Sri Lankan J. Biol. 2023, 8 (2): 4-19

DOI: https://doi.org/10.4038/sljb.v8i2.113

Review Open Access

Impact of Algal Research and its Potential for Industrial Applications: A Review

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Abstract

Marine biotechnology is a broad field with a profound and global sociological footprint. Within that sociological macrocosm, marine algae act as an emerging field of research that is exemplified by the superabundance of natural sources to harvest bioactive compounds. Algae synthesize a comprehensive array of bioactive compounds including polysaccharides, polyphenols, sterols, alkaloids, flavonoids, tannins, proteins, essential fatty acids, enzymes, vitamins, and carotenoids. Many of these bioactive compounds are composed of significant biological properties such as antioxidant, ultra-violet protective, anti-inflammatory, anti-wrinkling, skin-whitening, anti-microbial, anti-thrombotic, and anti-cancer activities. With the discovery of novel bioactive compounds from marine algae, it as a collective performs the role of a conveyer belt of ingredients for industrial applications, namely the pharmaceutical industry, cosmeceutical industry, nutraceutical industry, energy industry, and functional food industry, etc. New generations have now focused their attention towards natural, safe, and highly available bioproducts as it downplays the risks linked to consumption while providing benefits. Considering the rising demand for natural bioproducts globally, marine algae turn into biological factories with vast economic potential. Therefore, this mini-review mainly focuses on the impact of algal research and its potential for industrial applications.

Received: 02 April 2023

Accepted: 18 June.2023

Keywords:

Marine biotechnology
Macroalgae
Bioactive substances
Bioproducts
Algal researches
Industrial applications

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1 Introduction

The history of drug discovery using natural extracts goes back to 2600 BC when Mesopotamians were tabulating the use of Cypress and Myrrh plant oil extracts to treat a wide variety of diseases (Koyande *et al.*, 2021). Discovered oil extracts from ancient times, are still used by people as remedies to treat different ailments like cough, inflammation, and cold (Gordaliza, 2007). "*Ebers papyrus*" which is an Egyptian pharmaceutical record revealed that about 700 plant-based drugs were discovered by Egyptians in and around 2900 BC. Moreover, some Chinese and Greek physicians also discovered plant-based drugs during the early 1100 BC (Dias *et al*., 2012). Therefore, the history of natural extracts dates back to early 1100 BC and it leads to immense contribution to the development of medicinal chemistry and pharmaceutical industries (Sakthivel and Devi, 2019).

When considering plant distribution within the world, South Asia acts as a cluster for the growth of a wide variety of plant biota with high medicinal values (Natarajan *et al*., 2009; Watanabe *et al*., 1959). It is a region located near to the equator with about 29℃ of average temperature in its coastal areas and spans a climate range from tropical to temperate (Douglas, 2009). Due to these favorable climate conditions available within the coastal areas, it provides the habitat for lots of marine biosources including algae, and acts as a hub for different marine plant varieties to grow (Natarajan *et al*., 2009). Among these marine biosources, algae play a vital role in marine ecology as they have some specific, unique qualities and bioactive compounds (Sakthivel and Devi, 2019).

Algae are diverse from unicellular organisms a few microns in diameter to multicellular organisms about eighty meters long (Karuppiah and Li, 2015). They can be classified into two main segments macroalgae and microalgae (Hemasudha *et al*., 2019). Algae can be divided into four major phyla Phylum Chlorophyta, Phylum Rhodophyta, Phylum Phaeophyta, and Phylum Bacillariophyta based on their color which occurs as a result of the availability of photosynthetic pigments (Anbuchezhian *et al*., 2015; Hemasudha *et al*., 2019). Marine algae are usually composed of bioactive substances which are responsible for biological properties including antioxidant, UV-protective, anti-obesity, neuroprotective, antimicrobial, anti-nociceptive, anti-inflammatory, anti-wrinkling, skin whitening, anti-viral, anti-thrombotic, and anti-cancer activities (Sakthivel and Devi, 2019). Hence, it will be more important and profitable to develop bioproducts using bioactive constituents from these marine algae on an industrial basis (Sakthivel and Devi, 2019).

Mainly marine algae are composed of valuable secondary metabolites which are responsible for many biological functions within their life cycle strategies. Some macroalgae have triphasic life cycles and some have diphasic lifecycles. The prevalence of these secondary metabolites varies on the seasonal variations, life cycle strategies, and microclimatic conditions where the macroalgae grow in the ocean environment (Priyadharshini *et al.*, 2014). Among those secondary metabolites, polyphenols, sulfated polysaccharides, terpenoids, mycosporine-like amino acids, fatty acids, and peptides are enriched with unique bioactive properties and biocompatibility (Anbuchezhian et al. 2015; Narayanasamy et al. 2020). Those bioactive compounds compacted within those marine algae are responsible for their valuable features like antioxidant properties, anti-cancer properties, anti-diabetic properties, anti-bacterial properties, and anti-inflammatory properties (Rico *et al.*, 2017). Therefore, further research studies related to the bioactive compounds of marine algae are a prerequisite in this modern era.

Due to the considerable features earmarked in these marine algae, scientists began to conduct research based on them by substituting them as precursors for different industrial applications (Wang *et al.*, 2020). Among those industrial applications, the pharmaceutical industry, cosmeceutical industry, nutraceutical industry, functional food industry, and energy industry play a major role (Anbuchezhian *et al.*, 2015; Sanjeewa *et al.*, 2017). So far, several studies have been carried out to evaluate the therapeutic potential of the algal-derived extracts and compounds isolated. Therefore, this mini-review aimed to explain the impact of algal research and its potential for industrial applications (Table 1).

