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Review Article

Duckweed as an Alternative Protein Source in Aquaculture: Production Systems, Nutritional Characteristics, and Feeding Applications

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Abstract

The growth of global aquaculture has led to an increasing demand for sustainable, nutritionally adequate, and cost-effective alternatives to conventional fishmeal-based aquafeeds. Fishmeal remains a valuable protein source; however, its supply is limited and cost and environmental impact are increasing. Therefore, the search for alternative feed ingredients is expanding. Duckweed (Lemnaceae) is a promising candidate because of its rapid growth, high protein content, amino acid profile, and ability to recover nutrients from wastewater. This narrative review integrates the existing knowledge on production systems, their nutritional profile, and presence of anti-nutritional factors, feed safety, economic viability, and uses in aquaculture. Literature published between 1990 and 2026 was obtained from major databases, including PubMed, Scopus, Web of Science, DOAJ, and Google Scholar, using keywords related to duckweed, aquaculture, fish nutrition, fishmeal replacement, and sustainable aquafeeds. Reviewed feeding trials indicate that dietary inclusion levels of 15-30% generally allow good growth performance, feed conversion efficiency, and survival in several omnivorous and herbivorous fish species, especially Nile tilapia, common carp, and grass carp. Duckweed contains 15-45% crude protein with relatively balanced amino acid profile, but the nutritional composition varies among species and cultivation conditions. The main constraints are anti-nutritional compounds, variability in nutrient composition, heavy metal accumulation when cultivated in contaminated wastewater, drying costs, and regulatory challenges. Current evidence supports duckweed as partial replacement for conventional protein ingredients. Future research should focus on feed safety, production standardization, processing technologies, long-term feeding trials, and commercial-scale economic evaluation to wider adoption in sustainable aquaculture systems.

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INTRODUCTION

Aquaculture has become one of the fastest-growing sources of animal proteins in recent years, providing more than 50% of all fish consumed by people worldwide (Naylor *et al*., 2021). Between 2000 and 2025, aquaculture production increased nearly fourfold, reaching 130 million metric tons of food (Bennett *et al*., 2018; Hedden *et al*., 2021). Nevertheless, this development has increased demand for feed ingredients, placing pressure on limited natural resources.

Historically, fishmeal was a recognized source of protein used in aquafeed due to its excellent amino acid profile, high digestibility, and palatability (Tacon & Metian, 2018). However, fishmeal production volume has remained relatively constant over the past decades at 5-6 million tons annually due to constraints on wild fish catches (Hardy, 2010; Majluf *et al*., 2024; Shepherd & Jackson, 2013). Simultaneously, aquaculture's share of overall fishmeal consumption has increased from less than 30% to 75%. As a result, fishmeal prices increased rapidly from 500/ton (2000) to more than 2,000/ton (2020-2022) (Naylor *et al*., 2021).

There is ample literature on the subject of finding sustainable options for replacing fishmeal, with most of the attention being paid to the possibilities offered by plant proteins such as soybean meal. The problem with soybean meal is that its cultivation leads to deforestation (of the Amazonian biome, for example) along with the excessive consumption of freshwater (2000 to 3000 liters per kg of soybean) and greenhouse gases (Van Huis, 2020). Furthermore, soybeans contain anti-nutritional factors (e.g., trypsin inhibitors, lectins, and saponins) that require expensive heat treatment and can cause enteritis in fishes such as Atlantic salmon (Makkar *et al*., 2007).

Increasing global demand for aquatic foods has intensified the search for sustainable protein sources that can support aquaculture expansion while minimizing environmental impacts (Hua *et al*., 2019). Feed costs frequently account for more than 50% of total production expenses, and continued dependence on fishmeal and conventional plant proteins presents both economic and environmental challenges (Nunoo *et al*., 2014).

Therefore, duckweed is attracting increasing attention as a promising alternative due to its fast growth rate, efficient nutrient recovery capacity, favorable amino acid composition, and its ability to utilize nutrient-rich wastewater streams for biomass production. These properties make duckweed a potentially valuable element in circular bioeconomy systems where waste nutrients are converted into valuable feed resources. This narrative review summarizes current knowledge regarding duckweed production systems, nutritional characteristics, feeding applications, safety considerations, and economic feasibility in aquaculture while identifying key knowledge gaps and future research priorities. Special emphasis is placed on dietary inclusion levels, species-specific responses, and opportunities for nutrient recycling, and challenges to be overcome to support wider commercial adoption of duckweed-based aquafeeds. The review is narrative in nature and seeks to provide an in-depth review of the evidence available and to identify current knowledge gaps and future research priorities.

Review Methodology

Literature was identified in PubMed, Scopus, Web of Science, DOAJ, and Google Scholar by using combinations of the keywords "duckweed," *Lemnaceae*, "aquaculture," "fish nutrition," "fishmeal replacement," "aquafeed," "wastewater treatment," and "sustainable aquaculture." Preference was given to peer-reviewed articles and institutional repository articles about duckweed cultivation, nutritional composition, and aquaculture feeding experiments, environmental sustainability, feed safety, and economic viability. Studies that investigated topics related to duckweed production, nutritional profile, aquaculture feeding utilization, feed safety, environmental sustainability, or economic viability were selected for inclusion. Duplicates and irrelevant publications with regard to aquaculture applications were removed. The relevant literature was synthesized narratively to generate a synthesis of the current literature, key findings, gaps, and future perspectives. This study was performed as a narrative review and not as a systematic review or meta-analysis; hence, PRISMA guidelines and effect size analysis were not followed.

