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Fish Disease

Beneficial Activities of Fucoidan Polysaccharides Derived from Brown Seaweeds in Aquatic Organisms. A Review with Special Reference to the Egyptian Situation

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ABSTRACT

The aquaculture industry faces increasing challenges arising from the emergence of fish and shrimp diseases, making immunomodulators (beneficial substances that modify the immune response) an urgent necessity. For a long time, researchers have focused on identifying suitable, cost-effective, and environmentally safe immunostimulants. These products aim to enhance the immune systems and antioxidant capacity of fish and shrimp, improving their ability to resist pathogens. Fucoidan, a sulfated polysaccharide primarily derived from brown seaweed, has emerged as a promising candidate due to its wide range of biological functions. Fucoidan has garnered significant attention in aquaculture due to its diverse beneficial properties. It is increasingly being incorporated into aquafeed as a natural additive to improve the health and productivity of farmed fish and shellfish. Alongside other major seaweed polysaccharides like laminarin and alginic acid, fucoidan exhibits anti-inflammatory, immunomodulatory, antioxidant, antiviral, antibacterial, antitumor, anticoagulant, and growth-enhancing effects. This review focuses on the beneficial impacts of fucoidan in aquatic animals, emphasizing its structural features, extraction techniques, and therapeutic potential, with special attention to findings from Egyptian research.

Keywords: Fucoidan; Aquaculture; Fish; Immunity; Growth performance

1. INTRODUCTION

Fucoidans are complex polysaccharides rich in L-fucose and sulfate groups, found predominantly in brown algae and some marine invertebrates such as sea cucumbers and sea urchins. Initially identified as "fucoidan" upon its isolation from marine algae, this compound has drawn increasing interest over the last decade due to its multifaceted bioactivities.These include anticoagulants, antithrombotics, antivirals, anti-inflammatories, antioxidants, anticancers, and immunoregulatory effects among others. Its widespread availability from various affordable seaweed species makes fucoidan a highly attractive target for developing pharmaceuticals and functional foods. This article consolidates current insights into the structural characteristics and biological properties of fucoidan derived from brown algae and explores how these attributes influence its biological efficacy.

In several Asian countries, seaweed constitutes a fundamental part of traditional diets and medicine. Brown seaweeds, in particular, are known for their polysaccharide content, including carrageenan, alginate, and notably fucoidan, which is mainly located in the cell wall matrix. Fucoidan has been shown to possess broad-spectrum biological activities, ranging from anticoagulant and antiviral to anti-inflammatory and anticancer functions. Recent studies have also reported that it has potential applications in pharmaceutical formulations, cosmetic products, diagnostics, and adjunct therapies. Research in both livestock and aquaculture has highlighted fucoidan's positive health impacts due to its biofunctional properties. This review aims to summarize the utility of fucoidan in aquatic species, with a special focus on its relevance in Egyptian aquaculture systems.

2. Structure of Fucoidan

Fucoidans, classified as fucose-containing sulfated polysaccharides (FCSPs), exhibit structural diversity influenced by biological source, extraction timing, and species-specific traits (Jayawardena et al., 2019). These heteropolymers feature a fucose-dominated backbone with variable sulfation at C-2/C-4 positions, though terminal residues often lack sulfate groups (Li et al., 2023). Their architecture incorporates auxiliary monosaccharides (xylose, mannose, glucose, uronic acids) and demonstrates either α (1→2) or α (1→3) glycosidic linkages (Zvyagintseva et al., 1999). Acetyl moieties and sulfation at C-3 may occur sporadically (Ale et al., 2011), with molecular weights spanning 100–1600 kDa (Zhang et al., 2015).

<u>2.1. Structural Variations Across Species</u>

- **Fucus vesiculosus**: Predominantly α (1→3)-linked fucose with C-4 sulfation; branching via α (1→2)/α (1→4) bonds (Patankar et al., 1993).
- **Ascophyllum nodosum**: Alternating α (1→3)/α (1→4) linkages with 2-O-sulfation and 2,3-O-desulfation (Chevolot et al., 1999).
- **Fucus serratus**: Alternating 3-/4-linked fucopyranose chains, minor xylose substitutions (Bilan et al., 2006).

➢ **Galactofucans and Novel Configurations**

Sargassum stenophyllum produces galactofucans resembling sea cucumber chondroitin sulfates, featuring:

- ✓ **Type I**: Low-sulfate, glucuronic acid-rich chains.
- ✓ **Type II**: Heterogeneous chains with xylose, mannose, and uronic acids (Duarte et al., 2001). S. polycystum yields a unique sulfated galactofucan with 3-linked fucopyranose backbones and 4-sulfated 2-linked galactopyranose branches.

➢ **Laminariales and Chordariales Derivatives**

- **Laminaria japonica**: 75% 3-linked fucopyranose residues; 65% molar branching at C-2 (Wang et al., 2010).

