(ISSN: 0973-7049(P))

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(3): S.I (3), 553-572, 2026 www.thebioscan.com

The Multifaceted Role of Fucoxanthin: Enhancing Fish Health and Sustainable Aquaculture through Antioxidant, Anti-inflammatory, and Antimicrobial Properties

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DOI: https://doi.org/10.63001/tbs.2026.v21.i03.S.I(3).pp553-572

KEYWORDS

Fucoxanthin, marine microalgae, fish health, antioxidant properties, and anti-inflammatory effects.

Article Info

Received: 30.06.2026

Accepted: 19.07.2026

Published:29.07.2026

Abstract

Fucoxanthin, a carotenoid derived from marine microalgae, has garnered attention for its potential to enhance fish health and nutrition. Known for its diverse pharmacological properties, fucoxanthin offers antioxidant, anti-inflammatory, and nutritional benefits that can significantly improve fish well-being and aquaculture outcomes. As a potent antioxidant, fucoxanthin protects fish from oxidative stress by reducing damage from reactive oxygen species (ROS), thereby promoting growth and survival rates in aquaculture environments. Additionally, its anti-inflammatory effects may help reduce inflammation-related stress in fish, enhancing resilience against diseases that commonly affect aquaculture populations. From a nutritional perspective, incorporating fucoxanthin into fish feed can improve growth performance, feed efficiency, and immune responses, ultimately leading to healthier fish stocks. The study explores the potential benefits of fucoxanthin, a marine microalgae-derived carotenoid, in enhancing fish health and performance in aquaculture, focusing on its antioxidant, anti-inflammatory, and nutritional properties. Despite these promising benefits, challenges like bioavailability and scalable production must be addressed to maximize fucoxanthin's impact in aquaculture. Further research is needed to optimize its application and fully understand its long-term effects on fish health and growth.

Introduction

Aquaculture has emerged as a vital industry to meet the rising global demand for fish, but it faces numerous challenges, particularly from bacterial and fungal infections that threaten fish health, yield, and economic viability[1]. In aquaculture environments, conditions such as high stocking densities, water quality fluctuations, and stress from handling can exacerbate the spread of infectious agents, making fish populations vulnerable to bacterial diseases[2]. These infections are widespread across various aquaculture systems, affecting both freshwater and marine species and often leading to significant morbidity and mortality[3]. The economic impact of bacterial infections in aquaculture is substantial, as outbreaks can reduce fish quality, decrease production efficiency, and increase the costs associated

with disease management and stock replacement. A growing concern in aquaculture is the increased resistance of these bacterial pathogens to conventional antibiotics[4]. The excessive use of antibiotics in aquaculture has led to the development of antibiotic-resistant bacteria, which can diminish the effectiveness of treatments, complicate disease management, and pose potential health risks to consumers and the environment. This rising antibiotic resistance has highlighted the urgent need for alternative approaches to managing bacterial infections in aquaculture[5,6]. As a result, there is a strong interest in exploring natural, sustainable antibacterial compounds that can effectively control bacterial pathogens without contributing to antibiotic resistance. Fucoxanthin, a naturally occurring carotenoid derived from brown seaweeds and marine microalgae, has emerged as a promising candidate in this context. Known for its diverse pharmacological properties, fucoxanthin offers antioxidant, anti-inflammatory, and nutritional benefits that have the potential to enhance fish health and resilience in aquaculture[7]. In addition to promoting growth, survival, and immune responses in fish, fucoxanthin has demonstrated antibacterial properties against pathogens commonly found in aquaculture. Fucoxanthin has been found to inhibit the growth of bacteria like *Aeromonas* and *Vibrio*, potentially improving fish health and reducing reliance on antibiotics[8]. Its antibacterial effects are multifaceted, including disrupting bacterial cell membranes, increasing permeability, and leading to cell lysis. It also prevents the formation of biofilms, which protect bacteria from environmental stressors and antimicrobial agents[9,10]. This prevents biofilm formation, exposing bacterial cells to natural immune responses or treatments, making them easier to eliminate. Additionally, fucoxanthin induces reactive oxygen species, leading to oxidative stress and cell death. Given these promising attributes, fucoxanthin has the potential to serve as a natural antibacterial as well as antifungal agent in aquaculture, offering an alternative approach to managing dual infections[11,12]. This study aims to explore the antioxidant, anti-inflammatory activity, and antimicrobial efficacy of fucoxanthin in aquaculture, focusing on its specific mechanisms of action against prevalent pathogens and its broader impact on fish health and productivity. By advancing our understanding of fucoxanthin's antibacterial properties, this research seeks to address a critical gap in sustainable disease management in aquaculture, promoting healthier fish

populations and reducing the industry's reliance on antibiotics.