Literature review

Duckweed Overview: Classification, Biology, and Application to Aquaculture

"Duckweed" commonly refers to floating aquatic plants of the family *Lemnaceae*, whereas duckweed fern refers to species of the genus *Azolla*. Duckweed is classified as part of the family *Araceae*, and duckweed fern is part of the family *Salviniaceae*. The taxonomic classification of five recognized genera of duckweed are *Spirodela, Landoltia, Lemna, Wolffia*, and *Wolffiella* (Figure 1) (Yang *et al*., 2021).

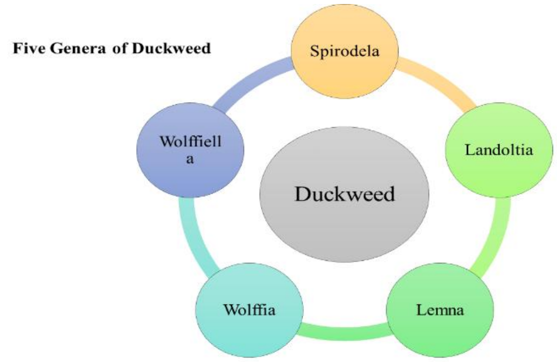

Figure 1: Taxonomic classification of the five recognized duckweed genera

Studies on Lemnaceae provide extensive information on the identification of and information about duckweed species (Bog *et al*., 2019; Braglia *et al*., 2021; K. Sree *et al*., 2016). The *Lemnaceae* family has five genera and approximately 35 species of aquatic monocotyledonous flowering plants with highly reduced morphology (Bog *et al*., 2019; Cabrera *et al*., 2008; Les *et al*., 2002; Sree *et al*., 2016; Sree & Appenroth, 2020). Members of this family lack stems and leaves and, in two genera, even roots. Due to small size, fast cloning, and the capability to float on the water surfaces, duckweed is ideal for biofuel and biomass production from wastes. From the five known genera: Wolffia (no roots, fronds less than 1 mm); *Wolffiella* (no roots, 2-5 mm), *Lemna* (single root, 2-5 mm); *Landoltia* (2-7 roots, 3-6 mm); and *Spirodela* (7-21 roots, 5-15 mm). The *Lemna minor* and *Spirodela polyrhiza* have been extensively studied for aquafeed applications due to their robust growth and adaptability. In contrast, *Wolffia* species remain relatively underutilized in commercial aquafeed production (Muller *et al*., 2025). The comparison of their morphology, nutrient composition, and suitability in aquafeed is presented in Table 1.

Table 1. Comparison of duckweed genera for aquafeed applications

Genus	Number of species	Roots per frond	Frond size (mm)	Protein range (% DM)	Suitability for fish feed	Key advantage / limitation
Wolffia	11	Rootless	<1	35–45	High	Difficult to harvest due to tiny size
Wolffiella	10	Rootless	2–5	30–40	Moderate	Poor mechanical harvest ability
Lemna	11	1 root	2–5	25–42	Very high	Most studied; easy to harvest
Landoltia	1	2–7	3–6	28–38	Moderate	Fast growth but lower protein
Spirodela	2	7–21	5–15	20–35	High	Large fronds; easy harvest; lower protein

Note: Data compiled from Bog *et al*. (2019); Cabrera *et al*. (2008); Leng (1999); Minich & Michael (2024); Sree *et al*. (2016).

Among duckweed species *Lemna minor* and *Spirodela polyrhiza* have been widely used in aquaculture, as their larger frond size facilitates mechanical harvesting, and their protein content is high when sufficient nitrogen is available (Rifai *et al*., 2024). *Wolffia arrhiza*, also known as water-meal, possesses the highest protein content among all duckweed species (up to 45% dry weight); however, it cannot be utilized in commercial fish feeding due to its exceedingly small size (< 1 mm) and lack of a cost-effective filtration mechanism, making it economically inefficient (Muller *et al*., 2025).

Duckweed species reproduce through vegetative budding, with each parent plant producing 2-10 daughter plants per generation. Under optimal environmental conditions (temperature 20-30°C, pH 6.0-7.0, adequate nitrogen and phosphorus supply, and light intensity of 150-300 μmol/m²/s), the generation period can be as short as 16 and 48 hours (Leng *et al*., 1995). This growth rate is faster than most land-based crops.

Biology and Production Systems

Duckweed is characterized as one of the simplest angiosperm forms, which lost its stem and leaves and, in some species of *Wolffia* and Wolffiella, even roots through evolutionary reduction. The plant is termed the frond, which is formed by the fusion of the stem and leaf and floats on the water surface. Duckweed propagates vegetatively via budding, wherein the daughter's fronds develop in the specialized reproductive pouch of the mother frond (Les *et al*., 2002). Under favorable conditions, the single frond gives birth to 10-20 daughter fronds within 10 days, yielding an annual dry weight of biomass exceeding 100 tons per hectare (Leng, 1999).