- **L. longipes/S. cichorioides**: Mixed (1→3)/ (1→4)/ (1→2) linkages with C-2/C-4 sulfation (Usoltseva et al., 2019).
- **Cladosiphon okamuranus**: Linear α (1→3)-fucopyranose backbone; 50% C-4 sulfation, occasional C-2 glucuronylation (Nagaoka et al., 1999). This interspecies variability underscores the importance of source selection for tailored fucoidan applications, Table 1 shows the Chemical compositions of some fucoidans.

Table 1. Chemical compositions of some fucoidans.

Brown seaweeds	**Chemical composition**	**Reference**
F. vesiculosus	fucose, sulfate	(Black et al.,1952, Nishino T et al.,1994)
F. evanescens C. Ag	fucose/sulfate/acetate (1/1.23/0.36)	(Bilan et al., 2002)
F. distichus	fucose/sulfate/acetate (1/1.21/0.08)	(Bilan et al., 2004)
F. serratus L	fucose/sulfate/acetate (1/1/0.1)	(Bilan et al., 2006)
Lessonia vadose	fucose/sulfate (1/1.12)	(Chandía et al., 2008)
Macrocytis pyrifera	fucose/galactose (18/1), sulfate	(Black et al., 1952)
Pelvetia wrightii	fucose/galactose (10/1), sulfate	(Anno et al., 1966)
Undaria pinnatifida (Mekabu)	fucose/galactose (1/1.1), sulfate	(Lee et al., 2004)
Ascophyllum nodosum	fucose (49%), xylose (10%), GlcA(11%), sulfate	(Percival et al., 1968)
Himanthalia lorea and Bifurcaria bifurcate	fucose, xylose, GlcA, sulfate	(Mian et al., 1973)
Padina pavonia	fucose, xylose, mannose, glucose, galactose, sulfate	(Hussein et al., 1980)
Laminaria angustata	fucose/galactose/sulfate (9/1/9)	(Kitamura et al 1991)
Ecklonia kurome	fucose, galactose, mannose, xylose, GlcA, sulfate	(Nishino et al., 1989)
Sargassum stenophyllum	fucose, galactose, mannose, GlcA, glucose, xylose, sulfate	(Duarate et al., 2001)
Adenocytis utricularis	fucose, galactose, mannose, sulfate	(Ponce et al., 2003)

Hizikia fusiforme	fucose, galactose, mannose, xylose, GlcA, sulfate	(Li et al., 2006)
Dictyota menstrualis	fucose/xylose/uronicacid/galactose/sulfate (1/0.8/0.7/0.8/0.4) and (1/0.3/0.4/1.5/1.3)	(Albuquerque et al., 2004)
Spatoglossum schroederi	fucose/xylose/galactose/sulfate (1/0.5/2/2)	(Rocha et al., 2005)

3. Fucoidan processing:

Polysaccharides, along with nucleic acids and peptides, constitute the three primary classes of biologically active macromolecules (Munoz-Bonilla et al., 2019). These carbohydrate polymers perform essential cellular functions, serving as structural components (e.g., cellulose and chitin in cell walls), energy reserves (e.g., starch and glycogen), and participating in cellular signalling and hydration processes (e.g., mucilage and alginic acid) (Amos et al., 2019; Helle et al., 2018). In brown algae, polysaccharides represent up to 75% of dry biomass, with notable examples including alginates, cellulose, fucoidans, and laminarins (DeJesus et al., 2015). Species-specific analyses reveal varying concentrations: Fucus (65.7% DW), Ascophyllum (69.6% DW), Saccharina (57.8% DW), and Sargassum (67.8% DW) (Afonso et al., 2019). Fucoidans, in particular, are sulfated L-fucose polymers that occur in brown algal cell walls and over 265 marine invertebrate genera (Deniaud-Bouët et al., 2017). These compounds contribute to cellular integrity through interactions with cellulose/hemicellulose networks and play roles in osmoregulation, reproduction, and intercellular communication (Zayed et al., 2018). Structurally, algal fucoidans demonstrate greater complexity than their invertebrate counterparts, featuring heterogeneous branching patterns (Li et al., 2017). The IUPAC recognizes "fucoidans" as an umbrella term encompassing various sulfated fucose polymers, including those initially characterized by Kylin (Citkowska et al., 2019). Research has established structure-activity relationships linking molecular characteristics (e.g., sulfation patterns, molecular weight) to biological effects.

- ✓ **Bioactive Properties**

Antitumor activity correlates with sulfate content and branching (Van Weelden et al., 2019). Anticoagulant effects depend on the molecular weight and sugar composition (Zhao et al., 2012). Antiviral potency associates with specific sulfation patterns (Wang et al., 2017).