2 Desirable bioactive constituents of marine algae for industrial applications

Marine algae are a rich source of bioactive metabolites that are beneficial to human health. They produce primary and secondary metabolites that exhibit excellent biological properties and are known to be ideal for drug development (Sanjeewa *et al.*, 2017). Bioactive compounds embedded in these seaweeds mainly are as amino acids, photosynthetic pigments, vitamins and minerals, polysaccharides and carbohydrates, polyphenols, sterols, and carotenoids (Smith, 2004). Marine brown algae are generally composed of alginate and fucan-like anionic polysaccharides and laminarin, mannitol and cellulose-like neutral polysaccharides. Similarly, marine red algae enriched with agars and carrageenans like sulfated galactans, porphyran, xylans, floridean starch, cellulose, and mannans whilst green algae are enriched with ulvan, cellulose, sulfated galactans, xylans, mannans, and starch (Descamps *et al.*, 2006). Apart from that, some sulfated galactans like alginates, agar, and carrageenans could function as hydrocolloids where they can be extensively used in

Table 1: Industrial application of marine alga

APPLICATION	DESCRIPTION	REFERENCES
Biomaterials	Algae-derived compounds, such as alginate and carrageenan, have gelling and thickening properties. They are used in the production of biodegradable plastics, textiles, and cosmetics.	(Capasso and Mannelli 2020)
Nutraceuticals	Algae are a source of various bioactive compounds, including antioxidants, omega-3 fatty acids, and pigments like astaxanthin. These compounds are used in the production of nutritional supplements and functional foods	(Besednova et al., 2020)
Wastewater treatment	Algae can be used in wastewater treatment plants to remove excess nutrients like nitrogen and phosphorus. They can help reduce water pollution and promote the recycling of nutrients.	(Besednova et al., 2020)
Carbon capture	Algae are a source of various bioactive compounds, including antioxidants, omega-3 fatty acids, and pigments like astaxanthin. These compounds are used in the production of nutritional supplements and functional foods	(Matos et al., 2017)
Biofuel production	Utilizing macroalgae as a feedstock for biofuel production	(Anbuchezhian, Karuppiah and Li, 2015)
Food and nutrition	Incorporating macroalgae as a nutritious food source	(Besednova et al., 2020)
Cosmetics	Incorporating macroalgae-derived compounds in cosmetic formulations	(Mohammed et al., 2019)
Pharmaceutical	Exploring macroalgae for potential drug discovery	(Capasso and Mannelli 2020).
Agriculture	Using macroalgae as a soil amendment or fertilizer	(Mohammed et al., 2019; Pati et al., 2016)
Bioremediation	Harnessing macroalgae to remove pollutants from aquatic ecosystems	(Mohammed et al., 2019; Pati et al., 2016)
Bioplastics	Organic renewable biomass extracted from marine algae can be utilized for the production of bioplastics. Moisture content barrier of red algal agar derived plastic film behaves much better than cassava starch derived bioplastic	(Yi et al., 2020)

the pharmaceutical, cosmetic and food industries in a large scale (Prieto and Lagaron, 2020). Because of these unique bioactive constituents present in marine algae, it is essential to study the functionalities and limitations of these bioactive compounds in advance. The natural extracts of marine algae have a wide range of molecular structures and unique biological functions which have huge potential for industrial applications (Haslam and Lee, 2013).

2.1 Primary metabolites found in marine algae

Marine algae produce primary metabolites mainly for their growth and reproduction (Rico *et al*., 2017; Mohammed *et al*., 2019). Among them, lipids, proteins, minerals, vitamins, enzymes, and carbohydrates play a vital role (Rico *et al.*, 2017). Marine algae are rich sources of lipids with high nutritional value. It accounts for 90% of the dry weight (Rico *et al.*, 2017). Marine algae consist of different types of lipids including phospholipids, glycolipids, non-polar glycerolipids, and saturated and unsaturated fatty acids (Rico *et al.*, 2017). The main lipids present in algae are found as membrane components and also as storage lipids (Mohammed *et al.*, 2019). Glycosylglcerides and phosphoglycerides are found as membrane components and triacylglycerols are found as storage lipids (Rico *et al.*, 2017). In general, some marine algae like *Laurencia popillose*, *Ulva fasciata*, and *Dilophys fasciola* are enriched with crude lipids which are known to be responsible for their specific biological activities like antitumor, antioxidant, antimicrobial and antiviral activities with various degrees (Rico *et al.*, 2017).

Marine algae has 70% protein content in their dry weight which is highly dependent on the season and the type of algae (Rico *et al.*, 2017). The protein content depends on the type of algae and marine green seaweeds contain 08 to 26 % of protein while the protein content of brown seaweeds varies from 05 to 26 % and red seaweeds contain 07 to 47 % of total algal dry weight (Anbuchezhian et al., 2015). Some studies were carried out to evaluate the protein level of commercially cultured *Saccharina latissima* and its wild type (naturally harvested) and confirmed that cultured one has more protein content than wild type (Gallagher and Donnison, 2009). Marine algae-derived proteins and peptides exhibit biological functions including anti-oxidant, anti-cancer, anti-hypertensive, anti-atherosclerotic, and immunomodulatory activities based on the type and amino acid sequences (Rico *et al*., 2017; Mohammed *et al*., 2019).

When considering carbohydrates, they are about 20%-75% of the total dry weight of marine algae. The greater portion of these algal carbohydrates is available as polysaccharide dietary fiber, which is not taken up by the human body (Besada *et al.*, 2009). Those carbohydrates exist within those algal varieties as glucose, sugars, and other polysaccharides where their digestibility is found to be very high (Rico *et al.*, 2017). It is also found that carbohydrates present in marine algae exhibited biological functions including anti-cancer, anti-microbial, anti-coagulant, anti-oxidant, and anti-viral activities (Hemasudha *et al*., 2019. Apart from that, some different Taxa (genera or species) of Rhodophyta contain sulfated polysaccharides which are responsible for the anti-viral effects against human viral infections (Wang *et al*. 2020). Some polysaccharides and fibers like alginate, fucoidans, laminaran, and porphyrin are responsible for the reduction of cholesterol absorption in the gut (Anbuchezhian, Karuppiah and Li, 2015). Accordingly, these algae-derived primary metabolites will be a potential industrial application for different bioproducts like foods, pharmaceuticals, cosmeceuticals, nutraceuticals, etc (Jensen, 1993; Rico et al., 2017; Mohammed et al., 2019)).

