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Promising Health Benefits of Fucoxanthin

Palukuri Yashwanth Kumar[1*], Ajay Kumar[1*], Samyuktha Sendhil[2], Nallusamy Duraisamy[3], Deepan Sundararaj[4], Sakthivel Muthu[5], Prathapavarma Digala[6*]

[1]*Department of Biosciences, School of Biological and Life sciences, Galgotias University, Greater Noida, 203201, Uttar Pradesh, India*

[2]*Department of Dermatology, Venereology and Leprosy Saveetha medical college hospital, Saveetha institute of medical and technical sciences (SIMATS), Saveetha University, Thandalam, Chennai, 602105, Tamil Nadu, India*

[3]*Department of Research, Meenakshi Academy of Higher Education and Research, K. K. Nagar, Chennai, Tamil Nadu, India*

[4]*Department of biotechnology, Vivekananda arts and science college for women, Veerachiplayam sangakri, salem, 637303, Tamil Nadu, India*

[5]*Center for Global Health Research, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences (SIMATS), Thandalam, Chennai, 602105, Tamil Nadu, India*

[6]*Department of Paramedical and Allied Health Science, School of Paramedical, Allied and Health Care Science, Mohan Babu University, Sree Sainath Nagar, Tirupati, 517102, Andhra Pradesh, India*

Abstract

Fucoxanthin, a unique carotenoid found in brown seaweed, contains an allenic bond in its structure along with a cyclic core, conjugated double bonds, and functional groups. It plays a crucial role in photosynthesis by absorbing and transferring light energy to chlorophyll a. It also exhibits health benefits, such as improving immunity and gut health and protective activities, including hepatic, neuro, and nephroprotective against various diseases, which makes it a promising pharmaceutical and dietary component for combating infectious disorders. Recent research focuses on the health-promoting properties of fucoxanthin, highlighting its various health promoting mechanisms, aiming to guide future biochemical studies toward developing new supplements utilizing fucoxanthin and its metabolites. This review provides a foundation for future health-promoting investigations focused on developing novel pharmaceutical and dietary supplements targeting fucoxanthin and its various metabolites

Keywords: *Anticancer activity, Gut Health, Immunomodulatory Activity, Neuroprotective and Nephroprsotective activity.*

Introduction

Fucoxanthin, a carotenoid predominantly found in marine brown algae, has garnered significant attention for its extensive health benefits and potential therapeutic applications. This compound, along with its metabolite fucoxanthinol, exhibits remarkable antioxidant and neuroprotective properties, particularly in the context of neurodegenerative diseases such as Alzheimer's and Parkinson's, by scavenging free radicals and activating the Nrf2/Keap1/ARE pathway to increase intracellular glutathione levels [1]. Clinical trials have demonstrated fucoxanthin's efficacy

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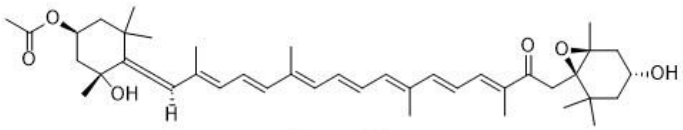
****Corresponding Authors: pratapvarmadigala@gmail.com***

in improving metabolic syndrome parameters, including reductions in body weight, body mass index, waist circumference, blood pressure, triglycerides, and enhanced insulin sensitivity and secretion [2]. Fucoxanthin's unique chemical structure, characterized by an allenic bond, contributes to its potent anti-inflammatory, anti-cancer, anti-obesity, and hepatoprotective effects, making it a valuable nutraceutical and pharmaceutical agent [3,4]. Specifically, its role in modulating lipid metabolism and oxidative stress has shown promise in managing non-alcoholic fatty liver disease (NAFLD. Despite its potential, the industrial production of fucoxanthin faces challenges related to cost-effectiveness and bioavailability, prompting research into microalgal production and advanced delivery systems to enhance its stability and absorption [6]. Fucoxanthin's anti-inflammatory properties have been highlighted in studies demonstrating its ability to mitigate inflammation-related diseases, including sepsis, by modulating key signaling pathways [7].

