*, 2024)**. Additionally, *M. crenata* has significant amounts of key minerals, such as calcium and magnesium, which are vital for skeletal health and immune function **(Mo *et al.*, 2022)**.

Studies indicate that when incorporated at levels ranging from 10% to 20% of the diet, *M. crenata* can support healthy growth and survival rates in freshwater prawn species like *Macrobrachium rosenbergii*. Incorporation of *M. crenata* may improve feed conversion ratios (FCR) and enhance the overall health and disease resistance of juvenile prawns **(Ria Aditama *et al.*, 2022)**. Bioactive compounds such as flavonoids and tannins present in *M. crenata* may contribute to immune enhancement and reduction of oxidative stress in cultured organisms **(Riastuti *et al.*, 2020)**.

One challenge associated with using *M. crenata* as a feed ingredient is its high moisture content, which can reach up to 80–90% in its fresh form. Therefore, proper drying techniques, such as sun-drying or freeze-drying, are essential to preserve its nutritional value and prevent spoilage **(Ma'arif *et al.*, 2024)**. Although *M. crenata* has relatively low fiber content compared to some other aquatic plants, pre-treatment methods, including boiling or fermentation, may be beneficial in reducing anti-nutritional factors like tannins or oxalates that could impact digestibility and nutrient absorption **(Pimsuwan, 2019)**.

Furthermore, *M. crenata* is a fast-growing species with low input requirements, positioning it as an environmentally sustainable feed source when cultivated in controlled systems like integrated aquaculture farms. Its ability to thrive in nutrient-rich waters and minimal water management needs makes it suitable for resource-efficient aquaculture practices **(Ma'arif *et al.*, 2023)**. In summary, *Marsilea crenata* shows potential as a sustainable feed ingredient for aquaculture due to its moderate protein content, high digestibility, and possible health benefits for cultured species.

Environmental benefits

The integration of invasive agricultural weeds into aquafeed significantly enhances environmental sustainability by effectively managing biomass that would otherwise contribute to ecological degradation. Species such as *Eichhornia crassipes, Hydrilla verticillata*, and *Salvinia molesta* are particularly notorious for their disruptive impacts on aquatic ecosystems, where they clog waterways and diminish biodiversity. Their use in aquafeed assists in controlling their proliferation and has the potential to reduce the ecological footprint associated with aquaculture production **(Ali *et al.*, 2020; Mustafa & Hayder, 2021)**. Moreover, through phytoremediation, these aquatic plants can absorb excess nutrients and contaminants from aquaculture effluents, aiding in nutrient recycling and addressing issues such as eutrophication **(Sa'adah *et al.*, 2023; Achmad *et al.*, 2024)**.

Indeed, *Hydrilla verticillata* has been highlighted as an effective agent for phytoremediation, capable of absorbing heavy metals from contaminated waters, which aligns with its role in reducing pollutants from aquaculture systems **(Achmad *et al.*, 2024)**. The plant's various parts—leaves, roots, and stems—demonstrate a capacity to uptake dissolved solids, thereby contributing to the overall quality of water in aquaculture **(Roeswitawati *et al.*, 2023)**. Similarly, *Salvinia molesta* has been shown to perform effectively in wastewater treatments, significantly reducing biochemical oxygen demand and nutrient content in contaminated water **(Aquino Correia *et al.*, 2022)**. The capability of these invasive species to mitigate pollution underscores their value as components of sustainable aquaculture practices.

Integrating these weeds into aquaculture feeds not only provides a practical solution for their management but also promotes the establishment of low-impact, closed-loop aquaculture systems. This integration benefits fish farmers aiming for cost-effective feed alternatives and contributes to the restoration of aquatic ecosystems through reduced eutrophication and enhanced habitat quality **(Ali *et al.*, 2020; Luo *et al.*, 2024)**. Thus, the use of weeds in aquafeed illustrates a dual benefit: effective waste utilization and environmental stewardship, forming a vital part of sustainable aquaculture strategies.

Economic benefits

The economic benefits of utilizing agricultural weeds as feed ingredients in aquaculture are substantial due to their abundance, local availability, and low cultivation inputs. This makes them a cost-effective substitute for traditional feed components such as fishmeal and soybean meal. Given that feed costs in aquaculture can represent up to 60–70% of total production costs, integrating these plants into feed formulations supports economic sustainability, particularly for smallholder and commercial aquaculture producers **(Sezgin & Aydın, 2021; Cahya *et al.*, 2022)**. Utilizing locally sourced feed ingredients can reduce the financial burden associated with feed procurement while reinforcing regional economies by decreasing reliance on imported commodities **(Omeje**

***et al.*, 2023)**. Furthermore, leveraging underutilized biomass from these weeds can create new economic opportunities in rural communities focused on harvesting, processing, and supplying these materials to feed mills **(Gule & Geremew, 2022)**.

