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Aquatic Weeds as Functional Ingredients for Aquaculture Feed Industry: Recent Advances, Challenges, Opportunities, New Product Development (NPD) and Sustainability

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Abstract: In recent years, there has been a lot of interest in the use of aquatic weeds as a valuable component in the development of aquaculture feed. Various species of aquatic weeds like *Ipomoea aquatica, Lemna minor, Pistia stratiotes, Eicchornia crassipes, Azolla pinnata Nymphaea nouchali,* and *Nymphaea lotus* have been identified and studied for their nutritional composition and potential benefits of fish production, health status, defense mechanism and disease resistance. The aquatic weed has a great potentiality to reduce the dependency on fish meal and offers environmental benefits in terms of weed management and habitat conservation in various waterbodies of Bangladesh. Thus, the conversion of these aquatic weeds into valuable products could play a crucial role in sustainability of the aquaculture industry and mitigating environmental hazards as well as pollution. Nevertheless, there are several challenges like variability of nutritional composition, presence of anti-nutritional factors, high fibre content, and potential health hazards need to be addressed for successfully use of aquatic weeds in fish feed. Semi-solid-state fermentation (SSSF) approaches can reduce the ANFs and fibre of fish feed for cost effective aquaculture feed. Furthermore, it is essential for scientists to understand the major phases involved in the development of novel goods. In summary, the incorporation of aquatic weeds in aquaculture feed will open up the new horizon for sustainability of aquaculture feed industry.

INTRODUCTION

One of the main reasons for the sharp rise in demand for fish and seafood is the enormous rise in global population. Aquaculture has a great potential to meet the protein need for global population and has a significant contribution to the raising global fish production, reaching about 82 million tons in 2018 (FAO, 2020). Fish feed plays a fundamental role in sustaining the aquaculture production in captivity.

However, fish nutrition is critical as feed is the most expensive part in the aquaculture system, being approximately 60% of the entire production cost (Craig *et al*., 2017; Prabu *et al*., 2017; Daniel, 2018). Protein and lipid are the vital components in the diets that are highly required by fish for their optimum growth, survival, and reproduction. Moreover, fish meal and fish oil are considered the best animal derived protein and lipid source in fish diet (Hodar *et al*., 2020). According to Shepherd and Jackson (2013) around 4.4 to 4.6 kg whole fish is often needed to generate 1 kg fish meal (FM), while Liland *et al*. (2012) reported that about 12.2 kg of fish is required to produce 1 kg fish oil. Marine pelagic fish such as mackerel, anchovies, herring, and sardines are some of the most significant sources of FM in aqua-diet (Merino *et al*., 2012). It is projected that the global aquaculture will not be able to meet its protein needs by 2050 because of FM production over reliance on marine fisheries resources (Jiang *et al*., 2018; Kari *et al*., 2022), which poses a serious problem for the entire world. Meanwhile, their limited supply, high price, and unavailability are the major constrains that drive up the feed cost. Therefore, the exploring and developing of alternative bio-active and functional nutrient ingredients from indigenous sources have recently caught substantial interest in the aqua-feed industry (Suma *et al*., 2023). The utilization of aquatic weeds may be the great option to fill the existing problem.

Aquatic weeds are the promising fish and animal feed ingredients that are widely distributed in the waterbodies of Bangladesh. Aquatic weeds' superior nutritional composition has recently allowed FM to be partially or completely replaced (Debnath *et al*., 2018; Ghosh *et al*., 2021; Nandi *et al*., 2023). Naseem *et al*. (2021) documented that aquatic weed meal comprises of about 11 to 32% crude protein, 2.9 to 16.81% crude lipid, 8 to 31% crude ash, and very high amino acids, minerals and vitamins content depending on the choice of ingredients used. According to another study, the use of these plants in the aquaculture feed has dual benefits of eco-friendly management of aquatic weeds and the potential to replace FM in fish feed formulation (Ali and Kaviraj, 2018).

