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Utilization of Aquatic Plants and Microalgae for Sustainable Aquaculture Production and Potential Biotechnological Applications

Job Ombiro Omweno[1,2]*, Omondi Argwings[2,3], Berrick Moturi Sieberi[1], Merceline Angima[2], Peter Maangi Ondieki[4]

[1]Department of Agriculture, Fisheries, Livestock Development, Cooperative Development and Irrigation, County Government of Kisii, Kisii, Kenya. PO Box 700 - 40200, Kisii Kenya.
[2]Department of Environment, Natural Resources and Aquatic Sciences, Kisii University, Kisii, Kenya. PO Box 408 - 40200, Kisii, Kenya.
[3]Department of Agriculture and Environmental Science, Sigalagala National Polytechnic, Kakamega, Kenya
[4]Kenya Marine and Fisheries Research Institute, Kegati Aquaculture Centre. PO Box 3259 - 40200, Kisii, Kenya.

*Correspondence: omwenojob@gmail.com

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ABSTRACT: Locally available feedstuffs, such as grain seed cakes, oilseeds, and vegetable waste, hold immense potential as alternative feed sources in fish farming. However, these plant-based ingredients have low crude protein content and lack essential fatty acids, which lowers palatability and feed conversion efficiencies, leading to suboptimal fish growth. Traditional feedstuffs like fishmeal and soybean meal face sustainability challenges such as local unavailability, the presence of anti-nutritional factors, and energy-intensive processing. The rising costs of commercial aqua-feeds and feed scarcity necessitate exploring alternative fish feed options. Aquatic plants like Ipomoea aquatica, *Lemna minor*, and *Azolla pinnata*, along with green and blue-green microalgae such as *Chlorella spp.* and *Arthrospira spp.* (Spirulina), are promising alternatives due to their high protein content, availability of essential omega-3 fatty acids such as EPA (Eicosapentaenoic acid) and DHA (Docosahexaenoic acid), and beneficial bioactive compounds. These plants and microalgae, with crude protein content ranging from 25% to 65%, can significantly enhance fish growth, health, and product quality by partially or entirely replacing fishmeal. Their nitrogen-fixing abilities contribute to their high protein levels. Additionally, these organisms have various biotechnological applications, including phytoremediation, Integrated Multi-trophic Aquaculture (IMTA), aquaponics, biofloc technology, and constructed wetlands. Despite their potential, challenges in scaling up and integrating these alternatives into existing systems remain. Collaborative efforts and advocacy among farmer groups are crucial for knowledge sharing and fostering sustainable biotechnological solutions. Long-term strategies should focus on upscaling local feed production and research and development to achieve self-sufficiency and cost-effective natural feed production systems in fish farming.

KEYWORDS: Sustainable aquaculture production; *Spirulina spp.*; *Azolla spp.*; fish farming; nutritional value

