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REVIEWING THE POSITIVE IMPACT OF SPIRULINA ON THE HEALTH OF FISH

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Abstract

Aquaculture plays a vital role in global protein production, underscoring the significance of preserving the health and well-being of farmed fish. Spirulina, a blue-green microalgae, is emerging as a promising dietary supplement in aquaculture due to its rich nutritional profile and potential health benefits. This systematic review delves into the existing literature to examine the impact of Spirulina supplementation on fish health. After analysing the selected studies, it was found that various fish species fed with Spirulina-enriched diets showed improved growth, enhanced immune responses, and increased antioxidant capacity. The presence of bioactive compounds, especially phycocyanin, contributes significantly to these health benefits. Despite challenges in determining optimal dosage and addressing environmental considerations, the incorporation of Spirulina into fish diets shows potential for enhancing aquaculture sustainability and productivity. Therefore, this review highlights Spirulina's potential as a beneficial dietary additive in maintaining the general health and welfare of cultured fish.

Key words*: aquaculture, enriched diets, fish health, spirulina.*

INTRODUCTION

Microalgae play a vital role in the aquatic food chain, widely used in aquaculture for the growth of aquatic animals. For example, microalgae serve as a primary food source for the larval stages of many aquatic species and contribute significantly to the overall health and productivity of aquatic ecosystems by improving water quality (Ma & Hu, 2023; Cai et al., 2021; Borowitzka, 1998). The chemical composition of algae provides basic information about their trophic potential. Microalgae are gaining popularity in aquaculture due to their moderate size, high nutritional value, rapid growth, and robust resistance to antioxidants and diseases (Mishra et al., 2022; Habib et al., 2008; Brown et al., 1997).

Algae, as the earliest life forms on Earth, reproduce independently, providing nutrients for the growth of other producers and the next trophic levels. Besides this, they also generate oxygen as a byproduct of their growth, contributing to around 70% of the Earth's free oxygen (Tietze, 2004).

Spirulina (*Arthrospira platensis* Gomont, 1892), a green-blue microalgae, is a symbiotic, multicellular, filamentous organism associated with nitrogen-fixing bacteria. Its unique features include the pigment phycocyanin for photosynthesis, giving it a distinct blue colour. Spirulina's reproduction involves binary fission, and its spiral configuration forms floating mats. It appeared approximately 3.6 billion years ago, utilizing dissolved carbon dioxide present in seawater as a source of nutrients (Vo et al., 2015).

Spirulina has been used therapeutically since the 8th century, initially discovered and utilized by ancient African civilizations and later by Aztecs in Central America (Ciferri, 1983).

Botanically classified as microalgae in the class Cyanophyceae, Spirulina's prokaryotic structure leads bacteriologists to categorize it as bacteria. Its morphological plasticity is influenced by genetic changes, environmental factors, and physico-chemical conditions (Richmond, 2004; Vonshak, 1997). Spirulina is rich in nutrients that transform this alga into a valuable food source and through the years, extensive studies on biochemical composition, safety consumption, physiological effects of enriched diets on animal organisms, and toxicity testing were carried out and proved that Spirulina is a useful feed ingredient for both human and animal consumption (Anvar & Nowruzi, 2021; Habib et al., 2008; Becker, 2007; Vonshak, 1997; Belay et al., 1993).

MATERIALS AND METHODS

In this review, we conducted a comprehensive literature search to gather and analyse existing research on the positive impacts of Spirulina on the health of fish. The primary databases used for the search included Google Scholar, Web of Science and Scopus. The search terms included combinations of keywords such as "Spirulina", "fish health", "aquaculture", "immune response", "growth performance”. Inclusion criteria were set to encompass the relevant peer-reviewed articles and reviews. Studies specifically addressing the effects of Spirulina supplementation on various health parameters of fish, such as growth performance, immune response, and overall health were included.
Articles were first screened by title and abstract for relevance, and then full texts were reviewed for detailed information. Data were extracted and synthesized to provide a comprehensive understanding of the current state of research on the topic.

