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# Spirulina (*Arthospira*) Spp. in aquaculture feeds: sustainable partial and whole fish meal replacer

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**Abstract**

Aquaculture industry is a main contributor to food security through providing high quality cheap protein. Fish meal is an essential part in the aquaculture feeds. Due to the fluctuations in the production quantities and market prices, relaying on fish meal may endanger the sustainability of the aquaculture industry. Spirulina Spp. (*Arthrospira*) produces a variety of high quality proteins, amino acids, minerals, and vitamins, which is comparable to that of fish meal especially protein quantity and amino acids quality. In addition to, it has a high concentration of bioactive compounds, such as phenols, pigments, and polysaccharides. Moreover, Spirulina is a sustainable and eco-friendly protein source that has the ability to replace the fish meal in the aquaculture diets either partially or completely, while maintaining the farm productivity. On the other hand, Spirulina production costs is still higher than fish meal, while ongoing research is trying to improve its inclusion cost-effectiveness in aquatic animals' diets. However, the inclusion of Spirulina in fishes and shrimps feed formulations could outweigh its higher prices via providing several profits to aqua farm such as improving growth performances and diseases resistance. Unfortunately, the exposure of Spirulina containing feeds to heat, light, and storage expose its bioactive principles to partial inactivation, leading to a reduction in the benefits of its inclusion.

## Introduction

The global aquaculture industry is the fastest growing protein-producing industry worldwide presenting a main contributor in food security. After the amount of captured wild fish reached its maximum and in the presence of high demand for seafood, the aquaculture industry is expected to grow exponentially **(FAO 2024)**. The sustainability of this industry relies mainly on the farm productivity and the feed availability **(Ahmed *et al.* 2022)** where the feed represents the highest operational cost **(Baki &**

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**Yucel 2017).**
Fish meal is an essential part in the aquaculture feeds due to its easily digestibility and high nutritional values including high quality protein and lipids, vitamins, and minerals (**Heuzé *et al.* 2015**). Unfortunately, fish meal production suffers several fluctuations in the production quantities and market prices (**Gasco *et al.* 2018**). Hence, these fluctuations are real threat that may impact the aqua farms productivity and consequently, the sustainability of the blue economy. So, to attain the sustainability for the aquaculture sector, its required to develop a sustainable alternative feed resources to cope with the shortage in traditional sources especially fish meal. However, accelerated progress toward reducing fish meal usage in aquaculture feeds while maintaining farm productivity is in the focus of ongoing researches. Moreover, upgraded fish diet components including essential fatty acids and amino acids, antioxidants, and prebiotics can reduce their waste, resulting in an increment in the fish farm productivity and fish flesh quality (**Nagappan *et al.* 2021**). Algal proteins are emerging as important alternative proteins. Furthermore, supplementing the diet of animal with algae can improve growth parameters, immunity, antibacterial and antiviral activity, and enriches the aquatic animals diets with bioactive compounds (**Abdallah *et al. 2023;* Kusmayadi *et al.* 2021**).
Spirulina (Arthrospira) Spp. is a filamentous cyanobacterium of the class Cyanophyceae. It is a type of a blue-green algae with photosynthetic activity where it can utilize sunlight energy and aquatic animals' wastes (C, N, P, S, K, and Fe etc.) to synthesize their biomass and to multiply (**Markous *et al.* 2014**). In aquaculture, Spirulina can enhance the growth, health status, and overall sustainability of the blue economy through producing a variety of high quality proteins, carbohydrates, lipids, minerals, and vitamins. In addition to, it has a high concentration of bioactive compounds, such as phenols, pigments, and polysaccharides (**Chaiklahan *et al.* 2013**), which all take part in a number of biological activities, such as antioxidant and anti-inflammatory activity (**AlFadhly *et al.* 2022a**). The primary objective of this review is therefore to assess and evaluate the existing knowledge on the suitability and benefits of using Spirulina on the expense of fish meal in the feeds of aquatic animals either partially or completely with an exploration to the potential limitations of its use in aquaculture.

