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Research

A REVIEW OF MARINE PORPHYRA SPECIES

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Abstract:
Porphyra, a red alga widely cultivated in East Asia, is valued for its nutritional, dietary, and medicinal properties. Key species like P. yezoensis and P. tenera dominate aquaculture, supported by advanced cultivation techniques. Its economic and ecological significance continues to grow globally, with applications in food, traditional medicine, and modern research. Porphyra haitanensis is rich in crude protein, carbohydrates, essential minerals, and pigments like chlorophyll A and phycoerythrin, with minimal heavy metals. Its bioactive polysaccharide, porphyran, contributes to its notable pharmacological properties. The taxonomy and physiology of algae reveal their diverse photosynthetic nature, with the red macroalga Porphyra thriving across tidal zones and exhibiting resilience to salinity variations. Metabolic studies highlight distinct biochemical profiles among brown, green, and red algae. Porphyra cultivation, rooted in ancient practices, has evolved into a billion-dollar industry driven by innovations in mariculture, such as conchocelis-based seeding and asexual reproduction techniques like archeospore utilization. These advancements enhance crop reliability and scalability, with Porphyra's high protein and nutrient content fueling global demand. Further research into its stress tolerance, reproductive biology, and ecological impact promises continued aquaculture advancements. Porphyra, a widely studied marine alga, exhibits diverse pharmacological activities, including antioxidant, anticancer, immunomodulatory, and anti-inflammatory effects. Key bioactive compounds such as polysaccharides, proteins, peptides, and mycosporine-like amino acids (MAAs) contribute to its therapeutic potential. Notably, Porphyra's polysaccharides enhance immune function, while proteins and peptides offer antihypertensive and antioxidative properties.

MAAs demonstrate significant UV protection and antioxidant activity. Additionally, Porphyra is a valuable source of vitamin B12, with potential implications for addressing vitamin B12 deficiency, particularly in vegetarian diets.

Key words: Porphyra, Nori, Rhodophyta, Protoflorideophyceae, Narawaensis.

Introduction:

Porphyra, commonly called Zicai or Ziyin in Chinese, is a highly valued red alga widely cultivated for its nutritional benefits. It is predominantly cultivated across Eastern Asia and, to a lesser extent, in Southeast Asia. This alga belongs to the family

Bangiaceae, order Bangiales, class Protoflorideophyceae, and phylum Rhodophyta, showcasing its significant role in red algae taxonomy (1). Currently, 279 species of Porphyra have been identified globally, highlighting this genus's diversity and ecological significance. Among these, 15 species are native to China, underscoring its regional importance. Notably, two species, Porphyra yezoensis and Porphyra tenera, are extensively cultivated in specific regions of China. P. yezoensis is predominantly grown in Nantong and Lianyungang of Jiangsu Province, while P. tenera is primarily cultivated in the provinces of Zhejiang and Fujian. These regions have become pivotal hubs for Porphyra aquaculture (2). Several Porphyra species, including Porphyra yezoensis, Porphyra tenera, Porphyra haitanensis, and Porphyra suborbiculata, hold traditional significance in Japanese cuisine. These species are commonly utilized as food in forms such as dried sheet laver and stewed laver prepared with soy sauce. A notable product derived from Porphyra is "Nori," a sheet- type dried food. Nori is not only a staple in Japanese gastronomy but also a rich source of dietary fiber, which constitutes nearly 40% of its total mass (3). Dried Porphyra contains rich nutritional and biofunctional components, making it a valuable dietary resource. It contains diverse nutrients, including proteins, vitamins (such as vitamin C and members of the vitamin B family), and essential minerals. Additionally, it is a significant source of dietary fiber, polyunsaturated fatty acids, carotenoids, saccharides, and mycosporine-like amino acids (MAAs) (4). Proteins constitute 25–30% of Porphyra's dry weight; compared to other vegetables, this relatively high protein content may provide a 5% increase in total nitrogen supply (5). Porphyra has become one of the most popular and flavorful algal species consumed throughout the year. Its culinary versatility has led to a significant increase in its consumption at home and in restaurants, where it is prepared in various ways, including with boiled rice and assorted mixtures such as red pepper spices, vegetables, fried egg, beef, or sliced raw fish. Despite its growing popularity, much remains unknown about the environmental requirements and tolerances of Porphyra cultivated in different geographic locations, as well as the specific identification of its species. The characteristics of Porphyra blades—such as color, size, and shape vary depending on environmental factors like water depth, salinity, temperature, photoperiod, and nutrient availability (6). Porphyra has been utilized for thousands of years in traditional Chinese medicine, where