1. Introduction

The escalating global demand for fish protein necessitates the expansion of aquaculture operations and diversification of production methods to bridge the supply gap [1]. However, conventional aquaculture practices have proven environmentally detrimental, contributing to water pollution and degradation of aquatic ecosystems. In Kenya, slow growth and development of aquaculture production are primarily attributed to the high cost of commercially produced aqua-feeds, rendering them unaffordable for many fish farmers [2]. Consequently, growth performance of cultured species is suboptimal, often characterized by stunted growth and low fish feed conversion efficiencies, which have been exacerbated by slow adoption rates of efficient aquaculture technologies [3, 2]. Simulation results suggest that Kenyan fish farmers could significantly benefit from adopting knowledge-based fish culture strategies, particularly by utilizing organic fertilizers to enhance natural food resources [4]. While organic fertilizers, especially those promoting microalgae and aquatic plant growth have proven effective in increasing fish production, their adoption remains low due to concerns about delayed nutrient release and potential eutrophication if applied in excess [5]. Furthermore, the excessive use of pelleted feed and fertilizer in fish farming has led to ecological challenges, including nutrient accumulation in sediment and eutrophication in water bodies [6]. Eutrophication adversely affects the aquatic ecosystems, accelerates the loss of biodiversity, and can lead to toxic algal blooms, posing risks to human and environmental health [7]. While small-scale fish farming benefits rural development and poverty alleviation, it is essential to consider broader sustainability implications and the needs of the most vulnerable sectors of society [8]. To meet the growing demand for fish protein, both commercial and resource-poor fish farmers must intensify production while minimizing environmental degradation caused energy driven feed production processes and large scale extraction of fish meal and other aquatic resources. Currently, fish feeds constitute a significant portion of total production costs, driving the exploration of alternative feeds like rice bran and wheat bran [2]. Local ingredients such as grains, oilseeds, vegetable wastes, and insects can also be processed into alternative fish feed. However, these alternatives often have lower nutritional quality and decompose in ponds, resulting in losses due to massive fish mortalities. Furthermore, their low crude protein content necessitates proper processing techniques and considerations for nutrient composition to improve palatability, digestibility and feed conversion efficiencies [9, 10]. Aquatic plants and microalgae also play a crucial role in phytoremediation. Studies have evaluated their efficiency in removing heavy metals from water and sediments across interconnected ecosystems using aquatic plants and microalgae. Notably, heavy metal contamination—particularly arsenic, cadmium, and lead—poses health risks when fish bioaccumulate and bioconcentrate these metals through aquatic food chains [11, 12]. While regular monitoring and adopting stringent regulations have proved essential, addressing the toxicological effects of heavy metals using plant-based biotechnological solutions is crucial for safe consumption of aquatic products. However, the presence of microplastics in some aquatic systems, such as those in India, have served to disrupt aquatic plant growth, causing physiological stress in aquatic organisms, and poses health risks to humans through bioaccumulation and ingestion [13]. This paper aimed at reviewing the utilization of aquatic plants and microalgae for sustainable aquaculture production and their potential biotechnological applications.

2. Sustainable Aquaculture Production using Aquatic Plants and Microalgae

2.1. Importance of sustainable fish farming in Kenya.

In Kenya, inland fish production primarily relies on natural water bodies dominated by Nile tilapia and Nile perch fisheries [1, 10]. Approximately 85% of Kenya's total fish production comes from these natural ecosystems, while aquaculture contributes only 15% [14]. Despite existing challenges and limitations, aquaculture remains crucial for meeting the growing demand for fish in Kenya and addressing poverty and malnutrition and sustainable fish farming plays a pivotal role in fulfilling the protein needs of the population. As wild fish stocks decline due to overfishing and environmental degradation, sustainable aquaculture practices become essential for food security and economic development [14, 15]. Embracing sustainable fish farming helps alleviate stress on freshwater resources caused by overfishing, pollution, habitat loss, and environmental degradation. Research into alternative protein sources—such as microbial and plant-based proteins—and integrated ecosystems is vital to reduce the ecological impact of aquaculture [16]. Integrating fish cultivation with small-scale poultry production, horticulture, or rice-growing schemes in ponds can enhance nutrient recycling and reduce production costs. Leveraging natural food chains based on primary producers offers a viable alternative to traditional farming practices, particularly for resource-poor farmers in rural settings [16].

2.2. Utilization of aquatic plants and microalgae for sustainable fish production.

Aquatic plants play a critical role in fish production and offer a sustainable, cost-effective alternative to artificial feeds in aquaculture. Research has demonstrated that fish thrive on natural plants, leading to good growth rates and increased disease resistance when fed with aquatic vegetation [3]. For instance, Nigerian Tilapia fed with the water fern *Azolla filiculoides* exhibited growth rates that were not significantly different from those fed commercial diets. Unlike fishmeal whose production depends on finite marine and freshwater resources, feeding fish with natural plants ensures a continuous food supply, as these plants can regrow and multiply in the production system over a short period of time. Integrating fish culture into existing farming systems using aquatic plants benefits small-scale farmers by improving livelihoods and maintaining ecosystem health, as shown in Figure 1. Participatory research can enable researchers to come up with recommended stocking regimes in farm ponds as a result of studying fish effects on pond ecology and nutrient recycling relative to aquatic plant productivity [17]. This approach enhances fish production without compromising water quality or the aquatic community's health [18]. By harnessing the natural productivity of freshwater ponds and wetlands, a sustainable, low-cost aquaculture system can be established for small-scale fish farmers in rural regions of Kenya. The system leverages the natural food chain within the pond ecosystem, benefiting both fish and plants [19].