Vitamins are another type of bioactive primary metabolites available within seaweeds that are responsible for their metabolic functions (Fu *et al.*, 2016). Their vitamin profile and composition vary according to the type of algae, their growth environment, growth stage, availability of light, growth season, the temperature of the seawater and geographical conditions (Mabeau and Fleurence, 1993). Brown algae are a large family of seaweeds that include numerous significant precursors to vitamin A. Their precursors are the pigments known as carotenoids and xanthophylls, which give these algae their characteristic brown color. Fucoxanthin is a major carotenoid present in brown algae. It has drawn interest for its possible health benefits and is well known for its antioxidant capabilities. Fucoxanthin has demonstrated promising results in encouraging weight reduction, improving metabolism, and demonstrating anticancer and anti-inflammatory actions, despite the fact that it does not directly convert to Vitamin A in the body (Smith et al., 2007). The well-known carotenoid beta-carotene serves as a precursor to vitamin A. Brown algae contain a xanthophyll called lutein. Lutein, a potent antioxidant that has been linked to eye health, is not immediately transformed into vitamin A (Mabeau and Fleurence, 1993). It builds up in the retina where it functions as a pigment that protects cells from oxidative damage brought on by damaging light wavelengths. Another significant xanthophyll found in brown algae is zeaxanthin. Zeaxanthin, like lutein, has antioxidant qualities but is not a direct precursor to vitamin A. It is mostly found in the retina and is thought to protect against age-related macular degeneration and damaging blue light by filtering it out(Mabeau and Fleurence, 1993) .

On most occasions, vitamin biosynthesis of marine algae mainly depends on the light intensity thus seaweeds grown in places where bright light availability is higher contain a higher content of ascorbate (Smith *et al.*, 2007). Seaweeds are ideal sources for a variety of water-soluble vitamins like vitamin C, vitamin B-1, vitamin B-2, vitamin B-12, and fat-soluble vitamins such as vitamin A and vitamin E (Hughes *et al.*, 2018). Moreover, algae grown on the surface of marine water contain a high amount of vitamin C compared to the algae grown at the bottom of the sea at about 9 to 18 m depth. Almost all seaweeds contain higher amounts of carotene or provitamin A ranging from 20 to 17 ppm (Hughes *et al.*, 2018). Apart from that, they are enriched with vitamin C where content ranges from 500 to 3000 ppm are found and they are investigated as a good source of vitamin B-12 or cobalamin as well (El-moselhy, 2004). Calcium, magnesium, iron, and copper are some important minerals available from seaweeds (El-moselhy, 2004). Among those minerals, calcium in seaweeds holds 4-7% of dry matter where recommended daily allowance of calcium is found to be 1000 mg (Vanniarachchy and Wijesekara, 2021). Some investigations revealed that 20 g of seaweed contains about 1400 mg of calcium. Our bodies can uptake the recommended daily allowance of calcium via a single portion of 20 g size seaweed meal. Magnesium is also highly available in seaweeds where a 20 g portion of seaweed provides more than 50% of the recommended daily allowance of magnesium. Iron and copper are also very important minerals that are directly involved in the body's functioning and repairing (Jayakody et al., 2021). Marine algae are accountable for high amounts of iron and copper compared to other food sources such as meat and fish (El-moselhy, 2004). Hence, these seaweeds can be utilized as food supplements to fulfill most of the important mineral requirements of the body (El-moselhy, 2004).

2.2 Secondary metabolites of marine algae

Marine algae are a rich source of secondary metabolites which provide human health benefits. The secondary metabolites present in marine algae include polyphenols, sulfated polysaccharides, carotenoids, peptides, amino acids, and fatty acids that are responsible for a wide range of biological activities (Protopapa *et al.*, 2019). Polyphenols are water-soluble secondary metabolites produced by living organisms that are composed of a phenolic group within its molecular structure (Kim *et al.*, 2015). Additionally, they are responsible for their strong anti-oxidant functionality and other owing biological functions. These polyphenolic compounds are further categorized into several other compounds such as phenolic acids, coumarins, lignins, tannins, lignans, flavonoids, and stilbenes (Olaniran and Okoh, 2019). These polyphenolic compounds are produced by living organisms using secondary metabolic pathways via the involvement of shikimic acid and acetate-malonate pathways (Karuppiah and Li, 2015). As recent research studies revealed, these polyphenols are responsible for the anti-inflammatory activities among marine algal varieties and also responsible for the inhibition of enzymes like α-Glucosidase, α-amylase, acetylcholinesterase, butyl cholinesterase, matrix metalloproteinase, hyaluronidase, and tyrosinase (Gunathilaka *et al.*, 2019). Some evidence expressed that, the marine algae *Chnoospora minima* is rich in phlorotannins which are responsible for its biological properties and significances (Hakim and Patel, 2020). Some common polyphenolic compounds found in marine algae and their chemical structures are shown in Figure 1.

Marine algae are rich in sulfated polysaccharides that exhibit several human-beneficial effects. These polysaccharides are interesting macromolecules available in seaweeds with a diverse range of bioactive properties (Sanjeewa *et al.*, 2017). Fucoidans, alginates, carrageenans, ulvan and laminarans are the main sulfated polysaccharides found in marine algae. Based on previous studies, fucoidan is reported to exhibit anti-diabetic, anti-inflammatory, and antioxidant potentials while laminarans are mainly used as prebiotics (Pirian *et al.*, 2017; Gunathilaka *et al.*, 2020). Alginic acid exhibits metal ion chelating ability, and thus, it is widely used in the pharmaceutical industry. Due to its floating, foamy, and viscous characteristics, alginic acid decreases reflux. Upon coming into contact with gastric acid, alginic acid precipitates to form a mechanical barrier, or "raft," that pushes the postprandial acid pocket away. It is believed that the creation of a raft happens quickly, frequently within a few seconds of dosage Combining alginic acid and an antacid reduced postprandial reflux in the upright position in the healthy volunteer's (Gunathilaka *et al.*, 2020; Hakim and Patel, 2020).