RESULTS AND DISCUSSIONS

Nutritional composition and active compounds of spirulina

Spirulina has captivated the attention of specialists in the field because of its essential biochemical compounds, surpassing many other microalgae species that have been studied (Henrikson, 2009). Spirulina can be easily and cost-effectively cultivated using low-cost culture media. It grows in water, can be harvested and processed easily, and has a significantly high content of macro and micronutrients. Spirulina has been commercially cultivated since the 1960s in various countries worldwide due to its high nutritional content, including high-quality proteins, carbohydrates, amino acids, vitamins, minerals, essential fatty acids, and other bioactive compounds like pigments (β-carotene) and phenolic acids (Vonshak, 1997; Becker, 1994). This composition (Figure 1) varies based on factors such as the source, culture conditions, and production season (Grosshagauer et al., 2020; Falquet, 2017; da Rosa et al., 2016; Vernès et al., 2015; Babadzhanov et al., 2004; Tokuşoglu, 2003; Phang et al., 2000). The 60-70% high protein content is much higher than that found in eggs, meat, milk, soybeans, or other cereals (Belay et al., 2008; Becker, 2007). It is also rich in B-group vitamins such as vitamin B12 (8 ppm) and provitamin A (0.2%), minerals like iron (0.1%), and polyunsaturated fatty acids representing 30% of total lipids, especially ω-6 fatty acids (up to 29.4-31.5% of total fatty acids), linoleic acid, stearidonic acid, arachidonic acid, eicosapentaenoic acid, and docosahexaenoic acid (El-Samragy, 2012; Habib et al., 2008). The presence of all essential amino acids constitutes 47% of the total protein, and among all essential amino acids present, valine, leucine, and isoleucine have the highest value (Belay et al., 2008; Becker, 2007). The cellular wall of Spirulina contains polysaccharides with an 86% digestibility, facilitating assimilation by the animal organism (Becker, 1994).
Spirulina is not only rich in nutrients but also serves as a source of phytopigments, including chlorophyll, carotenoids, and phycobiliproteins. These pigments play a vital role in capturing light within Spirulina. In 2013, Kuddus et al. found that the phycobiliproteins extracted from Spirulina are phycocyanin (C-PC), allophycocyanin (A-PC), and phycoerythrin (PE). Later, it was determined that phycocyanin represented up to 50% of phycobiliprotein content (Li et al., 2020).
Due to this valuable composition of useful nutrients, Spirulina became widely a nutritional supplement suitable for animal feed and humans, too (Kim, 2013; Qureshi et al., 1996; Glombitza & Koch, 1989).

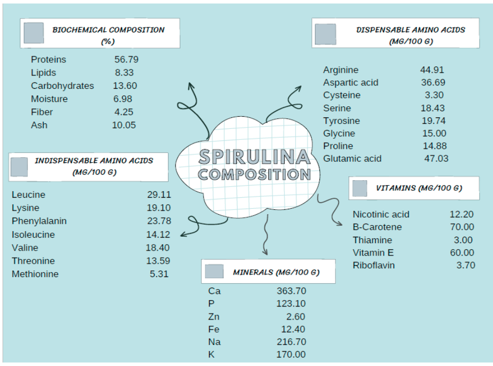

Figure 1. The composition of Spirulina and its bioactive constituents (after El-Moataaz et al., 2019)

Therefore, from the perspective of the biochemical composition, it has been proved that Spirulina is an excellent source of beneficial nutrients and healthful substances, as well as a good source of energy, making it a suitable addition to feed formulations.

Contribution of spirulina to human health

Global development of the Spirulina market primarily involves the utilization of dried whole Spirulina biomass, serving as a healthy dietary supplement for animals and humans, with the assumption that its consumption may promote, prevent, aid, or cure common diseases and malnutrition.

Since the 1980s, there have been found applications of Spirulina in healthy nutrition, animal feed, and biochemical products (Becker, 1988; Borowitzka, 1988).

Numerous commercial products contain Spirulina biomass, Spirulina extracts or its active ingredients and that could be included as additives in animal feed, health-improvement products for animals, natural food and cosmetic colourants, as well as purified biomolecules for medicine and biotechnology (Henrikson, 2009).

Further investigations on the bioactive properties of Spirulina (Teimouri et al., 2016; Kim et al., 2013; Andrews et al., 2011; Promya & Chitmanat, 2011) have highlighted improvements for both health and stress resistance of the organism, reinforcing the idea of its use in animal feed as a functional additive.

Due to its high iron content, Spirulina increases iron absorption by 60% compared to the regular iron supplement. Moreover, studies have indicated anaemia correction in rats and potential benefits in conditions such as arthritis, heart diseases, obesity, and zinc deficiency (Henrikson, 2009).