Additionally, its anti-cancer effects, particularly against breast cancer, are mediated through the inhibition of the NF-κB signaling pathway and other molecular mechanisms, offering a promising avenue for overcoming drug resistance in cancer therapy [8]. The global market for fucoxanthin is expanding, with significant contributions from Asian companies and emerging production in Israel and France, driven by advancements in eco-friendly extraction methods and the development of bio-based solvents [9]. Fucoxanthin is a multifaceted compound with a broad spectrum of health benefits. It necessitates further translational research to fully harness its therapeutic potential and ensure its practical application in human health [3]. In this review, we laid the groundwork for future research into health-promoting studies, focusing on creating new pharmaceutical and dietary supplements targeting fucoxanthin and its diverse metabolites.



Fucoxanthin

Figure 1. Chemical Structure of Fucoxanthin

Source and Bioavailability

Fucoxanthin, a carotenoid belonging to the xanthophyll class, is primarily sourced from marine algae, including brown macroalgae such as *Padina australis* and *Undaria pinnatifida*, and microalgae like *Chaetoceros gracilis* and *Phaeodactylum tricornutum* [3,10]. The unique chemical structure of fucoxanthin as shown Fig. 1, which includes an allenic bond, contributes to its diverse biological activities, such as antioxidative, anti-inflammatory, anticancer, antidiabetic, and anti-obesity effects [4,11]. Despite its potential health benefits, the bioavailability of fucoxanthin in the human body is limited due to its hydrophobic nature and low aqueous solubility, which hinders its clinical efficacy [12]. Various strategies have been explored to address this issue to enhance its bioavailability. For instance, encapsulating fucoxanthin in rhamnolipid fabricated BSA nanoparticles has been shown to improve its solubility and bioavailability significantly, as these nanoparticles protect fucoxanthin from external environmental factors and facilitate its release through diffusion [12]. Additionally, the use of delivery systems such as emulsions, nanoparticles, and hydrogels has been found to enhance the solubility and bioavailability of fucoxanthin, making it more effective in the human body [6]. The extraction methods also play a crucial role in determining the quality

and bioavailability of fucoxanthin. Eco-friendly and innovative extraction techniques, such as using bio-based solvents, aqueous two-phase systems, and centrifugal partition chromatography, are promising for obtaining high-quality fucoxanthin with better bioavailability [6]. Furthermore, the metabolism of fucoxanthin by gut microbes can influence its bioavailability and efficacy, suggesting that a deeper understanding of its interaction with the human microbiota is essential for optimizing its health benefits [6]. Despite the promising *in vitro* and *in vivo* findings, more clinical research is needed to fully understand fucoxanthin's pharmacokinetics, safety profile, and potential synergistic effects with existing therapeutics [3]. Overall, while fucoxanthin from both macroalgae and microalgae holds significant potential for nutraceutical and pharmaceutical applications, advancements in extraction techniques and delivery systems are crucial for enhancing its bioavailability and maximizing its health benefits in the human body (Fig.2 and Table 1).

