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Versatility of the Humble Seaweed in Biomanufacturing

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Abstract

Seaweeds are important marine organisms that have diverse biological characteristics. Seaweed is traditional food in Japanese and East Asian cultures and is used in the production of fertilizers and applications in the cosmetic industry. Recently, the contributions of seaweed to biomanufacturing have increased due to technological advances and its environmentally friendly products. Moreover, the unique properties of seaweed include the ability to form and control intracellular opalescence. The increasing importance of sustainability in industrial processes drives society to use seaweed as a model organism in biomanufacturing. Nevertheless, further understanding of seaweed biology, culture and scaling-up methods is required. The objective of this study is to emphasize the multiple uses of seaweed which may be beneficial and environmentally friendly.

Keywords: Eco-friendly; biodegradable; anticancer; antimicrobial; biopolymers; agar; alginate

1. Introduction

Seaweed is a popular biological resource that is extensively produced in biomanufacturing [1], [2]. Seaweed refers to macroscopic, multicellular marine sea algae that are green (*Chlorophytes*), brown (*Phaeophytes*) and red (*Rhodophytes*). Seaweed cultivation represents a sustainable and preventative measure against environmental issues such as eutrophication, acidification and global warming and yet, does not compete with human land use due to the environmentally friendly nature of seaweed. Macroalgae are also fast growing and dominant photosynthetic organisms with a yield of cultivation 6 to 40 times greater than land plants. Their natural hardy characteristics offers

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them the ability to grow in diverse environments without the need for pesticide control. An overview of seaweed applications in biomanufacturing is presented in Figure 1.

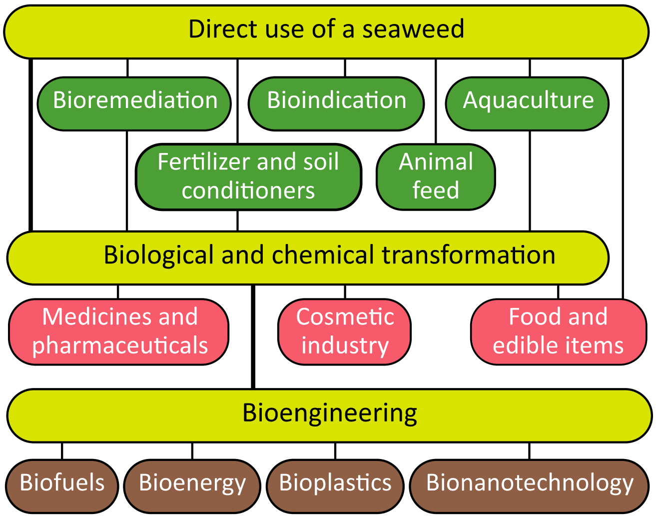

Fig. 1. Multiple uses of seaweed in biomanufacturing

2. Biological characteristics of seaweed

Seaweeds have many nutritional attributes such as protein and mineral content [3]. Several seaweeds contain polyunsaturated conjugated fatty acids [20] which have been reported to show anticarcinogenic, antiobese and hypolipidemic effects [4]. Some of these pigments include derivatives from chlorophyll, carotenoids including β-carotene, diterpenes, phycobiliproteins and xanthophylls such as fucoxanthin. Interestingly, seaweed consumption can also affect the human nervous system, but this is generally higher in brown seaweeds [5].

3. Applications of seaweed in biomanufacturing

3.1. Production of food and edibles

Commonplace in Japanese diet and other East Asian cultures, seaweed is currently recognized as a healthy food and its consumption is increasingly global demand (see Figure 2). Green algae such as *Monostroma latissiumum* and *Enteromorpha prolifera* are cultivated on a commercial scale to produce green laver [1]. Polysaccharides from seaweed are used in food thickening, concoctions and for making gelatinous dishes [7]. Integration of seaweed extracts into commercial food production can reduce the use of chemical preservatives [8] and enhance the health value of food products [9].

3.2. Animal feed

Seaweed such as *Ulva lactuca, Ruppia maritima* and *Chaetomorpha linum* is used as animal feed for livestock [10]. Other sea-weed based animal feed are fed to pigs [11] and chicken [12], including processed seaweed supplemented to shrimp feed [13]. The inclusion of animal feed in rabbit diets however, has fared less well [14]. Outcomes of using seaweed as animal feed in terms of rabbit health and meat production remain unclear.