2.3. Cultivation, nutritional value and utilization of aquatic plants and microalgae.

In aquaculture, there is a growing interest in utilizing aquatic plants and microalgae as sustainable feed sources for fish farming. These alternative feed sources, such as *Azolla*, *Spirulina*, *Ipomea*, and *Lemna*, offer numerous benefits to both the environment and the health of fish populations. Production of aquatic plants and microalgae in shallow small-sized ponds can contribute to fish nutrition, contribute to water quality improvement through biofiltrstion and promote ecosystem balance.

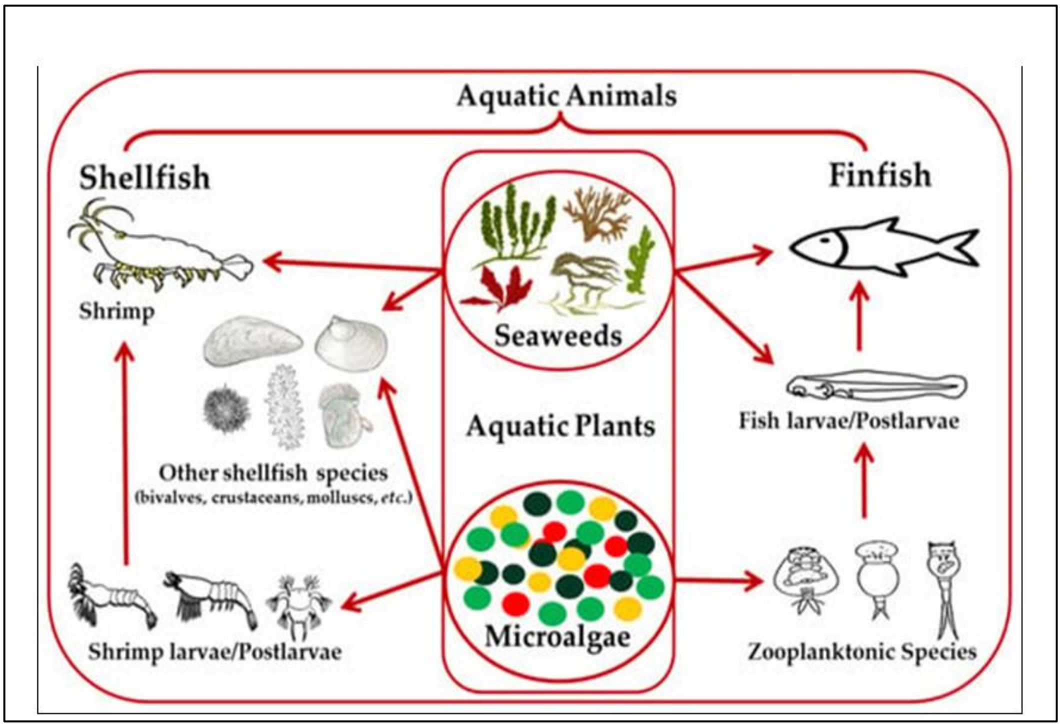

Figure 1. Schematic diagram of the integration between aquatic animals and plants [17].

2.3.1. Water fern (Azolla app.).

Azolla, a free-floating small-sized water fern, is capable of nitrogen fixation and plays a pivotal role in sustainable fish farming as a secondary food source for pond cultured fish [20]. *Azolla*'s simple structure and small size foster the growth of zooplankton and insects, providing additional sustenance for fish. The plant exhibits efficient conversion of atmospheric nitrogen into nitrates, accomplishing this task 10 to 20 times more efficiently than other crops [20]. It can fix up to 132-150 kg of nitrogen per hectare annually, providing sufficient available nitrogen that can promote fish production in aquaculture ponds [20]. Through photosynthesis, *Azolla* contributes to the dissolved oxygen level of water, which benefits fish growth and survival rates. Consequently, establishing *Azolla* plantations around fish ponds is highly recommended due to its efficiency in supporting aquaculture. Due to nitrogen fixing capabilities, *Azolla* contains high levels of protein rich in essential amino acids. It also contains vitamins (A, B12, and E) and minerals (iron, calcium, and phosphorus) [21–25]. *Azolla* exhibits rapid growth in various aquatic environments and can be cultivated in Shallow ponds of 20 - 30cm deep where it multiplies rapidly, harvested, and fed directly to fish or processed into pellets. It reduces the need for synthetic fertilizers and provides a cost-effective and environmentally friendly feed option [26].