A comparative experiment on mice specimens treated with Spirulina-derived carotenoids and others treated with synthetic β-carotene demonstrated the superior hepatoprotective effect of Spirulina's bioactive compounds (Chidambara Murthy et al., 2005).

Over time, Spirulina has revealed a wide range of physiological responses in animal organisms, including the substantial improvement of the immune system, with implications extending to human practices.

Therefore, Spirulina has been used in healthy food products such as soups, sauces, pasta, snacks, and instant drinks to enhance their nutritional value. From this point of view, studies have indicated positive results in treating severe malnutrition in children and in reducing blood glucose levels (Vonshak, 1997).

Other clinical studies (Habib et al., 2008) have highlighted multiple benefits of Spirulina, demonstrating the effectiveness of Spirulina capsules in reducing blood lipid levels and decreasing the white blood cell count in patients undergoing radiation and chemotherapy treatments. In support of this finding, investigations on mice exposed to lethal doses of radiation recorded increased survival rates due to the enhancement of the immune system in the specimens with Spirulina administration. Also, incorporated as an effective supplement in human patients' diet, Spirulina has been found to reduce blood lipid levels, enhance fatigue resistance, and elevate the levels of immunoglobulin A (IgA) and immunoglobulin M (IgM) in athletes (Habib et al., 2008). In a vitro study, Spirulina's phycocyanin has also demonstrated the ability to inhibit cells' growth in leukaemia (Liu et al., 2000).

Recently, Anvar & Nowruzi (2021), in their review, indicated that Spirulina was tested as a remedy for various diseases and a daily source of nutrients, being a promising healthy ingredient for the food industry in human nutrition. The authors considered Spirulina as a superfood and an optimal nutritional source for combating malnutrition.

The impact of spirulina in the aquaculture industry

Even from the 1960s, due to simultaneous trends of increasing fish-based product consumption and declining of fish global captures from natural waters, finding alternative protein sources for fish meal, whether plant-based or animal-based, has become essential for preparing balanced fish feed (Burel & Kaushik, 1965). Gladue & Maxey (1994) explored the idea of replacing fishmeal proteins with microalgae as a main protein source in artificial fish feed formulations in aquaculture. Over time, due to continuously decreasing fishmeal supply and rising costs, various algae and plants have been tested as alternative protein sources, with the converged purpose of enhancing the fish meat's colour, flavour, and quality, too (Becker, 2007).

In recent years, aquaculture researchers have focused on the nutritional use of Spirulina as a substitute for fishmeal or as functional feed for aquatic organisms (Table 1). This approach has proved beneficial apport to produce omnivorous and herbivorous fish species that naturally include algae in their diet (Rosas et al., 2019).

A study conducted by Teimouri et al. (2013), investigating various diets of *Spirulina platensis* at 0, 2.5, 5, 7.5, and 10%, alongside synthetic astaxanthin (50 mg), assessed their impact on skin and fillet pigment, as well as on the growth performance of rainbow trout (*Oncorhynchus mykiss*). Their findings revealed that the most significant influence of carotenoids on skin and fillet occurred at a 10% incorporation of *Spirulina platensis* into the fish diet. Additionally, it was demonstrated that Spirulina can replace synthetic astaxanthin in rainbow trout diets.

In terms of cost reduction in fish feed, El-Sheekh et al. (2014) found that incorporating Spirulina flour at a 75% inclusion rate in red tilapia feed resulted in reduced feeding expenses (cost/kg of feed), together with an increased profit index. Furthermore, Nakano & Wiegertjes (2020) have reported that the absence of cellulose from Spirulina's cell structure makes it easily digestible, thereby enhancing feeding appetite. This improvement in food intake and nutrient digestibility contributes to the fish's health enhancement (Figure 2) and the strengthening of their defence against infections due to reduced stress levels.