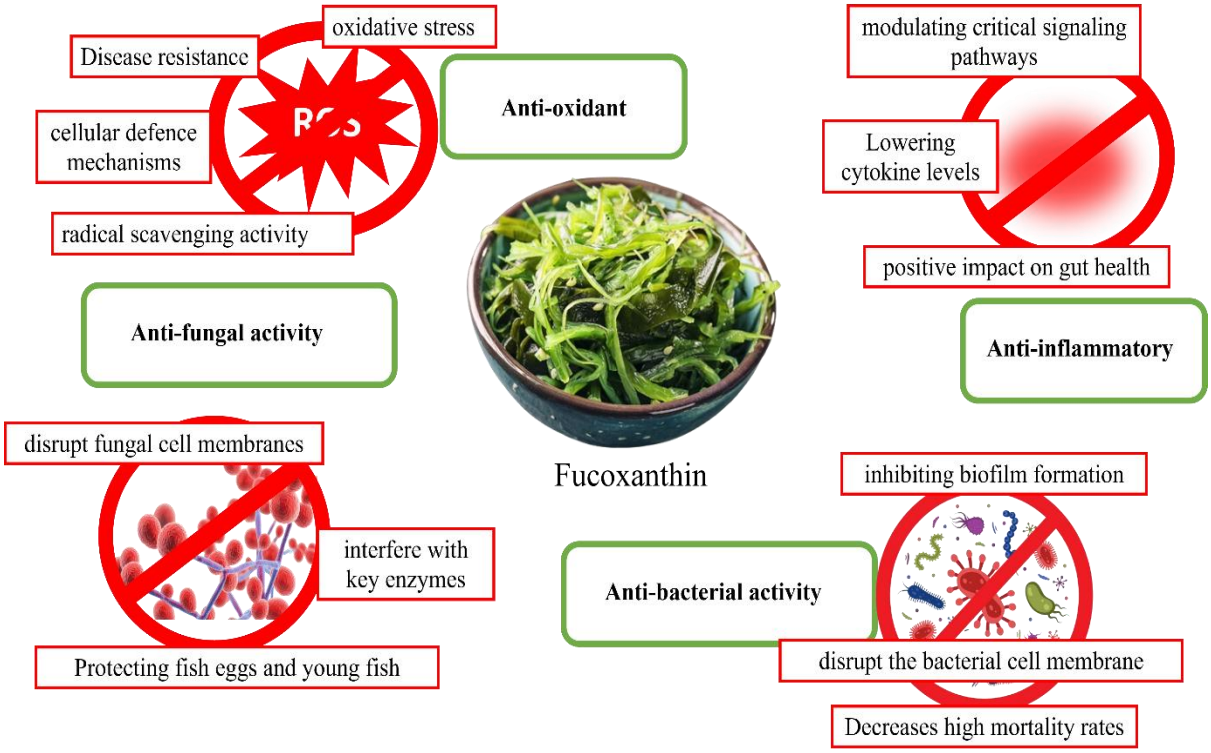

Figure 1. Comprehensive overview of fucoxanthin in the role of anti-oxidant antimicrobial, anti-fungal and anti-inflammatory activity

Antioxidant activity of Fucoxanthin in Enhancing Fish Health and Aquaculture Sustainability

Fucoxanthin, a carotenoid with strong antioxidant properties, is emerging as a valuable natural compound for enhancing fish health and nutrition in aquaculture. Its primary role in combating oxidative stress makes it a key contributor to overall fish well-being[13]. Oxidative stress results from an imbalance between free radicalsunstable molecules that can damage cellsand the body's ability to neutralize them. In fish, oxidative stress can lead to weakened immune function, impaired growth, and increased susceptibility to diseases. Incorporating fucoxanthin into fish diets helps to alleviate these challenges by protecting cells from oxidative damage and supporting a range of physiological processes critical for optimal health[14]. Fucoxanthin's antioxidant effects stem from its ability to neutralize reactive oxygen species (ROS), the harmful by-products of normal cellular processes that can cause oxidative damage if left unchecked. Research demonstrates that fucoxanthin's antioxidant activity is dose-dependent, with