It is crucial to note that the inclusion of plant protein in diets dramatically decreased the feed cost due to their local availability, low price, and abundance. However, a number of scientists have reported that the aquaculture feed industry should require an alternative protein supplement to replace high valued FM, which is highly appreciated but has a limited supply and a great demand (Bairagi *et al*., 2002; Yılmaz *et al*., 2004; Sadique *et al*., 2018). Therefore, several studies have been conducted to explore potential alternatives for FM by using novel protein source from aquatic weeds (Table 1). The key factor affecting the aquaculture industry's sustainability is access to high-quality and reasonable priced ingredients (Ghosh and Roy, 2017; Goswami *et al*., 2020). However, our current understanding on the utilization of aquatic weeds meal in animal diets, including their working mechanisms, animal health and environmental impacts, is limited, indicating significant gaps in knowledge in this area. In depth research is required to overcome the existing knowledge deficit and produce inexpensive, nutritionally sound and environmental friendly fish feed. This short review highlights the recent advances, challenges, opportunities, product development, and sustainability aspects associated with the use of aquatic weeds as a viable alternative to traditional feed ingredients in the aquaculture industry in order to examine the efficiency of aquatic weed meal-based diets in fish production and cost-effective management in future.

AQUATIC WEEDS USED FOR AQUACULTURE INDUSTRY

Near about 50 species of aquatic weeds are known to be used as either direct or indirect feed for both herbivorous and omnivorous fishes (Mandal *et al*., 2010; Akmal *et al*., 2014; Naseem *et al*., 2021). Aquatic weeds are undesirable plants that cause harm to the aquatic organisms and the environment (Ganguly *et al*., 2012). The aquaculture industry may profit from the sustainable use of these plant ingredients. Aquatic weeds such as water spinach *Ipomoea aquatica* (Nandi *et al*., 2023), duckweed *Lemna minor* (Patra, 2015), water lettuce *Pistia stratiotes* (Nisha and Geetha, 2017), water hyacinth *Eicchornia crassipes* (Hailu *et al*., 2020), mosquito fern *Azolla pinnata* (Das *et al*., 2018), water lily *Nymphaea pubescens* (Kamatit *et al*., 2016), and lotus meal *Nymphaea lotus* (Athanase *et al*., 2019) have recently caught profound insights as a partial or complete FM replacer in aqua-diets for fish growth enhancement, reproduction, health status, immune related gene expression, and disease resistance. The leaves, stems, roots or whole plants are generally used in fish feed formulation. Table 1 represents the various studies of using aquatic plants and their possible impacts on fish production. Figure 1 displays the aquatic weeds used in aquaculture activities for ingredient/ protein replacement, incorporation or additive in fish feed formulation.

Table 1: The effects of aquatic plant ingredients on fish performance

Aquatic weeds	Examined fish	Recommended levels	Experimental period	Key findings	References
Water spinach meal (Fermented)	Female Singhi (*Heteropneustes fossilis*)	50% of fish meal replacement in diets	3 months	Enhanced growth and reproductive parameters, egg quality and health status of fish.	Nandi *et al*. (2023)
Water spinach meal (dried)	Nile tilapia (*Oreochromis niloticus*)	25% of fish meal substituition in diets	56 days	Without showing negative impacts on growth, nutrient utilization, and biochemical composition of fish.	Yousif *et al*., (2019)
Duckweed meal	Major carp (*Labeo rohita*)	15% replacement of fish meal	4 months	Showed outstanding performance of fish and act as low-cost feed ingredient.	Patra, (2015)
	Common carp (*Cyprinus carpio*)	85% duckweed + 15% rice bran	3 months	Promoted growth and health status; served as low-cost feed.	Ghosh *et al*., (2021)
Fermented aquatic macrophytes	Nile tilapia (*Oreochromis niloticus*)	25% fermented duckweed + 15% fermented water fern in diets	56 days	Without affecting the growth and feed utilization of fish.	Velásquez *et al*., (2015)
Fermented *Pistia* leaves (PL)	Rohu (*Labeo rohita*)	12.5% FM replacement by 20% fermented PL in diets	80 days	Without exhibiting adverse impacts on growth, nutrient efficiency, and biochemical composition of fish.	Mandal and Ghosh, (2019)
Aquatic weed *Pistia stratiotes* meal	Indian major carp (*Labeo rohita*)	15% FM substituition with 30% water lettuce meal	80 days	Enhanced growth and feed utilization indices, carcass composition, blood parameters, and digestive enzyme activity.	Nisha and Geetha, (2017)
Water lettuce (WL) and water spinach (WS)	Nile tilapia (*Oreochromis niloticus*)	50% FM replacement by 50% WS or by combination of 25% WS + 25% WL	2 months	Increase SGR (% /day) of fish.	Manuel *et al*., (2020)
Water hyacinth (WH) meal	Grass carp (*Ctenopharyngodon idella*)	15% of water hyacinth leaf meal in diets	3 months	Enhanced fish weight gain, without showing negative impacts on liver and kidney health.	Mahmood *et al*., (2018)