3.3. Fertilizer and soil conditioners

Dried and cold-pressed seaweed is used in agriculture as plant fertilizer by both foliage and soil applications [15]. When applied to soil, the polysaccharide content in seaweed acts as soil, improves aeration and soil structure in clay soils [16]. Plants treated with seaweed fertilizers have shown improved physiological effects [17]. Residues from algae processed for other purposes, such as obtaining biofuels, may also be used as fertilizer [18]

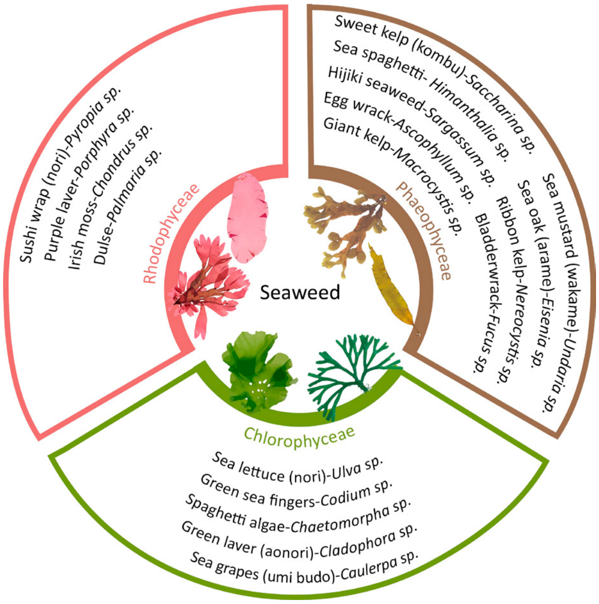

Fig. 2. Some commonly consumed seaweeds.

3.4. Aquaculture, bioremediation and bioindication

Seaweed farming supports marine biodiversity [19]. In animal cultures, the sustainability of seaweed cultivation increases when macroalgae remediates nutrient loading from wastes from animal cultures (i.e. fish, sea cucumber, mussel...) through Integrated Multitrophic Aquaculture (IMTA) [20]. Improved survival rates, immunity responses and bacterial resistance have been reported in farmed marine life [21], [22]. Extensive proliferation of seaweed called macroalgal blooms can occur because of nutrient enrichment, antagonistic changes in existing organisms, and impacts from sea hydrodynamics that favour rapid growth of the blooms [23]. Nevertheless, there are positive effects from macroalgal blooms, such as the increase of habitat complexity, provision of food to other organisms and alleviating problems related to eutrophication [24]. Seaweed resistance to microbial attack allows it to be a potential antifouling compound to be used in submerged marine structures [25]. Seaweeds can remove heavy nutrient loads in coastal waters from large-scale fish and shellfish farming [26]. Seaweed grown along coastline or through modern wastewater treatment plants (e.g. lagooning) can serve as biofilters and help in alleviating biological eutrophication [27]. The sessile characteristic, high metal uptake and ease of sampling of macroalgae such as *Ulva lactuca, Enteromorpha intestinalis, Padina gymnospora* and *Dictyota bartayresiana* makes them good bioindicators of contamination, especially at those sites where no sediment is present [27]–[29].

3.5. Medical and pharmaceutical use

Nutriceutical products made from seaweed are iodine-supplements and organic essential vitamins and minerals [30]. Halogenated sesquiterpenes from the red seaweed *Laurencia dendroidea* have larvicidal effects against the *Aedes aegypti* mosquito [31]. Laminarin from brown seaweed can stimulate the cell signaling pathway of dendritic cells during antigen-specific immune activation [32]. Sulphate polysaccharides from *Ulva fasciata* and *Agardhiella subulata* show anticoagulant properties without adverse effects to cellular metabolism [33]. Among the purported health outcomes from seaweed are enhanced immunomodulatory effects, improved gut and bone health, improved growth performance and reduced pathogen shedding in animals, and reduced risk of colon cancer, obesity and metabolic diseases in humans and inhibition of cancer growth [34]. Agar and agarose from seaweed are applied in industrial use, pharmaceuticals, separation and purification media for fine chemicals, hormones and enzymes [35]. Agar can provide constipation relief as a laxative because of its ability to stimulate bowel movement [36]. It is used in formulations for diagnostic anatomical imaging [37] and production of prosthetic dental casts [38]. Alginate is used as in chemical procedures such as producing medicinal tablets, dressings and biodegradable sutures for wounds, moulding material in industrial use and recombinant biocatalysts [39]. Although alginate was initially considered to have no nutritional value, there is evidence that it contains bioactive properties [40], [41]. Carrageenan extracted from red seaweed is used in drug delivery systems as agents for controlled drug release medications and extrusion aids for the preparation of tablets [42].