higher concentrations providing greater free radical scavenging capabilities[15,16]. Common assays, such as DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), confirm that fucoxanthin effectively reduces the levels of free radicals, helping to maintain cellular integrity. Fucoxanthin's antioxidant properties have been quantitatively assessed in multiple assays[17,18]. In a study the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, fucoxanthin exhibited an IC_{50} value of 201.2 ± 21.4 µg/mL. This IC_{50} value, which indicates the concentration required to inhibit 50% of free radicals, is moderate compared to ascorbic acid, which has a stronger scavenging effect with an IC50 of 70.3 ± 18.7 µg/mL[17]. Nonetheless, fucoxanthin's antioxidant potential remains substantial, especially given its natural origin and broad health benefits. In the FRAP (Ferric Reducing Antioxidant Power) assay, which measures antioxidant capacity in terms of reducing power, fucoxanthin demonstrated a value of 64.74 ± 3.93 mmol Fe^{2+}/g. This level of activity is significantly higher than β-carotene, which showed a reducing capacity of 6.55 ± 0.33 mmol Fe^{2+}/g. Moreover, fucoxanthin's FRAP results are on par with astaxanthin, another potent antioxidant, which registered a value of 63.97 ± 6.79 mmol Fe^{2+}/g[19]. These findings underscore fucoxanthin's efficacy in reducing oxidative agents, with its highest tested concentration (50 µg/mL) producing a notable increase in antioxidant activity in a dose-dependent manner. Further insights into fucoxanthin's antioxidant power come from studies involving the marine diatom *Odontellaaurita*. In these studies, fucoxanthin's radical scavenging activity was examined using DPPH and ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) assays. The DPPH assay demonstrated an EC50 (effective concentration for 50% scavenging) of 0.14 mg/mL, indicating strong antioxidant potential as the concentration increased. In the ABTS assay, fucoxanthin achieved a 90.3% scavenging rate at a concentration of 0.2 mg/mL, confirming its robust capacity to neutralize oxidative radicals and enhance cellular defense mechanisms[20]. This scavenging activity is crucial for maintaining oxidative stability in fish, which in turn supports overall health and immunity. Fucoxanthin, a natural antioxidant with multiple health benefits, is a valuable addition to fish diets. It safeguards fish cells from oxidative damage, which can lead to inflammation, immune suppression, and cellular dysfunction[21]. Fucoxanthin stabilizes

free radicals, protecting crucial cellular components like lipids, proteins, and DNA from damage. This protection is crucial for maintaining cellular health in high-stress environments, such as crowded tanks, fluctuating water conditions, or exposure to pollutants. Fucoxanthin's antioxidant properties also have a positive impact on the immune system, reducing inflammation and allowing the immune system to function more effectively[22]. This improves fish's withstand ability to diseases, parasites, and environmental challenges. Fucoxanthin's immunomodulatory effect makes it a valuable tool in improving disease resistance without relying on antibiotics or chemical interventions. Healthy gut function is essential for fish to absorb nutrients efficiently from their diets. Fucoxanthin's antioxidant effects help preserve gut integrity, promoting better feed conversion and nutrient utilization. Improved gut health translates into enhanced growth rates and overall fish performance, making fucoxanthin an asset for aquaculture operators seeking higher yields and improved fish quality. Fucoxanthin also plays a role in regulating metabolic processes essential for fish health[23]. Studies indicate that fucoxanthin enhances insulin sensitivity, supporting stable energy use and efficient metabolism. This helps fish cope with stress and challenging environmental conditions, contributing to steady growth and development. Fucoxanthin's comprehensive health benefits make it an ideal candidate for functional aquafeeds, which aim to improve fish welfare and production outcomes[24]. Incorporating fucoxanthin into aquafeeds not only enhances fish resilience to environmental stressors and diseases but also supports sustainable aquaculture practices by leveraging natural compounds with minimal side effects.