- ✓ **Purity Considerations**:

Co-extracted phenolics may confound antioxidant assessments (Hifney et al., 2016). Fractionation protocols significantly impact bioactivity profiles (Chauvierre et al., 2019). Experimental evidence suggests that discrete fucoidan fractions exhibit differential bioactivities - for instance, certain sulfation configurations demonstrate selective antiviral action against HSV-1, while distinct molecular weight fractions show varied cytotoxicity toward Caco-2 cells (Zayed et al., 2019). These findings underscore the importance of comprehensive characterization when evaluating fucoidan applications.

3.1. Downstream Processes

Fucoidans exist as negatively charged heteropolymers embedded in complex cellular matrices, where they interact with various structural components including alginate, cellulose, laminarin, polyphenolic compounds, and proteins (Hahn et al., 2012). Their sulfate ester groups confer both water solubility (Thinh et al., 2013) and strong binding affinity to adjacent cell wall constituents, particularly polyphenolic compounds (DeReviers et al., 1989). These molecular interactions necessitate multistep purification protocols to isolate high-purity fucoidan fractions, typically involving:

➢ **Sequential Processing Steps**:
Initial pretreatment to disrupt algal tissue.Selective extraction methods. Final purification through ethanol precipitation or cationic surfactant complexation (Yang et al., 2017)

➢ **Purification Challenges**:
Requirement for multiple washing steps. Need for differential precipitation techniques. Importance of removing co-extracted impurities (Zhang et al., 2020)

The complete isolation workflow, as illustrated in Figure 1, systematically addresses these challenges through three critical phases: pretreatment, extraction, and purification. This comprehensive approach ensures the removal of interfering substances while preserving the structural integrity of the target fucoidan molecules.

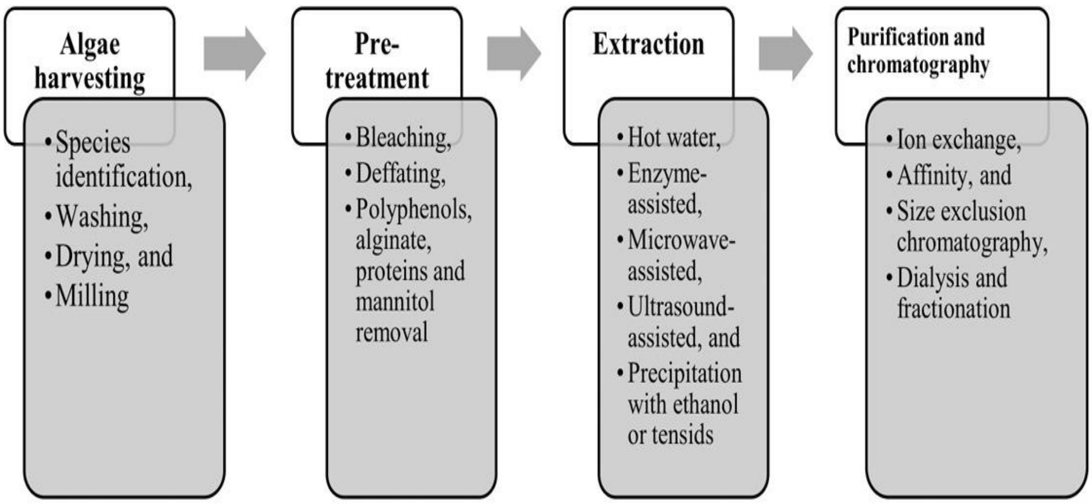

Figure 1. Steps of fucoidan processing (Zayed et al.,2020).

3.1.1. Pre-Treatment

Initial Processing:
Freshly collected algal biomass requires extensive washing with tap water to eliminate sand particles and epiphytic organisms before drying and mechanical grinding. This size reduction step enhances the surface area-to-mass ratio, facilitating subsequent extraction processes (Chollet et al., 2016).

Pre-treatment Optimization:
Critical pre-extraction steps serve multiple purposes: (1) liberating fucoidans from their native matrix, (2) enhancing extraction efficiency, and (3) minimizing co-extraction of interfering compounds. Common approaches include:

Depigmentation and Delipidation:
Sequential treatment with organic solvents (80-85% ethanol, acetone, or toluene).Effective removal of

chlorophylls, carotenoids, and lipids without affecting anionic fucoidans (Spicer et al., 2017).Parallel recovery of valuable nutraceuticals (fucoxanthin, PUFAs, fucosterol) (DaCosta et al., 2019).

Polyphenol Elimination:

Avoidance of activated charcoal due to nonspecific adsorption (Hahn et al., 2012).Alternative formaldehyde-ethanol mixtures for phlorotannin crosslinking (limited by toxicity concerns) (Imbs et al., 2015). Critical need for phenolic quantification in final products (Gall et al., 2015)

Alginate Removal:

Selective precipitation as calcium alginate complexes (4% CaCl). Filtration/centrifugation separation (Balboa et al., 2013)

3.1.2. Extraction Methodologies:

Fucoidan's polyanionic nature permits various extraction strategies:

Conventional Methods:

Aqueous extraction (hot/cold) with ethanol precipitation.pH-controlled systems (acidic/alkaline/buffered) requiring neutralization (Ale et al., 2013), Effects of solvents on the extraction/purification of FCSPs are shown in Figure 2.