**Nutritional Value of Spirulina**
**Cell wall**: as a member of cyanobacteria Spirulina cell wall lacks the cellulose that ease the digestibility of its contents (**Sasson 1997**). Moreover, the outer surface of Spirulina is smooth and lacks a coverage making it digestible by simple enzymatic systems (**Habib *et al.* 2008**)
**Protein:** Spirulina spp. contains about 60-70% protein by dry weight (**Hosseini *et al.* 2013**). Where, more than 85% of its protein is digested and assimilated within 18 h (**Sasson 1997**). Moreover, its amino acid profile makes it an exceptional source for all essential amino acids required by fishes (**Bortolini *et al.* 2022**). Thus, Spirulina provides an easily digestible balanced high quality protein source for fishes and shrimps.
**Vitamins and Minerals:** Spirulina is rich source for vitamins ($B_1$, $B_2$, $B_3$, $B_6$, $B_9$, and $B_{12}$ as well as A, E, C, and K), provitamin A, and β -carotene (**Stunda-Zujeva *et al.* 2023**). In addition, it contains 2.2–4.8% minerals (Ca, P, Mg, Na, Fe, Cu, Mn, Cr, Se, and Zn), which make spirulina excellent vitamins, minerals, and antioxidants source for aquatic organisms (**wan *et al.* 2016**)
**Fatty Acids:** Spirulina also encompasses about 5-6% fat, of which the polyunsaturated fatty acids (PUFAs) constitute about 1.5– 2.0% (**Serban *et al.* 2016**). Interestingly, spirulina contains a tiny amount of cholesterol (32.5 mg/100 g).
**Pigments:** the three main natural pigments in Spirulina includes carotenoids (Zeaxanthin, Diatoxanthin, and β-carotene), c-phycocyanin, and Chlorophyll (**Park *et al.* 2018**).
**Spirulina as a fish meal replacer:**
Fish meal is a marketable protein-rich flour made by drying and milling fish or fish by-products. It's highly nutritive rich in highly digestible protein, Docosahexaenoic acid, Eicosapentaenoic acid, vitamins, and minerals that commonly used in aquaculture feeds

(**Heuzé *et al.* 2015**). Worldwide, about 16 million tons of fisheries and aquaculture production is directed to manufacture fish meal and fish oil (**FAO 2022**). Nevertheless, due to its limited availability and production fluctuations dominated by changes in the catches besides the increasing in the demand for the fast-growing aquaculture industry, the sustainability of this industry have been endangered. In response, a pressure has been raised to provide unconventional high quality protein sources to cover the shortage in the fish meal production.

Spirulina contains easily digestible protein that is close to the fish meal protein in quality and quantity. In approve, after chemical analysis of Spirulina and fish meal, **Cao *et al.* (2018)** and **Sun *et al.* (2024b)** found that the total crude protein and essential amino acid (except histidine, methionine, and lysine) contents in Spirulina were comparable to that of their counter parts in the fish meal. These results clearly ensure the suitability of Spirulina to replace the fish meal in the diet of aquatic animals at least in terms of protein composition. Although, the authors found that white fish meal contains higher levels of phosphorus and crude lipid, spirulina contained greater proportion of linoleic and linolenic acids. The later result points to the need to consider representing supplementary source for lipid and phosphorus in fish's diets.