	Nile tilapia (*Oreochromis niloticus*)	15% or 30% fermented WH in fish diets	2 months	Showed highest relative growth rate and Fulton's condition factor.	Hailu *et al*., (2020)
Nymphaea lotus leaf meal (NLM)	African catfish (*Heterobranchus longifilis*)	20% of FM replacement	8 weeks	Without lowering the growth, nutrient efficiency, and survival of fish.	Athanase *et al*., (2019)
Azolla pinnata meal (Fresh)	Thai silver barb (*Barbonymus gonionotus*)	25% replacement of commercial diets	9 weeks	Exhibited no adverse impacts on growth indices and quality of product; served as economical viable diet ingredient.	Das *et al*., (2018)

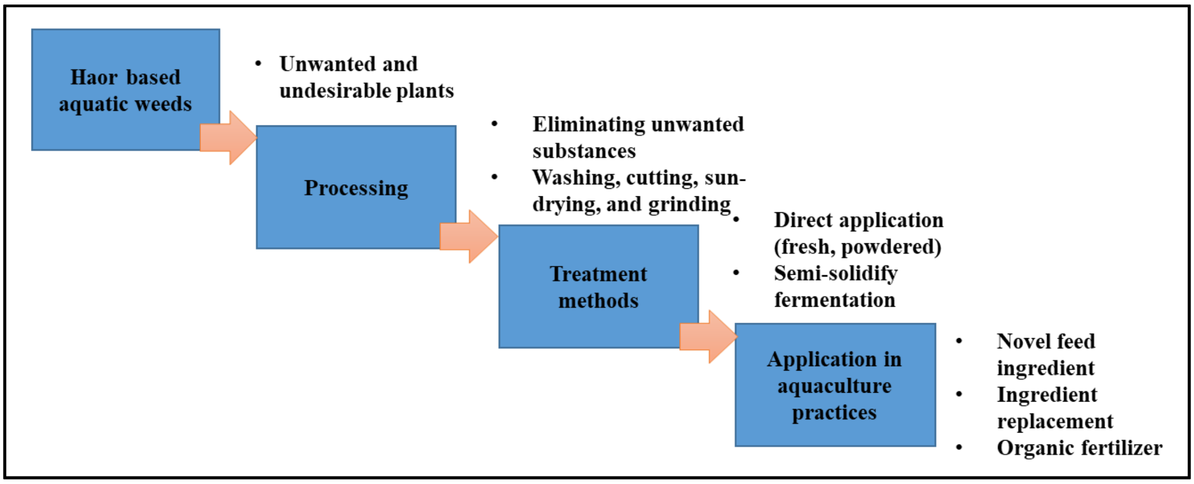

Figure 1: Conceptual overview of using aquatic weeds in Aquaculture practices

BRIEF LIST OF AQUATIC WEEDS FOUND IN BANGLADESH

Bangladesh is home to a rich diversity of aquatic weeds, with around 150 varieties identified in its waterbodies (Pasha, 1966). These weeds contribute to the country's diverse wetland ecosystem and support a range of flora and fauna. The abundance and accessibility of aquatic weeds in waterbodies ensure a steady supply of feed ingredients into the aqua-feed industry throughout the year. Additionally, their utilization as a natural feed resource helps in managing and controlling excessive weeds growth and maintaining the balance of ecosystem. Table 2 represents the list of most commonly available water weeds in Bangladesh with including their local names, common names, and scientific names.