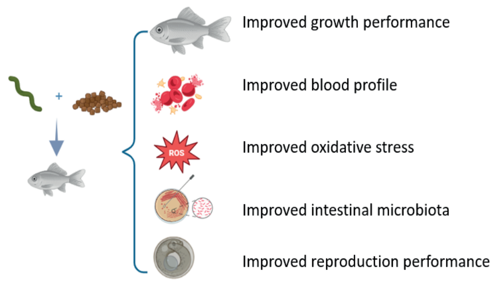

Figure 2. Effects of Spirulina on fish health (after Ragaza et al., 2020)

Table 1. Recent studies exploring the utilization of Spirulina as a supplement in fish feed

Fish species	Proportion of fishmeal or ingredient substituted in feed formulations by Spirulina	Impacts of substituting with Spirulina	References
Nile tilapia (*Oreochromis niloticus)*	0.2% inclusion	↓oxidative stress, ↓tissue damage (liver, kidney, spleen) caused by florfenicol and/or bacterial infection	Abu-Zahra et al. (2024)
Nile tilapia (*Oreochromis niloticus*)	1%, 2% & 3% inclusion	↑growth performance, ↑gene expression, ↑biochemical parameters	Abozaid et al. (2023)
Nile tilapia (*Oreochromis niloticus*)	0.2% & 0.4% inclusion	↑protection against imidacloprid toxicity, ↑growth, ↑haemato-biochemical parameters, ↑oxidant/antioxidant balance, ↑immunity	Abdel-Tawwab et al. (2021)
Nile tilapia (*Oreochromis niloticus*)	15% inclusion	↑fish body protein levels, ↑immune response against *A. hydrophila* infection, ↓oxidative stress,↑enzymatic antioxidants, ↓MDA levels, ↓histopathological changes	El-Habashi et al (2019)
Nile tilapia (*Oreochromis niloticus*)	5–50% inclusion	↑growth, ↑tissue characteristics	Bin Dohaish et al. (2018)
Nile tilapia (*Oreochromis niloticus*)	0.5% & 1% supplementation	↑antioxidant status (hepatic, renal) against diazinon toxicity	Abdelkhalek et al. (2017)
Nile tilapia (*Oreochromis niloticus*)	0%, 30%, 45%, 60% & 75% replacement	↓blood triglyceride levels, ↑productive performance in 30% group	Velasquez et al. (2016)
Nile tilapia (*Oreochromis niloticus*)	up to 1% supplementation	↑ blood serum defences, ↓lipid peroxidation	Abdelkhalet et al. (2015)
Nile tilapia (*Oreochromis niloticus*)	up to 10% supplementation	↑serum antioxidant activities, ↑growth, ↑resistance against *V. algynoliticus*	Abdel-Latif and Riad (2014)
Nile tilapia (*Oreochromis niloticus*)	0.5-2% supplementation	↑health of fish, ↑tissue protection, ↑antioxidant capacity	Ibrahem et al., (2013)
Tilapia (*Oreochromis* sp.)	Up to 43% replacement	↓feed conversion ratio (FCR) in Spirulina groups compared to	Hussein et al.,