The growth rate of duckweed is unique among other vascular plants. Duckweed under optimal growth conditions (temperature 20-30°C, pH 5.5-7.5, and adequate nutrition) has a doubling time of 1.3-4.5 days and sometimes even less, such as 16-48 hours, under highly nutrient-rich conditions (Leng *et al*., 1995). The relative growth rate (RGR) of *Lemna minor* reaches 0.2-0.3 g/day, whereas *Spirodela polyrhiza* shows slightly lower but more consistent productivity (Rifai *et al*., 2024). Comparative kinetic studies of the uptake of NH_4^+ and PO_4^+ showed that *Lemna minor* was more productive at high ratios of N:P ratios (16.70 g dry biomass/g NH_4), while *S. polyrhiza* performed better at low N:P ratios (19.31 g dry biomass/g PO_4^+) (Rifai *et al*., 2024). This differential productivity based on species ensures that the appropriate species are selected based on the nature of the wastewater, using *Lemna minor* with high-strength effluent and *S. polyrhiza* for nutrient-poor wastewater.

Production system

Extensive Systems: Natural ponds, lagoons, and swamps constitute the oldest. Duckweed is either indigenous or introduced and requires only periodic harvesting (Skillicorn *et al*., 1993). Minimal financial investment is needed, although productivity is relatively low (10-30 tons of dry weight/ha/year) and may fluctuate throughout the year depending on bird and insect activities (Leng, 1999)**.** Extensive systems find applications in aquaculture operations.

Intensive Systems: With an optimized hydroponic system, outputs exceeding 100 tons (dry weight) per hectare per year can be achieved (Minich & Michael, 2024). All macronutrients (N, P, K, Ca, Mg, S) and micronutrients (Fe, Mn, Zn, Cu, Mo, B) can be supplied via either modified Hoagland's solution or the NRC solution. Recirculating aquaculture systems (RAS) allow for the use of duckweed channels receiving water from fish production, which is then recycled back in to fish tanks. Many studies reported that nutrient-rich aquaculture effluents can enhance duckweed biomass productivity and protein accumulation, although protein concentrations vary according to species, nutrient availability, environmental conditions, and harvest management (Minich & Michael, 2024; Rifai *et al*., 2024). A stacked system, which involves vertical production with LED lighting and misting for fertilization, represents another intensification approach, enabling indoor cultivation regardless of seasons or geographical location (Muller *et al*., 2025).

Wastewater Integrated Systems

The optimal solution for low cost and low pollution is the use of wastewater during cultivation. Duckweed has proven effective in removing NH_4^+ and PO_4^{3-} from wastewater generated by fish farming operations (Costa *et al*., 2019). The uptake of these ions occurs following Michaelis-Menten kinetics; typically, the NH_4^+ uptake is larger than the PO_4^{3-} uptake due to a higher nitrogen assimilation rate (Rifai *et al*., 2024). The *Lemna*tec facility in Ireland managed to work on integrated systems for three years using duckweed in conjunction with rainbow trout breeding (Minich & Michael, 2024). However, the problem of heavy metal bioaccumulation remains unresolved.

For instance, fish farm wastewater, agricultural runoffs, and municipal sewage are typically nutrient-rich, but their release into natural water systems causes eutrophication because nutrients, such as nitrogen and phosphorus, are not efficiently used for primary biological productivity (Zhou *et al*., 2023). The use of these aquatic macrophytes in recycling the nutrients as well as biomass that can be used as a protein source is a double benefit strategy. The family of Lemnaceae is one such family that offers a very good example of the concept of a circular economy. It consists of rapid-growing plants, which are aquatic and require nutrient-rich water to grow (Skillicorn *et al*., 1993). This strategy differs prominently from the conventional "produce-use-dispose" linear model of typical aquafeed production cycles. In a circular bioeconomy, waste outputs from one process serve as raw materials for another one, interconnecting material flows (Zhou *et al*., 2023). The effluent streams produced by aquaculture are perfectly suitable for such an approach because fish release 70-80% of consumed nitrogen in the dissolved form and 50-75% of ingested phosphorus as well.

As a free-floating plant, it effectively absorbs such nutrients as ammonium (NH_4^+), nitrate (NO_3^-), and orthophosphate (PO_4^{3-}) from wastewater. Studies show that within 3-7 days, duckweed can remove 60-90% of total nitrogen and 50-80% of total phosphorus from wastewater (Rifai *et al*., 2024). The high capacity to absorb is due to several reasons: Firstly, the high surface-to-volume ratio of the leaves of the duckweed helps in fast uptake of nutrients; secondly, fast growth rates ensure that biomass keeps getting produced; thirdly, the associated microbes help in the process of nutrient absorption.