Table 2: List of aquatic weeds distributed in Bangladesh

Local name	Common name	Scientific name
Kolmi	Water spinach	*Ipomoea aquatica*
Topapana	Water lettuce	*Pistia stratiotes*
Kachuripana	Water hyacinth	*Eichhornia crassipes*
Khudipana	Duckweed	*Lemna minor*
Kutipana	Mosquito fern	*Azolla pinnata*
Gechu	Aponogeton	*Aponogeton* spp.
Malancha	Alligator weed	*Alternantera philoxerodies*
Hydrilla	Water thyme	*Hydrilla verticilata*
Shapla	Water lily	*Nymphaea nouchali*
Padma/ Komol	Lotus	*Nymphaea lotus*

Helencha	Water cress	*Enhydra fluctuans*
Bishkatali	Polygonum	*Polygonum glabrum*
Panikochu	Arrowhead	*Sagittaria* spp.
Dol	Asian waterweed	*Hygrorayza aristata*
Hugla	Common cattail	*Typha latifolia*
Kanaibashi	Dayflower	*Commerlina bengalensis*
Kanaidoga	Asiatic dayflower	*Commerlina appendiculata*
Hydrilla	Water thyme	*Hydrilla verticilata*
Najas	Brittle naiad	*Najas minor*
Vallisneria	Eel weed	*Vallisneria spiralis*

OVERVIEW OF SUSTAINABLY USE OF AQUATIC WEEDS IN AQUACULTURE PRACTICES

i. Water spinach *(I. aquatica)*

Water spinach, referred to as "Kolmi" locally, is abundant in various haor regions across Asian countries, including Bangladesh (Nandi *et al*., 2023). It has emerged as a dual purpose, being consumed directly by humans and also showing promise as a valuable ingredient in the aquaculture feed industry. Water spinach has great possibility in the aqua-feed formulation due to its high nutritional profile. Water spinach leaf contains about 26% crude protein, 6% crude lipid, 13% ash, 8% crude fibre, 48% carbohydrate, and 5% moisture in dry weight basis (Adedokun *et al*., 2019). Recent study reported that semi solid-state fermentation of water spinach with 0.001% *Lactobacillus acidophilus* and 10% molasses improve the nutritional value of it (Nandi *et al*., 2023). According to Yousif *et al*. (2019) water spinach can be used as a substitute for fish meal in Nile tilapia (*Oreochromis niloticus*) diets, up to 25%, without compromising the growth performances and nutrient utilization of that fish. In other studies, dietary supplementation of water spinach meal at 50 g/kg diet of Nile tilapia fries resulted in improved growth performance (Chepkirui *et al*., 2022; Mercy, 2021). Moreover, Manuel *et al*. (2020) reported that tilapia, fed with different proportions of water spinach showed outstanding performance in their study.

ii. Duckweed *(L. minor)*

Duckweed, locally known as "Khudipana," is an aquatic plant that floats freely and can be found in various freshwater bodies across Bangladesh, particularly in the haor regions. Duckweed is directly utilized as a feed by various herbivorous fish species in aquaculture ponds. The total biomass of duckweed can double within a span of 1 to 3 days, when environmental parameters are in optimum (Ziegler *et al*., 2015). Due to its availability, rapid growth rate, cost-effectiveness, and superior nutrient composition, duckweed is considered an excellent candidate for aqua-feed formulation. Duckweed proves to be a valuable nutrient source, with protein content exceeding 40 g/100g on a dry matter basis (Ahamad *et al*., 2003; Saha *et al*., 1999; Stadtlander *et al*., 2019), fiber content at 5 g/100g in dry weight (Chaturvedi *et al*., 2003; Irabor *et al*., 2022), and significant quantities of amino acids, phosphorus, and potassium (Stadtlander *et al*., 2019). The partial replacement of high-valued FM and soybean meal with duckweed meal (DM) has recently captured much attention of aquaculture nutritionists. For instance, DM replaced fish meal in *Clarias gariepinus* diets by approximately 40%, is suitable for excellent growth performance and feed utilization without exhibiting any negative impacts on fish (Irabor *et al*., 2022). A study by Fiordelmondo and his colleagues confirmed that incorporating DM in the fish diets replacing protein content up to 20 g/100g had no adverse effects on the growth and fillet quality of Rainbow trout (Fiordelmondo *et al*., 2022). Previous reports have documented that incorporating DM into aqua-diets at optimal levels is highly beneficial for achieving optimal growth performance of many fishes such as Tilapia, (Herawati *et al*., 2020), Rohu, *Labeo rohita* (Kaur *et al*., 2012), and Grass carp, *Ctenopharyngodon idella* (Srirangam, 2016).

iii. Water lettuce (*P. stratiotes*)