Furthermore, marine algal-derived accessory pigments are important as they exhibit several biological activities (Hakim and Patel, 2020). The majority of the seaweeds appear to be green in colour as a result of the presence of chlorophylls. It is investigated that some seaweeds appear to be red and brown in color as their chlorophyll is masked by accessory pigments such as carotenoids or phycobilins (Godínez-Ortega *et al.*, 2008).

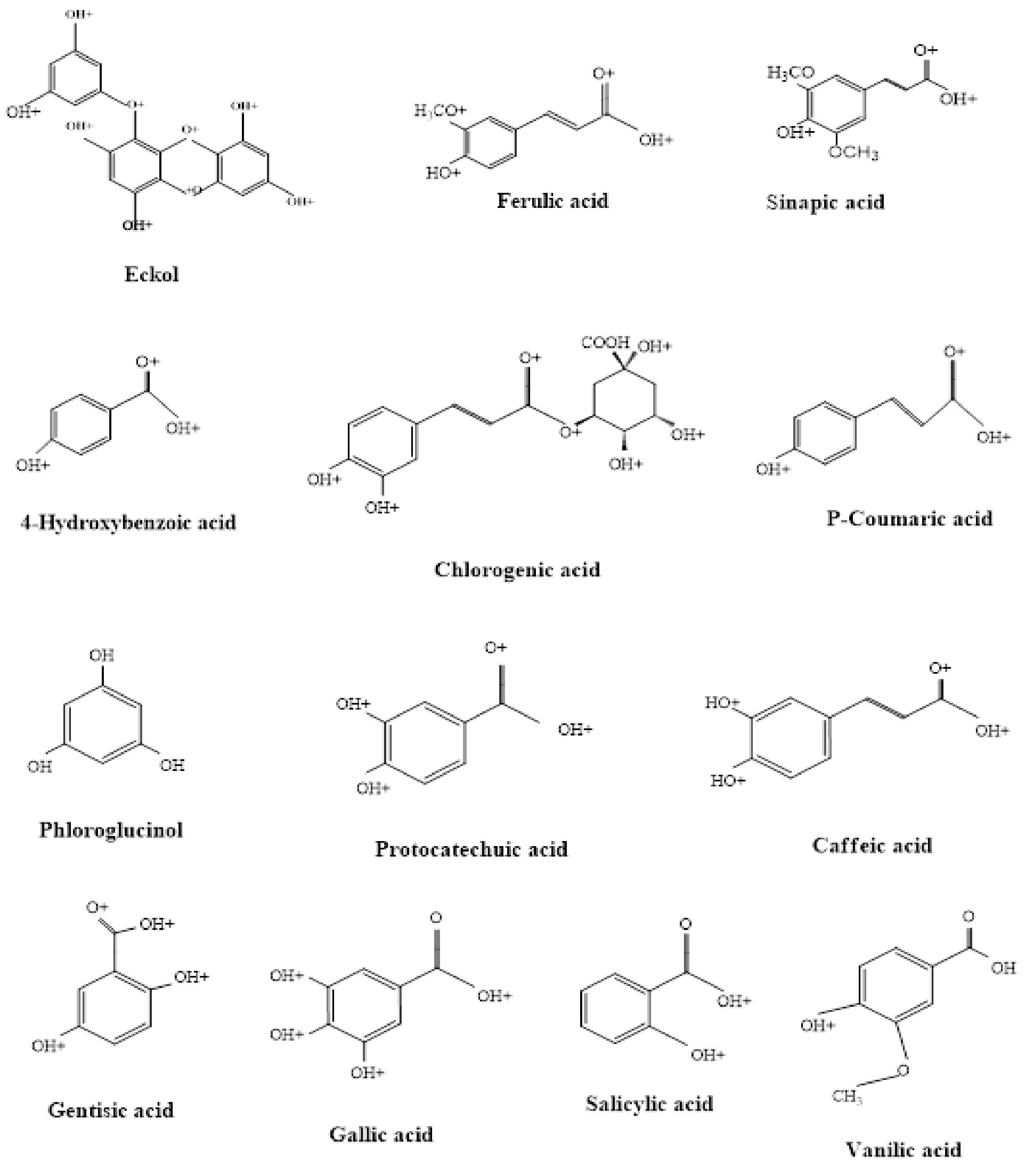

Figure 1: Common polyphenolic compounds found in marine algae and their chemical structures. (Hakim and Patel, 2020)

Algal carotenoids possess superior antioxidant activities which are responsible for the protection of seaweeds against photooxidative processes. Carotenes present in seaweeds are of two major types; β - carotenes and xanthophylls (Leavitt *et al.*, 1997). Fucoxanthin is the main carotenoid found in brown algae and reported to exhibit an antioxidant (Gunathilaka *et al.*, 2020), anti-diabetic (Gunathilaka *et al.*, 2020), and anti-cancer activities (Gunathilaka *et al.*, 2020). Previous studies have found that fucoxanthin extracted from *Sargassum hemiphyllum* exhibited α-amylase and α-glucosidase inhibitory activities together with enhancing the insulin release in cells (Gunathilaka *et al.*, 2020). Most of the algal varieties contain 0.1 to 2.0 % of carotenoids, while algal varieties including *Dunaliella spp.* composed up to 14% beta-carotene concentration if they grow under the ideal conditions of high salinity and high light intensity (Kelman *et al.*, 2012).

3 Algal research and impact of new findings on industrial applications

As different valuable bioactive constituents are prominent within the marine algae, research was conducted to use them as raw materials for a wide range of industries including pharmaceutical, cosmeceutical, pigment, bioplastic, nutraceutical , bioenergy, food-based industries, biofertilizer etc. (Pirian *et al*., 2017; Mohammed *et al*., 2019; Pati *et al*., 2016). Agar, carrageenan, alginates, ulvan, furcellaran, hypnean, funoran, iridophycan, phyllophoran, laminarin, fucoidan and mannitol are the major extracts that are utilized on industrial scale (Chennubhotla et al. 2013; Pati et al. 2016).