The protein content of duckweed is quite variable and depends on the species and growing conditions, usually varying between 20% and 45% of dry matter (Minich & Michael, 2024; Muller *et al*., 2025). This makes duckweed biomass an excellent feed resource for aquaculture applications. After drying and pelletizing the biomass, it can be included in fish diets to recycle nutrients to the stock being raised. Integrated multi-trophic analysis (IMTA) systems that incorporate duckweed have proven successful in different countries, reducing feed inputs by up to 15-30% (Minich & Michael, 2024). Overall, duckweed has two major advantages when compared to other plants in bioenergy production; these include fast growth rate and lack of competition with crops in terms of land use (the same advantages shared by microalgae). On the other hand, there are a number of advantages that duckweed does not have when compared to other plants. They include reduced water consumption, reduced CO_2 consumption, low-energy cultivation, ease of harvest, and low cost of biorefineries when compared to microalgae. It produces a smaller amount of biomass on a plant basis compared to terrestrial plants, and it is not benefited by low-energy cultivation or by atmospheric CO_2.

Optimization Factors

Light intensity is crucial in determining both growth rate and the protein-to-starch ratio. For optimal photosynthetic activity, duckweed requires a light intensity of 150-300 μmol/m²/s, corresponding to about 12-16 hours of photoperiod. Insufficient light levels slow growth and enhance starch accumulation while limiting protein synthesis, whereas excess lighting (>500 μmol/m²/s) can introduce photoinhibition and cellular damages (Muller *et al*., 2025).

pH management is essential in ensuring sufficient nutrient accessibility and appropriate metal ion speciation. Duckweed grows well in a pH level of 5.0-8.5 and functions best between pH 6.0 and 7.0. Very low or very high pH values (<5.0 or >8.5) inhibit the plant's uptake of ammonium ions by disrupting the equilibrium between ammonia and ammonium ions. This imbalance triggers an oxidative reaction (Duman *et al*., 2010).

Nitrogen concentration: Duckweed synthesizes more protein when grown in urea and ammonium nitrate compared to nitrate fertilizers because ammonium ions can be directly utilized in glutamine synthesis. High ammonium levels (>100 mg/L NH_4 N) can trigger phytotoxicity by chlorotic fronds and growth retardation (Liu, *et al*., 2021). The optimal nitrogen-phosphorus ratio varies in culture media, ranging from 10:1 to 20:1 depending on species (Rifai *et al*., 2024).

Nutritional Profile of Duckweed

Proximate Composition

Duckweed's nutritional composition exhibits remarkable variability based on species, cultivation conditions, and harvest timing. The proximate composition of duckweed compared to the optimum range of nutritional requirements for fish is compiled from diverse studies presented in Table 1 (data compiled from: Leng *et al*., 1995; Liu *et al*., 2021; Minich & Michael, 2024; Muller *et al*., 2025).

Table 2: Proximate Composition of duckweed

Component	% DM basis	Mean value (%)	Optimal range of nutrients for Fish
Crude Protein	15–45	29.5	28–38
Crude Lipid	3–7	5.0	5–15
Carbohydrates	30–50	40.0	20–40
Crude Fiber	10–20	14.5	<10
Ash	10–20	15.0	8–12

Feed value in aqua feed is largely determined by the amount of protein. Lipid content (3 to 7% dry matter) is relatively small but has a better profile. The lipids contained in duckweed are composed largely of PUFA, especially ALA (18:3n-3). However, the reduced composition of EPA and DHA in duckweed implies the need for supplementation with marine oil containing n-3 LC-PUFA (Muller *et al*., 2025).

Amino Acid profile

The amino acid profile of duckweed protein compared to fishmeal relating to the requirements for most essential amino acids in omnivorous fish (compiled from: Leng *et al*., 1995; Minich & Michael, 2024; NRC, 2011) (Table 3).

Table 4: Essential amino acid profile of protein in duckweed (Lemna spp.) and fishmeal compared to Tilapia fish requirements

Essential amino acid	Duckweed protein (%)	Fishmeal protein (%)	Tilapia fish Requirement
Arginine	5.5–6.5	6.0	4.2
Histidine	1.8–2.5	2.2	1.8
Isoleucine	3.5–4.2	4.0	3.1
Leucine	7.5–8.8	7.0	3.9
Lysine	5.2–6.8	7.0	5.0
Methionine + Cys	2.0–3.0	3.5	2.2
Phenylalanine + Tyr	6.0–7.5	6.5	5.0
Threonine	3.8–4.5	4.0	3.6
Tryptophan	1.0–1.5	1.2	1.0
Valine	4.5–5.5	5.0	3.6

The dominant types of amino acids found in duckweed include lysine and leucine, hence making this type of feed very compatible with cereal because of its deficiency of lysine. Methionine forms the first limiting amino acid. Whenever feeding programs have more than 25 percent of duckweed used, it is recommended that crystalline methionine or any other feed rich in methionine should be included (Tacon & Metian, 2018).

Micronutrients and Bioactive Compounds

Calcium and phosphorus as bioavailable minerals get absorbed into duckweed from the culture media, thus being great sources of calcium, phosphorus, magnesium, potassium, iron, and zinc (Leng, 1999). The calcium-to-phosphorus ratios (1:1-2:1) are consistent with the needs of freshwater fish, eliminating extra mineral supplementations (NRC, 2011). Some of the vitamins that are found in duckweed include beta-carotene (precursor of vitamin A), riboflavin, folate, and vitamin E. The concentration level of beta-carotene ranges from 100 to 300 mg/kg dry weight, playing a significant role in pigmentation in fish. It has been demonstrated in several studies that duckweed protein-derived peptides possess beneficial biological properties, including antimicrobial, antihypertensive, antidiabetic, and antioxidative activities (Liu *et al*., 2021; Muller *et al*., 2025). The mineral composition of duckweed compared to other cereal crops presented in Table 5 (data compiled from: Appenroth *et al*., 2017; Hiththatiyage *et al*., 2026; Miltko *et al*., 2024; Spranghers *et al*., 2017).