Water lettuce, or "Topapana," is an aquatic plant that resembles a flower and floats on the water surface. It is commonly found in ponds, ditches, rice fields, and wetlands throughout Bangladesh. Recently, researchers have increasingly utilized water lettuce as a promising ingredient in feed formulation due to its favorable nutrient availability. Water lettuce leaves consist of approximately 7% crude protein, 2% ether extract, 35% ash, 18% fiber, 38% carbohydrate, and 5% moisture, while the roots contain approximately 3% crude protein, 2% ether extract, 45% ash, 21% fiber, 45% carbohydrate, and 5% moisture, along with a rich array of mineral contents (Wasagu *et al*., 2013). It has reported that the partial substitution of maize meal with water lettuce leaf meal (WLLM) at approximately 50% in *Clarias gariepinus* diets improve growth and nutrient utilization indices and the values were greatly reduced when the inclusion levels of WLLM up to 75 or 100% in experimental diets (Adedokun *et al*., 2017). Furthermore, a study by Nisha and Geetha, (2017) stated that the inclusion of WLLM in diets as a fish meal replacer by up to 30 g/100g significantly improved growth performance, feed efficiency, blood hematological parameters, and digestive enzyme activities and also low cost and economically viable feed for *Labeo rohita* production. Likewise, significantly the highest growth and feed utilization of *L. rohita* were recorded in diets with 45 g/100g *Pistia stratiotes* meal, but the fish overall performance could dramatically fall when the levels of this ingredient was >45 g/100g in fish diets (Ray and Das, 1996).

iv. Water hyacinth (*E. crassipes*)

Water hyacinth, also known as Kachuripana, is a free-floating aquatic weed predominantly found in several tropical countries (Adeyemi and Osubor, 2016). Excessive water hyacinth growth leads to negative consequences such as diminished dissolved oxygen concentration, decreased fish population, increased evapotranspiration, transportation disruption, and serve as a habitat for disease causing organism (Pratiwi and Andhikawati, 2021). Conversely, Kachuripana has great potential as an inexpensive protein source in fish diets. The nutritive value of *E. crassipes* is significantly higher, with crude protein levels ranging from 10.1% to 11.2%, crude lipid levels ranging from 1.1% to 1.8%, crude fiber levels ranging from 26.1% to 27.4%, and crude ash levels ranging from 12.3% to 12.4% in the entire plant (except roots) (Hossain *et al*., 2015). Water hyacinth fermented with *Aspergillus niger* at levels up to 12g/ 100g reduce fibre and improve protein percentage (Suharman *et al*., 2021). Several studies have been conducted to evaluate the effects of different levels of water hyacinth meal (WHM) supplementation on the growth performance and nutrient utilization in *Cyprinus carpio* (Sarker and Aziz, 2017), *Ctenopharyngodon idella* (Sayed-Lafi *et al*., 2018), *Oreochromis niloticus* (Hailu *et al*., 2020), and *Clarias gariepinus* (Konyeme *et al*., 2021). Yuniati *et al*. (2018) documented that *Pangasianodon hypophthalmus* diet supplemented with WHM at approximately 25g/ 100g improve growth, nutrient digestibility and digestive enzyme activity. In addition, water hyacinth has anti-microbial properties due to the presence of many secondary metabolites (Pratiwi and Andhikawati, 2021).

v. Mosquito fern (*A. pinnata*)

Mosquito fern or Kutipana, a free-floating aquatic weed from the Azollaceae family that grows with *Anabaena azollae*, is regarded as a valuable aqua-feed ingredient due to its excellent nutritional profile, simple cultivation techniques, and impressive yield (Prabina and Kumar, 2010). Mosquito fern emerges as a notable protein source with an abundance of essential amino acid that surpasses those found in wheat meal, maize, offal, and other similar sources (Cherryl *et al*., 2014). The proximate composition of mosquito fern includes: crude protein 22.25%, crude lipid 2.45%, crude ash 25.50%, crude fibre 11.19%, and very high amino acids, minerals and retinol (dry weight basis) (Mangesh *et al*., 2018). Recently, numerous studies have been conducted to discover the impacts of *Azolla* meal (AM) on fish production, as demonstrated by the works of Magouz *et al*. (2020), Ibrahim *et al*. (2021), de la Cruz *et al*. (2023), and Refaey *et al*. (2023). An eight-week feeding trial on *Barbonymus gonionotus* fed with a diet containing 25g/ 100g AM exhibited no adverse effects on growth performance, while also offering low-cost feed production (Das *et al*., 2018). Ismail *et al*. (2022) also found that AM that was fermented with *B. subtilis* resulted in significant enhancements in the growth performance, defense mechanism, and specific disease resistance of Nile tilapia, when the inclusion level was around 30%.