In addition to, the inclusion of Spirulina in aquaculture feeds provide several benefits for the farm productivity such as enhancing the growth performance. Spirulina acted as a feed attractant for aquatic animals (**Silva-Neto *et al.* 2012**) and increased the activity of lipase, amylase, and protease enzymes in the digestive tract of fishes (**Adel *et al.* 2016; Eissa *et al.* 2024**). Moreover, ***Abozaid et al. (2023)*** found that its inclusion in the aquaculture feeds increased the expression of growth hormone, insulin-like growth factor1&2, and myostatin genes. Furthermore, substituting fish meal with Spirulina improves the floatability and expansion ratio of the formulated feed (**Hakim *et al.* 2021**). From other point of view, Spirulina could enhance the growth performance and food conversion ratio via modifying the intestinal microbiota. For instance, 15% Spirulina inclusion in zebrafish diets significantly, decreased the pathogenic Vibrio and increased the abundance of gut Cetobacterium (beneficial bacteria), which could produce vitamin B12 (**Ma *et al.* 2022**). Thus, it's suggested that Spirulina could be used successfully, to replace fish meal protein in aquatic animals' diets either partially or completely without affecting aquatic animals' growth performances.

The quantitative meta-analysis of **Li *et al.* (2022)** established that the optimal levels of Spirulina to replace fish meal were 22.03%-24.53% in fish's diet without negative impacts on the growth performance and feed utilization. The ability of Spirulina to replace the whole the fish meal in the diet of aquatic animals have shown accomplishments in some species while it failed in other.

**Partial replacement of fish meal with Spirulina in fishes feeds**

Dietary *Spirulina* and 0.3 % of its polysaccharide extract were represented in the diet of largemouth bass (*Micropterus salmoides)* at 3–6 % of the diet for 56 days, taking the place of fish meal induced an improvement in the growth performance, antioxidant activity, intestinal trypsin, amylase, and lipase activities, liver health, and intestinal microbiota (**Zhang *et al.* 2024**). Moreover, replacing fish meal with selenium fortified-spirulina (5%) in the diet of Asian seabass, (*Lates calcarifer*) for 56 days improved growth parameters, antioxidant status, and hepatocyte and enterocyte health as well as immunity, survival, and diseases resistance to *Vibrio harveyi* infection (**Siddik *et al.* 2022**). However, the authors found that the higher replacement rate (10%) didn't affect growth performance, while the 20% replacement rate caused a decrement in the mentioned values. Furthermore, replacing 8% of fishmeal by Spirulina (52.8 g/kg) in diet of juvenile Caspian brown trout (*Salmo trutta caspius*) significantly improved body performance and composition as well as pigmentation including optical fillet and skin parameters (luminosity, redness, and yellowness) after 70 days feeding trial (**Roohani *et al.* 2019**). Furthermore, incorporation of Spirulina in the diet of Gangetic mystus (*Mystus cavasius)* by 7.5–10% instead of fish meal for 10 weeks endorsed the growth, feed utilization, and immunological parameters as well as the resistance to *Aeromonas hydrophila* challenge (**Al Mamun *et al.* 2023**).

In a progress, substituting 15% of fish meal in the feed for 8 weeks improved the growth performance, antioxidants activity, and expression of growth-related genes (ghrelin, leptin, and Insulin like growth factor1) in Nile tilapia (*Oreochromis niloticus*) exposed to heavy metal toxicity (**Saleh *et al.* 2022**). Similarly in the ornamental Guppy (*Poecilia Reticulata*), the later replacement rate for 60 days enhanced the growth parameters and skin pigmentation (**Bisht *et al.* 2023**). Meanwhile, after 10 weeks feeding trial, **Sun *et al.* (2024**a&b) suggested that the best substitution rate of fish meal with spirulina powder in the diet of Zig-zag eel (*Mastacembelus armatus*, MA) is about 11% and shouldn't surpass 15% where, a higher percentage induced intestinal stress through enrichment in inflammation-related pathways, such as coagulation cascades and complement *p*. activities. Interestingly, substituting 20% of fish meal with Spirulina (10% inclusion rate) in the diet of rainbow trout (*Oncorhynchus mykiss*) for 12 weeks reduced the weight loss by 50% during 3 weeks starvation period (**Güroy *et al.* 2011**).