3.1 Pharmaceutical industry

The influence of the bioactive constituents of marine algae on the pharmaceutical industry is increasing due to the presence of bioactive secondary metabolites (Capasso and Mannelli 2020). Seaweed cultivation for industrial applications is very profitable due to their high availability within the South Asian region, Europe and America (Hemasudha *et al*., 2019). Among that, pharmaceutical industries have used these marine algae as an alternative precursor for drug development (Besednova *et al*., 2020). Alginate or alginic acid can be considered an algal cell wall polysaccharide which is available in the cell walls of marine brown algae in larger quantities. The majority of this algal polysaccharide is widely introduced along with its salts for the production of pharmacological products including gels, concentrated emulsions, and suspensions (El-moselhy, 2004). As a result of the binding capacity of these alginates, they can be utilized as thickening agents and stabilizers in the pharmaceutical industry (Khotimchenko *et al.*, 2001). Previous studies concluded that sodium alginates can be used to treat wounds in conjunction with other drugs. Some drugs like algiporecike composed of sodium alginate, furacillin and calcium alginate are responsible for antimicrobial activities and thus can be used to heal wounds (Khotimchenko *et al.*, 2001). Some investigations have hypothesized that calcium alginates are responsible for the secretion of calcium ions which in turn induce fibroblast proliferation and promote the process of wound healing. Interestingly, these are also applicable to act as an anti-irritative drink for the gastrointestinal tract (Doyle *et al.*, 1996). Previous research studies related to the biogenic synthesis of metal and metal oxide nanoparticles via marine algae lead to the production of biosensors, biocatalysts, anti-bacterial drugs, hyperthermia treatment of tumor, and vector delivery of therapeutic drugs for cancer treatments (Fawcett *et al*., 2017; Patra and Muthuraman 2013; Kelman *et al*., 2012). Apart from that, those findings showed that they can be used for environmental remediation such as reducing radiation exposure from contaminated soil, groundwater, or surface water. and labeling for immunoassays (Fawcett *et al.*, 2017). In addition to that, these marine algae are responsible to synthesize metal nanoparticles like silver, gold, cadmium sulphite nanoparticles, ferrous oxide nanoparticles, zinc oxide, copper oxide and palladium nanoparticles, and other metal oxide nanoparticles (Priyadharshini *et al*., 2014; Fawcett *et al.*, 2017). This green nanotechnology is responsible for the production of eco-friendly, innocuous, and safe reagents and these green synthesized nanoparticles can be utilized in different ways for *in vivo* biomedical applications including biological fluid detoxification, hyperthermia, repairing tissues, drug delivery, and contrast enhancement of magnetic resonance imaging (MRI). Magnetic nanoparticles synthesized using marine algae are able to attach and interact with nearby drugs, enzymes, proteins, and antibodies, and they are able to reach target organs, tissue, or cells with the aid of an external magnetic field (Laurent *et al.*, 2008). So, these findings directly enhance the potential for marine algae biomass use in the pharmaceutical industry (Patra and Muthuraman, 2013).

In addition, some research findings have concluded that the brown algal polyphenols and phlorotannins act as cancer chemo-preventive agents against photo-carcinogenesis and other adverse effects of UVB (Type B ultra-violet rays) exposure (Anbuchezhian, *et al*., 2015). Some studies have reported that, *Padina boergesenii* (Phaeophyta) distributed in the Gulf of Manns is composed of a myriad of biological activities like anti-diabetic activity, antioxidant activity, hepatoprotective activity, chemo-preventive effects, and herbivory effects which are then ideal for drug development (Karthikeyan *et al.*, 2011). Recent research has revealed that *Padina gymnospora* and *Sargassum wightii* have significant effect on bacterial activities. Some studies confirmed that *G. edulis* and *G. gracilis* own antibacterial activities by testing against Gram-positive and Gram-negative bacteria and they also confirmed that the same algae had antioxidant activities (Hemasudha *et al*., 2019; Capillo *et al.*, 2018). Furthermore, several studies have focused on the identification of water-soluble anti-tumor active compounds from various seaweed, including *G. edulis* (Sakthivela, *et al*., 2016) ; Patra and Muthuraman, 2013). The same study revealed that *G. edulis* and *C. minima* algae contains high anti-proliferative activity which in turn contributes for their anti-cancer activity (Samuthirapandi Muniasamyb and Devi, 2016). It has been noted that the marine alga *G.edulis* collected from the southeast coast of India has polyunsaturated esters that display potent antibacterial activity against several human pathogens (Sakthivel and Devi, 2014; Pirian *et al*., 2017). Similarly, phycocyanin extracted from *S. platensis* has the ability to act against liver cancer and it also exhibits anti-diabetic and anti-inflammatory effects. Some algae extracts can be used in the aquaculture industry as an anti-pathogenic agent (Choudhury *et al*., 2005). Some previous studies revealed that fucoidans which is a major bioactive constituent present in brown algae are responsible for the induction of apoptosis in cancer cells which is a very important investigation for anti-cancer drug designing (Sanjeewa *et al*., 2017). Interestingly, algal bioactive compounds can be used for the development of novel antibacterial drugs (Choudhury et al., 2005; Sanjeewa *et al*., 2017).