Table 1: Antioxidant and Health Benefits of Fucoxanthin in Enhancing Fish Health and Promoting Sustainable Aquaculture

Anti-Oxidative Aspect	Details	Key Findings/Values	Impact on Fish Health & Aquaculture
Role in Combating Oxidative Stress	Fucoxanthin neutralizes reactive oxygen species (ROS), reducing	Alleviates oxidative stress, which weakens immune function and growth.	Protects against cell damage, improves overall fish health, and reduces disease risk.

	oxidative damage and supporting physiological processes.		
Antioxidant Mechanisms	Neutralizes free radicals (ROS) and enhances cellular integrity.	Dose-dependent activity; higher concentrations provide stronger free radical scavenging capabilities.	Supports cell stability and reduces oxidative stress.
DPPH Radical Scavenging Assay	Measures free radical scavenging activity of antioxidants.	Fucoxanthin IC50: 201.2 ± 21.4 µg/mL; Ascorbic Acid IC50: 70.3 ± 18.7 µg/mL.	Moderate scavenging effect compared to ascorbic acid but substantial due to natural benefits.
FRAP Assay (Ferric Reducing Power)	Assesses antioxidant capacity by measuring reducing power.	Fucoxanthin: 64.74 ± 3.93 mmol Fe^{2+}/g; Astaxanthin: 63.97 ± 6.79 mmol Fe^{2+}/g.	Comparable antioxidant activity to astaxanthin, a potent antioxidant.
DPPH & ABTS Assays on Marine Diatom	Evaluates fucoxanthin's scavenging activity in marine diatom (Odontellaaurita).	DPPH EC50: 0.14 mg/mL; ABTS scavenging rate: 90.3% at 0.2 mg/mL.	Strong antioxidant potential with dose-dependent increase in scavenging activity.
Effects on Immune System	Fucoxanthin reduces oxidative damage, leading to enhanced immune function.	Reduces inflammation, supports immune defense mechanisms.	Improved disease resistance without reliance on antibiotics.
Gut Health and Feed Efficiency	Fucoxanthin helps preserve gut integrity, improving nutrient absorption and feed conversion.	Promotes better feed efficiency and gut health, supporting fish growth.	Enhanced growth rates and overall fish performance, leading to higher yields.

Regulation of Metabolic Processes	Enhances insulin sensitivity and supports stable energy metabolism, helping fish cope with stress.	Regulates metabolism for steady growth and development.	Contributes to resilience against environmental challenges.
Sustainability in Aquaculture	Fucoxanthin provides a natural, side-effect-free solution for enhancing fish health and reducing environmental stressors.	Supports sustainable practices by reducing the need for antibiotics or chemical interventions.	Aligns with goals of sustainable aquaculture by improving fish health naturally.

Anti-inflammatory Activity of Fucoxanthin in Enhancing Fish Health and Gut Function

Fucoxanthin's anti-inflammatory make it a valuable natural compound for enhancing fish health and nutrition in aquaculture. Inflammation, a common challenge in fish farming, can be triggered by multiple factors, including environmental stressors like temperature fluctuations, exposure to toxins, the presence of pathogens, and poor-quality diets[8,25]. Chronic or prolonged inflammation not only hampers growth and performance but also weakens the immune system, making fish more prone to diseases and reducing their overall welfare. This is where fucoxanthin, a carotenoid derived from brown seaweed, comes into play. Fucoxanthin is known to exert significant anti-inflammatory effects by modulating critical signaling pathways. One of the key pathways influenced by fucoxanthin is the interferon regulatory factor 3 (IRF3) pathway, which is integral in regulating innate immune responses[26,27]. By targeting this pathway, fucoxanthin reduces the production of pro-inflammatory cytokines—molecules that mediate and exacerbate inflammation[8,21]. Lowering cytokine levels helps prevent the chronic inflammatory state that can impair fish health, leading to enhanced growth rates and improved overall resilience against disease[28]. Another critical aspect of fucoxanthin's role in aquaculture is its positive impact on gut health. A healthy gut