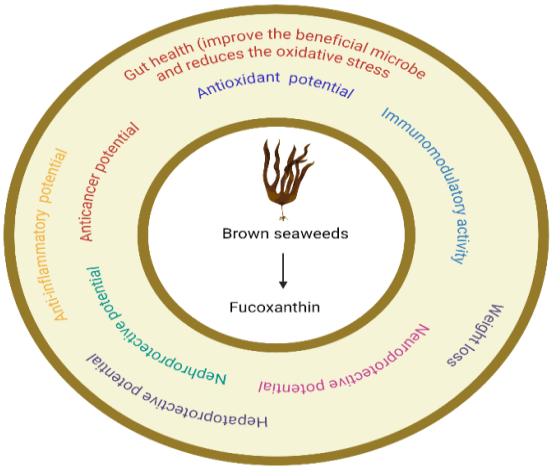


Figure 2. Promising Health Benefits of Fucoxanthin

Immunomodulatory Potential

Fucoxanthin, a natural carotenoid derived from brown algae, has demonstrated significant immunomodulatory effects across various studies. It has been shown to suppress excessive inflammatory responses, which are crucial for improving survival in sepsis patients. This is achieved by targeting interferon regulatory factor 3 (IRF3) to inhibit its phosphorylation, thereby reducing pro-inflammatory cytokine levels and reactive oxygen species production and altering immune cell composition in a mouse model of sepsis [13]. Additionally, fucoxanthin immobilized on aluminium-silicon carrier particles has enhanced the survival and proliferation of both mature and naïve immunocytes without exhibiting toxicity, indicating its safety and potential for therapeutic use [14]. In food allergies, fucoxanthin supplementation has been shown to inhibit food anaphylaxis and the production of immunoglobulins and histamine while enhancing the intestinal epithelial barrier and promoting beneficial gut flora, thus preventing food allergies effectively [15]. Fucoxanthin also exhibits anti-inflammatory properties by inhibiting NF-κB and NLRP3 inflammasome activation. Inflammasomes are large complexes formed in the cytosol that gather in response to infection or stress signals. They trigger inflammatory responses by activating caspase-1, which then leads to the cleavage and unusual release of proinflammatory cytokines IL-1β and IL-18, even though these cytokines lack a signal peptide, which are critical pathways in the production of pro-inflammatory cytokines like IL-1β, IL-6, and

TNF-α, thereby suggesting its potential in treating inflammatory and neurodegenerative diseases [16]. Its antitubercular properties have been highlighted through its bacteriostatic action against *Mycobacterium tuberculosis*, inhibiting critical enzymes involved in bacterial cell wall biosynthesis, which could also reduce susceptibility to autoimmune diseases associated with tuberculosis [17]. In acute lung injury (ALI), fucoxanthin has been shown to down-regulate the NF-κB signalling pathway and inhibit the TLR4/MyD88 axis, thereby reducing inflammation and improving lung function in LPS-induced ALI models [18]. Furthermore, fucoxanthin's ability to modulate immune responses extends to atopic diseases, where it suppresses GATA3 expression, thereby inhibiting the production of type 2 cytokines and promoting regulatory T cell activity, which could be beneficial in treating conditions like atopic dermatitis and allergic asthma[19]. In asthma models, fucoxanthin has demonstrated significant anti-asthma activity by reducing reactive oxygen species and inflammatory cytokine markers, suggesting its potential as a novel therapeutic agent for asthma [20]. Additionally, fucoxanthin's impact on gut microbiota in sepsis models has been noted, where it promotes beneficial bacteria and short-chain fatty acid production, further supporting its role in maintaining gut homeostasis and reducing inflammation [21]. These studies underscore fucoxanthin's broad-spectrum immunomodulatory effects, making it a promising candidate for treating various inflammatory, infectious, and autoimmune diseases.

Gut Health

Fucoxanthin, a carotenoid derived from brown algae, exerts its protective effects on the gut microbiome through multiple molecular mechanisms, primarily involving modulation of gut microbiota composition, enhancement of the intestinal barrier, and anti-inflammatory actions. Fucoxanthin has been shown to significantly alter the structure of the intestinal flora, increasing beneficial bacteria such as *Verrucomicrobiota* and *Akkermansia* spp. While reducing harmful bacteria like *Morganella* spp., *Proteus* spp., *Escherichia* spp., and *Klebsiella* spp. This modulation is associated with a reduction in pro-inflammatory cytokines (IL-6, IL-1β, and TNF-α) and an increase in short-chain fatty acids (SCFAs) like acetic and propionic acids, which are crucial for maintaining gut homeostasis and reducing sepsis-induced mortality [22]. Additionally, Fucoxanthin enhances the intestinal epithelial barrier by up-regulating tight junction (TJ) proteins and promoting the secretion of regenerating islet-derived protein III-gamma (RegIIIγ) and secretory IgA (sIgA), which are essential for gut integrity and immune defence [15]. The anti-inflammatory properties of Fucoxanthin are further supported by its ability to induce the secretion of anti-inflammatory cytokines (IL-10 and TGF-β) by regulatory T (Treg) cells while decreasing levels of pro-inflammatory factors (IL-4, TNF-α, IL-17, and IL-1β), thereby facilitating intestinal inflammation [15]. Fucoxanthin's antioxidant properties also protect cell components from reactive oxygen species (ROS), contributing to its broad pharmacological activities, including anti-cancer, anti-obesity, and anti-fibrotic effects [22]. Studies have shown that carotenoids, including Fucoxanthin, can modulate gut microbiota composition, promoting beneficial bacteria and SCFA production, enhancing tight junction protein expression, and reducing intestinal permeability, collectively protecting the gut epithelium from pathogens and toxins [23]. In obesity models, Fucoxanthin has been demonstrated to alleviate gut dysbiosis by inhibiting the growth of obesity- and inflammation-related bacteria such as *Lachnospiraceae* and *Erysipelotrichaceae* while promoting beneficial bacteria like