it is valued for its therapeutic properties. It is believed to be effective in resolving phlegm, softening hard masses, reducing fever, and promoting diuresis. Recent pharmacological studies have supported its potential in treating a variety of conditions, including goiter, hypertension, bronchitis, laryngitis, edema,

and measles. In addition to these uses, Porphyra has shown significance in modern research for a range of bioactive properties. These include immunological regulation, antihyperglycemic, antihypolipidemic, antitumor, antioxidative, antiaging, anticoagulant, and liver protective effects (7).

Chemical constituents

The dry weight composition of Porphyra haitanensis includes 34.9–37.2% crude protein, 46.9– 49.3% carbohydrate, 1.68–2.09% crude fat, and 8.75–9.92% ash. Its pigment contents are significant, with chlorophyll A ranging from 601–646 mg/100g, carotenoids from 120–130 mg/100g, phycoerythrin (PE) from 1289–1802 mg/100g, and phycocyanin (PC) from 1255– 1743 mg/100g. P. haitanensis is also rich in free amino acids and essential inorganic elements, including K, Na, Mg, Fe, P, and Zn, while containing only trace amounts of heavy metals such as Cu, Cd, and Cr. The pharmacological activities of Porphyra are attributed to its proteins and carbohydrates, with porphyran, a specific type of polysaccharide, being extensively studied for its various bioactive properties (8).

Taxonomy And Physiological Characteristics

The biological system of algae is complex and heterogeneous, distinguished by their photosynthetic nature. Based on their coloration, algae are broadly classified into three major groups: brown algae (Phaeophyceae), red algae (Rhodophyceae), and green algae (Chlorophyceae). The genus Porphyra is a red macroalga belonging to the division Rhodophyta, class Rhodophyceae, order Bangiales, and family Bangiaceae. Species of Porphyra are distributed globally, with some of the most commonly occurring species being Porphyra yezoensis, Porphyra tenera, and Porphyra haitanensis.

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These species thrive in different tidal regions, such as the low-tide zone (e.g., Porphyra dioica and Porphyra umbilicalis), the low-intertidal zone (e.g., Porphyra leucosticta and Porphyra purpurea), and the subtidal zone (e.g., Porphyra amplissima). Salinity is a critical factor influencing the growth of Porphyra. However, research by Stekoll et al. demonstrated that variations in salinity of 20 to 40% did not significantly affect the growth of Porphyra abbottae, Porphyra torta, and Porphyra pseudolinearis. A broad-scale metabolic survey conducted by Belghit et al. revealed distinct differences in the metabolic content of brown, green, and red algae, reflecting their taxonomic classifications. These metabolic differences were particularly evident in the composition of amino acids, amino acid derivatives, and peptide metabolites (9).

Cultivation

The cultivation of Porphyra is older than the establishment of modern aquaculture practices. Fishermen, aware of the seasonal appearance of Porphyra blades in the wild, enhanced their harvests by improving the availability of hard substrata along the shoreline, which facilitated the growth of Porphyra. By the late 16th and early 17th centuries, this cultivation technique had spread to Japan, Korea, and China. In Japan and Korea, the practice involved inserting bamboo stakes into soft sediments along the shore, a method known as the ‘bamboo-Hibi planting’ technique used for cultivating nori. In contrast, early practices in China, particularly in Pingtan, involved rock-cleaning techniques for xi hai, where lime was used to remove attached algae and invertebrates from rocks before the autumn arrival of the Porphyra conchospores, or 'seed.' Despite these advancements, the life history of Porphyra remained poorly understood, and the reasons behind annual fluctuations in blade abundance remained a mystery (10).