Progressively, raw Spirulina can successfully replace 20% of fish meal in the diet of juvenile barramundi, (*Lates calcarifer*) for eight weeks without interrupting its growing indices, while 40% replacement rate do (**Vo *et al.* 2020**). The authors found that 40% replacement rate with enzymatic-treated Spirulina negatively impacted the growth indices, both diets with 40% replacement (raw and enzymatic-treated Spirulina) induced alterations in liver, muscle, and intestinal cells. Continuously, when *spirulina pacifica* was included in the diet of parrot fish (*Oplegnathus fasciatus*) replacing 45% of fish meal for eight weeks, didn't induce significant negative effects on growth performance while, 15% and 30% replacement rate yielded better hematological and immunological values and enhanced the growth performance (**Kim *et al.* 2013**). On the other hand, a 9-week feeding trial proved the suitability of Spirulina *maxima* to replace 20% and 40% of fish meal in the diet of *Oreochromis mossambicus* (Peters), fry with insignificant difference ($P>0.05$) in the growth rate and protein utilization values while, the higher inclusion rate significantly lowered the growth and feeding parameters (**Olvera-Novoa *et al.* 1998**).

Consequently, in fingerlings of silver seabream (*Rhabdosargus sarba*), spirulina meal was successful as a substitution for 50% of fish meal for 60 days with no difference in the growth rate and feed conversion efficiency (**El-Sayed. 1994**). In consistence, Spirulina can take the place of 50% of fish meal in the diet of Nile tilapia for 58 days without disrupting its growth performance, survival rat, and proximate body composition (**Al-Nadabi *et al.* 2024**). Furthermore, **Palmegiano *et al.* (2008**) effectively replaced 62.5% of fish meal with Spirulina and the whole fish oil with plant oil in the diet of white sturgeon (*Acipenser transmontanus*) for 71 days without causing any adverse effects on its growth performance or survival rate. Eventually, **Palmegiano *et al.* (2005)** found the ability of Spirulina to replace 90% of fish meal (60% inclusion) in the diet of Siberian sturgeon (*Acipenser baeri*) juveniles for 12 weeks with improving growth parameters, although 75% replacement rate (50% inclusion) induced the best result. However, spirulina failed to replace fish meal completely in brook trout (*Salvelinus fontinalis*), rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta fario*), and African catfish (*Clarias gariepinus*) in 10-week feeding trials where it caused reductions in growth performances and alterations in fillet traits such as color and fatty acid patterns (**Rosenau *et al.* 2021; Rosenau *et al.* 2022**).

**Full replacement of fish meal with Spirulina in fishes feeds**

Spirulina and linseed oil (50%) do well in replacing fish meal and fish oil in mullets (*Mugil liza*) diet in 75 days feeding trial with an increment in antioxidant responses, improvement in its growth performance, and modulation in the fillet quality without negative impact on fillet fatty acids content (**Rosas *et al.* 2019**). In this study, the full replacement negatively affected the mentioned parameters but still better than the control values. Concurrently, **El-Sheekh *et al.* (2014)** found that Spirulina could replace 75% and 100% of fish meal in the diet of hybrid red tilapia (*Oreochromis niloticus x Oreochromis mossambicus*) fries for 65 days with a significant increment in growth and immune

parameters as well as carcass composition and protein productive value. Furthermore, in the diet of juvenile rainbow trout, spirulina could fill the place of fish meal for 56 days without significant difference in growth performance from the control diet (**Dietz *et al.* 2023**). Also, it was possible for spirulina to substitute the whole fish meal in the diet of juvenile gibel carp (*Carassius gibelio*) for 60 days without significant alterations in growth indices, digestive enzyme, antioxidant activities, and immune responses. Interestingly, supplementing the fully replaced diet with 2% dicalcium phosphate or 0.28% coated lysine showed a better nutrient digestibility, antioxidant activity, and immune and growth parameters (**Cao *et al.* 2018**). Moreover, combined use of Spirulina and Chlorella vulgaris (1:1) instead of whole fish meal for 60 days in the feed of rainbow trout significantly, improved its growing parameters and intestinal measurements, although better results was obtained after 50% replacement rate (**Velichkova *et al.* 2024**).