Lactobacillus, *Bifidobacterium*, and butyrate-producing bacteria, which are associated with reduced inflammation and improved gut health [24]. Furthermore, Fucoxanthin's ability to modulate the gut microbiota is linked to its anti-obesity effects, as evidenced by changes in the Firmicutes/Bacteroidetes ratio and the abundance of specific bacterial taxa in both cecal and fecal samples [25]. Overall, the molecular mechanisms by which Fucoxanthin exerts its protective effects on the gut microbiome involve a complex interplay of microbiota modulation, enhancement of gut barrier function, and anti-inflammatory and antioxidant activities, making it a promising functional food ingredient for gut health and disease prevention.

Anticancer Potential

Fucoxanthin, a natural carotenoid found in brown seaweed, has demonstrated significant anticancer properties across various types of cancer by affecting multiple cellular processes. In ovarian cancer, fucoxanthin induces apoptosis, a programmed cell death mechanism, inhibiting tumor growth and metastasis [26]. It also acts as a novel ferroptosis inducer in tongue cancer by increasing reactive oxygen species (ROS) levels and decreasing mitochondrial membrane potential (MMP), glutathione (GSH), and superoxide dismutase (SOD) levels, leading to cell death [27]. In colorectal cancer, fucoxanthin suppresses tumour growth by modulating proteins involved in cell growth, adhesion, and the cell cycle, such as glycated-decorin (Gc-DCN) and c-MYC [28]. For triple-negative breast cancer (TNBC), fucoxanthin has shown efficacy in reducing cell viability, inducing cell cycle arrest at the G1 phase, and promoting apoptosis, particularly in MDA-MB-231 cells, while also inhibiting migration and angiogenesis by downregulating VEGF-A and VEGF-C expression [29,30]. In oral cancer, fucoxanthin inhibits cell proliferation and induces apoptosis and cell cycle arrest at the G1 phase by affecting the AKT/mTOR signaling pathway which is a signal transduction network in eukaryotic cells that controls cell growth, survival, and the progression of the cell cycle. and glycolysis-related proteins [31]. Fucoxanthin's broad-spectrum anticancer effects, which include modulating miRNA, inhibiting cytokines like TNF-α, and affecting growth factors such as VEGF, are crucial for cancer cell proliferation and survival, further supporting its potential in treating various types of cancer [29]. In multidrug-resistant ovarian cancer cells, fucoxanthin induces apoptosis similarly in both cisplatin-resistant and parental cell lines. However, it does not reverse cisplatin resistance, indicating its potential as a standalone therapeutic agent [29]. Moreover, in lung adenocarcinoma (LUAD) cells, fucoxanthin inhibits proliferation, induces apoptosis, and reverses epithelial-mesenchymal transition (EMT), thereby reducing cell motility and invasion, which are critical for metastasis [32]. These studies highlight fucoxanthin's multifaceted mechanisms in inhibiting cancer cell growth, including apoptosis induction, cell cycle arrest, inhibition of migration and invasion, and modulation of key signaling pathways, making it a promising candidate for cancer therapy.