Establishment of greenhouses for culturing conchocelis on shells, such as oyster shells.

Seeding of conchospores onto nets, which were then outplanted into the sea.

Harvesting of Porphyra from the nets.

Production of dried sheets of Porphyra using purpose-built equipment to process a chopped slurry of the crop.

Parallel developments occurred in China and South Korea (11).

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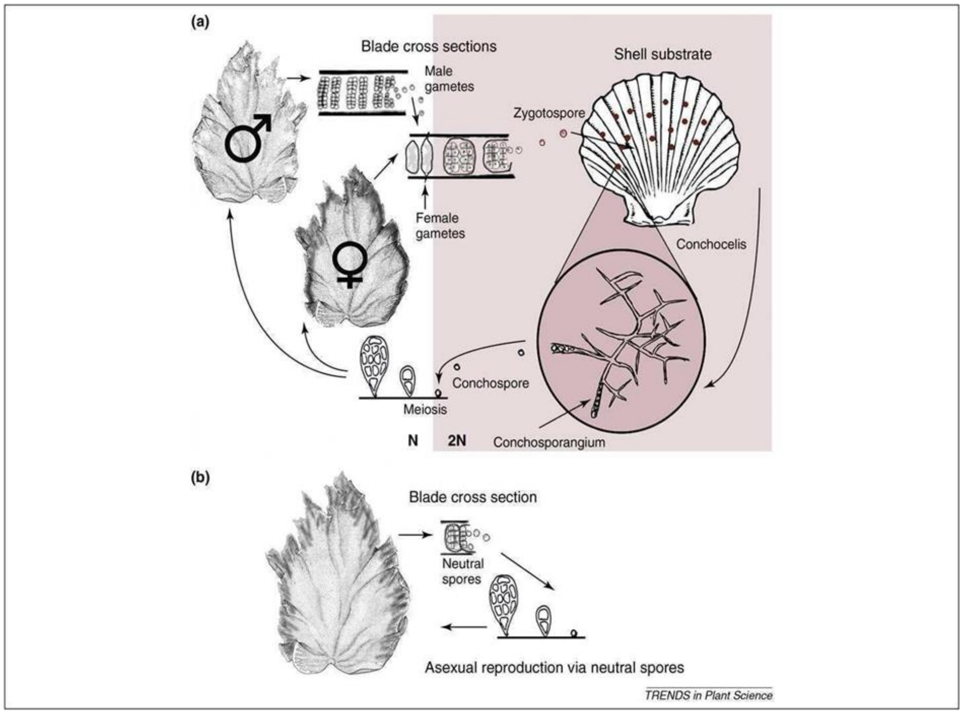
Examples of Porphyra cultivation. (a) Porphyra yezoensis conchocelis growing in oyster shells (purple patches on shells); (b) nori nets wound onto a paddle wheel for seeding by P. yezoensis conchospores from conchocelis shells (underwater in foreground); (c) nori-harvesting boat: this boat runs under the nets, shearing nori from them; (d) dried P. umbilicalis on rocks during low tide; (e) juvenile blades of P. umbilicalis haplotype, P.um1, the subject of the complete genome sequencing project; (f) neutral spores releasing from the blade margin of P. umbilicalis, scale bar = 50 mm; (g) Porphyra haitanensis mariculture farm (China), showing nets floating on the surfaceand raised for desiccation to kill fouling organisms (10).