3.6. Cosmetic industry

Bioactive compounds sourced from seaweed are beneficial for dermatological functions [43]. Crude extracts from brown seaweeds *Turbularia conoides* and *Padina tetrastomatica* show high free radical scavenging and antioxidant activity compared to red seaweeds [44]. Other potential cosmetic functions are as skin-whitening and anti-wrinkle ingredients [45].

4. Bioengineering

Bioengineering integrates methods and technologies from biological principles and engineering to develop novel products, processes or solutions [46].

4.1. Biofuels

Seaweed have several advantages compared to terrestrial plants, particularly in its use as certain biofuels through biodigestion and transesterification. The advantages are a three or four-fold efficiency on photosynthesis compared to terrestrial plants, no competition for habitat, reduction in eutrophication and the environmentally friendly nature of seaweed cultivation. In fact, the bioproperties of seaweed support pretreatment and further anaerobic fermentation, thus enabling the biodigestion process to generate fuel [47]. These biodigestion processes may generate bioethanol, biobutanol, biomethanol, biodimethyleter, hydrogen sulphide, carbon dioxide, nitrogen and water [48]. *Macrocystis pirifera*, *Ulva* spp., and *Saccharina latissima* have three times the methanogenic potential of terrestrial plants [49]. The transesterification process is enabled by the high content of oils in seaweed (e.g. *Laminaria saccharina*) whereby biodiesel is produced in transesterification with alcohol and a catalyst. Recent studies found higher energy return of investment (EROI) in obtaining biofuels from seaweed compared to common land crops (e.g. corn, sugarcane) [50], [51]. Other biofuel outputs from seaweed are bio-crude and bio-chars obtained from the transformation of macroalgal biomass through recent methods such as hydrothermal liquefaction, pyrolysis and hydrothermal catalytic gasification. Researchers have reported higher energy output achieved from these methods compared to fuels generated from other anaerobic methods [52], [53]. In addition, the simple method of direct combustion of algal biomass into hot gasses for energy production may be more efficient than a coal-fired power plant especially when ash and alkali residue contents are reduced together with moisture content through different pretreatments [18].

4.2. Bioplastics

Plastics recovered from crude are expected to have similar characteristics to those obtained from primary producers and can be obtained from the same organic material that creates crude [54]. Bio-based materials are biodegradable products mainly obtained either by the direct production of polymers or by producing bio-based monomers followed by their biochemical polymerization [55]. The bioplastic may be high, medium or low density, and may be fabricated in accordance with methods commonly known in the art (e.g. injection moulding) and be the substrate of traditional synthetic polymers (e.g. nylon). However, those that originated directly from seaweed would be environmentally friendlier due to the biodegradability and renewability of biopolymers [56]. The bypass of toxicity problems associated with traditional plastics (PVC, BPA and other resins or unstable chemicals) makes bioplastics especially useful in those activities directly related with human feeding, such as food packaging and agricultural applications [57]. Due to their biocompatibility, biodegradation, non-cytotoxicity and antimicrobial properties, biopolymers from seaweed are also an excellent material for use in implantable materials, wound dressing, pill disintegrators, ligament and tendon tissue engineering, to prepare moulds in dentistry or bone fixation parts [55], [57]. Moreover, bioplastics from seaweeds are reported to be more resistant to microwave radiation, less brittle and durable [54]. Polysaccharides from seaweed are extracted for polymer manufacturing, or fermented to produce lactic acid and its polymers [58]. Biological conversions of algae-derived polysaccharides and lipids through enzyme reactions produce different types of polyester. Poly(3-hydroxybutyrate) (PHB) and Poly(3-hydroxyalkanoate) (PHA) are polyesters considered as green substitutes for conventional nonbiodegradable plastic because of their similar properties to those of polypropylene [55]. While polysaccharides from algae are mainly used for biomedical or food applications, alginate is a natural polymer from brown algae with adhesive effect that can be combined with paper to create a biodegradable natural fibre composite durable enough to make furniture [58] or with calcium fibres to create cloth material [57] .

