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# A REVIEW ON DIVERSIFIED USAGE OF SEAWEEDS AND ITS POTENTIAL FOR PRODUCTION AND UTILIZATION IN BANGLADESH

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## Abstract

Seaweed are the magnificent plants of the sea; these are available in the coastal zones throughout the world. They are generally classified into Chlorophyta (green algae), Phaeophyta (brown algae) and Rhodophyta (red algae). Use of seaweed as food has strong roots in Asian countries, but the extent and scope of seaweeds utilization in this modern world is increasing for human consumption, medicine, hydrocolloid production, cosmetics, animal feed additive, fertilizers and soil conditioners, etc. Seaweed based products that have been known, and clinically documented bioactivity, have potential to become value-added functional products. However, seaweed is almost unknown to mass population in Bangladesh. So far, there are approximately 250 species in Bangladesh; of those, 20 are commercially important which remain available in abundance during October to April. Bangladesh has a high potential for seaweed farming due to favorable climatic conditions and availability of long 710 km coastal areas. To utilize seaweed resources, some experimental approaches have been tried. Both the government institutions, non-governmental organizations (NGOs) and international organizations like WorldFish have taken initiatives for mass scale farming of seaweed with mixed successes. Further, the efforts in seaweed cultivation, and its utilization through product and process development could help exploring new arena of investment and income as well as fetching substantial foreign exchange to contribute to the much-cherished blue economy dream of the country. This article provides a comprehensive review of diversified usage of seaweeds at the global level, and its potentials for farming and utilization in Bangladesh.

**Key words:** Seaweeds, Ocean, Cosmetics, Blue Economy, Bioactive Compounds

## Introduction

Seaweeds are the wonder plants of the sea (Krishnamurthy, 2005) and is the common name for countless species of marine plants and algae that grow in the ocean as well as in rivers, lakes, and other water bodies (NOAA, 2024). Seaweeds are macroscopic algae (nonflowering stemless water plants which do not have root systems or flowers, leaves, stems, fruits and seeds) found attached to the solid bottom substrate of rocks, dead corals, pebbles, shells and other plant materials below the high-water mark or remain drifted in the oceans (Pati et al., 2016; McHugh, 2003). Since the ancient time seaweeds have been used for various purposes by the Romans, Egyptians, Japanese, and Chinese (NOAA, 2024; Dillehay et al., 2008). Utilization of seaweed as human food was once confined only in Japan, China and Republic of Korea but now spread to mass people of North America, South America, Europe and Australia (McHugh, 2003; Kilinç et al., 2013). Apart from conventional seaweed food products like Japanese Nori or Purple Laver and Korean Wakame, seaweed food products like burger, juice, sandwich, chocolate, ice-cream, cake, salad, biscuit, chips etc. are produced on commercial basis (Sarkar, 2015). Seaweed is known as functional food because of their richness in PUFA, minerals and certain vitamins and several bioactive substances like polysaccharides, proteins, and polyphenols (Holdt & Kraan, 2011). The extent and scope of seaweeds utilization in this modern world is increasing for human consumption, medicine, hydrocolloid production, cosmetics, animal feed, fish feed, fertilizers and soil conditioners etc. (McHugh, 2003; Kilinç et al., 2013; Gade et al., 2013). Biologically active compounds of seaweeds have been demonstrated to play a significant role in prevention of certain degenerative diseases such as cancer, oxidative stress, inflammation (Khan et al., 2008), arthritis, allergy (Zuercher et al., 2006), obesity (Miyashita, 2009), lipedema (Mohamed et al., 2012), diabetes, and hypertension (Wada et al., 2011). The most remarkable utilization of seaweed is found in phycocolloid or hydrocolloid industry and cosmetic industry, biofuel industry, pharmaceutical industry for the development of drugs for Alzheimers' disease, cancer and gastric ulcer, wastewater treatment industry, bioplastic industry (NOAA, 2024; McHugh, 2003; Gade et al., 2013). Therefore, seaweed derived active components, whose immense biochemical diversity looks like to become a rich source of novel chemical entities for the use as functional ingredients in many industrial applications such as functional foods, pharmaceuticals and cosmeceuticals and others (Wijesinghe & Jeon, 2012). Recently seaweed as human food has gained too much importance in context to food security problems, considering its nutritional facts (Majumder, 2010). People are becoming increasingly health conscious and looking for foods with special bioactive functions (Forssell et al., 2006). With their various social, environmental and economic contributions and benefits, the potential contributions of seaweed to multiple Sustainable Development Goals (SDGs) have been recognized (Bjerregaard et al., 2016). However, seaweed is almost unknown to mass population in Bangladesh and the scenario of utilization of seaweed in different economically valuable ways is quite opposite here except only insignificant portion of yearly available seaweed biomass is used by few tribal community seaweed harvesters of St. Martins' Island, seaweed has not yet been properly utilized in this country (Majumder, 2010; Sarkar et al., 2016).