3.2 Cosmeceutical industry

Recent research on algal biotechnology carried out by South Asian scientists has revealed that bioactive compounds derived from seaweeds such as phycocolloids alginate or carrageenan can be found in cosmetics like face creams, face wash, shampoo, hand and body creams, or lotions (Besednova *et al*., 2020). These extracts are useful in many ways, including rheumatic pain relief or cellulite removal (Karuppiah and Li, 2015). Moreover, previous studies have confirmed that some marine algal-derived bioactive constituents such as phlorotannins, tyrosinase inhibitors, and sulphated polysaccharides are used in the cosmeceutical industry as their isolated compounds have diverse functional roles as secondary metabolites (Karuppiah and Li, 2015). In addition to that, fucoxanthin derived from *Luminaria japonica* is composed of tyrosinase inhibitors which are responsible for the suppression of tyrosinase activity in UVB (Type B ultra-violet) irradiated guinea pig and melanogenesis in UVB irradiated mice (Karuppiah and Li, 2015). Similarly, the oral treatment of these mice using fucoxanthin gradually suppressed skin mRNA expression related to melanogenesis which in turn is responsible for the blocking of melanin synthesis and hence it is advantageous in the skin whitening cosmetic production (Karuppiah and Li, 2015). Furthermore, phloroglucinol in brown algae is known to suppress tyrosinase inhibition as they have the ability to chelate copper in this tyrosinase enzyme. Since these marine algae are rich in a wide range of bioactive constituents, they can be used to produce a wide variety of cosmetics including skin moisturizing care, skin anti-aging products, skin-photo protection products, skin whitening products, etc. (Mohammed *et al.*, 2019). Further, marine brown algae *Chnoospora minima* and *Sargassum polycystum* are reported to exhibit collagenase and elastase inhibitory activity, UV protective effects, skin whitening effects and anti-wrinkling effects (El-moselhy, 2004). In addition to that, the ethyl acetate extracts of *Nannochloropsis oculata* and *Gracilaria gracilis* have considerable amounts of phenolic and flavonoid compounds which are responsible for its antioxidant effect (Khalili and Dehpour, 2018). Some literature sources have reported that the agar-agar, agarose, hypnean, furcellaran, iota and kappa-carrageenan derived from red algae and alginic acid and fucoidan derived from brown algae are beneficial and desirable for the production of cosmeceutical formulations (Thomas *et al*., 2020).

3.3 Nutraceutical industry

The term "nutraceutical" refers to a food or component thereof that offers the body medical or health advantages, including the prevention and treatment of disease. Marine algae are known as “sea vegetables” which are widely consumed as food by coastal communities, particularly in East Asian countries and some parts of Europe (Pati *et al*., 2016; Komatsu *et al*., 2007). Seaweeds owing a long history of utilization as a processed or raw food across the globe and they are available almost throughout the year in large quantities (Besada *et al*., 2009; Bona, 2006). Marine algae enriched with protein, vitamins, trace minerals, and dietary fiber content has gained importance in many countries for exploitation of the natural renewable resource (Pati *et al,*. 2016; Jayakody *et al*., 2019). In addition to that, marine macroalgae were found to be enriched with dietary fiber with a content ranging from 33 g to 50 g to 100 g dry weight placing them as an important candidate in the development of new functional foods ,(Anbuchezhian, Karuppiah and Li, 2015). The studies on the nutritional potential of marine algae have shown that they contain great nutritional potential which in turn can be used as alternative dietary sources (Gunathilaka et al. 2019; Torres et al. 2019). The nutritional composition of the algal species depends on the season, environment, and geographical regions (Anbuchezhian, Karuppiah and Li, 2015). It is found that the moisture percentage of these fresh marine algae is very high and it is take up around 94% of the total algal biomass (Anbuchezhian, Karuppiah and Li, 2015). Apart from that, some studies concluded that algal ash content lies around 55% dry weight and it is also enriched with macro-minerals including Na, K, Ca, Mg, and trace elements of Fe, Zn, Mn, and Cu (Pati et al. 2016; Rosemary et al. 2019). These minerals are attributed to different types of associated ions with charged polysaccharides where the bioavailability of these minerals depends on the polysaccharide digestibility and the type of bond between the mineral and the polysaccharides (Anbuchezhian, Karuppiah and Li, 2015). Some brown and red algae are responsible for the production of chloride-like halogenated compounds while some green algae are enriched with protein (Anbuchezhian, Karuppiah and Li, 2015). The protein content of seaweeds for example, *G. corticata* and *G. edulis* are generally high ; thus can be considered as superior marine sourcs for food proteins (Francavilla *et al.*, 2013). According to the availability of high protein and amino acid content, red sea vegetables or Rhodophyta are investigated to be an ideal potential source of food proteins for the production of nutraceuticals on an industrial basis (Wijesekara and Kim, 2015). The majority of sea vegetables are able to be utilized as precursors for many algal-derived food products including cheese, jam, wine, soup, noodles, and tea (Wijesekara and Kim, 2015). Moreover, these algal species contain all essential amino acids, aspartic acids, and glutamic acids (Arulkumar *et al*., 2018; Jayakody *et al*., 2019). The fat content of these marine algae is generally found to be enriched with high-quality oil, comprising mainly essential and polyunsaturated fatty acids including omega-3 and omega-6. Moreover, some studies revealed that seaweeds are an excellent source of dietary fiber which is mainly derived from non-digestible polysaccharides where that are resistant to human digestive enzymes (Vanniarachchy and Wijesekara, 2019). Therefore, these findings enhance the potential of algal-derived bioactive compounds to use in large-scale bioproduct designing and development processes mainly in the nutraceutical industry.

3.4 Functional food industry

The functional food industry is another industrial application related to marine algae where many seaweeds can be directly consumed only after the minor preprocessing (Besednova *et al.*, 2020). The phycocolloids which are made up of simple sugars are used as functional food factors (Torres *et al.*, 2019). Hydrocolloids which are widely utilized for the extraction of agar, carrageenans, and alginates have attained brilliant commercial significance as they act as compulsory ingredients for many industries, particularly food production and confectionaries (Besada *et al.*, 2009). Gelling agents and viscous materials which are isolated from red and brown seaweeds are especially used in food preparations from history (Bono *et al*., 2014). Red and brown algae are usually used in food preparations for centuries back (Torres *et al.*, 2019). These polysaccharides extracted from marine algae are very significant as they own high molecular weights, high viscosity, and excellent gelling, stabilizing, and emulsifying properties which are important in bakery products as well (Chennubhotla *et al*., 2013). *Gracilaria species* is mainly utilized for the production of food-grade agar in India because it is reported to have consisted of 3-linked-β-D-galactopyranose and 4-linked-3,6-anhydro-α-L- galactopyranose (Sakthivel and Devi 2014; De Almeida *et al*., 2011). Furthermore, *G. edulis* species also can be used as stabilizing agents and gelling agents in the desert such as pies, icings, and jelly candies (Torres *et al.*, 2019).