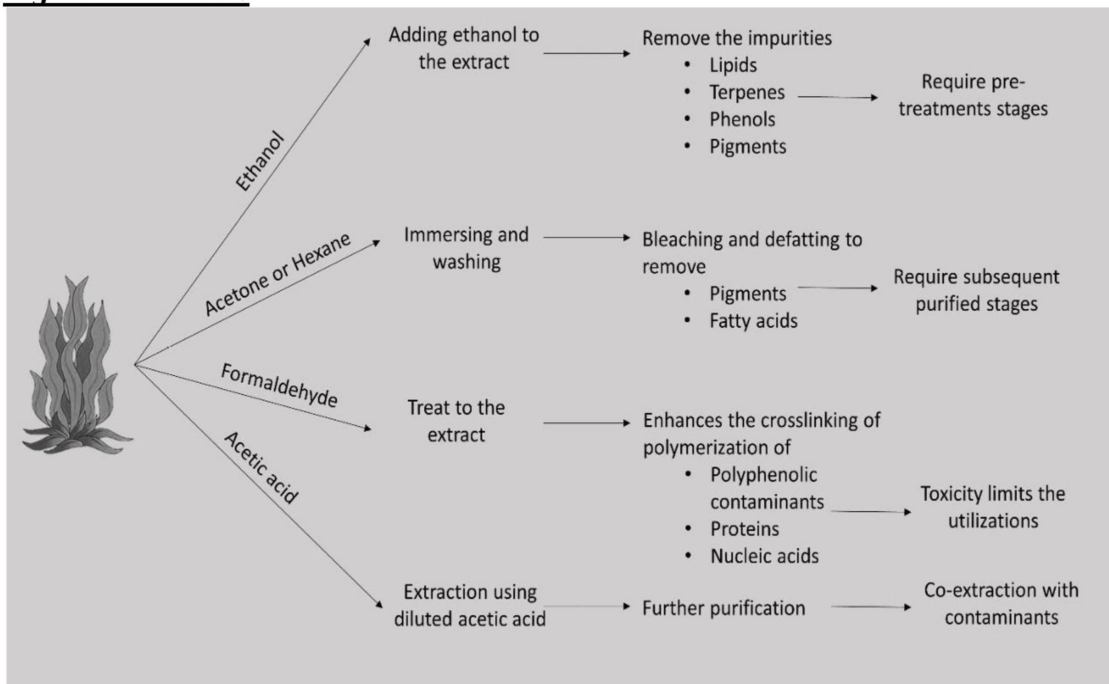

Figure 2. Effects of solvents on the extraction/purification of FCSPs (Jayawardena et al., 2022).

Advanced Techniques:

Hydrothermal-assisted extraction (HAE) with ultrasonic enhancement (Garcia-Vaquero et al., 2019).Subcritical water extraction preserving native structure (Alboofetileh et al., 2019). Enzyme-assisted extraction (EAE) using alginate lyase/cellulase (Qin et al., 2018)

Innovative Approaches:

Vacuum-assisted low-temperature extraction.EDTA-mediated simultaneous extraction/depigmentation (Zhao et al., 2018).

Scale-up Considerations:

Process optimization typically initiates at bench scale (5-10 g biomass) to determine critical parameters (solvent ratio, temperature, duration) before industrial translation (500-1000 g batches). Quality assessment employs FTIR, monosaccharide analysis, and elemental composition (Hahn et al., 2016). This comprehensive approach addresses both yield optimization and structural preservation while minimizing the co-extraction of interfering compounds. The multi-stage protocol ensures production of high-purity fucoidans suitable for pharmacological applications.

3.1.3. Separation Physical Methods

Filtration, dialysis, and centrifugation processes are commonly employed for both algal biomass and precipitates during downstream processing following pre-treatment and extraction (Xing et al., 2013 and Lee et al., 2019). Cross-flow filtration and water dialysis typically utilize membranes with specific molecular weight cutoffs (MWCO) to isolate fucoidans from smaller molecules, taking advantage of fucoidans' high molecular weight (Somasundaram et al., 2016). These methods also enable fractionation, separating low molecular weight fucoidans (LMWF) from their high molecular weight counterparts (HMWF) (Yoo et al., 2019). Centrifugal concentrators (Vivaspin®) with appropriate MWCO membranes can simultaneously perform filtration, concentration, and fractionation, similar to protein purification protocols. However, when dealing with large quantities or high concentrations of salts and contaminants, these concentrators become less practical and cost-effective due to membrane clogging and degradation issues.