An alternative approach for culturing Porphyra could involve bypassing the conchocelis culture stage by seeding nets with archeospores, asexual spores produced by the blades of some Porphyra species. Archeospores have already become significant in the commercial culture of P. yezoensis. Juvenile blades growing on nets release archeospores, thereby amplifying crop biomass compared to initial net seeding with conchospores. Successful seeding of bare nets placed beneath a conchospore-seeded net of P. yezoensis was demonstrated on a Chinese farm, potentially leading to future efficiencies in net seeding practices. Recent studies have reported that calcium ions (Ca^{2+}) influence the proportion of archeosporangia on P. yezoensis blades in artificial growth media, which may have commercial applications. Further research is required to test and measure the role of calcium influx, as well as the influence of other ions, in this process under typical seawater ion concentrations (12). A primary reason for the growing interest in developing P. umbilicalis as a mariculture crop in the northwestern Atlantic is its substantial production of neutral spores, a type of asexual spore produced by the blade, in comparison to other sympatric Porphyra species. Many Porphyra species with commercially favorable traits produce few or no asexual spores. Investigations into the regulatory elements controlling the production of different types of asexual spores are essential to understanding reproductive evolution in this ancient group of eukaryotes and to advancing the use of asexual spores in the continued development of aquaculture. In P. yezoensis, archeospores are produced on juvenile blades; as these blades mature, they develop gametangia, leading to sexual reproduction. This suggests that two distinct genetic networks govern reproduction in such species, with archeospore production following an ancestral asexual pathway. In contrast, neutral spores of P. umbilicalis in the northwestern Atlantic are produced on mature blades at sites where gametangia would normally develop, highlighting a divergence in reproductive strategies between these species

(13). Neutral sporangia in P. umbilicalis each contain 16 spores, which is identical to the number of zygotospores produced following fertilization. This number of spores could also be generated from three fewer cell divisions than the process that produces male gametes (128 gametes per male gametangium) in sexually reproducing P. umbilicalis. The position of the neutral sporangia and the stage at which they develop suggests that this asexual pathway shares genetic components related to gametogenesis. Work on the differentiation of the germ line in other algae and angiosperm plants indicates that a regulatory protein or a miRNA in Porphyra that suppresses or fails to Activate sexual reproduction in asexual blades exists, given that sexual reproduction occurs in other P. umbilicalis populations. In the green alga Volvox, sexuality is determined by a few genes. Reproduction in Volvox is controlled by the gonidia less protein (GLS), which causes asymmetric cell division.



Porphyra umbilicalis life history showing the typical heteromorphic life history (a) and reproduction of the blade by an asexual pathway involving neutral spores (b) (10).

Following cell division, the resulting distinct cell states are maintained by repressor proteins. In larger cells, late gonidia (LAG) proteins inhibit somatic cell expression, while the somatic regenerator protein (REGA) suppresses gonidial differentiation by halting chloroplast biogenesis. A newly recognized hermaphroditic species of Porphyra, Porphyra migitae, uniquely develops both archeospores and neutral spores on the blade, in addition to male and female gametes. This species may serve as a valuable model for studying developmental pathways in Porphyra.

The high-stress tolerance exhibited by many Porphyra species is a key factor contributing to the success of commercial cultivation in the open sea. Farmers raise nets seeded with either

P. yezoensis or P. haitanensis out of the sea for several hours a day, multiple times a week, particularly early in the growing season. This aerial drying process kills fouling organisms (e.g., macroalgal spores, diatoms, and invertebrate larvae) through desiccation, while Porphyra survives. One exception to this desiccation treatment is Ulva species (green algae), although their growth can be suppressed by regulating Porphyra net-seeding densities and applying longer desiccation treatments when infestations occur (10).