2.3.2. Blue-green microalgae (Spirulina, Arthrospira spp).

Spirulina (*Arthrospira spp.*) is a nutrient-rich filamentous blue-green microalga which also supports sustainable fish farming by enhancing fish growth, disease resistance, and overall survival [27]. The microalga is a complete protein source with essential amino acids, essential fatty acids, including omega- 3 fatty acids, such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) and vitamins (B complex and E), minerals (iron and zinc), and antioxidants, which are beneficial for both human and animal consumption [28, 29]. *Spirulina* contains bioactive compounds such as phycocyanin and carotenoids [30]. These have been utilized to promote fish growth performance and overall health. For instance, incorporation of

Spirulina into diets of commercially important shellfish species such as prawns and finfish species [31, 32]. This has been reported to produce high quality fillets to meet the increasing demand for nutritious fish products without necessarily increasing the cost of inputs [33]. Both *Azolla* and Spirulina offer high digestibility and bioavailability [21–23, 34, 35]. *Spirulina* spp. can replace a portion of traditional fishmeal in diets without compromising growth performance, feed utilization, or nutrient digestibility [31, 36]. Farmers can manipulate the level of *Spirulina* colonization by regulating water salinity, offering potential for increased fish production with minimal input [37]. *Spirulina*'s nutritional profile provides a viable option recommended for formulating fish diets, addressing sustainability and environmental concerns in aquaculture systems.

2.3.3. Duckweed, Lemna minor.

Like *Azolla*, Duckweed, *Lemna minor* is a small, free-floating aquatic plant with nitrogen fixing ability that thrives in diverse environments, including ponds, lakes, and even local and industrial wastewater [38]. Their rapid growth and adaptability make them suitable for practical applications. These rapid growth capabilities can be utilized for phytoremediation by sequestering excess nutrients from wastewater [39]. However, to optimize duckweed cultivation for industrial applications, specific culture requirements which vary according to specific duckweed species being cultivated must be considered. Duckweeds, including *Lemna minor*, have been explored for various purposes. They contain essential nutrients such as proteins, carbohydrates, and fats, making them valuable for food and feed applications and secondary metabolites which can benefit Pharmaceutical applications [39]. Current research on *L. minor* needs to explore its potential for various applications, emphasizing optimized cultivation methods. Duckweed can be integrated into aquaculture for sustainable practices, including nutrient recycling and protein-rich feed material production.

2.3.4. Water spinach, Ipomea aquatica.

Water spinach, *Ipomoea aquatica* is a large versatile floating aquatic plant which is propagated from seeds and cuttings. It contains essential amino acids, vitamins (A, C, and E), minerals (iron, calcium, and potassium), and omega- 3 fatty acids such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which comprise of ~ 3% of total fatty acids (Table 1). It also contains antioxidants that help protect cells from oxidative damage and plant fibre, which aids digestion and supports gut health [40, 41]. The plant grows in moist soil and waterlogged areas with moderate temperatures and contains nutritious edible leaves and tender shoots which highly palatable to fish and other farm animals [40]. Water spinach can be cultivated in aquaponics systems, where it grows alongside fish, which often results in higher yields and better sensory qualities [40]. *Ipomea aquatica* (water spinach) and *Lemna* (duckweed) are aquatic plants rich in protein, fiber, vitamins, and minerals. These alternative feed sources can be cultivated alongside fish ponds, providing natural forage, oxygenation, and nutrient cycling to promote fish growth [29].

Table 1. Comparative nutritional content of aquatic plants and microalgae.

Plant/Micro algae (spp.)	**Moisture %**	**Average (Av.) Dry weight**						**Reference**
		Av. Ash %	**Av. Lipid %**	**Av. Crude Protein %**	**Av. Crude Fibre %**	**Minerals g/100g**	**Vitamin K IU/100g**	

Azolla spp	77.5	31.3	12.4	27.2	11.1	2000 Iron 1500 Calcium	1500	[42]
Spirulina	70.2	7.5	8.0	64.1	8.1	2000 Iron 1000 Calcium	1000	[43]
Lemna spp	75.0	15.0	24	33.5	28.9	1500 Iron 1000 Calcium	1000	[44]
Ipomea aquatica	72.83	10.8	11.0	19.6	14.7	1000 Iron 500 Calcium	500	[45]

Note: IU stands for International Unit or quantity of biological substance converted from metric unit (such as grams or micrograms) using a conversion factor and Av. for Average content in dry biomass.