3.1.4. Purification

Despite these purification steps, residual contaminants often remain, leaving the fucoidans in a crude state (Zayed et al., 2018). Some researchers have implemented simple, non-chromatographic methods such as bleaching with NaClO2 in dilute HCl followed by precipitation using cetyltrimethylammonium bromide (Ustyuzhanina et al., 2013), or cold overnight incubation in calcium acetate buffer (20 mM, pH 6.5-7.5) with subsequent dialysis (Saboural et al., 2014). Membrane filtration has also proven effective for producing fucoidan fractions of varying molecular weights (Garcia-Vaquero et al., 2017).

Most chromatographic techniques exploit the permanent negative charges from sulfate ester groups on the fucoidan backbone for selective capture. However, interference can occur from carboxylated (e.g., alginate) and phosphorylated (e.g., nucleic acids) compounds (Hahn et al., 2016 and Lee et al., 2012), making solvent pH crucial during purification. Options include using anion exchange resins like DEAE-cellulose with 0.1 M sodium phosphate buffer at pH 7.2 (Palanisamy et al., 2018), or cationic dyes (e.g., toluidine blue), modified resins, or chitosan in buffered solutions (Zayed et al., 2018; Abdella et al., 2020). Both anion exchange and dye affinity chromatography typically require high-concentration NaCl elution solvents, necessitating additional purification steps like gel permeation chromatography (Cong et al., 2016) or dialysis (Palanisamy et al., 2018) to remove salts, which increases production costs.

Recent innovations include novel purification techniques such as molecularly imprinted polymers (MIP) for selective solid phase extraction of fucoidans and other seaweed polymers (Li et al., 2017 and Guthrie et al., 2019), including MIPs modified with deep eutectic solvents. Abdella et al. (2020) developed an eco-friendly, time-efficient purification method using genipin-crosslinked toluidine blue immobilized on chitosan beads, leveraging fucoidans' affinity for cationic thiazine dyes. These procedures are summarized in Figure 3.

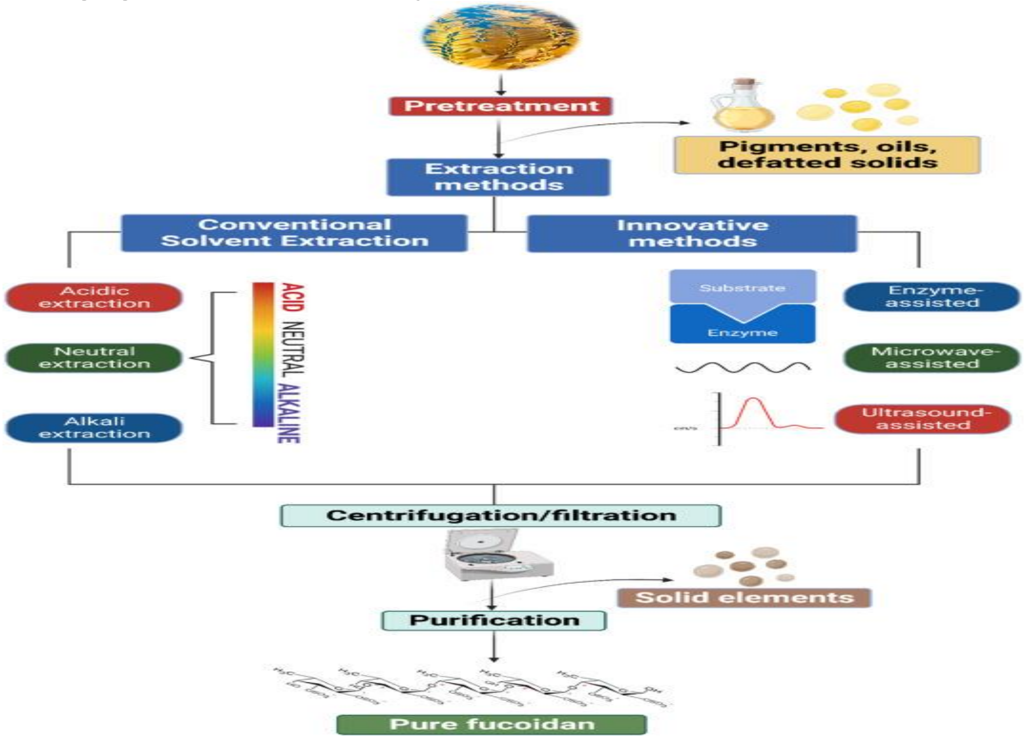

Figure 3. Procedures of fucoidan processing (Mensah et al., 2023).