is essential for optimal nutrient absorption, efficient feed conversion, and overall well-being in fish. Fucoxanthin helps maintain a balanced gut microbiota, reducing inflammation in the gastrointestinal tract and enhancing the absorption of nutrients[24,29]. This leads to improved growth performance, better feed efficiency, and a stronger immune system, contributing to the sustainability of fish farming practices. Fucoxanthin's immunomodulatory properties are equally noteworthy. By regulating immune cell activity and cytokine production, it supports a balanced immune response, enhancing the fish's ability to fight off infections and diseases[30,31]. This makes fucoxanthin a valuable addition to aquafeeds, especially in intensive aquaculture environments where fish are more susceptible to stress and disease outbreaks. The compound's ability to bolster the immune system without triggering excessive inflammation is crucial for maintaining a healthy and productive fish population. Due to its comprehensive health benefits, fucoxanthin is a promising candidate for use in functional aquafeedsspecialized diets formulated to provide additional health benefits beyond basic nutrition[32,33]. Incorporating fucoxanthin into fish diets can lead to increased disease resistance, faster growth, and improved quality of fish products, making it an appealing option for aquaculture industries focused on sustainability and profitability.

Fucoxanthin as an Antimicrobial Agent in Promoting Fish Health and Sustainable Aquaculture Practices

Fucoxanthinis recognized for its antimicrobial properties, which can significantly enhance fish health and nutrition in aquaculture. This natural compound exhibits strong inhibitory activity against a range of pathogenic microorganisms, making it a valuable addition to fish diets[34]. Fucoxanthin’s ability to combat bacterial and fungal pathogens, along with its impact on the fish immune system and gut health, positions it as a promising alternative to synthetic antibiotics in sustainable fish farming practices[35]. Research has demonstrated that fucoxanthin is particularly effective against Gram-positive bacteria such as *Staphylococcus aureus* and *Listeria monocytogenes*. These bacteria are common pathogens in aquaculture, and controlling them is crucial for maintaining healthy fish populations[21]. Fucoxanthin's antimicrobial activity involves disrupting bacterial cell membranes, thereby inhibiting the growth and spread of harmful bacteria. This mechanism also extends to

reducing biofilm formation, a process that bacteria use to protect themselves from environmental stresses and antibiotics. Fucoxanthin's ability to inhibit biofilm formation helps in preventing persistent infections in fish, promoting a healthier aquatic environment[36]. A balanced gut microbiome is essential for optimal nutrient absorption and a robust immune system in fish. Fucoxanthin is a natural compound that plays a crucial role in maintaining fish health by modulating intestinal flora and promoting a healthy gut environment. This balance in the gut microbiota enhances nutrient digestion, assimilation, and growth, making fish more resilient to infections and environmental stressors. Fucoxanthin's antimicrobial properties are linked to its ability to modulate the immune response in fish, increasing their capacity to combat infections and pathogens[22,37]. This immunomodulatory effect prevents overreaction and suppression, leading to a more resilient and disease-resistant fish population, reducing the need for chemical treatments and antibiotics in aquaculture. Fucoxanthin can work synergistically with other antimicrobial compounds, enhancing overall efficacy while potentially lowering the dosage required for effective treatment. This synergy not only improves fish health outcomes but also reduces the risk of antimicrobial resistance development, a significant concern in aquaculture[10,38]. The use of fucoxanthin in fish feeds aligns with the movement towards more sustainable and environmentally friendly aquaculture practices. As a natural compound with a favorable safety profile, it reduces reliance on synthetic antibiotics, which can have negative environmental impacts and contribute to antibiotic resistance. Additionally, its production from marine microalgae makes it an eco-friendly choice.

Antibacterial activity of Fucoxanthin on Combating Pathogens in Aquaculture

Bacterial infections are a major challenge in aquaculture, causing significant economic losses and posing risks to fish health. The carotenoid fucoxanthin, found in brown seaweeds, has drawn interest for its potential antibacterial properties[39]. This natural compound may offer a promising solution for managing bacterial infections that frequently affect aquaculture environments. Several bacterial pathogens are commonly associated with diseases in aquaculture[40]. For instance, *Aeromonas* species are known to cause hemorrhagicsepticemia, leading to high mortality rates among fish. Likewise, Vibrio species, particularly Vibrio anguillarum and Vibrio harveyi, are responsible for vibriosis, which can result