2.4. Strategies for sustainable fish feed management in aquaculture.

Effective feed management strategies, including rationing and adjusting feeding frequency based on water quality and fish behavior, optimize feed utilization and maintain fish health [46]. Water quality management practices, such as aeration and partial water changes, reduce reliance on excessive feed and promote fish well-being. Forming or joining fish farmer groups facilitates knowledge sharing, resource pooling, and bulk purchase options for alternative feed ingredients [47]. Advocacy efforts directed towards local authorities and agricultural extension services raise awareness of feed challenges and promote solutions like local feed production and exploration of alternative feed sources. The use of algae in integrated aquaculture has also been recently reviewed by Turan [48]. Establishing small-scale fish feed production facilities using locally available ingredients are recommended as a sustainable and cost-effective solution to feed scarcity. Supporting research and development initiatives focused on developing alternative, cost-effective, and locally-produced fish feed formulations further enhance the self-sufficiency and sustainability of fish farming practices [49]. Integrating *Azolla* into fish farming systems in Kenya has the potential to enhance sustainability and resilience. By reducing reliance on imported feed ingredients and minimizing nutrient runoff from fish ponds, *Azolla* can contribute to the conservation of natural resources and the promotion of agroecological principles (Table 2). Furthermore, the cultivation of *Azolla* can create additional income opportunities for small-scale fish farmers and contribute to the diversification of aquaculture production systems in Kenya.

Table 2. Potential application of aquatic plants in agroecological fish farming.

Technology	Description	Conventional use of aquatic plants	Innovative use of Aquatic plants	References
Polyculture	The cultivation of multiple fish species in the same aquaculture system, to improve resource utilization, nutrient cycling, and overall productivity.	Water hyacinth, duckweed, and water lettuce are used to provide additional nutrients and habitat for the cultured fish.	*Azolla, Spirulina* and *Lemna minor* can be used as protein source plant alternatives, owing to their nitrogen fixing capabilities and nutrient sources for cultured fish	Conventional use: [50] Innovative use: [51, 52]
Integrated Multi-Trophic Aquaculture (IMTA)	The cultivation of different aquatic species (e.g., fish, shellfish, seaweed) that occupy different trophic levels, allowing for the recycling of nutrients and waste products.	Seaweeds and other aquatic plants are often used to absorb the nutrients and waste products from the fish and shellfish components of the IMTA system.	*Azolla*, *Spirulina*, and *Lemna* can be integrated into the IMTA system to serve as additional nutrient sinks, helping to remove excess nutrients and improve the water quality and nutrient sources for the cultured species.	Conventional use: [53] Innovative use: [54, 55]

Technology	Description	Conventional use of aquatic plants	Innovative use of Aquatic plants	References
Aquaponics	Aquaponics combines aquaculture and hydroponics to create a closed-loop, symbiotic system where the waste from the aquatic animals is used to fertilize the plants, and the plants help to purify the water for the aquatic animals.	Leafy greens, herbs, and other vegetables are commonly grown in the hydroponic component of an aquaponics system.	*Azolla*, *Ipomoea aquatica*, *Spirulina* and *Lemna* can be cultivated in aquaponics, providing additional nutrient removal, oxygenation, and food sources for the aquatic animals contributing to the overall efficiency and sustainability of system.	Conventional use: [56] Innovative use: [57, 58]
Biofloc Technology	A system that promotes the growth of beneficial microorganisms (biofloc) in the aquaculture system, which can be used as a food source for the cultured species, reducing the need for external feed inputs	Aquatic plants are not typically used in biofloc systems, as the focus is on the cultivation of the microbial community.	*Azolla* and *Lemna* spp. can be integrated into biofloc systems to provide additional food sources and habitat for the cultured fish species, while Spirulina can be used as a nutritional supplement to enhance the quality of the biofloc biomass.	Conventional use: [59] Innovative use: [60, 61]
Constructed Wetlands	The use of natural or engineered wetland systems to treat and purify the effluent from aquaculture operations, removing nutrients, organic matter, and other pollutants.	Emergent aquatic plants like reeds, cattails, and bulrushes are commonly used in constructed wetlands to remove nutrients and other pollutants from the aquaculture effluent.	*Azolla*, *Spirulin*a, and *Lemna* can be incorporated into the constructed wetland system, providing additional nutrient removal capabilities and contributing to the overall efficiency of the effluent treatment process	Conventional use: [62] Innovative use: [63, 64]

Note: Integration of aquatic plants and microalgae into the food production and water management systems to enhances sustainability, productivity, and environmental friendliness of fish farming operations.