**Partial replacement of fish meal with Spirulina in shrimp's diet**

When Spirulina was represented in the shrimp farming industry, demonstrate several benefits to cultivators that reduce the total cost and deliver a noteworthy cost/performance ratio. Generally, **Li *et al.* (2022)** stated that the optimal levels of Spirulina to replace fish meal in shrimp diets were 14.95%-24.85% without negative impact on the growing performance and feed assimilation. In consistence, Spirulina improved growth performance of white shrimp (*Litopenaeus vannamei*) when replaced 20% of fish meal in its diet for 60 days while, the 40% replacement level caused no significant, improvement in the growing parameters (**Zidan *et al.* 2021**). In addition to, a 50 days feeding experiment, demonstrated that substitution of 25% of fish meal with Spirulina in the nutrition of *Litopenaeus vannamei* improved immunological markers, including an increment in granular haemocyte percentage while, when the replacement level reached 75% it didn't alter growth indices. However, as the replacement level reached 100% the growth parameters were significantly reduced **(Macias-Sancho *et al.* 2014**). Furthermore, Spirulina meal was suggested to take the place of 50% of *Chaetoceros muelleri* in the feed of *Litopenaeus schmitti* larvae during the growth from protozoea substage I to mysis substage I achieving advances in the growth indices while, 100% replacement reduced the growth (**Jaime-Ceballos *et al.* 2006**). Furthermore, when Spirulina was mixed to an equal amount of carp diet (27% protein), induced an improvement in the growth performance and pigment character of *Litopenaeus vannamei* after 11 week feeding trials (**Hanel *et al.* 2007**)

**Full replacement of fish meal with Spirulina in shrimp's diet**

Spirulina proved its availability to fully replace the fish meal in the feed of shrimps, which agree with the findings of **Pakarvan *et al.* (2017**) who establish that the full replacement of fish meal with spirulina for 8 weeks is possible in the diet of *Litopenaeus vannamei* with insignificant reduction in the growth performance. The authors found that the activities of trypsin and chymotrypsin were significantly higher in 50% substitution rate in comparison to shrimp fed the control diet. Moreover, the full replacement of fish meal in diet of the giant freshwater prawn (*Macrobrachium rosenbergii*) for 90 days, significantly improved growth indices, survival rate, and feed utilization however, a better performance was obtained at 50% substitution rate. Meanwhile, in this study, the digestive enzyme measurements were unchanged (**Radhakrishnan *et al.* 2019**).

**Potential Limitations**

**Cost:** Spirulina can be more expensive than other conventional feed ingredients, which may increase the overall production costs. However, although inclusion of Spirulina may elevate the production costs, its benefits such as improvements in Feed conversion ratio, growth performance, and immune responses may outweigh this elevation in the production costs.

**Stability in Feeds:** The exposure of Spirulina to heat and light during feed preparation as well as storage can degrade some bioactive compound present in Spirulina resulting in reductions in the effectiveness of these bioactive compounds causing a decrease of the benefits gained from its inclusion.

**Reduced amount of methionine**
**In some cases, Spirulina may reduce the feed digestibility**
**Future Research and Applications**
Current research is focused on reducing spirulina production costs, improving its cost-effectiveness in feed formulations, and discovering its full range of health benefits for aquatic animals. Another growing area of interest, is the development of spirulina-based bioactive compounds as immunostimulants and growth promoters and their uses in aquaculture industry.

## Conclusion

- Fishing for production of fishmeal deprives aquatic ecosystems of their resources.
- Spirulina is normal part of the aquatic animals' food chain and can be produced in aquaculture.
- Replacing fish meal with spirulina in the feed of aqua farm can decrease fishing pressure on natural fish stocks for production of fish meal.
- Spirulina is a valuable resource in aquaculture but more expensive than conventional feed ingredients, although its benefits such as growth and health improvements may outweigh its higher cost.

Further researches especially for cost reductions and cost effectiveness are necessary to maximize its potential use across various aquaculture systems.

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