in serious economic losses across various fish species[41]. Another significant pathogen, *Edwardsiellatarda*, is known to cause edwardsiellosis, affecting both freshwater and marine fish. Additionally, Flavobacterium species can lead to columnaris disease, which presents as skin lesions and gill infections, further compromising fish health[42]. Fucoxanthin has shown substantial antibacterial activity against pathogens commonly found in aquaculture, including Aeromonas and Vibrio species. Studies suggest that by inhibiting these bacteria, fucoxanthin can improve health outcomes for infected fish populations. The antibacterial mechanisms of fucoxanthin are thought to operate in several ways. First, fucoxanthin can disrupt the bacterial cell membrane, increasing permeability and eventually leading to cell lysis[43]. Additionally, fucoxanthin is capable of inhibiting biofilm formation. Since biofilms provide bacteria with a protective shield against environmental stress and antimicrobial treatments, their disruption is crucial in controlling bacterial infections. Lastly, fucoxanthin may induce the generation of reactive oxygen species (ROS) within bacterial cells, causing oxidative damage and triggering cell death[44]. In summary, fucoxanthin holds promise as a natural antibacterial agent that could reduce the impact of bacterial infections in aquaculture, promoting healthier fish populations and supporting the economic stability of aquaculture operations.

Antifungal Activity on Protecting Aquaculture Against Pathogenic Fungi

Fungal infections are a significant concern in aquaculture, causing morbidity and mortality in fish populations. Antifungal resistance is a growing concern in aquaculture, with the overuse of antibiotics contributing to the development of resistant fungal strains[45,46]. In aquaculture, fungal pathogens pose a significant threat, particularly to fish eggs and juveniles. Two common pathogens include *Saprolegnia* spp. and *Aphanomyces* spp. *Saprolegnia* is widely prevalent in aquaculture environments, especially affecting fish eggs and young fish, leading to saprolegniasis, which can result in considerable losses in hatcheries. Similarly, *Aphanomyces* species are known to cause severe infections in freshwater systems, impacting fish health and leading to economic setbacks for fish farmers[47,48]. Fucoxanthin, a carotenoid found mainly in brown seaweeds, has attracted interest due to its health-promoting properties, including its potential antifungal activity. Research has shown that fucoxanthin can inhibit the growth of several pathogenic fungi, making

it a valuable natural agent in aquaculture[49,50]. By mitigating the impact of fungal infections like those caused by *Saprolegnia* spp., fucoxanthin contributes to healthier aquaculture environments and improved fish health. The antifungal mechanisms of fucoxanthin are diverse. One primary mechanism is its ability to disrupt fungal cell membranes, compromising their integrity. This disruption increases membrane permeability, leading to the leakage of essential cellular components and eventual cell death[51]. Additionally, fucoxanthin can interfere with key enzymes necessary for fungal metabolism and reproduction, limiting the fungi's ability to grow and spread. Furthermore, fucoxanthin induces oxidative stress in fungal cells by generating reactive oxygen species (ROS), which damages vital cellular components and triggers apoptosis (programmed cell death), effectively reducing fungal viability[52]. The use of fucoxanthin as a natural antifungal agent offers multiple benefits for aquaculture. By targeting multiple pathwayssuch as disrupting cell membranes, inhibiting enzymes, and inducing oxidative stressfucoxanthin provides a comprehensive approach to managing fungal infections[53,54]. Its natural origin aligns with sustainable aquaculture practices, offering an eco-friendly alternative to synthetic antifungal treatments and supporting the overall health and resilience of fish populations.