vi. Lotus (*N. lotus*)

Lotus is an herbaceous aquatic weed that is either perennial or occasionally annual and its leaves float on or submerge in water (Haroon, 2010). This plant contains phytochemicals with significant potential for use in the feeds and pharmaceuticals sector (Debbarma *et al*., 2022). According to Haroon (2022) lotus is widely used as feed, animal nutrition, medicinal purposes, industrial applications, economic and ecological welfare. It is now considered as the nutritionally sound ingredient and widely employed in the aqua-feed industry to formulate low cost fish feed. It contains about 16.3% crude protein, 5.61% crude lipid, 15.63% crude ash, and 18.46% crude fibre (Idowu *et al*., 2019). Some studies have been investigated to conclude the effects of lotus leaf meal (LLM) on fish production. For instance, the inclusion of 25% LM in African catfish *C. gariepinus* diets replace maize meal without showing any negative effects on growth, feed intake, and health status (Idowu *et al*., 2019). Athanase *et al*. (2019) also found positive effects on the African catfish growth performance and nutrient utilization after fed with 20g/ 100g LLM in diets.

vii. Water lily (*N. nouchali*)

The water lily is a perennial aquatic plant classified under the Nymphaeacea family, characterized by its floating leaves and flowers on the water surface (Abelti *et al*., 2023). It is a tremendous source of nutrients, carbohydrates, foods, medicines, phytochemicals, and phenolic compounds (Abelti *et al*., 2023). According to Anand *et al*. (2019) water lily has approximately 76.5% carbohydrate, 10.76% crude protein, 2.4% crude lipid, 3% crude fiber, and significant amounts of vitamins and minerals. Although no studies have been conducted yet on the utilization of *N. nouchali* meal as a fish feed ingredient and its effects on fish production, but it holds promising potential as a viable option for the aquaculture industry in the future.

BENEFITS OF USING AQUATIC WEEDS IN AQUACULTURE INDUSTRY

Aquatic weeds hold a significant position in aquaculture systems and their control represents a global challenge. Because of their fast growth rate, ease of adaptation, and nonexistence of natural adversaries make the plants aggressive, disturbing, and problematic to control (Dissanayaka *et al*., 2023). Failure to effectively control of excessive aquatic weed growth can result in decreased ecosystem productivity, as the weeds consume nutrients and potentially obstruct sunlight, leading to cause hypoxia or anoxia (Giri, 2020). Resultantly, adequate management or conversion of them into valuable products becomes crucial. The utilization of aquatic weeds for aqua-feed formulation is a viable and eco-friendly strategy that lessens the environmental hazards, maintains the balance of the ecosystem, and offers cheap protein source in the aquaculture industry. According to Dorothy *et al*. (2018) plant-derived ingredients are frequently employed in aqua-diets because of their sustainability, availability, and affordability. Numerous researchers (Hundare *et al*., 2018; Magouz *et al*., 2020; Manuel *et al*., 2020; Ghosh *et al*., 2021; Pratiwi and Andhikawati, 2021; Nandi *et al*., 2023) have investigated the efficacy of incorporating different aquatic ingredients into fish diets. Aquatic weeds found in haor basin serve multiple purposes, including being used as a direct feed for herbivorous fish (Dorothy *et al*., 2018), utilized for compost production (Dissanayaka *et al*., 2023), and employed as a dietary supplement for fish (Bag *et al*., 2011; Tran *et al*., 2020). Dietary inclusion of aquatic weeds in fish diet significantly promotes the fish growth, health status (Gangadhar *et al*., 2015; Ali and Kaviraj, 2018; Magouz *et al*., 2020; Manuel *et al*., 2020; Prasetyo *et al*., 2021), reproductive performance, egg quality (Nandi *et al*., 2023), disease resistance (Verma *et al*., 2021; Santhos *et al*., 2023) and also contributes to reducing the cost of feed (Das *et al*., 2018; Nandi *et al*., 2023). In addition, aquatic weeds act as a biological filter for the absorption of inorganic nutrients from water that fostering healthy environment for fish growth (Roslan *et al*., 2021). According to FAO, (2020) aquaculture production is projected to reach around 109 MT by 2030 and surpassing fisheries production by 2050 to become the primary global source of aquatic protein. Therefore, the identification and development of sustainable protein source from aquatic plants will play a significant role in enhancing global aquaculture production.

