Review Article

Marine Algae-Derived Bioactive Compounds and Biomaterials: Pharmaceutical Applications and Therapeutic Advances in Medical and Dental Sciences

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ABSTRACT

Marine algae and their derivatives have gained substantial notice in the scientific community because of their rich source of bioactive compounds, which include carbohydrates, lipids, proteins, and pigments. These compounds have shown promising applications in both medical and dental sciences. A literature search (2000-2025) using PubMed, Scopus, and Google Scholar identified studies on marine algae bioactives, which were screened, extracted, and narratively synthesized for medical and dental applications. In the medical field, biomaterials sourced from marine algae display a range of biological activities that make them valuable for developing therapeutic agents and pharmaceutical products. In dental science, marine algae are used in the formulation of dental materials, such as bioactive glass and hydrogels, which aid in tissue regeneration and repair. Additionally, their anti-inflammatory and antimicrobial properties contribute to improved oral health. This review highlights the potential of marine algae as a sustainable and versatile resource for advancing medical and dental applications.

Keywords: Bioactive, Biomaterial, Hydrogel, Marine algae.

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INTRODUCTION

Algae, derived from the Latin term historically associated with Hepaticae and introduced by Linnaeus in 1753, represent a diverse group of chlorophyll-containing organisms ranging from microscopic unicellular forms to giant seaweeds exceeding 70 M in length (El Gamal, 2010). They are broadly classified into macroalgae and microalgae, with macroalgae comprising green (Chlorophyceae), brown (Phaeophyceae), and red algae (Rhodophyceae). Marine algae grow rapidly without requiring freshwater, arable land, or fertilizers, making them an environmentally sustainable resource (Veluchamy *et al.*, 2020). Rich in bioactive compounds such as carotenoids, omega-3 fatty acids, essential amino acids, vitamins, minerals, flavonoids, polysaccharides, tannins, and bromophenols, marine algae possess significant nutritional and therapeutic value (Achankunju *et al.*, 2023; Kaliaperumal *et al.*, 2015; Rashad *et al.*, 2020). They are widely used in food, animal feed, fertilizers, traditional medicine, pharmaceuticals, cosmetics, textiles, and biofuel production (Duc *et al.*, 2021; Kavitha *et al.*, 2019). Algae also play a crucial ecological role by contributing to oxygen production and serving as the primary food source in marine ecosystems (Xie *et al.*, 2022).

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METHODOLOGY

A literature search was conducted from 2000 to 2025 using PubMed, Scopus, and Google Scholar to identify relevant studies on marine algae-derived bioactive compounds and their medical and dental applications. Retrieved articles were screened for relevance, relevant data were extracted, and the findings were narratively synthesized to provide a comprehensive overview of current evidence and emerging therapeutic applications.

Biocompatibility of marine algae

Marine algae exhibit strong biocompatibility, making them promising for biomedical applications. Brown algae-derived 3D scaffolds supported HFF cell proliferation with no adverse effects in rats, and purification of sodium alginate improved safety without altering its properties (Paudel *et al.*, 2014). Red algae j-carrageenan hydrogels showed no cytotoxicity, low oxidative stress, and minimal inflammation *in vivo* (Popa *et al.*, 2014). Green algae cellulose scaffolds from *Cladophora* and *Ulva* enhanced fibroblast viability and supported long-term growth (Bar-Shai *et al.*, 2021). Microalgae like *Spirulina, Chlorella*, and diatoms were largely non-toxic *in vitro* and *in vivo*, with *Spirulina*-based treatments showing selective cancer cell toxicity and safe clearance in mice (Zhong *et al.*, 2021).