Table 6: Mineral content (mg/100 g) of duckweed compared to cereals and grains (dry weight basis)

Plant	Ca	P	Na	K	Mg	Fe	Mn	Cu	Zn
Duckweed	1.22–3.25	1.21–2.13	0.01–0.07	3.97–9.37	190–460	<0.1	8–34	0.2–0.4	2.6-9.2
Chickpea	0.17	0.45	-	0.994	169.00	4	3	-	4
Corn	-	-	0.06–0.20	-	-	-	3.00–7.00	2–4	10–30
Rice	-	-	<0.05	0.15-0.28	80-150	10-20	20-50	1-7	10-50
Soybean	-	-	0.04-0.33	-	-	-	30-60	13-18	40-60
Wheat	0.03–0.06	0.09–0.20	0.37–0.40	0.09–0.22	22–68	1.60–2.60	0.62–1.96	0.37–0.55	0.90–1.90

Antinutritional Factors (ANFs) and treatment strategies

Duckweed consists of different ANFs that negatively impact nutrient utilization if not effectively controlled (Makkar *et al*., 2007): Oxalates (0.5-3% DM) bind calcium ions and negatively impact nutrient uptake and mineral availability. The content of oxalates is higher in rapidly growing and high-protein tissues (Leng *et al*., 1995). Blanching (brief boiling) lowers the content of oxalates from 30 to 50%, but this process is highly energy-consuming for commercial processing (Muller *et al*., 2025). Tannins (0.2-1.5% DM) impede digestive enzymes and reduce protein digestibility (Makkar *et al*., 2007). Tannin levels rise in case of stress conditions (nutrient shortage, high irradiance). Crude fiber (10-20% DM) inhibits the digestibility of nutrients in carnivorous fish with simple stomachs. Carnivorous fish (e.g. *salmonids*) are more vulnerable to fiber content than omnivorous (e.g., tilapia and carp) and herbivorous species (NRC, 2011). Strategies for solving ANF constraints consist of drying through solar/mechanical technology, fermentation (*lactic acid bacteria*); enzymatic (c*ellulase, phytase*) digestion, and restricting the inclusion level up to 30% (Minich & Michael, 2024; Muller *et al*., 2025).

Potential as a Feed Source for Farmed Fish

Recent studies have strengthened the argument for duckweed as a sustainable protein source for aquaculture feeds. The previous study reported that the inclusion level of duckweed between 15% and 30% generally improved growth performance and feed conversion efficiency of diverse species of farmed fish. Particularly, *Lemna and Spirodela spp.,* owing to their high protein content and better amino acid profile when incorporated in formulation (Minich & Michael, 2024).

Although most feeding trials report beneficial effects of moderate duckweed inclusion, considerable variability exists across studies (Minich & Michael, 2024; Muller *et al*., 2025). Such variation is likely associated with differences in duckweed species, nutrient composition, culture conditions, feed processing methods, fish developmental stage, and digestive physiology. This variability also explains why inclusion levels that perform well in herbivorous species may not necessarily produce similar results in omnivorous or carnivorous fish.

The nutritional value of duckweed is mainly based on its protein content, which ranges between 20% and 45% depending on species, nutrient availability, and cultivation conditions (Minich & Michael, 2024; Muller *et al*., 2025). Nutrient composition remains highly variable among species and cultivation systems (Song *et al*., 2025; Wang *et al*., 2010; Yin *et al*., 2026). Also, findings showed that feeding grass carp with *Spirodela polyrhiza* significantly enhanced their growth performance, feed utilization, antioxidant activity, immune response, and gut microbial diversity (Song *et al*., 2026). The authors found the 25% inclusion level to have the best overall performance. This is in line with previous studies that have shown that moderate inclusion levels of duckweed are more advantageous than complete replacement of fishmeal (Song *et al*., 2025). Although the available evidence showed the variability of inclusion of duckweed in aquafeeds (Glencross, 2020; Hardy, 2010). This variability may be due to differences in duckweed species, cultivation systems, processing methods, and fish physiology, which may explain many of the contrasting results reported in the literature.

Feeding strategies

The following are the three methods of feeding duckweed to fish:

(a) Live grazing: The live grazing method involves the direct grazing of fish on the duckweed grown in culture ponds (Skillicorn *et al*., 1993). This method is appropriate for herbivorous and omnivorous fish species such as tilapia, grass carp, and silver carp. The major disadvantage of this method is that it lacks control over feed consumption and nutrient content.

(b) Dried flakes or meal and (c) Pelleted feed with duckweed meal: Pelleted feeds allow specific formulation and are an appropriate way for commercial operations (Leng, 1999; Minich & Michael, 2024).