4. Beneficial health effects of fucoidan in aquatic organisms: The beneficial effects and health benefits of fucoidan in fish are illustrated in Figure 4

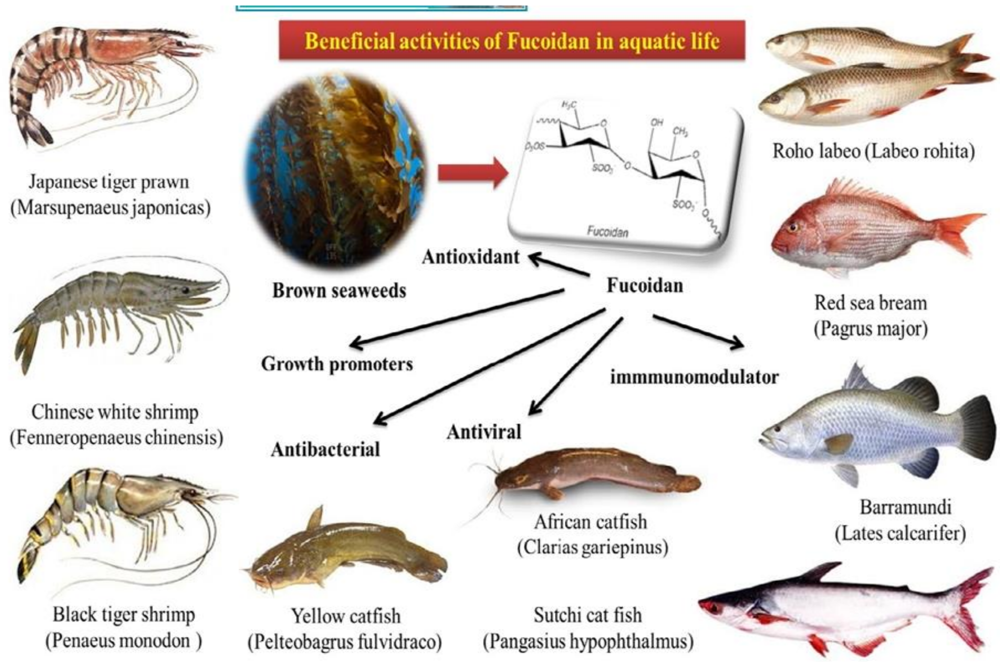

Figure 4. Beneficial application of fucoidan in aquaculture (Saeed et al., 2021).

4.1. Growth enhancement by fucoidan

Fucoidan has demonstrated multiple biological effects in vertebrates, though its growth-enhancing properties in fish remain relatively understudied. Research by Traifalgar et al. (2010) revealed that supplementing the diet of Marsupenaeus japonicas juveniles with increasing fucoidan concentrations significantly enhanced body weight (BW), weight gain, specific growth rate, and protein retention while reducing feed conversion ratios. Similar growth improvements were observed in Penaeus monodon with 0.1-0.3% dietary fucoidan supplementation (Sivagnanavelmurugan et al., 2014). Asian seabass showed enhanced growth at 1% fucoidan inclusion (Tuller et al., 2012), while Labeo rohita exhibited synergistic growth benefits when fucoidan was combined with methionine (Nazir et al., 2017).

Studies on juvenile barramundi (Lates calcarifer) demonstrated superior growth performance with 10 g/kg fucoidan supplementation compared to 0.5 g/kg, as evidenced by increased weight, length, and muscle fiber area (Tuller et al., 2014). The growth-promoting effects appear dose-dependent, as reported by Hossain et al. (2016) and confirmed in M. japonicas after 8 weeks of supplementation (Traifalgar et al., 2010). Potential mechanisms include myostatin inhibition (Ramazanov et al., 2003) and improved feed utilization, supported by reduced blood urea nitrogen and AST levels indicating enhanced protein metabolism and organ function (Sony et al., 2019).

Enhanced digestive enzyme secretion following fucoidan supplementation may contribute to better nutrient utilization (Ozório et al., 2015). Similar growth benefits were observed with algal meals from Ascophyllum nodosum and U. pinnatifida in red sea bream (Yone et al., 1986; Nakagawa et al., 1997). Notably, fucoidan modulates lipid metabolism by converting cholesterol to bile acids without altering whole-body composition, with maximal lipid content observed at 0.4% supplementation (Sony et al., 2019). This lipid-enhancing effect was also documented in M. japonicas (Traifalgar et al., 2010). Higher fucoidan concentrations (≥1%) proved effective for sutchi catfish (Pangasianodon hypophthalmus) growth promotion (Prabu et al., 2016).

4.2. Antioxidative activity of fucoidan

Fucoidan serves as a powerful natural antioxidant with demonstrated efficacy in counteracting disorders linked to oxidative stress. Its antioxidant mechanism involves the suppression of reactive oxygen species, particularly hydroxyl and superoxide radicals, thereby preventing lipid peroxidation. Research indicates that these antioxidant properties are strongly influenced by two key structural features: the degree of sulfation and the molecular weight of the polysaccharide (Li et al., 2006; Wang et al., 2008).

Experimental evidence shows that fucoidan supplementation in diets can significantly reduce markers of oxidative damage. In yellow catfish (Pelteobagrus fulvidraco), fucoidan administration led to decreased lipid peroxidation (Yang et al., 2014). Similar antioxidant effects were observed in zebrafish (Danio rerio) models and juvenile red sea bream (Pagrus major) when treated with fucoidan extracted from Ecklonia cava (Kim et al., 2014; Sony et al., 2019). These findings collectively highlight fucoidan's potential as an effective natural compound for managing oxidative stress in aquatic species.