Fish species	Proportion of fishmeal or ingredient substituted in feed formulations by Spirulina	Impacts of substituting with Spirulina	References
larvae or juveniles		control diet (corn-gluten meal)	(2013)
Hybrid red tilapia *(Oreochromis niloticus x Oreochromis mossambicus*)	75% replacement	↑growth performance, ↑feed efficiency, ↑ immunity capacity	El-Sheekh et al. (2014)
Rainbow trout (*Oncorhynchus mykiss*) juvenile	250, 500, 1000 & 2500 mg supplementation	↑growth performance, ↑survival rate, ↑FCR, in 250 mg extract of Spirulina group	Kermani et al. (2020)
Rainbow trout (*Oncorhynchus mykiss*)	2.5% & 5% supplementation	↑histological parameters, ↑immune-related gene expression in mucosal tissues and fish resistance against *Y. ruckeri*	Sheikhzadeh et al. (2019)
Rainbow trout (*Oncorhynchus mykiss*)	up to 10% supplementation	↓oxidative stress, ↑increased antioxidant level	Teimouri et al. (2019)
Rainbow trout (*Oncorhynchus mykiss*)	10% supplementation	↑red and white blood counts, ↑haemoglobin, ↑total protein, ↑albumin	Yeganeh et al. (2015)
Rainbow trout (*Oncorhynchus mykiss*)	50 g and 100 g/kg supplementation	↑muscle quality, ↓lipid accumulation, ↑polyunsaturated fatty acids (PUFAs) content (natural antioxidant), ↓reduces lipid peroxidation, ↓postmortem deterioration, ↑human health indicators	Teimouri et al. (2015)
Rainbow trout (*Oncorhynchus mykiss*)	7.5% replacement	↑weight gain	Teimouri et al. (2013)
Caspian brown trout (*Salmo trutta caspius*)	6% & 8% supplementation	↑growth, ↑carcass composition, ↑colouration	Roohani et al. (2019)
Common carp (*Cyprinus carpio*)	10mg/kg supplementation	↑haematological profile, ↑biochemical blood status, ↑growth performance	Ahmed et al. (2023)
Common carp (*Cyprinus carpio*)	0.1, 0.3 & 0.5 supplementation	↑growth performance	Abdulrahman (2014)
Gibel carp (*Carassius auratus*)	up to 100% replacement	↑antioxidant activities, ↑immune system	Cao et al. (2018)
Grass Carp juvenile *(Ctenopharyngodon idella*)	up to 5% supplementation	↑growth performance, ↑antioxidant status, ↑digestive enzyme activity, ↑innate immune status	Faheem et al. (2022)
Persian sturgeon (*Acipenser persicus*)	2.5%, 5% & 7.5% supplementation	↑haematological status, ↑artificial reproduction efficiency in the group with 7.5% Spirulina	Akhoundian et al (2023)
Beluga Sturgeon (*Huso huso*)	up to 10% inclusion	↑growth performance, ↑immune response, ↑disease resistance, ↑ digestive enzyme activity	Adel et al. (2016)
Sabah giant grouper	5% enriched diet	↑growth performance, ↑intestinal microbial function	Man et al. (2020)
Oscar fish (*Astronotus ocellatus*)	55 g/kg supplementation	↑growth performance, ↑feeding parameters, ↑protease activity, ↑ protein content, ↓fat content, ↑immune biochemical status, ↑blood profile, ↑digestive enzyme activities, ↑overall pigmentation	Mohammadiazarm et al. (2021)
Parrot fish (*Oplegnathus fasciatus*)	5% replacement of protein	↑weight gain, ↑protein efficiency ratios, ↑feed intake, ↓feed conversion ratios compared to the control diet (fishmeal)	Kim et al. (2013)

Integration of spirulina in fish feed to boost the immune system and enhance growth performance

The usual ingredients in aquaculture feedstuff are seeds, cereals, and different animal by-products meals which are considered costly components. Therefore, the feeding costs are seen to reach, in general, 60-70% of the operational costs in intensive and semi-intensive aquaculture systems (Singh, 2006). Long-time research has been focused on replacing expensive components, either in part or entirely, with other products. For example, extensive investigations have been conducted to assess various alternative protein sources as partial or complete replacements for fishmeal in different fish species. The examined references have indicated that supplementing fish diets with additives like Spirulina involves multiple nuances related to their targeted effects on various physiological aspects.

Adel et al. (2016) have emphasized Spirulina's ability to improve growth parameters, with notable effects observed, especially at a 10% inclusion rate in great sturgeon's diet. These results regarding enhanced growth, increased activity of digestive enzymes, and improved immune response have contributed to heightening the organism's resistance to bacterial disease. In 2019, another study conducted by El-Habashi et al. obtained similar findings on Nile tilapia. They observed that the supplementation of dried microalgae significantly enhanced fish body protein and immune response against specific infections, while also improving the oxidative stress markers and mitigating histopathological changes.

Recently, Abozaid et al. (2023) investigated the optimal levels of Spirulina incorporation in Nile tilapia diets and found significant enhancements in growth performance, gene expression, and biochemical parameters at a 1% inclusion rate. Nevertheless, they advised against exceeding this optimal level due to potential adverse effects on certain physiological aspects.

Further, Abu-Zahra et al. (2024) revealed the synergistic impact of Spirulina and antibiotics, highlighting the potential risks associated with antibiotic overuse in aquaculture. They recommended for use of alternative additives, such as immunostimulants, in disease treatments to minimize the emerging environmental hazards and bacterial resistance.

Research on rainbow trout (Teimouri et al., 2019; Sheikhzadeh et al., 2019) recorded the antioxidant and immunomodulatory effects of Spirulina, showcasing its potential as a beneficial dietary supplement for fish farming.

The positive effects of Spirulina supplementation on growth performance and stress resistance in rainbow trout were also studied by Kermani (2020).

In the case of grass carp, adding Spirulina up to 5% improved growth performance, antioxidant levels, digestive enzymes, and innate immune indicators (Faheem et al., 2022).