Substitution Levels and Growth Performance

Minich & Michael (2024) suggested that the inclusion rate of duckweed in the 15% to 30% range results in positive effects on growth and feed efficiency in fish without adverse effects on survival rate. Although most studies report growth responses at moderate inclusion levels (15-30%), substantial variation exists among fish species. Omnivorous species such as Nile tilapia and common carp consistently utilize duckweed more efficiently than carnivorous fish. This variation likely reflects differences in digestive physiology and tolerance to dietary fiber. Consequently, the suitability of duckweed appears strongly species-dependent rather than universally applicable (Fasakin *et al*., 1999; Minich & Michael, 2024). Different fiber contents, anti-nutritional factors, and protein make up differences will be a cause for many of the variations that are found. Hence, generalized suggestions must be taken with caution, and feeding studies on species are required before going into full commercial production.

How each organism responds differently to the feeding of duckweed depends on their body's physiology. The herbivore category, which includes the grass carp and silver carp, can cope with 50% of duckweed because they have long intestines. In addition, there are more cellulose enzymes produced in the intestines by the gut microorganisms of the herbivores. The tilapia, common carp, and catfish, being omnivores, have good results with 15-30% of duckweed.

Species-specific growth response

Tilapia (*Oreochromis spp*.) is the fish species that has been most widely used in duckweed-based feeding systems since the fish have omnivorous feeding behavior and high tolerance for plant protein sources. In a previous study, an eight-week feeding experiment was performed on juvenile tilapia using different inclusion rates of duckweed (*Lemna minor*; 0%, 10%, 20%, and 30%) in their diets (Effiong, 2019). A 20% inclusion rate of duckweed in the fish diets led to the best growth performance, with the fish gaining an average weight of 63.2 g in 56 days—marking a 32.7% improvement over the control diet group.

The beneficial effect on growth and feed utilization is also influenced by nitrogen and phosphorus content in the tanks' suggesting the viability of duckweed-based diets relating to improving water quality within integrated aquaculture systems (Alkhamis, 2024). Also, growth rates at the inclusion levels of 20% were comparable to the control group, while higher inclusion levels of 30% slightly decreased growth rates; however, complete replacement resulted in significantly lower growth performance (Fasakin *et al*., 1999). This suggests that duckweed functions more effectively as a partial than as a full protein source supplement in tilapia feed.

The common carp (*Cyprinus carpio*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus cirrhosus*) were tested under the same conditions and showed comparable results to that of tilapia. Generally, the optimum percentage for including duckweed in the diet of these cyprinids was found to be between 15 and 25%, which equals the substitution of 25–40% of the total amount of fishmeal proteins used (Minich & Michael, 2024; Tacon & Metian, 2018). Thus, the use of duckweed as an ingredient in fish feed provides not only better growth and productivity but also helps lower the cost of feeds and dependence on traditional sources of protein.

Limited information is available regarding the use of duckweed in catfish diets compared to tilapia and carp fish species. However, from what can be deduced from the few studies carried out, duckweed could be used partially to achieve optimal growth at lower costs (Minich & Michael, 2024).

Physiological and Health Impacts

Inclusion of duckweed in aquafeeds affects several body systems. Increased activity of digestive enzymes has always been observed, especially when tilapia was fed diets supplemented with 20% duckweed. According to an earlier study, there was a marked increase in the activity of amylase, protease, and lipase (Alkhamis, 2024). This indicates that duckweed stimulates digestive enzyme secretion. Moreover, the moderate level of fiber in duckweed helps to improve gut development and feed digestion in fish that consume both plant-based and animal feeds.

This plant may be promising in terms of the immune system support and oxidation stress mitigation in fish (Muller *et al*., 2025). According to the results of a recent metagenomics study, the inclusion of moderate doses of the plant in feed (15-20%) may positively influence the microbiota composition by stimulating the proliferation of the probiotic bacteria such as *Lactobacillus and Bacillus species*. It has also been shown that it improves the processes of nutrient intake and immunological reactions (Minich & Michael, 2024). However, high inclusion levels, which exceed 40%, may cause enteritis in fish, probably because of the increased number of fibers and anti-nutritional elements.

One of the major drawbacks associated with the utilization of duckweed as a feed additive lies in the high ability of this plant to accumulate toxic metals from wastewaters. Arsenic levels in the duckweed samples collected from the RAS effluents were 2.8-4.5 mg/kg, while lead content varied between 1.5 and 3.2 mg/kg and cadmium between 0.8 and 1 mg/kg (Mkandawire & Dudel, 2005; Rahman *et al*., 2007). The values above are higher than those set as the maximum permissible limits for these elements by European Union (EU) Directive 2002/32/EC concerning the composition of feed materials (As < 2 mg/kg, Cd < 1 mg/kg, Pb < 5 mg/kg /kg in most animal feed types). Duckweed grown on untreated water thus cannot be used as an animal feed source in the EU.

Economic feasibility and scalability

There are various aspects that influence the profitability of duckweed cultivation, including the infrastructure used, the technologies required for harvest, the availability of a labor force, the need for drying, and the environment in which the duckweed grows. The combination of duckweed cultivation with wastewater treatment plants would make the process more profitable because of the affordable means of getting nutrients, along with environmental benefits gained from this process (Rifai & Permata, 2023; Zhou *et al*., 2023). However, significant investments in transportation, drying facilities, harvesting equipment, and quality control systems are necessary for large-scale commercialization. Because freshly harvested biomass has high moisture content, drying continues to be the most energy-intensive step. As a result, different production systems and geographical areas have different levels of economic competitiveness (Muller *et al*., 2025).