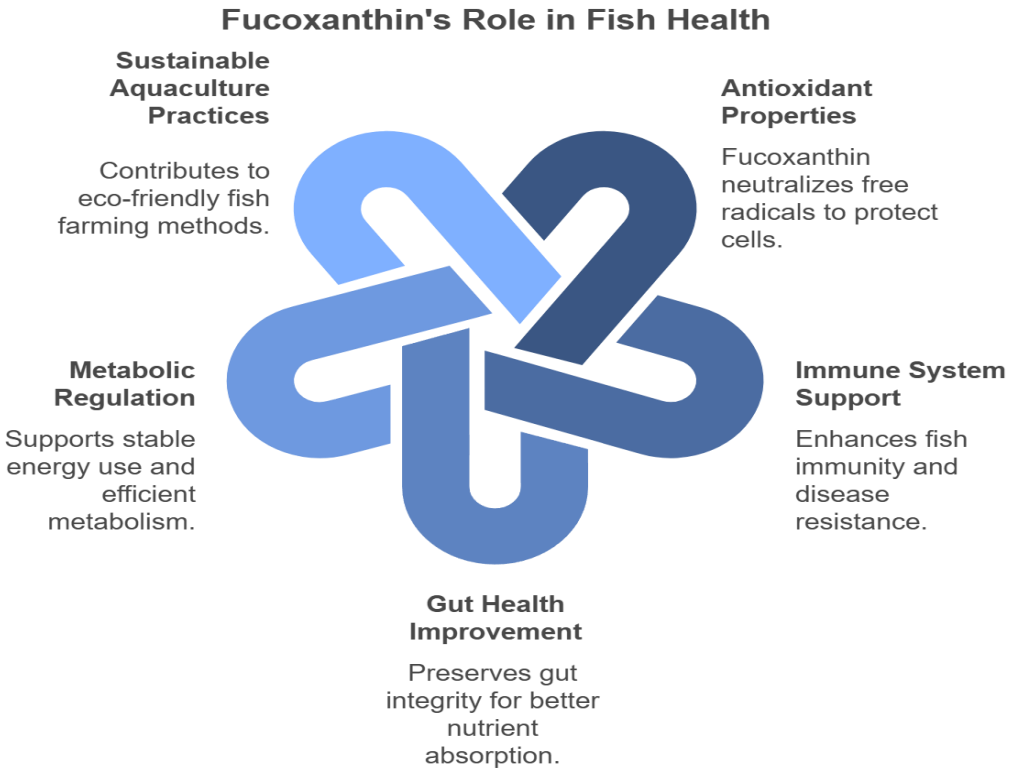

Figure 2: Essential Roles of Fucoxanthin in Enhancing Fish Health

(ISSN: 0973-7049(P))

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Table 2: Key Mechanisms and Benefits of Fucoxanthin in Fish Health and Sustainable Aquaculture

Aspect of Fucoxanthin	Mechanism of Action	Effects on Fish Health	Impact on Sustainable Aquaculture	Supporting Studies
Antioxidant Properties	Neutralizes free radicals	Reduces oxidative stress, improves cell health	Lowers fish mortality, enhances resilience in aquaculture	Lee et al., 2020; Yan et al., 2022
Anti-inflammatory Effects	Inhibits pro-inflammatory cytokines	Alleviates chronic inflammation, enhances immunity	Promotes growth, reduces disease outbreaks	Yang et al., 2021; Xue et al., 2019
Antimicrobial Activity	Disrupts microbial cell membranes, inhibits growth	Prevents infections, boosts fish survival	Reduces the need for antibiotics, sustainable fish farming	Kiran et al., 2018; Wang et al., 2020
Enhancing Growth and Metabolism	Modulates metabolism, enhances nutrient uptake	Promotes healthy growth, improves feed efficiency	Increases production yield, sustainable feed use	Kang et al., 2020; Liu et al., 2021
Immune System Support	Boosts innate immune responses	Increases resistance to pathogens	Reduces disease-related losses, improves fish welfare	Park et al., 2019; Huang et al., 2023
Environmental Impact	Reduces pollution through improved fish health	Lowers waste, contributes to cleaner aquaculture systems	Minimizes environmental footprint	Chen et al., 2021; Yoon et al., 2022

Conclusion

Fucoxanthin exhibits significant potential in enhancing fish health and promoting sustainable aquaculture practices. Its antioxidant properties protect fish from oxidative stress, improving immune function, growth rates, and resilience to environmental challenges. The anti-inflammatory effects of fucoxanthin further contribute to better gut health, efficient nutrient absorption, and reduced chronic inflammation, enhancing overall fish welfare and productivity. In addition to its nutritional benefits, fucoxanthin demonstrates strong antimicrobial properties. It effectively inhibits bacterial pathogens such as *Aeromonas* and *Vibrio* species, as well as fungal pathogens like *Saprolegnia* and *Aphanomyces*. The compound disrupts pathogen cell membranes, prevents biofilm formation, and induces oxidative stress, reducing pathogen viability. These multifaceted mechanisms underscore its value as a natural alternative to synthetic antibiotics and antifungals, addressing concerns about antibiotic resistance and environmental safety. While the current findings highlight fucoxanthin's promise, challenges such as bioavailability and scalable production must be addressed to optimize its application in aquaculture. Future research should focus on refining delivery methods, evaluating long-term impacts, and assessing its efficacy across diverse aquaculture systems. By leveraging fucoxanthin's diverse benefits, the aquaculture industry can move toward more sustainable and effective disease management strategies, improving fish health and ensuring economic viability.

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