3.5 Bioenergy industry

As energy depletion is a rising problem nowadays, scientists have changed their investigation pathway toward marine biosources as they are available on a large scale which also can be used as an alternative to energy generation (Adenle, Haslam and Lee, 2013). The algal derived biofuels avoid some of the previous drawbacks associated with non-renewable energy sources including fossil fuels as algal biomass are renewable kind of energy sources that are highly available within the South Asian region (Adenle et al. 2013; Chennubhotla et al. 2013). In addition to that, this algal biofuel act as a promising alternative for renewing energy sources like crop-based biofuels as they have some drawbacks to compete with food crops (Adenle, Haslam and Lee, 2013). To get rid of this negative phenomenon, algal biofuel can be utilized as a platform for the energy industry. As some studies revealed, various microalgae species produce different types of fatty acids as a result of exposing different stress conditions. Depending on the type of algae either macro or microalgae, these findings lead to the commercial cultivation of those algal varieties for biodiesel production on a large scale. Some recent research identified algal varieties as one promising source of biofuels where harvested biomass can be converted into a carbon-neutral fuel source (Anbuchezhian, Karuppiah and Li, 2015). In general, seaweeds are one of the most valuable sources of biomass which are responsible for liquid fuel production (Anbuchezhian, Karuppiah and Li, 2015). Their biomass can be utilized for the preparation of biofuels including bioethanol, hydrogen gas, biodiesel etc. . Algal-derived biofuels are usually composed of carbon, hydrogen, oxygen, nitrogen, and phosphorous into 106:263:110:16:1 ratio, and they are composed of both carbohydrates and lipids (Anbuchezhian, Karuppiah and Li, 2015). This carbohydrate can be directly converted into bioethanol via fermentation while algal lipids can be converted into biodiesel via transesterification. As these biofuels don't compete with water and food sources, own a fast growth rate, and are able to capture carbon dioxide, they are very beneficial to use as an alternative for energy generation. As these algae-derived fuels consist of low-temperature fuel properties and energy density, they can be used as jet fuels also (Anbuchezhian, Karuppiah and Li, 2015). And the biomass of these algae is also essential for making biogas. Simply, algal derived biodiesel is found to be similar to petroleum-derived diesel, and also it is estimated that this biodiesel consumption can reduce air pollution and cancer risks compared to traditional petroleum-derived diesel. Apart from that, seaweeds are an important source to absorb solar energy which is responsible for the conversion of carbon dioxide into biofuel. For the fermentation of algal biomass to obtain bioethanol, it is ideal to use microorganisms like *Saccharomyces cerevisiae* and *Zymomonas mobilis* as some reports concluded (Anbuchezhian, Karuppiah and Li, 2015). At the same time, *Pichia angophorae* is found as an ideal microorganism for bioethanol production from marine algae. It is evidenced from previous research studies that the *Gelidium amansii* and *Laminaria japonica* are ideal for bio-hydrogen production via oxygen-free fermentation protocols (Anbuchezhian, Karuppiah and Li, 2015).

3.6 Pigment industry

Marine algae are categorized into three types based on the pigments they contain. Green algae, they own chlorophylls which are greenish pigments with a porphyrin ring (Hakim and Patel 2020). Chlorophyll absorbs the energy via sunlight and thus gives the color to green algal species/ taxa, (Madhyastha and Vatsala, 2007). In addition to that, algal secondary metabolites such as carotenoids have red, orange, or yellow colors which are insoluble in organic solvents (Karuppiah and Li, 2015). Recent reports published after several investigations have confirmed that these compounds have the ability to prevent or eliminate human non-infectious diseases like cancer, cardiovascular problems, atherosclerosis, rheumatoid arthritis, and cataracts, etc. A common pigment involved in the photosynthetic process in macroalgae, carotenoids, has demonstrated a number of bioactivities. The amount of dietary provitamin A that can be transformed into vitamin A, a micronutrient essential to treat vitamin A deficiency in advance (Kelman *et al.*, 2012). These algal pigments are investigated as superior precursors with high therapeutic and nutritional value where carotenoids are found to be ideal for the treatments of some cancer types in advance (Faulks and Southon, 2005). Almost all of the microalgal β-carotene and astaxanthin pigments have antioxidant effects which have a high potential to utilize in pharmaceutical and cosmeceutical industries. In addition to that, β-carotene is recognized as a good coloring agent where it can be used conventionally as a food and drink colorant and able to use as a dietary food supplements or food additive as well (Matos *et al.*, 2017).

3.7 Biofertilizer industry

The majority of the coastal communities use marine algae as biofertilizers as manure in farming practices as they are enriched with different macro- and micronutrients (Mohammed *et al*., 2019; Pati *et al*., 2016). In certain parts of the world, the biomass of marine algae including *Ascophyllum*, *Ecklonia,* and *Fucus* is mixed with sand and applied in farming (Anbuchezhian et al., 2015). It is found that these seaweeds contain a comparable amount of nitrogen and potassium like animal manure and organic fertilizers and a low amount of phosphorus content (Karuppiah and Li, 2015). The content of carbohydrates in brown marine algae is high (Wuang *et al.*, 2016). There are some commercially prepared seaweed fertilizers such as "Afrikelp" which is comprised of dried seaweed *E. maxima* (Karuppiah and Li, 2015). A brown seaweed *Ascophyllum* is used to avoid topsoil erosion as they form strong gels when added with calcium, because its alginate content is somewhat high ((El-moselhy, 2004)). Some investigations have revealed that seaweed-derived biofertilizers also increase the biochemical potential of plants as their extract contains micronutrients, auxins, cytokinins, and other growth-promoting constituents which are responsible for the enhancement of cell size and cell division (Anbuchezhian et al. 2015; Wuang et al. 2016). Some experiments carried out by Rama Rao *et al*., in 1991 have revealed that the yield and quality of the fruits of *Zizyphus mauritiana* was enhanced with the treatment of *Sargassum wightii* extracts (Wuang et al. 2016). Some studies have reported that 0.2% of *Ascophyllum nodosum* algae extract sprayed in *Daucus carota* showed significant defense against fungi diseases caused by *Alternaria radicina* and *Botrytis cinerea* (Anbuchezhian, Karuppiah and Li, 2015). Similarly, based on the previous studies, the plant root and shoot growth are induced when applying Ragi by liquid fertilizers derived from *Ulva lactuca*, *Sargassum wightii* and *Gelidella acerosa*. Application of the 1% algal extract of *Gracillaria edulis* to the soil is known to maximize the germination, growth, and development of some plants as some reports showed,(Anbuchezhian, Karuppiah and Li, 2015). Some literature proved that the extracts of some marine algae like *Gracillaria verucosa* and *Chaetomorpha linum* display excellent results on vegetative growth of vegetables and the *Sargassum wightii* extracts have enhanced the height and number of branches in *Arachis hypogaea* plant (Anbuchezhian, Karuppiah and Li, 2015). Apart from that, *Sargassum johnstonii* extract increases the vegetative growth of *Lycopersicon esculentum* and also it confirmed that the application of biofertilizers derived from marine algae with traditional fertilizers yielded positive results on plant growth enhancement and is responsible for the early flowering of those fruiting plants as well (Anbuchezhian, Karuppiah and Li, 2015). In addition to that, recent findings show the enhancement of the pigment concentrations, protein, total soluble sugar, reducing sugar, starch, phenol, lycope free amino acids and vitamin C content after treating several plants with liquid extracts of marine algae (Anbuchezhian, Karuppiah and Li, 2015). Therefore, marine algae biomass is contributing to the enhancement of soil status and plant health as well. Hence, these findings are important in producing algal-derived biofertilizers on a large scale instead of chemical fertilizers.