4.3. Bionanotechnology

Metal nanoparticles (NPs) may be biologically synthesized from living organisms such as bacteria, yeasts, fungi and plants and used in a wide range of areas including medicine, pharmaceutical industry and water treatment [59]. The large surface to mass ratio in nanoparticles, due to their small size, enhances their ability to adsorb and carry other compounds such as drugs, probes and protein [60]. Biological applications of metal nanoparticles include labelling, biosensors, acaricides, medical imaging, drug delivery and anti-cancer treatments [61]. Several attempts have been made to research seaweed-mediated synthesis of metal nanoparticles [62]. Seaweeds are potentially suitable for remediation because their bioactive compounds contain functional groups which can reduce the ions of aqueous metals and stabilize metal nanoparticles as capping agents [63] . Amongst some of the metal nanoparticles that have been synthesized from seaweed are silver (Ag), gold (Au), iron (Fe) and platinum (Pt) [61]. Silver nanoparticles (Ag-NPs) are known for their catalytic activity, conductivity, antidiabetic, antimicrobial, anticancer, antifungal and wound healing properties [64]. Silver nanoparticles synthesized from green seaweed *Gracilaria edulis* showed effective antidiabetic and antibacterial activity against various bacterial pathogens [65]. Iron nanoparticles (Fe-NPs) synthesized from brown seaweed *Dictyota dicotoma* increased inhibitory effect when combined with antibiotics [66]. Gold nanoparticles synthesized from the calcareous red seaweed *Corallina officinalis* showed cytotoxic effects against the human breast cancer (MCF-7) cell line [67]. Platinum nanoparticles synthesized from the brown seaweed *Padina gymnospora* showed catalytic anti-microbial, scavenging effects, haemolytic and antioxidant activities against pathogenic bacterial strains. There is also evidence of metal oxide nanoparticles synthesized from seaweed of which structural electronic geometries allows them to function in catalytic processes, electronics, magnetic storage media and solar energy conversion [68]. Although research on seaweed-derived nanoparticles has shown promising results in several biomedical and environmental functions, the exact mechanisms of the biosynthesis of nanoparticles is still not well understood [69].

5. Conclusion

Figure 3 summarises our findings on the uses of seaweed in biomanufacturing. Seaweed is a natural resource with immense potential in biomanufacturing because of the following reasons: its accelerated growth and regeneration; lesser likelihood of technical difficulties occurring from scaling-up microalgae cultivation; potential to address global environmental issues and avoidance of conflict or competition with other land-based activities. Their numerous natural properties and bioactive compounds make seaweed a useful source of new applications, especially in the food, pharmaceutical and medical fields. Seaweed byproducts may have revolutionary uses, including the potential to treat cancer, to power engines and the creation of biodegradable plastics. Nevertheless, economical funding and further research on biomanufacturing processes are needed in order to develop competitive, healthy and more sustainable methods than traditional medicine or oil-based products.

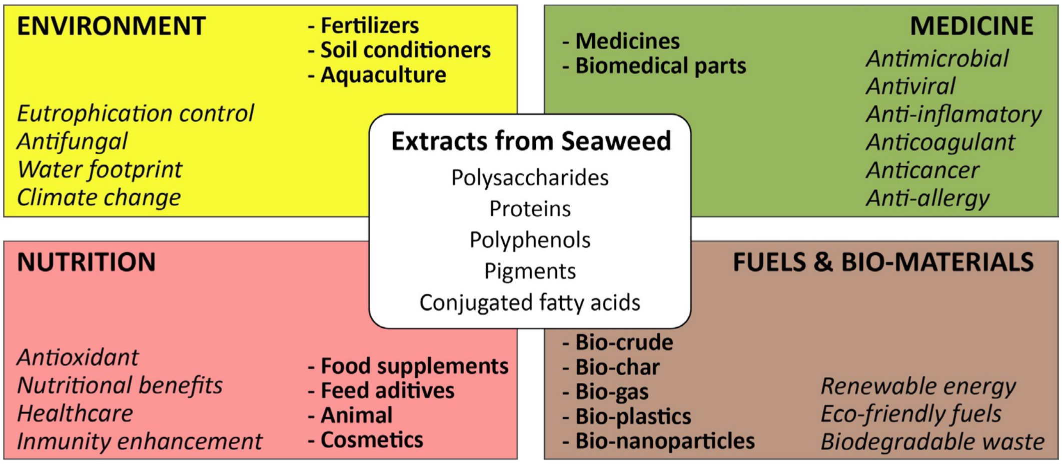

Fig. 3. Versatility of the humble seaweed in biomanufacturing.

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