Hepatoprotective Potential

Fucoxanthin, a carotenoid derived from marine brown algae, exhibits significant hepatoprotective effects through multiple mechanisms. One primary mechanism is its ability to modulate lipid metabolism and reduce hepatic lipid accumulation, which is crucial in conditions like metabolic-associated fatty liver disease (MAFLD) and non-alcoholic fatty liver disease (NAFLD). Fucoxanthin enhances the expression of PPARα and CPT1, which are involved in fatty acid oxidation while suppressing FASN and SREBP1c, which are associated with lipogenesis. This modulation is mediated

through the activation of the AMPK pathway, which also regulates the KEAP1/Nrf2/ARE signaling pathway to exert antioxidative effects and stimulates the PGC1α/NRF1 axis to enhance mitochondrial biogenesis [33, 34]. Additionally, fucoxanthin has been shown to protect against paracetamol-induced acute liver injury by reducing oxidative stress and inflammation. It decreases the expression of pro-inflammatory cytokines such as TNF-α, IL-1, and IL-6 and increases the expression of anti-inflammatory markers like IL-10 and IL-22, thereby mitigating liver damage [35]. Fucoxanthin also exhibits hepatoprotective effects against hepatotoxic contaminants like zearalenone (ZEA) by inhibiting the production of pro-inflammatory cytokines and activating the PI3K/AKT/NRF2 signalling pathway, which enhances the expression of antioxidant enzymes like HO-1 [36]. In the context of chronic liver diseases (CLD) such as NAFLD, fucoxanthin's role extends to inducing thermogenesis, altering lipid metabolism, and promoting anti-inflammatory and antioxidant activities through various signalling pathways, including β3-adrenergic receptor, PGC-1, AMPK, PPAR, SREBP, NF-κB, MAPK, AKT, SMAD2/3, and PI3K/Akt pathways [37]. Furthermore, fucoxanthin's ability to modulate oxidative stress and inflammatory responses is evident in its action against alcohol-induced liver injury, where it activates the Nrf2-mediated signalling pathway and downregulates the TLR4-mediated NF-κB signalling pathway, reducing oxidative lesions and inflammation [38]. The compound also shows potential in preventing liver fibrosis by modulating metabolic reprogramming in hepatic stellate cells (HSC), reducing mitochondrial respiration, and increasing glycolysis, which is crucial during liver injury [39]. Additionally, fucoxanthin's hepatoprotective properties are supported by its ability to reduce oxidative stress and inflammatory levels in liver cells, as demonstrated in various in vitro and in vivo models [5, 40]. Collectively, these multifaceted mechanisms underscore fucoxanthin's potential as a therapeutic agent for various liver diseases, highlighting its antioxidative, anti-inflammatory, and lipid-regulating properties.

Neuroprotective Potential

Fucoxanthin, a carotenoid found predominantly in marine brown algae, exhibits significant neuroprotective effects through multiple mechanisms. One primary mechanism is its potent antioxidant activity, which helps mitigate oxidative stress, a critical factor in neurodegenerative diseases. Fucoxanthin and its metabolite fucoxanthinol have been shown to scavenge free radicals in neuronal membranes and cytoplasm, thereby reducing oxidative damage and enhancing intracellular glutathione (GSH) levels through the activation of the Nrf2/Keap1/ARE pathway [40]. Additionally, fucoxanthin inhibits acetylcholinesterase (AChE) activity, which is beneficial in conditions like Alzheimer's disease (AD) by preventing the breakdown of acetylcholine, thus improving neuronal communication [41, 42]. Fucoxanthin also promotes mitochondrial health by increasing mitochondrial membrane potential and reducing cytotoxicity and apoptosis in retinal ganglion cells under glutamate excitotoxicity when injured or damaged nerve cells release the intracellular neurotransmitter glutamate into extracellular spaces, primarily by enhancing parkin-mediated mitophagy Mitophagy is a specific form of autophagy that targets and eliminates damaged or malfunctioning mitochondria from cells [43]. Furthermore, it regulates apoptosis-related proteins such as Bcl-2 and Bax. It enhances the expression of Nrf2 and its downstream detoxifying enzymes, contributing to its anti-apoptotic effects against amyloid-β (Aβ)-induced neuronal injury [44]. Fucoxanthin's neuroprotective role is also linked to its ability to modulate the