Economic assessment studies currently show that duckweed-based aquafeed is economically competitive compared to commercially available feeds under some specific conditions, which include using freely available wastewater (or zero-cost nutrients), the ability to acquire land cheaply or land that is not arable, and subsidized labor costs or the existence of mechanical harvesting technologies (Minich & Michael, 2024).

Scaling up from a pilot project of a 10-100 m² area to a commercial-scale project exceeding one hectare will entail very high investments in the beginning, especially in relation to the lining, harvesting, and drying system. Consistency in relation to feedstock production will be the major engineering issue that will need to be addressed. The production cost of duckweed feed for tilapia was estimated at €0.85-1.10 per kg of duckweed meal, comparable with that of imported soybean meal, which was €0.90-1.20 per kg. Nevertheless, it can only be achieved if duckweed is produced from free-flowing wastewater and labor cost remains less than €5 per day. In rich countries where labor cost and mechanization in relation to harvesting and forced-air drying are higher; the production cost becomes higher too. In this case, the cost of duckweed meals becomes higher than other plant meals (Minich & Michael, 2024).

Synthesis of Evidence and Implications

The evidence in the review shows that there is great potential in duckweed as a substitute for aquafeeds; nonetheless, the use of the crop is dependent on factors such as variability in nutrients, species differences, feed safety issues, and cost. Duckweed has become a popular substitute for fish feed due to its fast-growing nature, productivity, amino acid composition, and ability to recapture nutrients from wastewater (Minich & Michael, 2024; Zhou *et al*., 2023). Species of the family *Lemnaceae* are among the fastest-growing flowering plants and can produce protein-rich biomass while utilizing nutrient-rich water resources that would otherwise contribute to environmental pollution (Leng *et al*., 1995; Muller *et al*., 2025). Due to these properties, duckweed becomes an excellent candidate for use in circular bioeconomy approaches to increase the sustainability of aquaculture production.

The data available shows that duckweed can substitute some amount of traditional protein sources in aquafeed without decreasing the quality of fish growth performance. Based on the review of feeding experiments with different fish species, the recommended level of diet incorporation ranges from 15% to 30% (Minich & Michael, 2024). Fasakin *et al*. (1999) and Effiong (2019), who demonstrated that moderate levels of duckweed inclusion improved growth performance in Nile tilapia compared with conventional diets, reported similar findings. Song *et al*. (2026) further reported enhanced growth performance, feed utilization, antioxidant status, and gut microbial diversity in grass carp fed diets containing duckweed supplements.

Despite these encouraging findings, responses to duckweed inclusion vary considerably among fish species and experimental conditions. Such variability may be attributed to differences in duckweed species, cultivation environment, nutrient composition, processing methods, fish developmental stage, and digestive physiology (Glencross *et al*., 2020; Minich & Michael, 2024). Omnivorous and herbivorous fish species generally demonstrate greater efficiency in utilizing duckweed-based diets because of their increased capacity to digest plant-derived ingredients and tolerate higher dietary fiber levels. In contrast, carnivorous species often exhibit lower tolerance to high-fiber ingredients and may experience reduced performance at elevated inclusion levels (Krogdahl *et al*., 2010; NRC, 2011). Yet, one of the major nutritional disadvantages of duckweed for the carnivorous fish species is the extremely high fiber content in it. For this reason, nutrition requirements for each species remain important for getting the most benefits from the usage of duckweed in aquaculture.

One of the most serious problems that hinder commercial application of duckweed is the great variation in the composition of its nutrients. Depending on the species of duckweed, nutrient availability, growing conditions, and time of harvesting, the percentage of protein may differ from 15% to 45% of the dry mass (Leng *et al*., 1995; Muller *et al*., 2025). Similar variations have been observed in amino acid profiles, mineral concentrations, carbohydrate content, and fiber levels (Appenroth *et al*., 2017; Sree & Appenroth, 2020). This variable nature presents difficulties in standardizing feeds and may even account for some of the performance results observed through feeding experiments. For these reasons, better cultivation practices and quality control methods will have to be developed to produce consistent feed for use in commercial aquaculture facilities.

In addition, the duckweed will have to be compared with other alternative protein sources such as insect meals, microalgae, and single-cell proteins. While insect meals are known to have higher levels of digestibility and microalgae higher levels of long-chain omega-3 fatty acids, duckweed stands out because of its dual ability

(Shah *et al*., 2018). By converting waste nutrients into valuable feed resources, duckweed contributes directly to circular bioeconomy principles and environmental sustainability (Zhou *et al*., 2023). Thus, its value extends beyond simple nutrient provision and includes important ecosystem-service functions such as wastewater treatment and nutrient recycling.