4.3. Immunomodulatory, Antimicrobial, and Antiviral Activities

Sulfated fucoidans have emerged as promising immunostimulants and functional feed supplements in aquatic farming systems, drawing considerable attention from both industry and researchers (El-Boshy et al., 2014; Peixoto et al., 2016). These marine polysaccharides potentiate macrophage activity, enhancing phagocytic capacity and lysozyme secretion (Choi et al., 2005; Yang et al., 2008). Experimental evidence demonstrates that Sargassum fusiforme-derived polysaccharide supplements (0.1-0.5% inclusion) significantly increased muscular lysozyme activity in Fenneropenaeus chinensis (Huang et al., 2006). Comparable immunoenhancement has been documented in teleost species, where dietary fucoidan supplementation improved circulating lysozyme activity, serum protein profiles, and antioxidant capacity. Haematological parameters in both Pelteobagrus fulvidraco (Yang et al., 2014) and Pagrus major juveniles (Sony et al., 2019).

Pathogen Inhibition and Immune Modulation

The compound demonstrates notable antimicrobial efficacy against multiple aquatic pathogens (Immanuel et al., 2012; Kitikiew et al., 2013). Its immunostimulatory mechanism involves dual activation of innate immune components (natural killer cells). Adaptive immune elements (T cells, dendritic cells) thereby establish robust antimicrobial defenses. Studies utilizing Sargassum polycystum-extracted fucoidan revealed protective effects in Penaeus monodon against Escherichia coli, Staphylococcus aureus, and Vibrio harveyi infections (Chotigeat et al., 2004; Immanuel et al., 2012). Similarly, Turbinaria ornata-sourced fucoidan exhibited inhibitory activity against Yersinia enterocolitica and Vibrio parahaemolyticus in ornamental marine species (Marudhupandi and Kumar, 2013).

Disease Resistance Enhancement

Beyond antimicrobial action, fucoidan (3% dietary inclusion) has shown immunopotentiating effects in Pangasianodon hypophthalmus (Prabu et al., 2016). Labeo rohita (Nazir et al., 2017). Notably, Laminaria japonica-derived fucoidan increased resistance in Clarias gariepinus against Aeromonas hydrophila challenge (El-Boshy et al., 2014), while also improving growth performance and Vibrio parahaemolyticus resistance in Penaeus monodon (Sivagnanavelmurugan et al., 2014).

Antiviral Potential

The sulfated polysaccharide presents antiviral properties with favourable toxicity profiles compared to synthetic antivirals. Its dual mechanism involves: Blocking viral entry. Suppressing viral replication (Mandal et al., 2007; Ponce et al., 2003). The sulfate moieties appear critical for immunostimulation against viral pathogens (Ponce et al., 2003). Practical applications include: Cladosiphon okamuranus fucoidan-mediated protection of Marsupenaeus japonicus against WSSV (Takahashi et al., 1998). WSSV neutralization in Penaeus monodon via phagocytosis-activating protein gene regulation (Deachamag et al., 2006).

5. Applied Research on Fucoidan in Egyptian Aquaculture

Table 2 summarizes key research articles and reviews on fucoidan in Egypt, providing valuable insights for future studies. These works highlight fucoidan's potential as a sustainable feed additive to enhance growth, immunity, and disease resistance in aquaculture species.

Table 2. Applied research on Fucoidan in aquaculture in Egypt.

Research subject	Type of research	Reference
The anticancer activity	Experimental study	**(Al-Duais et al., 2025)**
Seed treatment with macroalgal-derived fucoidan and nanohydroxyapatite mitigates	Experimental study	**(Gomaa et al., 2025)**
Protective Effects against Osteoarthritis	Experimental study	**(Chiang et al., 2024)**
preparation, evaluation, and cytotoxicity study	Review article	**(Obiedallah et al., 2024)**
Anti-Inflammatory, Antidiabetic,	Experimental study	**(Deaconu et al., 2024)**
The Antioxidant and Anti-Inflammatory Properties	Experimental study	**(Brezoiu et al., 2024)**
Recent biotechnological applications	Review article	**(Eladl et al., 2024)**
Optimizing the fucoidan extraction	Experimental study	**(El-Sheekh et al., 2024)**
Fucoidan in Delivery Systems	Review article	**(Haggag et al., 2023)**
Fucoidan's Molecular	Review article	**(Zayed et al., 2023)**
Treat gastric ulcer injury through managing inflammation.	Experimental study	**(Selim et al., 2023)**
Fucoidan as probiotic	Review article	**(Elwakil et al., 2023)**
Chemical Composition, Antioxidant, and Antitumor Activity	Experimental study	**(El-Sheekh et al., 2023)**
Antiangiogenic drugs	Experimental study	**(Abdollah et al., 2023)**
A spectroscopic response	Experimental study	**(Abdella et al., 2023)**
Characterization and Cytotoxic Activity	Experimental study	**(Zayed et al., 2023)**
Selective 2-desulfation of tetrasaccharide-repeating sulfated fucans	Experimental study	**(Kim et al., 2022)**
The Sea Cucumber Thyonella gemmata	Experimental study	**(Dwivedi et al., 2023)**