Pharmacological activity and applications of marine algae in medical science

Marine algae are increasingly recognized for their wide-ranging medical applications due to their rich content of bioactive compounds (Table 1). For skin health, substances like fucoidans, fucoxanthin, and phlorotannins offer antioxidant, anti-inflammatory, and photoprotective benefits, while compounds such as ascophyllan support skin whitening and anti-cancer effects. Compounds like dieckol, fucoxanthin, and fucosterol reduce lipid peroxidation, DNA damage, and boost antioxidant enzymes. Red algae peptides, including those from *Pyropia yezoensis*, show strong ACE inhibition. Phlorotannins from *Sargassum fusiforme* and *Ecklonia cava*, like dieckol and phlorofucofuroeckol A, lower blood pressure and boost nitric oxide (Fernando *et al.*, 2022).

Algae also show strong antidiabetic, antioxidant, and neuroprotective activities-helping regulate blood glucose, protect against oxidative stress, and improve cognitive function. Extracts from *Ascophyllum nodosum*, alginates, and agar aid in regulating glucose and starch digestion. Phlorofucofuroeckol-A and Ecklonia polyphenols help prevent diabetes complications by inhibiting AGE, ACE, and oxidative stress (Jimenez-Lopez *et al.*, 2021).

Their anticancer properties are driven by compounds like fucoidan and phlorofucofuroeckol A, which inhibit cancer cell growth and enhance chemotherapy outcomes (Biris-Dorhoi *et al.*, 2022). Compounds like fucofuroeckol-A enhance fungal susceptibility to treatments like fluconazole. Marine algae possess broad-spectrum antiviral properties by inhibiting viral entry, replication, and spread. Phlorotannins from *Ecklonia cava* inhibit HIV replication, while compounds like Griffithsin and ulvan target HSV and encephalitis viruses. Additionally, marine algae demonstrate antibacterial, and antiparasitic effects through mechanisms like disrupting cell membranes, inhibiting pathogen replication, and enhancing immune defense (Besednova *et al.*, 2021). Beyond infection and chronic disease management, marine algae support cardiovascular health with antihypertensive, anticoagulant, and antihyperlipidemic properties, attributed to compounds like phlorotannins and sulfated polysaccharides (Seca *et al.*, 2018).

Their anti-inflammatory, hepatoprotective, and anti-allergic effects further expand their therapeutic value. Wound healing is a complex process that benefits from suitable dressings like hydrogels, which provide mechanical support and maintain moisture. Alginate-based dressings, available as films, hydrogels, foams, and more, form gels upon contact with fluid and are highly absorbent but unsuitable for dry wounds. Compared to traditional dressings, alginate hydrogels are non-toxic, absorb water well, don't stick to wound tissue, and enable lateral wicking by drawing exudate away from the wound to healthy skin, minimizing damage during removal (Thomas *et al.*, 2011).

In biomedical engineering, marine-derived polysaccharides are used in drug delivery systems, wound healing, and tissue engineering due to their biocompatibility, biodegradability, and ability to mimic natural tissues. Carrageenan and fucoidan-based microspheres and nanoparticles provide tailored release and therapeutic effects like anticoagulation. Alginate encapsulation protects drugs, allowing delayed release and improved stability and efficacy. Marine biomaterials like κ-carrageenan hydrogels support cell growth, chondrogenesis, and matrix formation in tissue engineering. Alginate hydrogels provide biocompatible scaffolds resembling the extracellular matrix, ideal for bone regeneration. From enhancing immune function to supporting bone and liver health, algae-derived substances like fucoidan, carrageenan, alginate, and ulvan represent versatile and natural alternatives for a wide range of medical applications (Zhang *et al.*, 2021).

Applications of marine algae in dental sciences

Marine algae have shown significant potential in dentistry due to their antimicrobial, anti-inflammatory, and anticariogenic properties (Table 2). Marine algae show strong antimicrobial activity against oral pathogens causing dental caries, including *Streptococcus mutans* and *Candida albicans.* Cariogenic bacteria like *Streptococcus mutans* and *Lactobacillus* metabolize sugars into acids, causing dental caries. Endotoxins, also known as Lipopolysaccharides (LPS), can trigger severe immune responses, leading to conditions like sepsis and septic shock. It has been found that marine algae extract, fucoidan, possesses such properties (Oka *et al.*, 2020).