PI3K/Akt signaling pathway, which is crucial for cell survival and autophagy, as well as the biosynthesis of acetylcholine, thereby providing a multifaceted approach to neuroprotection [42]. Moreover, it has been observed to upregulate DJ-1, an oxidative stress-sensing protein, which further protects neurons against ROS-mediated mitochondrial dysfunction[45]. In Parkinson's disease (PD) models, fucoxanthin reduces cytotoxicity and apoptosis induced by high concentrations of levodopa (l-DA) by improving mitochondrial membrane potential and suppressing ROS overexpression, as well as inhibiting the ERK/JNK-c-Jun system and caspase-3 protein expression [45]. The compound's ability to penetrate the blood-brain barrier and its low bioavailability are areas of ongoing research, with potential improvements in brain-targeted delivery systems being explored to enhance its therapeutic efficacy [46]. Lastly, fucoxanthin's neuroprotective effects, which include cytoprotection under oxidative stress and differential gene expression related to hormesis, further underscore its potential as a therapeutic agent for age-related neurodegenerative diseases. Collectively, these mechanisms highlight fucoxanthin's comprehensive neuroprotective properties, making it a promising candidate for the prevention and treatment of various neurological disorders.

Nephroprotective Potential

Fucoxanthin, a marine carotenoid, exhibits significant nephroprotective effects through multiple pathways, primarily by mitigating oxidative stress and inflammation. In renal ischemia/reperfusion (I/R) injury, fucoxanthin has been shown to improve renal function and tissue structure by inhibiting reactive oxygen species (ROS) levels and apoptosis. This protective effect is mediated through the upregulation of the Sirt1/Nrf2/HO-1 signaling pathway, which is crucial for reducing oxidative stress-induced apoptosis [47]. In the context of diabetic nephropathy (DN), fucoxanthin attenuates high glucose-induced oxidative stress in kidney mesangial cells by decreasing ROS levels and modulating early epigenomic and transcriptomic changes. This includes regulating pathways such as interleukin regulation, Toll-like receptor pathway, and PKA phosphorylation pathways, which are crucial for glucose metabolism and cellular stress responses [48]. Additionally, fucoxanthin demonstrates radioprotective effects by modulating the apelin-13/APJ/NF-κB signalling pathway, reducing oxidative stress markers like malondialdehyde, and enhancing antioxidant defences such as reduced glutathione and glutathione peroxidase. This decreases inflammation and improves organ tissue architecture, including the kidneys [49]. Furthermore, fucoxanthin has been shown to protect against cadmium-induced renal dysfunction by reducing blood urea nitrogen, creatinine, and lipid peroxidation levels while increasing antioxidant enzyme levels, thereby confirming its role in preventing renal damage [50]. The molecular mechanisms underlying these protective effects include the upregulation of AMP-activated protein kinase (AMPK) and the inhibition of protein kinase C, which reduces ROS generation and improves mitochondrial function and apoptosis in endothelial cells exposed to oxidized low-density lipoprotein (oxLDL) [51]. In diabetic retinopathy, which shares common pathways with nephropathy, fucoxanthin reduces inflammation and maintains the integrity of the blood-retinal barrier by enhancing antioxidant enzyme activity and reducing oxidative stress [52]. These studies highlight the multifaceted nephroprotective mechanisms of fucoxanthin, involving the modulation of oxidative stress, inflammation, and critical signaling pathways, thereby offering potential therapeutic benefits for various kidney-related diseases.