Feed safety remains one of the most significant barriers to widespread adoption of duckweed in aquaculture. While duckweed efficiently removes nitrogen and phosphorus from wastewater, it can also accumulate undesirable contaminants, including arsenic, cadmium, lead, and other heavy metals (Van Der Spiegel *et al*., 2013; Zhou *et al*., 2023). Mukherjee *et al*. (2004) reported elevated concentrations of heavy metals in duckweed cultivated using recirculating aquaculture system effluents, highlighting potential challenges for regulatory compliance. Similar concerns have been identified by the European Food Safety Authority (Allergens et al., 2021), which emphasized the importance of contaminant monitoring when evaluating novel feed ingredients. Therefore, comprehensive monitoring systems, certification programs, and contaminant-control measures will be required before duckweed can be widely adopted as a commercial feed ingredient.

Processing requirements represent another important limitation. Freshly harvested duckweed typically contains more than 90% moisture, making drying one of the most energy-intensive stages of feed production (Müller *et al*., 2025). Furthermore, anti-nutritional compounds such as oxalates, tannins, and excessive fiber may reduce nutrient utilization if not adequately managed (Makkar *et al*., 2007). Various processing techniques, including fermentation, enzymatic treatment, and improved drying technologies, have been proposed to enhance nutrient availability and improve feed efficiency (Minich & Michael, 2024; Muller *et al*., 2025). Such approaches may improve the practicality and commercial viability of duckweed-based feeds.

Collectively, available evidence suggests that duckweed possesses considerable potential as a sustainable ingredient for aquaculture feeds. Its rapid growth, relatively high protein content, favorable amino acid profile, and ability to recover nutrients from wastewater distinguish it from many conventional plant protein sources. Furthermore, duckweed production aligns well with circular bioeconomy principles by transforming waste nutrients into valuable biomass (Zhou *et al*., 2023; Minich & Michael, 2024).

However, there are still a number of challenges that need to be overcome before widespread use is achieved. The nutritional content varies greatly from one species to another and from one cultivation environment to another, while there are still some unresolved issues related to antinutritional substances and contamination. Thus, future research needs to concentrate on improving cultivation practices, assessing the safety of the feed, developing processing techniques, and creating specific diets for different duckweed species (Muller *et al*., 2025; Song *et al*., 2026).

Economic competitiveness remains highly dependent on local production conditions. Integrated production systems combining wastewater treatment with duckweed cultivation may generate additional value through nutrient recovery, reduced treatment costs, and feed biomass production (Rifai *et al*., 2024; Zhou *et al*., 2023). However, there are still some challenges facing commercialization on a larger scale about harvesting facilities, drying, transportation, storage, labor requirements, and quality control systems. Therefore, even though pilot-scale studies indicate the presence of profitability; further commercial-scale studies need to be conducted before making any conclusions regarding profitability.

In conclusion, from the information discussed above, it can be noted that duckweed has the potential to be used as an aquafeed ingredient because of its fast growth rate, nutrient value, and sustainability by way of nutrient cycling. Nevertheless, some issues need to be addressed about the commercialization of duckweed as an aqua feed.

Limitations of the Review

There are several drawbacks associated with this review. First, since this was done in the form of a narrative review, there was no application of systematic-review procedures and meta-analysis techniques. Therefore, selection bias cannot be excluded. The literature review was performed depending on its relevancy to the objectives of the review, and this is another possible drawback, as is the possibility of the existence of selection bias. Another possible problem might be the differences among duckweed species, cultivation conditions, methods of feed preparation, and species of fish used for research in the papers. Nevertheless, despite all the limitations, this review covers current knowledge about the use of duckweed as a protein source.

CONCLUSION

The current evidence suggests that there is substantial promise in the use of duckweed as a sustainable aquafeed ingredient owing to its rapid growth, high protein content, good amino acid profile, and capacity to remove nutrients from wastewaters. Most of the research indicates that the inclusion of 15-30% of duckweed in the diet is feasible in terms of growth performance and feed utilization of omnivorous and herbivorous fishes. Nonetheless, its use is hampered by variations in nutrient composition, the presence of anti-nutritional factors, the risk of heavy metal accumulation, costly processing, and regulatory issues. Current evidence indicates that duckweed should be considered an effective partial replacement rather than a complete replacement for conventional protein sources in aquafeeds. Future advances in cultivation, feed safety, breeding, and processing will be necessary for commercial adoption of duckweed as an aquafeed ingredient.

Even though the current literature provides some promising results regarding the use of duckweed as a sustainable feed ingredient, responses of fish to feeding on duckweed may differ depending on their species, cultivation system, and processing method used. Species-specific feeding trials and standardized production practices are essential for optimal utilization of its potential. Duckweed may play an important role in the implementation of circular bioeconomy practices through simultaneous nutrient recovery, wastewater treatment, and aquafeed production.

Recommendations and Future Perspectives

Presently, duckweed appears to be more effective as a partial substitute for other conventional protein sources rather than being used as the sole protein source. In view of the current evidence, it can be concluded that the inclusion rates of 15-30% of duckweed in the diet are proposed for omnivorous and herbivorous fish.

Future research needs to focus on carrying out feeding trials; the safety of the feed; contaminants present; and developing methods of cost-effective processing of the protein source. The development of standardization of cultivation and quality assurance procedures is necessary to minimize differences in nutrient content in the feed.

Future research should concentrate on evaluating the process's comm ercial viability, studying carnivorous fish, and integrating an integrated biorefinery approach.

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