Ascophyllum nodosum (kelp) reduces dental plaque and calculus by breaking bonds on the tooth surfaces. Its antiplaque effects are attributed to esterified mannitol, laminaran, and sulfated uronic acids. This kelp can be used in powders, suspensions, or tablets. These properties make it a promising natural agent for dental hygiene products. *Pleurochrysis carterae* and *Emiliania huxleyi* also possess calcifying properties beneficial for tooth mineralization. Algae-derived compounds such as fucoidan, eckols, and chitooligosaccharides also support pulp regeneration, manage periodontitis, treat aphthous ulcers, and alleviate temporomandibular joint pain (Huang *et al.*, 2021; Mikulewicz *et al.*, 2015).

Moreover, algae-based materials like alginate play vital roles in advanced dental applications, including drug delivery, bioactive coatings, and tissue engineering. These biomaterials support endodontic healing, periodontal regeneration, and bone formation, while also offering innovative solutions for conditions like oral mucositis, oral submucous fibrosis, and salivary gland damage. Fucoidan reduces setting times, making it a promising additive for pulp-capping materials. Fucoidan, known for its anti-inflammatory and antioxidant properties, was shown to improve saliva flow, reduce fibrosis, increase mucin-rich tissue, and preserve salivary and myoepithelial cells, helping to alleviate salivary gland dysfunction after radioiodine therapy. Fucoidan from marine algae supports bone regeneration in periodontal therapy by enhancing osteocalcin release when combined with tricalcium phosphate-chitosan scaffolds. It stimulates osteogenic differentiation in human mesenchymal stromal cells. Fucoidan combined with polydopamine boosts alkaline phosphatase activity and upregulates key osteogenic markers in periodontal ligament stem cells.

Fucoidan combined with deoxycholic acid forms nano-micelles that enhance drug retention, accelerate healing, reduce inflammatory cell infiltration, and inhibit NF-κB activity, showing superior anti-inflammatory effects compared to standard cannabidiol treatments. Fucoidan shows therapeutic promise by targeting the MEG3 gene and myofibroblast markers, regulating miR-181a and Egr1 to inhibit fibrosis and improve OSF outcomes.

Table 1: Pharmacological activity and applications of marine algae in medical science.

Author & Year	Algae Species	Pharmacological Activity and Medical application
Kim *et al*. (2018)	Marine algae carbohydrates	Skin protection
Wang *et al*. (2017)	Marine algae	Skin health; biomedical applications
Jimenez-Lopez *et al*. (2021)	*Ascophyllum nodosum, Sargassum japonica*	Antioxidant, antimicrobial, antiviral, antidiabetic
Fernando *et al*. (2022)	*Ecklonia cava, E. stolonifera*	Antioxidant, anticancer, anti-inflammatory, neuroprotective
Hans *et al*. (2021)	Sulfated polysaccharides	Antiviral; skin protection
Biriș-Dorhoi *et al*. (2022)	Various marine algae	Antidiabetic, anticancer, neuroprotective
Abdul *et al*. (2016)	Fucosterol (Brown algae)	Antioxidant, antidiabetic, anticancer, anti-inflammatory
Cheong *et al*. (2022)	Alginate, agar, fucoidan, carrageenan, ulvan	Cardioprotective; antidiabetic; therapeutic polysaccharides
Thomas and Kim (2011)	Brown algae polyphenols	Anti-inflammatory; antiviral; neuroprotective
Hannan *et al*. (2020)	*Porphyra haitanesis*	Antioxidant; neuroprotective
de Jesus Raposo *et al*. (2013)	Marine microalgae	Neuroprotective; health applications
Fitton *et al*. (2015)	Fucoidan	Anticancer; immunomodulatory
Kim and Pangestuti (2011)	Fucoxanthin	Anticancer; anti-inflammatory
Besednova *et al*. (2021)	Marine algae polyphenols	Antiviral
Geahchan *et al*. (2021)	Fucoidan, carrageenan	Antiviral (COVID-19)
Pagarete *et al*. (2021)	*Ecklonia cava, Ulva* spp.	Antiviral
Silva *et al*. (2012)	Sulfated polysaccharides	Drug delivery; tissue engineering
Pereira (2022)	Sargassum, *Ulva, Gracilaria*	Antimicrobial; therapeutic uses
Shannon and Abu-Ghannam (2016)	Marine algae	Antibacterial
Swamy (2011)	Marine algae	Antibacterial
Amaro *et al*. (2011)	Chlorella, Oscillatoria	Antifungal
Pérez *et al*. (2016)	*Odonthalia corymbifera, Dictyota* spp.	Antifungal; antiprotozoal
Seca and Pinto (2018)	Marine seaweeds	Antihypertensive
Vo *et al*. (2012)	Marine algae	Anti-inflammatory; anti-allergic
Qureshi *et al*. (2019)	κ-Carrageenan	Drug delivery
Zhang *et al*. (2021)	Alginate	Drug delivery; tissue engineering
Zhang and Zhao (2020)	Alginate	Wound healing