Pharmacological Activities

Antioxidant Properties of Porphyra: The antioxidative potential of Porphyra has been extensively studied. Zhao et al. explored the antioxidant activity of degraded porphyrans with varying molecular weights. Their findings revealed that antioxidant activity increases as molecular weight decreases. Similarly, Zhang et al. isolated a low-molecular-weight porphyran from P. haitanensis and chemically modified it to produce sulfated, acetylated, phosphorylated, and benzoylated derivatives. Among these, the benzoylated derivative exhibited the highest antioxidant activity in three different assays, marking it as a promising candidate for future investigations. In a mouse in vivo study, a sulfated galactan fraction (F1) isolated from P. haitanensis, which demonstrated a typical porphyran structure, was administered intraperitoneally. This treatment significantly reduced lipid peroxidation in aging mice and enhanced antioxidant biomarkers such as total antioxidant capacity, superoxide dismutase activity, and glutathione peroxidase (GSH-

Px) activity. These results underscore the significant antioxidative potential of F1 in vivo models (14).

Hypolipidemic effect: One study investigated the effect of dietary porphyran on glucose metabolism in KK-Ay mice (a model for type 2 diabetes). The results suggested that dietary porphyran might improve glucose metabolism in diabetes through the upregulation of adiponectin levels. In addition, certain effects of dietary porphyran on the hindgut environment might contribute to improved glucose metabolism. Zhang et al. reported a novel polysaccharide–iron complex (LPPC) that could increase the red blood cell count, hemoglobin levels, serum iron levels, as well as the spleen index, spleen mass, and total mass of mice with iron deficiency anemia. In addition, porphyran supplementation was shown to significantly decrease apolipoprotein B100 secretion in HepG2 cells through a mechanism partially associated with the suppression of cellular lipid synthesis. This was the first study to elucidate the mechanism for the hypolipidemic effect of porphyrin (15).

Immunomodulatory activity: A previous investigation explored the immunomodulatory efficacy of porphyran isolated from Porphyra vietnamenis. Oral administration of porphyran (200–500 mg/kg) to Wistar albino rats evoked a significant increase in weights of the thymus and spleen, as well as increased lymphoid organ cellularity. In addition, it was observed that there were significant increases in the total leukocyte and lymphocyte counts ($P < .005$), increased neutrophil adhesion to nylon fibers, and dose-dependent increases in antibody titers. A decreased response to the delayed-type hypersensitivity (DTH) reaction induced by sheep red blood cells was also recorded. Porphyran was found to induce a potent phagocytic response and produce significant changes in the formation of formazan crystals. Porphyran also prevented myelosuppression in cyclophosphamide-treated rats. In total, the results indicated

that P. vietnamenis possesses immunomodulatory activities and has the potential to prevent autoimmune diseases (16).

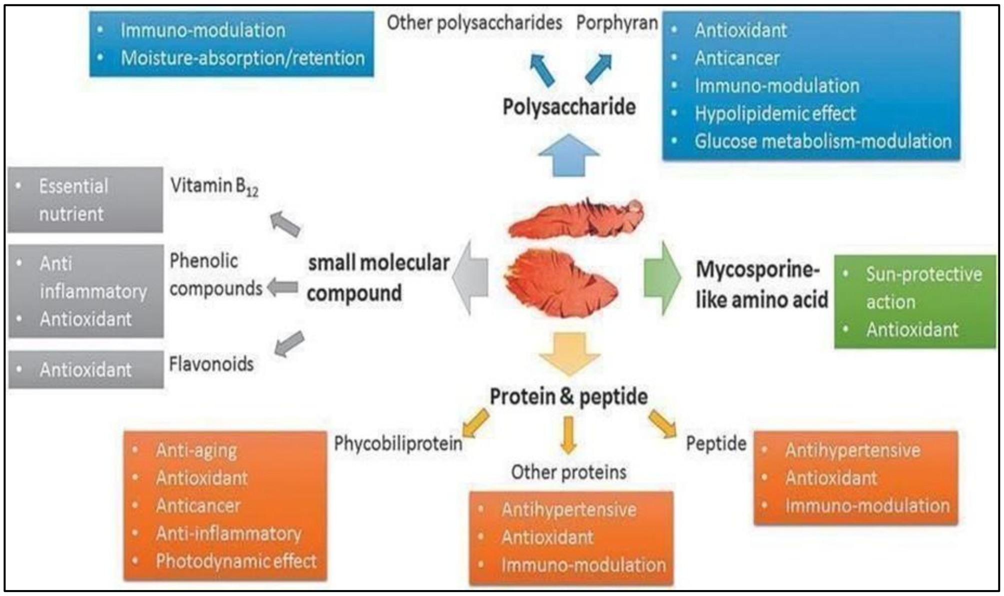
Antiallergic activity: The antiallergic activity of porphyran was studied in Balb/c mice using the contact hypersensitivity (CHS) reaction, which is commonly used as a model to evaluate the antiallergic activity of food and food components. The investigators found that the oral administration of porphyran (2% in drinking water) suppressed the CHS reaction (ear edema) induced by 2,4,6-trinitrochlorobenzene. They also found that porphyran suppressed serum IgE levels and the production of interferon-gamma (IFN-c) in the challenged ear lobe. These findings indicated that oral porphyrin suppressed the CHS reaction by decreasing serum IgE levels and the production of IFN-c in the challenged ear lobe (17).