Table 1. Health Promoting Activity of Fucoxanthin

Health-promoting activity	**Protection mechanisms**	**Reference**
Immunomodulatory potential	Suppress excessive inflammatory responses on sepsis	[13]
	Enhanced the survival and proliferation of both mature and naïve immunocytes	[14]
	Enhancing the intestinal epithelial barrier and promoting beneficial gut flora effectively prevents food allergies by inhibiting food anaphylaxis	[15]
	bacteriostatic action against Mycobacterium tuberculosis	[17]
	improving lung function and decreasing inflammation in ALI models induced by LPS	[18]
	Suppressing GATA3 expression can hinder the synthesis of type 2 cytokines and enhance regulatory T cell function, offering potential benefits in managing disorders such as atopic dermatitis and allergic asthma.	[19]
	reduction of reactive oxygen species and inflammatory cytokine markers demonstrates anti-asthma activity.	[20]
Gut health	Increasing beneficial bacteria and reducing harmful bacteria in the gut can help decrease inflammation and improve the presence of short-chain fatty acids, ultimately playing a crucial role in maintaining gut balance and reducing mortality from sepsis.	[21]
	The maintenance of gut integrity and immune defence in the intestinal epithelial barrier is supported by the enhancement of tight junction proteins and the secretion of RegIIIγ and sIgA.	[15,58,59]
	Promoting the right balance of bacteria in the gut helps produce	[22,23,]

	helpful substances, strengthens the gut lining, and reduces the risk of harm from germs and toxins.	
Anti-cancer	Modulating the gut microbiota is linked to its anti-obesity properties, shown by changes in the Firmicutes/Bacteroidetes ratio and specific bacterial groups in the cecum and faeces.	[25]
	Induces ferroptosis in tongue cancer involves increased ROS and decreased MMP, GSH, and SOD levels, ultimately causing cell death.	[27]
	inhibits colorectal cancer by affecting proteins involved in cell growth, attachment, and the cell cycle	[28]
	reducing cell viability, inducing cell cycle arrest at the G1 phase, and promoting apoptosis in cancer cells	[29,30,31,32]
Hepatoprotective potential	enhance mitochondrial biogenesis and reduce liver injury	[33]
	paracetamol-induced acute liver injury by reducing oxidative stress and inflammation	[35]
	enhances the expression of antioxidant enzymes and protective liver injury	[36]
	reduce oxidative stress and inflammatory levels in liver cells	[40]
Neuroprotective potential	preventing the breakdown of acetylcholine, thus improving neuronal communication	[41]
	anti-apoptotic effects against amyloid-β (Aβ)-induced neuronal injury	[44]
	protects neurons against ROS-mediated mitochondrial dysfunction	[45]
Nephroprotective potential	Reduce oxidative stress induced by irradiation and protect kidney	[49]
	Reduce oxidative stress and protect against cadmium-induced	[50]

	renal dysfunction	
	Reduce oxidative stress and protect renal in diabetic retinopathy	[52]

Clinical Trials

Recent clinical trials and studies have highlighted the multifaceted health benefits of fucoxanthin, a carotenoid found in brown algae, with promising results across various medical conditions. A randomized, double-blind, placebo-controlled clinical trial involving 28 patients with metabolic syndrome (MetS) demonstrated that fucoxanthin administration significantly reduced body weight, body mass index, waist circumference, systolic and diastolic blood pressure, and triglycerides while enhancing insulin sensitivity and secretion. Additionally, fucoxanthin has shown potential in reducing excessive inflammatory responses, as evidenced by its ability to inhibit interferon regulatory factor 3 (IRF3) phosphorylation, thereby ameliorating sepsis and improving survival rates in a mouse model. Despite its broad pharmacological activities, including anti-cancer, anti-inflammatory, and anti-obesity effects, clinical research on fucoxanthin remains limited, with only one clinical study on obesity management reported in the last five years [3]. Fucoxanthin's anti-inflammatory properties have been further corroborated by its ability to decrease lipopolysaccharide (LPS)-induced inflammation and improve survival in septic mice, suggesting its potential as a therapeutic ingredient against inflammation-associated disorders [7]. In the context of nonalcoholic fatty liver disease (NAFLD), fucoxanthin has been shown to alleviate oxidative stress and inflammation in liver cells via the AMPK and Nrf2 signaling pathways, highlighting its potential as an anti-NAFLD agent [5]. Moreover, fucoxanthin has demonstrated efficacy in preventing cancer metastasis by inhibiting the adhesion and transendothelial migration of circulating tumor cells (CTCs), thereby reducing the formation of lung micrometastatic foci in breast cancer models [53]. Its role in enhancing the intestinal epithelial barrier and reshaping the intestinal flora has also been noted, particularly in food allergies, where it reduces allergic symptoms and inflammation in sensitized mice [32]. Fucoxanthin's anti-tumor effects extend to lung adenocarcinoma cells, where it has been shown to inhibit proliferation, induce apoptosis, and reverse epithelial-mesenchymal transition (EMT), suggesting its potential as an anti-tumor agent for lung cancer patients[32]. Furthermore, fucoxanthin's broad health benefits include antimicrobial, antioxidant, and hepatoprotective properties, making it a potent pharmacological and nutritional ingredient [4]. In acute lung injury (ALI) models, fucoxanthin has been found to inhibit NF-κB activation and reduce pro-inflammatory cytokine expression, thereby mitigating lung tissue damage and neutrophil infiltration [54]. These findings underscore fucoxanthin's therapeutic potential across a range of diseases, although further clinical research is needed to establish its efficacy and safety in human populations fully.