3. Sustainability and Economic Considerations.

The cultivation of aquatic plants as microalgae as alternative protein sources for fish feed offers potential sustainability benefits, as it can be integrated in the circular economy (Figure 2). For instance, Spirulina can be produced using non-arable land and brackish water, reducing pressure on terrestrial resources and freshwater ecosystems [65]. Furthermore, the use of Spirulina in fish diets may contribute to reducing the reliance on wild fish stocks for fishmeal production, thereby supporting the long-term sustainability of aquaculture [3, 66]. From an economic perspective, the cost-effectiveness of incorporating Spirulina into fish feed warrants further investigation, considering factors such as production scale, processing methods, and market demand. In Kenya, utilizing locally available ingredients such as grains, oilseeds, and vegetable wastes for fish feed involves specific processing techniques to enhance their nutritional value and digestibility. Grains such as maize and sorghum are typically ground into fine meals to improve their digestibility for fish. Oilseeds, including soybeans and sunflower seeds, are often roasted or extruded to deactivate anti-nutritional factors such as trypsin inhibitors, thereby increasing protein availability. Fermentation is another technique employed for soybeans, breaking down complex proteins and fibers into more digestible forms. Vegetable wastes, such as carrot tops and cabbage leaves, are usually dried and ground before being added to fish feed. Drying reduces moisture content, preventing spoilage and concentrating nutrients. In some cases, fermentation of these vegetable wastes is used to improve digestibility by breaking down complex carbohydrates and fibers. After processing, these ingredients are mixed according to the specific dietary needs of different fish species. The mixture is then pelletized, a process that involves grinding the ingredients into a fine powder, blending with other ingredients, binders and water, and passing through a pellet mill to produce floating pellets for tilapia and sinking pellets for bottom feeders such as catfish. Pelletization enhances feed stability in water, improves intake, and ensures better and efficient utilization of feed by fish. These techniques are essential for optimizing the nutritional quality and digestibility of alternative feed sources, thereby supporting sustainable fish farming practices in Kenya [67].

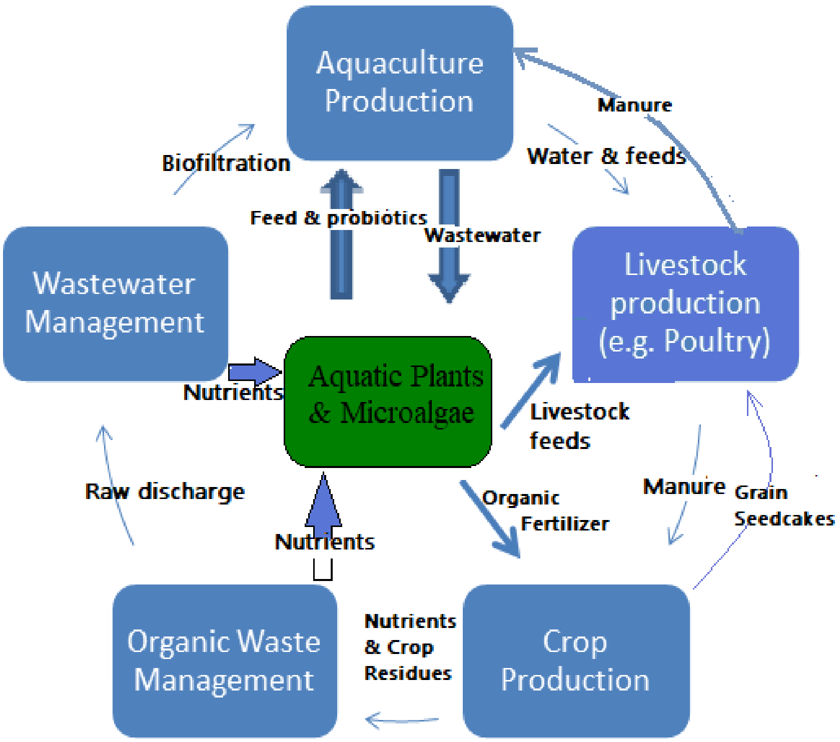

Figure 2. Potential integration of aquatic plants and microalgae in conventional farming systems' circular economy.