In Bangladesh, seaweeds remain available throughout the whole southern coast bordering the Bay of Bengal from Sundarbans mangrove forest to St. Martin's Island during October to April.

So far, 193 seaweed species including 19 commercially important species have been reported (Sarkar et al., 2016).

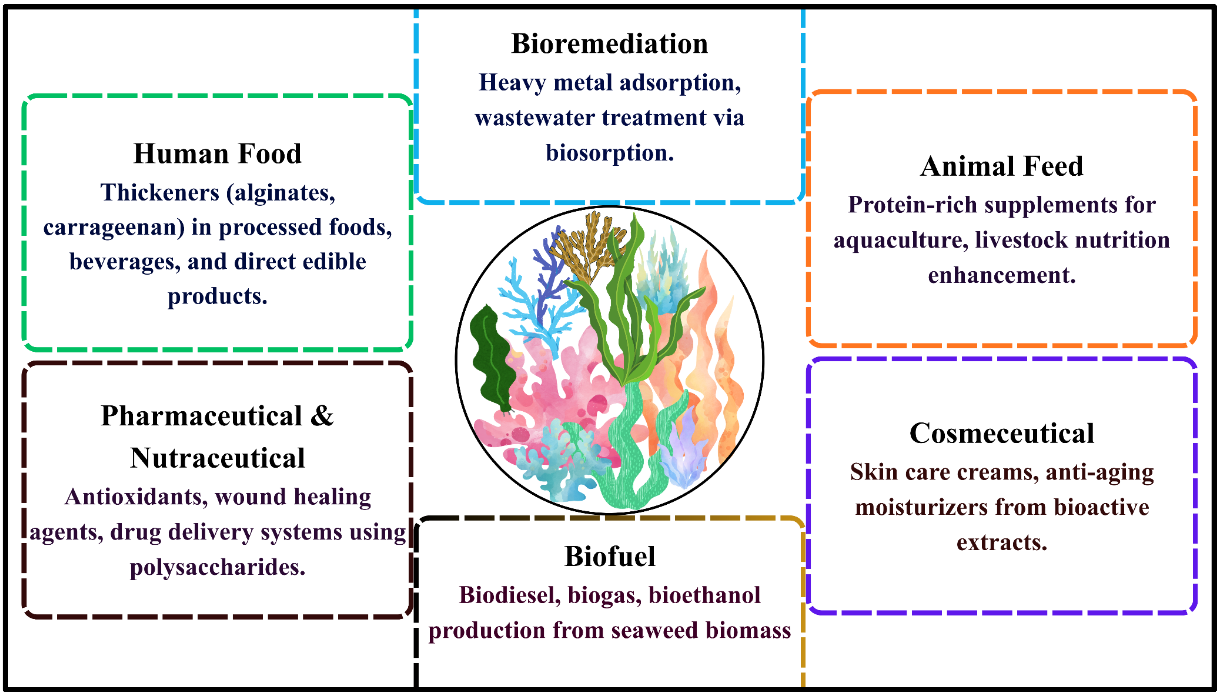

**Figure 1.** Diversified Usage of Seaweeds in Different Aspects

To utilize unused seaweed resource properly, approach to manufacture value added seaweed foods, functional foods, and cosmetic and pharmaceutical product is necessary as in context of Bangladesh. Recently some recent experimental approaches on seaweeds' utilization have been reported (DoF, 2014; COAST Trust, 2013). Very few institutional research has been started here to make proper use of this valuable sea resource and to contribute to blue economy. However, this review is to know the seaweed including its diversified utilization and potentials of production and utilization in Bangladesh.