Table 2: Applications of marine algae in dental sciences.

Author & Year	Algae Species	Dental applications
Anil *et al*. (2017)	Seaweed polysaccharides	Dental biomaterials and tissue engineering
Oka *et al*. (2020)	Fucoidan	Oral healthcare
Rieuwpassa and Khairunnisa (2024)	*Gracilaria* sp.	Periodontitis treatment
Zamimi *et al*. (2020)	Various seaweeds	Antimicrobial against oral pathogens
Murugaboopathy *et al*. (2021)	Marine algal extracts	Antimicrobial against oral pathogens
Sangavi *et al*. (2024)	Padina boergesenii	Anticariogenic activity
Herawati and Sumanik (2019)	*Sargassum* sp.	Antibacterial against *Porphyromonas gingivalis*
Sujatha *et al*. (2012)	Green seaweeds	Antibacterial against oral bacteria
Huang *et al*. (2021)	Marine bioactive compounds	Oral health promotion
Jun *et al*. (2018)	Sulfated polysaccharides	Antibiofilm and antimicrobial activity
Carrilho and Bretz (2023)	Lithothamnion calcareum	Enamel remineralization
Paudel *et al*. (2014)	Ishige okamurae	Anti-inflammatory (dental pulp)
Pradhan *et al*. (2020)	Enteromorpha compressa	Anticancer activity against oral cancer
Bechir *et al*. (2014)	Marine algae extracts	Treatment of recurrent aphthous stomatitis
Hudiyati *et al*. (2024)	Fucoidan	Periodontal regeneration and implantology
Ewers (2005)	Marine algae-derived biomaterial	Bone grafting
Galindo-Moreno *et al*. (2020)	Algae-derived hydroxyapatite	Bone regeneration for implants
Lin *et al*. (2022)	Alginate	Endodontic applications
Wuttke *et al*. (2024)	Alginate	Periodontal probiotic delivery
Kavitha *et al*. (2019)	Turbinaria conoides	Alginate hydrogel for regenerative applications

Fucoidan injections reduce tooth movement during orthodontic retention by improving bone mineral density. It increases anti-inflammatory macrophages (F4/80+CD206+) and markers like IL-10 and arginase 1, while lowering pro-inflammatory cytokines (IL-6, IL-1β, TNF-α) which enhances tooth stability via the STAT3 pathway. Their role in modulating inflammation, promoting cell proliferation, and inhibiting osteoclastic activity makes marine algae promising natural agents in both restorative and preventive dental care (Hudiyati *et al.*, 2024).