3.1. Benefits of integrating aquatic plants and microalgae in aquaculture.

The sustainability of aquaculture is significantly challenged by the overreliance on conventional feed ingredients such as fishmeal and fish oil. These ingredients are not only costly but also contribute to the depletion of natural fish stocks [10]. Aquatic plants offer a plethora of nutritional benefits to cultured fish, including proteins, essential amino acids, fatty acids, vitamins, and minerals [68]. For instance, microalgae such as Chlorella and Spirulina are renown renowned for their high protein content and beneficial fatty acids like DHA and [68]. While Macroalgae such as *Porphyra* spp and *Laminaria japonica* are often cultivated and utilized directly for human consumption, microalgae are vital components in polyculture systems and in phytoremediation/ bioremediation. Periphyton not only provides natural food for fish and other aquatic animals but its production has been actively advocated by aquaculturists as a means of increasing aquaculture productivity [69, 70], promoting improved livelihoods in an ecologically sustainable manner. However, further research is necessary to consider more ecologically sustainable production methods. Periphyton is not solely composed of algae and certainly cannot be regarded as macroalgae. However, Periphyton is not solely composed of algae and certainly cannot be regarded as macroalgae. Microalgal biotechnology only really began to develop in the middle of the last century but it has numerous commercial applications. Algal products can be used to enhance the nutritional value of food and animal feed owing to their chemical composition; they play a crucial role in aquaculture. Microalgal biotechnology only really began to develop in the middle of the last century but it has numerous commercial applications. Laboratory investigations have also been carried out to evaluate both microalgae and macro-algae, mainly blue-green algae (Cyanobacteria) and green algae (Chlorophyta) as possible alternative protein sources for farmed fish because of their high protein content and productivity. These plants are also rich in bioactive compounds, making them suitable for use as direct feed or as feed additives to enhance the nutritional profile of aquafeeds. Other microalgae species, such as *Nannochloropsis* and *Tetraselmis*, are particularly valuable due to their high content of essential fatty acids and vitamins. Additionally, macroalgae such as *Ulva* and *Laminaria* offer high crude fiber content and bioactive compounds that promote growth and health in fish [71]. Many floating aquatic plants, such as duckweed (*Lemna minor*) and water fern (*Azolla* species), are rich in crude protein, fatty acids, and minerals. These plants can be sustainably harvested and used as partial replacements for fishmeal. For example, the inclusion of microalgae in tilapia diets has been shown to improve growth rates and feed conversion efficiency, while utilization of seaweed extracts as feed additives have been found to enhance the immune response and disease resistance in shrimp [72]. The use of aquatic plants to partially or wholly replace fishmeal in aquaculture feeds can significantly reduce the environmental footprint of aquaculture operations [10]. Aquatic plants can be easily cultivated in controlled environments using organic wastes as fertilizers, reducing the need for wild fish stocks and minimizing habitat destruction (Table 3).

Table 3. Comparison of three major feed/crude protein sources used in aquaculture production.

Feed category	Challenges/benefits associated	Impact of upscaling the production
Imported Fishmeal & fish oils	Intensive energy requirements for processing Local unavailability, making it expensive	Environmental and resource degradation due to excessive extraction and intensive energy processing Increased cost of feed
Conventional & locally available feedstuffs	Inadequate fatty acids and crude protein content High crude fiber content Presence of anti-nutritional compounds Low palatability and low digestibility of feed	Poor growth performance due to low feed conversion efficiencies in most cultured species Poor water quality due to underutilization of feed Increased stress to fish, resulting in suboptimal growth performance
Microalgae and Aquatic Plants	High crude protein levels due to nitrogen-fixing capabilities, efficient protein synthesis, and high nutrient absorption Faster growth and regeneration Beneficial bioactive compounds & nutrition supplements High water and nutrient absorption capacity and storage	Possible integration to boost natural food production and reduce overexploitation of natural resources Regular harvesting for available and continuous aqua-feed supply Improvement of water quality and water balance Improved fish growth, product quality, and environmental sustainability

Additionally, many aquatic plants possess phytoremediation properties, meaning they can absorb and detoxify pollutants from water, thereby improving water quality in aquaculture systems. The cultivation of aquatic plants for use in aquafeeds requires minimal resources and can be harvested year-round, increasing the profitability of aquaculture operations [73]. Cultivating locally available aquatic plants not only reduces feed costs but also promotes integrated farming, opening new markets and creating additional revenue streams for aquaculture farmers. Aquatic plants provide sustainable feed ingredients and additives in aquaculture production. Besides their nutritional benefits, the cultivation of aquatic plants offers environmental advantages and economic feasibility, ensuring the long-term viability of this vital food production sector.