In a recent study, Akhoundian et al. (2023) found notable physiological benefits of incorporating Spirulina into the diet of Persian sturgeon fry. However, they also emphasized the need for further research before implementing Spirulina enriched diet commercially in sturgeon culture.

Integration of spirulina in fish feed to improve fish haematological status and oxidative stress

Generally, fish are more susceptible to diseases when they experience stress triggered by adverse environmental conditions, poor management practices, or a reaction to the limited availability of essential nutrients in their diet (Oliva-Teles et al., 2015).

The evaluation of haematological status is an important and accessible tool in determining the health and wellness of fish. It has been demonstrated that the characteristics of the haematologic indicators have a strong correlation with the animal's reaction to its environment, indicating that some influence may be exerted on histological characteristics by the rearing conditions (Gabriel et al., 2004). These biomarkers offer valuable insights into the fish's circulatory system and how they react to environmental and stress stimuli. Through the analysis of haematological and biochemical blood parameters, it can be identified conditions like anaemia, inflammation, or infections, thereby facilitating health monitoring and the implementation of prophylactic/treatment strategies to enhance the living conditions of fish in both aquaculture and natural settings. (Lataretu, 2013).

The protective efficacy of *Spirulina platensis* against ethidium bromide toxicity in tilapia fish (*Oreochromis niloticus*) was investigated by Abdullah et al. (2024) and they observed that most of the histological and histochemical parameters have returned to baseline levels following *Spirulina platensis* supplementation. These results reinforced previous findings drawn by Sayed et al. (2015; 2017) attributed to *Spirulina platensis*' bioactive compounds, including C-phycocyanin, provitamin A (β-carotene), minerals, vitamins, proteins, carbohydrates, and lipids, which are possessing antioxidant and anti-inflammatory properties, helpful in maintaining the membranes' structural integrity in liver and kidney by scavenging free radicals (Salah El-Din et al., 2021).

The presence of specific pesticides in the water resulted from agricultural practices exposes fish to oxidative stress, causing significant harm to their health. For example, common carp (*Cyprinus carpio*) exposed to atrazine (428 μg/L) and Spirulina (1%), either separately or in combination, for 40 days, demonstrated a significant increase in lipid and DNA oxidative damage markers, and a significant decrease in antioxidant biomarkers. However, the addition of 1% Spirulina to the diet led to a significant decrease in hepatotoxic and inflammatory effects induced by atrazine-induced oxidative stress (Toughan et al., 2018).

Abdelkhalek et al. (2017) observed the protective effects of Spirulina against intoxication induced by certain chemicals and pesticides in Nile tilapia, attributing this to its antioxidant properties capable of mitigating oxidative damage.

High protective effects against toxicity were observed by Abdel-Tawwab (2021) in Nile tilapia fed with Spirulina, as well as the improvement of various physiological parameters.

In the study conducted by Adel et al. (2016) related to the beneficial addition of Spirulina into the diet of the great sturgeon (*Huso huso*), there has been observed a decrease in triglyceride values in comparison with the control group, an increase in haemoglobin concentration, haematocrit value, and neutrophil count, beside the other physiological responses previously mentioned above.

A scientific investigation was undertaken to assess the immunostimulatory impact of a combination of Spirulina and a β-glucan additive (MacroGard®) in *Acipenser stellatus*. The experimental protocol involved feeding the fish with a diet comprising 3% of their body weight, containing 0.1% MacroGard® and 0.5% Spirulina, over 12 weeks. Substantial enhancements in both body metrics and haematological parameters were observed following this feeding regime (Salehi-Farsani et al., 2016).

CONCLUSIONS

In summary, the research underscores the benefits of integrating Spirulina into fish diets, highlighting its potential to enhance growth, support stress resilience, and reinforce immune function. These findings suggest that Spirulina supplementation offers protection against various stressors such as bacterial infections and chemical toxins. However, careful consideration of optimal dosage and avoidance of over-supplementation are imperative to prevent adverse effects on fish health. Consequently, Spirulina emerges as a promising stimulant in aquaculture, for commercial application. Nevertheless, more investigations are necessary to elucidate the underlying mechanisms and ensure the efficacy and responsible utilisation of this technology in fish farming. Overall, Spirulina represents a valuable tool in mitigating the impact of environmental stressors and promoting the health and stress resilience of fish, particularly in aquaculture conditions. where the feeding management allows custom-enriched diets with this alga.

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