CHALLENGES ASSOCIATED WITH THE USE OF AQUATIC WEEDS

Although aquatic weeds are commonly used as a beneficial food item for fish and other animals but their excessive supplementation levels in diets have adverse health impacts. The presence of anti-nutritional factors (ANFs) and high crude fibre may decline the value of plant-based feed. According to Kari *et al*. (2023) fish may benefit from very low inclusion of ANFs but not from their high levels. ANFs are detrimental compounds present in plants that lower the bioavailability of nutrients (Ramireddy and Radhakrishnan, 2021) and also affect the growth performance, feed intake, and health of fish (Ramteke *et al*., 2019). ANFs identified from several aquatic weeds include tannin, steroid, phytic acid (Ekunseitan *et al*., 2013; Ali and Kaviraj, 2018), oxalate, cyanide (Suleiman *et al*., 2020; Falaye *et al*., 2022), trypsine inhibitor (Khan and Ghosh, 2013; Mandal and Ghosh, 2019), and saponin (Ekunseitan *et al*., 2013; Falaye *et al*., 2022) (Table 3). These deleterious substances affect the gut epithelial mucosae to create excessive amounts of mucus, which in turn to reduce the activities of intestine and also change the cellular and chemical response (Small, 2022).

Several approaches such as fermentation, sprouting, soaking, heating, autoclaving, and genetic manipulation have been practiced to exclude anti-nutritional substances from plant products (Thakur and Kumar, 2017; Samtiya *et al*., 2020). Among them, semi solid-state fermentation (SSSF) is widely used ANFs removal technique in aqua-feed industrial sector (Zulhisyam *et al*., 2020; Kari *et al*., 2021 & 2022; Nandi *et al*., 2023). According to Bowyer *et al*. (2020) SSSF is a viable method for promoting diet nutrients by significantly lowering harmful chemicals from plant materials. This method has received significant accolades for raising aquaculture output. For instance, stinging catfish fed with different levels of *Lactobacillus* fermented *I. aquatica* diets demonstrated notable improvement in fish growth and reproductive performance as well as health status (Nandi *et al*., 2023). Correspondingly, when Nile tilapia fed with *Bacillus* fermented *Azolla pinnata* diets at levels up to 30% enhanced growth, immune response, amylase activity, and disease resistance (Ismail *et al*., 2022).

Table 3: List of the most typical distributed anti-nutritional factors (ANFs) in aquatic weeds

Haor based weeds	Anti-nutritional factors (ANFs)	Reference
Nymphaea lotus	Steroid	Ekunseitan *et al*. (2013)
Ipomoea aquatica	Tannin, steroid	Ekunseitan *et al*. (2013)
	Tannin, phytate, trypsine inhibitor	Khan and Ghosh (2013)
	Phytic acid and tannic acid	Ali and Kaviraj (2018)
Eicchornia crassipes	Tannin, phytate, oxalate, cyanide	Suleiman *et al*. (2020)
	phytate	Khan and Ghosh, (2013)
Pistia stratiotes	Phytate	Khan and Ghosh (2013)
Pistia sp.	Trypsine inhibitor, tannin and phytic acid	Mandal and Ghosh (2019)
Lemna major	Phytate	Khan and Ghosh (2013)
	Trypsine inhibitor, tannin, phytate and calcium oxalate	Kalita *et al*. (2008)
Leersia hexandra	Tannin and steriod	Ekunseitan *et al*. (2013)
Lemna minor	Tannin, cyanide, saponin, oxalate, alkaloid, phytate	Falaye *et al*. (2022)
Azolla pinnata	Trypsine inhibitor	Maity and Patra (2003)
Polygonum lenigerum	Tannin and steriod	Ekunseitan *et al*. (2013)
Panicum subalbidum	Tannin, steriod, and low saponin	Ekunseitan *et al*. (2013)
Paspalum scrobiculatum	Tannin and steriod	Ekunseitan *et al*. (2013)
Salvinia cuculata	Trypsine inhibitor, tannin, phytate and calcium oxalate	Kalita *et al*. (2008)
Trapa natans	Trypsine inhibitor, tannin, phytate and calcium oxalate	Kalita *et al*. (2008)