3.8 Bioplastics

Plastics are polymers that take a long period to degrade (Yi *et al.*, 2020). As a solution for the accumulation of such kinds of xenobiotics (Chemicals that are not normally produced or anticipated to be present in an organism are referred to as xenobiotics) in the environment, bioplastic production attempts taken by scientists are prominent nowadays (Abdo and Ali 2019; Menetrez 2012). Recent findings revealed that the organic renewable biomass extracted from marine algae can be utilized to produce plastics called bioplastics (Yi *et al.*, 2020). These bioplastics are eco-friendly and can be degraded by microorganisms and reduce the accumulation of waste in the environment. Recent research suggests that using microbial consortia could enhance the effectiveness of plastic biodegradation. This study uses a sequential and induced enrichment strategy to identify and characterize microbial communities that break down plastic in artificially contaminated microcosms(Yi et al., 2020). It is also found that s moisture content barrier of red algal agar-derived plastic film behaves much better than cassava starch-derived bioplastics they are somewhat similar to the properties of low-density polyethylene plastics (Milledge and Heaven, 2013). So, for further expansion and commercialization of this bioplastic production using marine algae, it is essential to carry out more research related to this field of marine biotechnology in the future.

4 Discussion

Marine algae are important sources of bioactive metabolites. The use of bioactive metabolites of marine algae could offer industrial benefits including work as raw materials for the pharmaceutical industry, cosmeceutical industry, functional food industry, nutraceutical industry, energy generation, pigment industry, biofertilizer industry, and biofuel industry (Milledge and Heaven, 2013).

As marine algae are composed of desired biosources prerequisite for bioproducts development, novel research is conducted worldwide related to this field via mining novel compounds with the use of modern technologies such as omics technology, whole genome sequencing, and finding putative genes, environmental DNA, and metabarcoding, etc.. With the advancement of synthetic product development in the recent era, it is identified that synthetics cause lots of negative effects. As a result of that, demand for natural products became more popular among the new generation. Therefore, marine algae were employed as an alternative applying to almost all of the synthetic products and it became the turning point for the popularization of this algal research all over the world. Now, bioproducts development using algal-derived primary and secondary metabolites is highly available within the world (Chennubhotla, Rao and Rao, 2013)

The cultivation of seaweeds, particularly those used to extract hydrocolloids and those grown for food, can, in fact, help to boost a nation's economy. Seaweeds are important marine resources that have several advantages for sustainable economic growth. Seaweed mariculture and integrated multitrophic aquaculture (IMA) of seaweeds are significant for the reasons. Seaweeds are abundant in hydrocolloids, which are widely employed in a variety of industries, including food, medicine, cosmetics, and biofuels. Developing nations can create lucrative enterprises and make huge amounts of money through exports by producing and harvesting these priceless substances (Neori et al., 2004). The mariculture of seaweed and associated industries produce jobs in numerous sectors. Growing seaweed industries can create jobs for nearby communities, fostering economic growth and lowering unemployment rates. These jobs range from seaweed cultivation, harvesting, and processing to the production of value-added products (Neori et al., 2004).

Seaweeds are a renewable resource that can be harvested or grown responsibly without destroying existing natural supplies. Countries can guarantee the long-term supply of seaweed resources by putting ethical mariculture methods into place, promoting both economic development and environmental preservation.

Seaweed, fish, and shellfish are just a few of the species that can be grown in an integrated multitrophic aquaculture (IMA) system. By offering ecosystem services including nitrogen uptake and water filtering, seaweeds play a crucial part in IMA. Countries can increase their aquaculture production by integrating seaweeds.

Algal bioactive constituents are renewable natural ingredients which also highly available throughout the world . They are easy to culture as the marine environment and surrounding conditions are sufficient for their growth and development. Therefore, these biosources can be isolated using cost-effective and easy protocols. Due to their biocompatibility, biological activity, availability, and consistency, they will be ideal precursors for industrial applications on a large scale where we can earn more than invest. Some marine algae utilized in different industries are shown in Figure 2.

5 Conclusion

This review paper mainly explains the bioactive compounds of marine algae with their potential biological effects in relation to industrial applications. The bioactive secondary metabolites present in marine algae exhibited several biological activities which in turn lead to promoting many industries including pharmaceutical industries, nutraceutical industries, cosmeceutical industries, food and beverage industries, etc. Thus, marine algae are a potential source to utilize in the formulation of promising bioproducts on an industrial basis in the future.

6 Conflict of interest

The authors declare no conflict of interest related to this article

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