Potential Challenges

Fucoxanthin, a carotenoid derived from brown seaweeds, has garnered significant attention for its potential health benefits, including anti-cancer, anti-inflammatory, and neuroprotective effects. However, its clinical application faces several challenges. One major issue is its poor bioavailability, which refers to the proportion of the administered dose that reaches the systemic circulation and is available to produce a therapeutic effect. This necessitates high concentrations to achieve therapeutic effects in vivo, potentially

limiting its clinical use [55]. Despite its promising pharmacological properties, including the ability to penetrate the blood-brain barrier and act on multiple targets related to neurodegenerative disorders, the concentration required for effective treatment remains a significant hurdle [55]. Additionally, while fucoxanthin has shown efficacy in various in vitro and in vivo models, such as inducing G1 cell cycle arrest in cancer cells through the upregulation of GADD45A, translating these findings into clinical settings has been slow [56]. The limited number of clinical studies, particularly in areas beyond obesity management, further underscores the gap between laboratory research and practical application [3]. Moreover, fucoxanthin's pharmacokinetics, safety, and functional stability need more comprehensive evaluation to ensure its efficacy and safety in human subjects [3]. Another challenge is the need for more activity-oriented translational research to fully understand the diverse molecular mechanisms underlying its health benefits [3]. Despite these challenges, fucoxanthin remains a promising candidate for various therapeutic applications, including neuroprotection and cancer treatment, due to its multi-targeted action and safety profile [3]. Furthermore, its potential use in protecting eyesight from light damage is a fascinating aspect of its versatility as a functional food ingredient or pharmaceutical agent [57]. To overcome these obstacles, new strategies are being developed to enhance its bioavailability and efficacy, such as using metabolites that may produce potent in vivo effects [3]. While fucoxanthin holds considerable promise, addressing these challenges through rigorous clinical research and innovative formulation techniques is crucial for its successful application in human health management.

Conclusion

Fucoxanthin, derived from marine brown algae, exhibits neuroprotective effects in models of Alzheimer's and Parkinson's disease by acting as a potent antioxidant. It mitigates neurotoxicity induced by Beta-Amyloid and 6-hydroxydopamine by elevating glutathione levels. Additionally, it demonstrates promise in ameliorating metabolic syndrome and reducing inflammation in conditions such as sepsis by downregulating pro-inflammatory cytokines. The compound also exerts hepatoprotective effects in non-alcoholic fatty liver disease by modulating lipid metabolism and oxidative stress. In oncology, it showcases potential as a therapeutic agent by inhibiting cancer cell proliferation and metastasis. Its anti-inflammatory and antioxidant properties extend to various inflammation-related diseases and show potential in managing diabetes, obesity, and liver cirrhosis. In the realm of neurological disorders, fucoxanthin regulates apoptosis, reduces oxidative stress, and holds promise, despite challenges related to its bioavailability and blood-brain barrier permeability. Lastly, it enhances the intestinal epithelial barrier and modulates intestinal flora, offering the potential to alleviate food allergies. In summary, fucoxanthin presents a wide array of health-promoting potential therapeutic applications.

Conflict of Interest

None

Source of Funding

None

Credit Authorship Contribution Statement

P. Yashwanth Kumar and Dr Prathapavarma Digala: Conceptualization, Writing draft, Samyuktha Sendhil: Writing- review and editing

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