Current marine algae-based dental products

Anil *et al*. explain that agar, from red algae, and alginate, from brown seaweeds are marine hydrocolloids used in dental impressions. Alginate impression material, which is inexpensive and easy to handle, and frequently used to make impressions in general clinical settings is extracted by crushing brown algae in hot alkaline solution to form sodium alginate, which is then filtered, acidified to alginic acid, and dehydrated with alcohol. Adding sodium carbonate converts it back to sodium alginate, dried and milled (Anil *et al.*, 2017; Kitamura *et al.*, 2015).

Alginate and carrageenan, extracted from brown and red seaweeds, respectively, are key ingredients in toothpaste for their gel-forming, stabilizing, and thickening properties. Carrageenan, especially iota type, is commonly added at ~1% for tooth decay treatment. Algal extracts like *Laminaria japonica* and *Aphanizomenon flosaquae* offer antimicrobial benefits and are used in dental gels. Fucoidan from marine algae is also incorporated into toothpaste formulations (Anil *et al.*, 2017).

Seaweed-based chewing gums enriched with minerals help protect teeth from acid damage and promote remineralization. Algal extracts, such as from *Enteromorpha linza* and green algae species, show antimicrobial and antifungal effects against oral bacteria linked to tooth decay and gum disease. A study with 55 participants found *E. linza* mouthwash reduced gum bleeding, swelling, and plaque, matching commercial products. Methanol extracts of *Ulva fasciata* and others showed strong antibacterial activity (Mikulewicz *et al.*, 2015).

Biopolymeric films, including polylactic acid, are used in dentistry for regeneration, drug delivery, and preventing caries and biofilms. They aid restorative, prosthetic, periodontal, and implant therapies, reducing corrosion and friction. Nanocapsules with bioadhesive properties are being developed (Sudhakar *et al.*, 2024).

Bio-inks made from natural biopolymers like carrageenan and alginate offer biocompatibility and versatility for 3D printing in dentistry. They have excellent rheological properties and blend well with other materials. They are used for 3D models, guides, scaffolds, membranes, dentures, and prostheses in various dental fields, including oral surgery and prosthodontics (Sudhakar *et al.*, 2024).

AlgiPore/C GRAFT/AlgOss (ACA) is a hydroxyapatite bioceramic from marine algae with a microporous structure that supports bone growth and implant osseointegration. Symbios® Biphasic BGM modifies ACA with ß-tricalcium phosphate for faster resorption and bone regeneration, though clinical data is limited. Biopolymer-based membranes are preferred for their biocompatibility and tissue-mimicking properties (Sudhakar *et al.*, 2024).

CONCLUSION

Marine algae play a significant role in various fields due to their biocompatibility, biodegradability, anti-inflammatory, and antimicrobial effects. These natural resources are utilized in applications ranging from pharmaceuticals to food supplements, and notably in dentistry for periodontal therapy, bone regeneration, dental implant coatings, prevention of dental caries, etc, with compounds like alginate and fucoidan. Additionally, marine algae extracts have shown promise in treating conditions such as mucositis, and oral submucous fibrosis, and enhancing salivary flow in patients undergoing radioiodine therapy, offering innovative solutions for improving oral health and clinical outcome.

ABBREVIATIONS

ACE: Angiotensin-Converting Enzyme; **AGE:** Advanced Glycation End-products; **HIV:** Human Immunodeficiency Virus; **HSV:** Herpes Simplex Virus; **LPS:** Lipopolysaccharides; **NF-κB:** Nuclear Factor kappa-light-chain-enhancer of activated B cells; **IL-10:** Interleukin-10; **IL-6:** Interleukin-6; **IL-1β:** Interleukin-1 beta; **TNF-α:** Tumor Necrosis Factor alpha; **STAT3:** Signal Transducer and Activator of Transcription 3; **OSF:** Oral Submucous Fibrosis; **ACA:** AlgiPore/C GRAFT/AlgOss; **HFF:** Human Foreskin Fibroblast.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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