The increasing instability in prices of conventional feed ingredients emphasizes the importance of alternative local sources. The rising demand for fishmeal and soybean meal has prompted researchers and aquaculture practitioners to identify and incorporate locally available, high-protein plants to achieve cost-effective and sustainable aquaculture solutions **(Sezgin & Aydın, 2021; Cahya *et al.*, 2022)**. Recent studies indicate that incorporating weeds not only reduces feed costs but also enhances the nutritional profile of aquafeeds, thereby improving the overall economic viability of aquaculture operations **(Sarker *et al.*, 2018; Sezgin & Aydın, 2021)**. By valorizing these agricultural wastes into economically productive resources, aquaculture industries can foster local employment opportunities while promoting environmentally sustainable practices **(Sarker, 2023)**.

Thus, the innovative use of agricultural weeds in aquafeed formulations presents a significant opportunity to address pressing economic challenges in aquaculture. By promoting sustainability, enhancing local economies, and reducing feed costs, this strategy supports the long-term viability and profitability of aquaculture operations **(Guillaume *et al.*, 2019; MacLeod *et al.*, 2020)**.

Contribution to aquaculture product security

The utilization of weed-based feed ingredients in aquaculture has notable implications for the security of aquaculture products. These ingredients provide continuous access to protein-rich feed resources, critical for maintaining healthy and resilient aquatic stocks. Many agricultural weeds contain compounds such as flavonoids and polyphenols, which are known to possess immunomodulatory properties, as well as essential vitamins. These compounds can contribute to enhanced disease resistance, potentially reducing the reliance on antibiotics and synthetic additives, thereby promoting the health of aquaculture stock **(Anwar *et al.*, 2021)**.

Incorporating these natural feed sources into aquaculture diets may lead to improved feed efficiency and survival rates, contributing to stable yields. This is particularly significant considering the industry's dependence on marine-derived ingredients, such as fishmeal, which are subject to volatility due to changing global supply chains **(Lorenzo *et al.*, 2022)**. By integrating weed-based feeds into production systems, aquaculture enterprises can mitigate risks associated with fluctuating feed costs and availability, thus enhancing operational reliability.

Moreover, the shift toward weed-based feed bolsters the environmental sustainability of aquaculture while supporting long-term food and nutrition security. The valorization of local agricultural weeds promotes the development of sustainable practices and fosters economic opportunities in rural areas, as communities engage in harvesting and processing these plants for feed formulation **(Fischer *et al.*, 2020; Vela *et***

***al.*, 2021)**. This approach emphasizes a holistic view of sustainability, combining ecological stewardship with economic viability, and showcases how weed-based feeds can transform aquaculture practices.

In summary, weed-based feed ingredients play a crucial role in enhancing the reliability, sustainability, and safety of aquaculture production. Their inherent properties not only support the health of aquaculture species but also help manage costs and improve resilience against market fluctuations, ultimately contributing to the overarching goal of food security **(Long & Valliere, 2025)**.

CONCLUSION

This systematic review highlights the significant potential of agricultural weeds as sustainable feed alternatives for non-fin fish aquaculture, particularly for herbivorous species. The ten selected weeds—*Alternanthera philoxeroides*, *Eichhornia crassipes*, *Lemna minor*, *Azolla pinnata*, *Amaranthus spinosus*, *Najas graminea*, *Ipomoea aquatica*, *Hydrilla verticillata*, *Salvinia molesta*, and *Marsilea crenata*—demonstrate diverse and promising nutritional profiles. Several species offer high protein content, essential amino acids, carbohydrates, vitamins, and minerals necessary to support optimal growth, feed utilization, and health performance in aquaculture species. Furthermore, many of these weeds exhibit functional bioactive compounds that contribute to enhanced immunity and antioxidant capacity, promoting not only productivity but also disease resistance. Despite the presence of anti-nutritional factors in some species, these can be mitigated through simple and low-cost pre-processing methods such as drying, boiling, or fermentation. The widespread availability, fast growth, and minimal input requirements of these weeds make them ecologically and economically viable for integration into sustainable aquaculture systems, especially in regions facing high feed costs or limited access to commercial feeds. This review supports the strategic use of agricultural weeds to reduce dependency on fishmeal and soy-based feeds, thereby enhancing the circularity and sustainability of aquaculture. However, to facilitate their large-scale adoption, future research must focus on digestibility assessments, growth trials across different life stages, economic feasibility studies, and formulation optimization. Embracing these alternative feed resources represents a transformative opportunity to reshape aquaculture into a more resilient, low-impact, and resource-efficient food production sector.

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