## Species Diversity

Seaweed is available in the coastal climatic zones throughout the world *i.e.* from the warm tropics to the icy polar regions (McHugh, 2003; Razia, 2018). Seaweeds are macroalgae; the classification into divisions is based on various properties such as pigmentation, chemical nature of photosynthetic storage product, the organization of photosynthetic membranes, and other morphological features. They are sub classified in four different groups (Kaliaperumal & Chennubhotla, 2017), as brown (Phaeophyta, about 2,000 species), red (Rhodophyta, about over 7,200 species) or green (Chlorophyta, more than 1,800 species) (Guiry, 2014), some of which are edible, and blue-green algae (Cyanophyta, up to 1,500 species), which are toxic in some extent (MacArtain et al., 2007).

The diversity and abundance of seaweed depend on many environmental, chemical and biological factors (Kaliaperumal & Chennubhotla, 2017). They are found in relatively shallow coastal waters, estuaries, intertidal and deep-sea areas up to 180 meters in depth. Seaweed can be collected from the wild but is now increasingly cultivated. It falls into three broad groups based on pigmentation: brown, red and green seaweed (excluding the toxic blue algae) (Kilinç et al., 2013).

There are more than 10,000 kinds of seaweeds in the coastal climatic zones throughout the world and generally, are classified into Chlorophyta (green algae), Phaeophyta (brown algae) and Rhodophyta (red algae) (McHugh, 2003; Torres et al., 2019; Critchley et al., 2019). Pereira et al. (2009) reported that the most used are 221 species of algae, including 125 Rhodophyta (Red algae), 64 Phaeophyta (Brown algae) and 32 Chlorophyta (Green algae). They also summarized the species as per usage; about 145 species are used (66%) directly in food (79 Rhodophyta, 38 Phaeophyta and 28 Chlorophyta). In phycocolloid industry, 101 species are used (41 alginophytes, algae that produce alginic acid, 33 agarophytes, algae producing agar and 27 carrageenophytes, algae producing carrageenan). 24 species are used in traditional medicine, 25 species in agriculture, animal feed and fertilizers, and about 12 species are cultivated in marine agronomy (Pereira et al., 2009).

There is lack of very fundamental information and statistics regarding seaweeds distribution, total seaweeds and commercially important species available, abundance, seasonal availability, status and approaches for utilization in Bangladesh (Majumder, 2010). A recent study revealed that 32 species of seaweeds are abundant along the coast of Bangladesh and among those 14 species are commercially important (Hossain et al., 2021). The abundance and diversity of algae have made them prime material for human use as a source of food, feed, medicine, chemicals, fertilizers, and so on.

## Global Distribution

Seaweed is found growing throughout the world oceans and seas (McHugh, 2003; Razia, 2018; Guiry, 2014; Lobban, 2000). Worldwide suitable seaweeds farming area covers 48 million km$^2$ of marine ecosystem in 132 countries, though only 37-44 countries are currently active in seaweed production (Froehlich et al., 2019).

Use of seaweed as food has strong roots in Asian countries such as China, Japan and the Republic of Korea, but demand for seaweed as food has now also spread to North America, South America and Europe. China is by far the largest seaweed producer followed by the Republic of Korea and Japan but today seaweeds are produced in all continents (Kilinç et al., 2013). In India, 1,153 species of seaweeds, including forms and varieties have been reported (Rao & Mantri, 2006).

Seaweed for food is usually cultivated in Asia while they are harvested in the wild in Europe. The main species cultivated for food are *Saccharina japonica* (Japanese kelp), *Euchema* species, *Gracilaria* species, *Pyropia* and *Porphyra* (nori), *U. pinnatifida* (wakame). Other species such as *Sargassum fusiforme* and *Caulerpa spp.* are farmed in small quantities (FAO, 2012).

Carrageenan is an extract from red seaweed which is widely used mostly as a thickener and gelling agent in the food industry. China accounts for 57% of global seaweed output, but for carrageenan seaweeds it imports 92% from Indonesia, 3% from the Philippines, and 5% from other countries (Malaysia, Tanzania, Vietnam, Madagascar); Indonesia supplies 90–95% of China's carrageenan seaweed imports, while the Philippines contributes about 3%, and all other countries together about 5% (FAO, 2013; Zhang et al., 2023).