NEW PRODUCTS DEVELOPMENT: AQUATIC WEEDS TO WEALTH

New product development in aquaculture involves a systematic process of identifying market needs, generating ideas, evaluating feasibility, designing and developing prototypes, testing and validation, and finally introducing the new products to the aquaculture sector. There is a need for innovative methods and technological advancements to convert aquatic weed and other waste materials into valuable and marketable products (Duque-Acevedo *et al*. 2020). Banga and Kumar (2019) stated that utilizing unwanted plant products to generate wealth is an effective strategy for reducing environmental effluence, enhancing food safety, and stimulating economic growth. Scientists involved in development of new plant products for use in aquaculture should have a comprehensive understanding of the marketing system, customer demands, and competition (Kari *et al*., 2023). Scientists should consider eight (8) fundamental steps when developing new products from aquatic weeds and plants (Figure 2). Idea generation is the preliminary step in the development of a new product. Scientists should prioritize research as a top priority in order to generate a multitude of novel ideas (Nik Ahmed Ariff *et al*., 2013), which involves exploring methods to visualize, communicate, transfer (Ariff *et al*., 2012), and convert theoretical concepts (Jamaluddin *et al*., 2015) before being established best possible idea. Following that, scientists engage in concept development and testing, develop marketing approaches, conduct business analysis, embark on product development, carry out test marketing, and finally proceed with commercialization. In the context of new product development, commercialization represents the ultimate and pivotal step, where the products are distributed to consumers for sale.

Figure 2: New product development approach (Reid et al., 2016)

AQUATIC WEEDS: PROSPECTS AND FUTURE FEED FOR AQUACULTURE INDUSTRY

Aquatic weeds hold promising prospects as a future feed resource for the aquaculture feed industry. Their abundance, sustainability, nutritional profile, cost-effectiveness, and positive environmental impact make them an attractive alternative to traditional feed ingredients. Additionally, aquatic weeds are a valuable feed resource for fish due to their substantial content of protein, lipid, ash, fiber, carbohydrate, minerals, and vitamins. These nutrient-rich components make them highly beneficial for the nutritional needs of aquaculture species and other animals. Their prolific growth makes them sustainable and readily available feed ingredients for sustainable aquaculture. Though several species of aquatic weeds are available in Bangladesh, very few species are examined and tested on fish to determine their impacts on fish production. Despite the presence of numerous aquatic weeds in Bangladesh, only a limited number of them have been thoroughly studied and evaluated for their effects on fish production. However, the utilization of other aquatic weeds such as *Alternantera philoxerodies, Aponogeton* spp., *Enhydra fluctuans, Polygonum glabrum, Sagittaria* spp., *Hydrilla verticilata, Typha latifolia, Commerlina bengalensis, Commerlina appendiculata, Najas minor, Vallisneria spiralis, Nymphoides aquatica, Aponogeton* spp*., Cartophyllum demersum, Spirodela polyrrhiza, Oxalis corniculata, Ipomoea carnea, Leersia hexandra* and others, in the fish feed industry have great potential for future development of aquaculture feeds.

CONCLUSION AND RECOMMENDATION

Haor based aquatic weeds have emerged as a nutritionally balanced fish feed ingredients for the aquaculture feed industry, with recent technological advances highlighting their potential benefits. They offer cost-effective and sustainable alternatives to traditional feed ingredients, reducing the pressure on wild fish stocks and increasing the circular economy. However, challenges associated with the improper management of aquatic weeds may result in ecosystem destruction and animal health concern. Hence, the utilization and development of nutrient ingredients from these plant products in aquaculture sector is a great option for the sustainability and growth of aquaculture industry, supporting ecosystem restoration, and fostering an efficient and eco-friendly method to feed formulation. Despite this, the scarcity of standardized regulation and guidelines for use haor aquatic plants in fish feed poses a possible barrier for large scale industrial implementation and market acceptance as well. Therefore, continued research, policy support, collaboration and promotion marketing are recommended for the exploitation of plant products in the field of aquaculture feed formulation.

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