Macrophage-Stimulating Activity: In a parallel study, the polysaccharide fraction derived from Porphyra yezoensis (PASF) underwent structural and functional assessments to elucidate its macrophage-stimulating properties. Desulfation of PASF resulted in a reduction of its macrophage-stimulating activity in vitro, while further sulfation did not significantly alter the activity. Among seven fractions obtained through anion-exchange chromatography of PASF, those with either a lower or higher sulfate content exhibited stronger activity compared to fractions with medium levels of sulfate content. These findings highlight the importance of sulfate groups in PASF as contributors to its macrophage-stimulating activity. However, the studyalso indicates that an increase in the number of sulfate groups does not necessarily enhance the activity, suggesting a nuanced relationship between sulfate group composition and macrophage activation (16).

Porphyra polysaccharides: Porphyra polysaccharides (PPs) exhibit significant immunomodulatory and pharmacological properties. Studies have shown that PPs enhance immune function by increasing interferon-gamma (IFN-γ) levels, natural killer (NK) cell activity, and spleen gland/body weight ratios in treated mice. At higher doses (2000 mg/kg), PPs promote delayed-type hypersensitivity (DTH) responses, stimulate splenic lymphocyte proliferation, and boost interleukin-2 (IL-2) production and antibody generation. They also improve carbon granular clearance at doses of 1000–2000 mg/kg. Beyond immunomodulation, PPs possess antioxidant, anticoagulant, antifatigue, and anticancer properties, highlighting their broad therapeutic potential (18).

Potential for Human Applications

The pharmacological results obtained from animal models and cell-based in vitro studies suggest a need for controlled clinical investigations to evaluate the antioxidant effects of Porphyra-derived compounds in humans.



Bioactive compounds and their bioactivities obtained from Porphyra species (16).

Summary

Porphyra, commonly known as nori, is a highly nutritious and economically significant red alga with a wide range of applications in nutrition, medicine, and aquaculture. It is a rich source of proteins, bioactive polysaccharides, vitamins, and essential minerals, contributing to both traditional diets and modern pharmacological research. Its ability to thrive in diverse environmental conditions and its high adaptability to various cultivation techniques have propelled the mariculture industry to a billion-dollar scale, with Japan and China leading its global production.

Advanced research into Porphyra's genetics, life cycle, and stress tolerance has further enhanced its cultivation efficiency and economic value. Its diverse bioactivities, including antioxidant, antitumor, immunomodulatory, and hypolipidemic effects, underline its potential in modern medicine. Additionally, Porphyra's ecological role and high vitamin B12 content make it a vital dietary component, especially for vegetarians. The continued exploration of its bioactive compounds and environmental adaptability will further solidify its position as a cornerstone of global aquaculture and nutritional science

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