Fucoidan/hyaluronic	Experimental study	**(Moustafa et al., 2023)**
Health benefits and potential applications of fucoidan	Review article	**(Abdel-Latif et al., 2022)**
Expression and Biochemical Characterization	Experimental study	**(Qiu et al., 2022)**
Effect against Enterococcus faecalis	Experimental study	**(Tang et al., 2022)**
Sulfated Galactofucans	Review article	**(Zayed et al., 2022)**
In Vitro Evaluation and In Vivo Anti-Inflammatory Study	Experimental study	**(Abdelkader et al., 2022)**
Curative effects of fucoidan on acetic acid-induced ulcerative colitis	Experimental study	**(Bagalagel et al., 2022)**
The prospective effect of fucoidan on splenic dysfunction	Experimental study	**(Basha et al., 2022)**
Anticancer, Enhanced Antibacterial, and Free Radical Scavenging Potential of Fucoidan-	Experimental study	**(Rajeshkumar et al., 2021)**
Comparison & Antioxidant Activity of Different Molecular Weight Fractions	Experimental study	**(Yu et al., 2021)**
Synthesis of nanoparticles and their potential applications	Review article	**(Yosri et al., 2021)**
In vitro biological activities and in vivo hepatoprotection	Review article	**(Atya et al., 2021)**
Fucoidan ameliorates acute and sub-chronic in vivo toxicity	Experimental study	**(Mahgoub et al., 2021)**
Growth Behavior and Blood Metabolites and Toxic Effects	Experimental study	**(Abdel-Warith et al., 2021)**
Modulates hepato-renal oxidative stress and DNA damage	Experimental study	**(Abdel-Daim et al., 2020)**
Growth and metastasis of pancreatic cancer	Experimental study	**(Etman et al., 2020)**
Protection against damage in cardiac, hepatic, and renal tissues	Experimental study	**(Abdel-Daim et al., 2020)**
Hepatocellular Carcinoma	Experimental study	**(El-Far et al., 2020)**
Purity, Physicochemical & Chemical Properties	Review article	**(Zayed et al., 2020)**
The effect on growth performance, intestinal pathology, and antioxidant	Experimental study	**(Mahgoub et al., 2020)**

Oxidative Stress, Inflammation, DNA Damage, and Hepatorenal Injuries	Experimental study	**(Aleissa et al., 2020)**
the impact of abiotic stress	Experimental study	**(El-Katony et al., 2020)**
Downstream Processes and Recent Applications	Review article	**(Zayed et al., 2020)**
Effects on the hematic indicators and antioxidative responses	Experimental study	**(Abdel-Daim et al., 2020)**
Chitosan-toluidine blue beads for purification of fucoidans	Review article	**(Abdella et al., 2019)**
A natural biopolymer in cancer combating	Experimental study	**(Etman et al., 2019)**
Molecular Mechanisms	Reviewarticle	**(Sajadimajd et al., 2019)**
Challenges and opportunities	Review article	**(Zayed et al., 2019)**
Induced hepatic, renal, and cardiac oxidative stress and inflammatory injuries	Experimental study	**(AlKahtane et al., 2019)**
Treatment of pancreatic cancer	Review article	**(Etman et al., 2019)**
Physicochemical Comparison properties	Experimental study	**(Lu et al., 2018)**
Antioxidant properties	Experimental study	**(Hifney et al., 2018)**
Physicochemical and Biological Characterization	Experimental study	**(Zayed et al., 2016)**
Suppressing oxidative stress and inflammatory cytokines	Experimental study	**(Heeba et al., 2015)**
Enhancement the non-specific immune response and disease resistance	Experimental study	**(El-Boshy et al., 2014)**

CONCLUSIONS AND RECOMMENDATIONS

Brown seaweeds represent a rich marine resource containing numerous bioactive compounds, particularly sulfated polysaccharides like fucoidan (FCD). This comprehensive review examines FCD's biological activities and explores its potential as a functional aquafeed ingredient for finfish species. Our analysis highlights FCD's growth-promoting, antioxidant, and immunostimulant properties in fish, with special emphasis on Egyptian aquaculture research. Additionally, we detail critical aspects of fucoidan production, extraction methods, and structural characteristics from brown seaweeds. This review serves to promote awareness of brown algal fucoidans as both a valuable research subject and a sustainable material for industrial applications in aquaculture and beyond. The findings underscore the need for further research to unlock FCD's full potential as a natural alternative in animal nutrition and health management.

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