3.2. *Challenges or limitations associated with integrating these alternative feeds into mainstream aquaculture practices.*

Integrating aquatic plants such as *Spirulina* spp., *Ipomea aquatica*, *Lemna minor*, and *Azolla* spp. into mainstream fish farming in Kenya offers promising avenues for sustainable aquaculture, yet it comes with several challenges and limitations. One primary challenge is cost-effectiveness. While these plants can be grown locally, the initial setup costs for cultivating them at a scale sufficient to meet the demands of commercial fish farming can be significant. This includes costs for infrastructure, such as ponds or tanks, and for maintaining optimal growing conditions. Additionally, although these plants can reduce feed costs over time, the upfront investment may be a barrier for small-scale farmers [74]. Scalability is another critical issue. While small-scale integration of these plants might be feasible, scaling up to meet the nutritional requirements of large fish farms poses logistical challenges. Consistent production and harvesting methods need to be developed to ensure a reliable supply of these plants. This requires not only technological investment but also training for farmers to manage and optimize plant growth effectively [75]. Regulatory considerations also play a crucial role. The use of alternative feed sources must comply with national and international standards to ensure they do not introduce contaminants or negatively impact fish health. In Kenya, regulatory frameworks for aquaculture are still evolving, and there might be a lack of specific guidelines addressing the use of these plants as fish feed. This regulatory uncertainty can deter investment and innovation in this area. Moreover, ensuring that these plants do not become invasive species when used in open water systems is a significant environmental concern that requires strict monitoring and control measures [76]. Expanding on these challenges, the limited awareness and technical know-how among local farmers present another barrier. Many fish farmers in Kenya may not be familiar with the benefits or cultivation techniques for these aquatic plants. This knowledge gap necessitates extensive training and extension services to educate farmers on the advantages, cultivation practices, and optimal integration of these plants into fish diets. Without this knowledge, farmers might hesitate to adopt these alternatives, preferring traditional feeds they are more accustomed to. Furthermore, the variability in climate and water quality across different regions in Kenya can affect the growth and nutrient content of these plants. Spirulina, for instance, requires specific conditions of temperature, pH, and light, which may not be uniformly available across all farming regions. Similarly, *Ipomea aquatica*, *Lemna minor*, and *Azolla* spp. may face challenges related to water quality, such as contamination with pollutants or pathogens, which can compromise their safety and nutritional value for fish [74].

4. Conclusion and recommendations

Aquatic plants and microalgae provide alternative protein sources to address challenges related to the scarcity and energy-intensive processing of traditional fishmeal. They also offer nutritional value, potential health benefits, and sustainability advantages. Integrating these plants and microalgae into biotechnological applications (such as biofloc systems, aquaponics, and integrated multi-trophic aquaculture), offers a high potential to reduce production costs and enhance environmental sustainability. Effective production management strategies are crucial for promoting sustainability and resilience in fish farming. Collaboration among stakeholders plays a key role in achieving these goals. Integrating aquatic plant production into existing fish farming systems requires on-farm trials to assess feasibility and scalability. Sustainable fish farming’s future depends on innovative feeding strategies, leveraging local resources, and utilizing alternative protein sources like Spirulina and Azolla spp. To fully realize the benefits, further research is needed to optimize inclusion levels of aquatic plants and microalgae in different fish species' diets. The study will also assess their long-term effects on fish health and product quality and evaluate the economic feasibility for large-scale production and utilization, considering factors like scale, processing methods, and market demand.

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Conflict of Interest

The authors declare that they have no conflicts of interest related to the publication of this review paper. Secondary data sources were reviewed and compiled with an aim of contributing to sustainable fish farming practices in Kenya through the use of aquatic plants and microalgae. No financial, personal or professional relationships influenced the review process or the interpretation of the results.

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