According to FAO Fisheries and Aquaculture Statistics (2016), global marine algal production exceeded 27.3 million tonnes in 2014, reflecting the continued expansion of seaweed aquaculture (Kaliaperumal & Chennubhotla, 2017). The China and Indonesia were the leading seaweed farming countries in 2014, each produced more than 10 million tonnes, the Philippines and the South Korea over 1 million tonnes, whilst the North Korea, Japan, Malaysia and Zanzibar produced over 100,000 tonnes each. In the Americas, only Chile has appeared in the farming statistics tables, with 12,836 tonnes of cultivated *Gracilaria*. Most European and African countries do not produce seaweeds and the few countries that do produce minute quantities (Buschmann et al., 2017).

World seaweed cultivation increased from 4.2 million tonnes in 1990 to 34.7 million tonnes in 2019. FAO statistics record 27 seaweed species items cultivated in 2019. Five genera accounted for over 95 % of global cultivated seaweed production in 2019; they are *Laminaria/Saccharina* (35.4 %), *Kappaphycus/Eucheuma* (33.5 %), *Gracilaria* (10.5 %), *Porphyra/Pyropia* (8.6 %), and *Undaria* (7.4 %) (Cai et al., 2021).

High regional imbalance in seaweed production has been reported by FAO (2019).
- 35.8 million tonnes of world seaweed production contributed by 49 countries/territories.
- 97 % of the world production from Asia and seven of the top ten seaweed producing countries were from Eastern or South-eastern Asia.
- Production in Asia, Africa and Oceania is dominated by cultivation whereas in America and Europe are dominated by wild collection (Cai et al., 2021).

Now China, Japan and the Republic of Korea are the largest consumers of seaweed as food. However, as nationals from these countries have migrated to other parts of the world, the demand for seaweed for food has followed them, as, for example, in some parts of the United States of America and South America (Kilinç et al., 2013). Thereby, seaweed is widely used on the globe now.

## Seaweeds Species in the Bay of Bengal

The coastal zone of Bangladesh covers an area of 47,201 km$^2$, 32% of the country, being the landmass of 19 districts (Ahmad, 2019). The southern coast of Bangladesh has an excellent prospect for seaweeds farming due to favorable environmental conditions and natural availability of commercially important species (Hossain et al., 2021).

Taxonomic identification of available seaweeds of Bangladesh is yet to be in a good stage. However, Sarkar et al. (2016) reported about 193 seaweed species of 94 genera belonging to only three major divisions *i.e.* Chlorophyta-green algae, Phaeophyta-brown algae, Rhodophyta-red algae are available in Bangladesh waters. Among the available seaweed species, 19 species of 14 genera are considered as economically important as reported by them (Sarkar et al., 2016). However, Aftab Uddin (2019) compiled the past records that confirmed the availability of 244 seaweeds species in the coastal waters of Bangladesh (Uddin, 2019). Recently, Bangladesh Fisheries Research Institute have provided a species checklist with taxonomic descriptions of 132 seaweed species, of which 28 species belong to Chlorophyta, 35 to Ochrophyta and 69 to Rhodophyta (BFRI, 2020). In addition, Al et al. (2020) recorded 34 seaweed species from the west coast of Saint Martin's Island of which 7 species belong to Chlorophyta, 10 to Ochrophyta and 17 to Rhodophyta.

Reviewing all the available literatures, there are approximately 250 species of seaweeds in Bangladesh, accounting 45% Rhodophyta, 31% Ochrophyta and 24% Chlorophyta. Of those, 32 species (8 species of Chlorophyta, 12 Ochrophyta and 12 Rhodophyta) are abundant in the coastal waters of Bangladesh (Hossain et al., 2020).

In Cox's Bazar region, about 155 seaweed species are found and are very abundant at Shilkhali/Shaplapur coast, Jaillapara, Shahparirdip area of Teknaf, Nuniarchara, Nazirartek of Bakkhali-Moheshkhali river estuary, Moheshkhali Island and planted mangrove forest or Parabon region (Sarkar et al., 2016). Natural seaweed beds are found at Nuniarchara to Nazirartek areas and Moheshkhali Channel estuary comprising *Hypnea musciformis* and *Enteromorpha intestinalis* as the main seaweed species of seaweed beds.

About 140 seaweed species are found in St. Martin's Island. Seaweeds are more abundant in western coast of St. Martin Island than eastern coast whereas are not available at northern coast (Sarkar et al., 2016). *Sargassum coriifolium*, *Chaetomorpha moniligera*, *Gracilaria verrucosa*, *Colpomenia sinuosa* etc. seaweed species are found from southern coast. In eastern coast, *Sargassum coriifolium*, *Hypnea musciformis*, *H. pannosa*, *Hydroclathrus clathratus*, *Colpomenia sinuosa*, *Padina arborescens*, *Chaetomorpha moniligera*, *Gracilaria verrucosa* etc. seaweed species are found, whereas in western coast, *Gracilaria textorii*, *Hypnea musciformis*, *H. pannosa*, *Petalonia fascia*, *Dictyopteris divaricatum*, *Sargassum coriifolium*, *Enteromorpha compressa*, *Colpomenia sinuosa*, *Gracilaria verrucosa*, *Chaetomorpha moniligera*, *Hydroclathrus clathratus* etc. species are found. Therefore, presence of rocky substratum and Geographical position of St. Martin Island causes variation in distribution of seaweeds around St. Martin's Island (Majumder, 2010).

Favorable climatic, environmental conditions and interconnected network of waterways make natural availability of seaweeds throughout whole Sundarbans mangrove forest where benthic forms of seaweeds naturally grow in inter-tidal areas on pneumatophores of mangrove tree, other wooden logs and barks of trees. Around 60 seaweed species are found from Sundarbans and among those, *Boodliopsissun darbanensis*, *Ulva lactuca* and *U. intestinalis*, *Catenella repen*, *C. nipae*, Gelidium, Polysiphonia, Ceramium, Bostrychia, Compsopogon etc. are available (Sarkar et al., 2016).

Among all the identified seaweeds in Bangladesh, Hossain et al. (2020) recognized 14 potential cultivable seaweeds include 4 species of Chlorophyta (green seaweed) and 10 species of Rhodophyta (red seaweed). Most cultivable seaweed species in Bangladesh are *Hypnea musciformis*, *Ulva intestinalis, Ulva lactuca, Caulerpa racemosa, Gracilaria spinuligera, Gracilaria tenuistipitata, Gracilariopsis longissima* and *Catenella nipae* for the expansion of seaweed farming (Hossain et al., 2020). Majumder (2010) documented ten seaweed species as commercially important, whereas DoF (2014) considered 20 seaweed species as commercially important (Majumder, 2010; DoF, 2014).

## Various Applications of Seaweed

Most people do not realize how important marine macro-algae are, both ecologically and commercially. Potentials for diverse utilization of seaweed are placing them in growing interest as frontiers in the modern world for nourishing the people and the planet.

## 1. Historic perspectives

Human and seaweed interactions seem to date back to the Neolithic period (Dillehay et al., 2008; Ainis et al., 2014; Erlandson et al., 2015). Uses of Seaweed have been cited as early as 2,500 years ago in Chinese literature (Erlandson et al., 2015), but the earliest written record of their human usage originates from China, about 1,700 years ago (Yang et al., 2017). It is used worldwide because it contains vitamins, minerals, and fiber. For at least 1,500 years, the Japanese are using a mixture of raw fish, sticky rice, and other ingredients in a seaweed called Nori (Kilinç et al., 2013).

For centuries, coastal populations harvested a wide variety of seaweeds from all algal groups. Initially, seaweed was most often used for domestic purposes as food and feed, whereas later, industrial uses (gels, fertilizers) emerged (Delaney et al., 2016). Early examples of utilization of seaweeds for medicinal purposes include the Chinese use of brown algae for goitre (16th century, Chinese herbal, 'Pen Tsae Kan Mu'), Gelidium for intestinal afflictions and dehydrated Laminaria stripes for the dilation of the cervix in difficult childbirths (Fleurence & Levine, 2016).

Seaweeds as a source of hydrocolloids dates to 1658, when the gelling properties of agar, extracted with hot water from a red seaweed, were first discovered in Japan. In 1750's, an English physician successfully used ash from kelp (Phaeophyceae) which is rich in iodine to treat goitre. Kelp was also used to treat obesity in 19th century, and agar was used as a laxative. A hydrocolloid, carrageen, found initially in the red seaweed *Chondrus crispus* was known in Ireland since 1810. Extracts of Irish Moss, another red seaweed, contain carrageenan and were popular as thickening agents in the nineteenth century. Algenic acid, a hydrocolloid found in all brown seaweeds, was discovered first by Charles Stanford in the 1880s. It was not until the 1930s that extracts of brown seaweed, containing alginate, were produced commercially, and sold as thickening and gelling agents. Development of a large-scale alginate industry began in California and in Scotland in the late 1920s and early 1930s, respectively. *Laminaria japonica* was cultivated in China from the 1950s for several health benefits (Kilinç et al., 2013).

Utilization of seaweeds expanded rapidly after the Second World War in many countries including India (Kilinç et al., 2013; Rao & Mantri, 2006), when the focus was set on a possible insufficient protein supply due to the rapid increase of the world population. In the 1950's, it was found that *Gracilaria* spp. treated with alkali produced higher strength gels. At the end of 1990s, the discoveries of bioactive compounds were made by using marine algae, bacteria and invertebrates (Mayer & Lehmann, 2000).

Many types of seaweed contain anti-inflammatory and antimicrobial agents. Their known medicinal effects have been taking up for thousands of years; the ancient Romans used them to treat wounds, burns, and rashes. Anecdotal evidence also suggests that the ancient Egyptians may have used them as a treatment for breast cancer. While dietary soy was long credited for the low rate of cancer in Japan (Pati et al., 2016; Murphy et al., 2014; Pooja, 2014).

The long history of seaweed utilization for a variety of purposes has led to the gradual realization that some of their constituents are more superior and valuable in comparison to their counterparts on land.

## 2. Human food

Humankind is no stranger to the use of algae as a food source, because most seaweed species have no intrinsic toxins and they are edible. About 700 edible seaweed species (including around 195 brown seaweeds, 345 red seaweeds and 125 green seaweeds) are documented from dates back centuries for human consumption (Pereira, 2016).

Edible seaweeds were widely consumed in several cultures, especially in Asian countries (e.g., Japan, China, Korea, Taiwan, Singapore, Thailand, Brunei, Cambodia, and Vietnam, but also in South Africa, Indonesia, Malaysia, Belize, Peru, Chile, the Canadian Maritimes, Scandinavia, South West England, Ireland, Wales, California, Philippines, and Scotland) as fresh, dried, or ingredients in prepared foods (Kilinç et al., 2013).

In Japan, the red seaweed nori (Pyropia and Porphyra), is a traditional wrapping for sushi and is eaten in soups. Wakame (*Undaria pinnatifida*) and kombu (*Saccharina japonica*) are cultivated for food in many maritime countries, particularly in Asia, Japan, Korea and China seaweeds are used as a source of food, industrial applications and for fertilizer (Pati et al., 2016; Hasan & Rina, 2009).

Kombu in Japan, and Kunbu in Chinese (The common food item with low cost but highly nutritious) is used in the preparation of soups, fish, meat dishes, and as a vegetable with rice. Some seaweed has excellent dietary content, mainly protein, some carbohydrates, vitamins A, B, B2 and C. An additional advantage is that it is low in calories and very suitable for vegetarians of all kinds. As the seaweed has high protein content as it is being used by many of the countries like Japan, China, Korea, Malaysia, Thailand, Indonesia, Philippines and other Southeast Asia (Pati et al., 2016).

Consumption of seaweed in Japan has been reported as high as 5.3 g/day (Matsumura, 2001). It is therefore not surprising that Korea, Japan, and parts of China, consume the greatest proportion of the 2 billion kilograms of seaweed harvested each year for human consumption (Jensen, 1993).

For centuries, seaweed has been consumed in Asia; it was not a usual part of the Western diet (Jiménez-Escrig & Sánchez-Muniz, 2000). Low consumer awareness regarding the potential health benefits of seaweed challenges its use in the daily diet (Kadam & Prabhasankar, 2010). However, seaweed consumption in Western countries is increasing in popularity, most of the seaweed harvested is utilized in the manufacture of hydrocolloids (Smit, 2004). Up to now, mostly used by specific sub-populations in Europe (namely in Iceland, Scotland, Ireland, Wales and France) (Mahadevan, 2015; Tiwari & Troy, 2015; Mendis & Kim, 2011). In fact, after being used for centuries as a staple food particularly in Asian countries, seaweeds are expected to become a relevant food and food ingredient in the European market. Seaweed was brought to the spotlight in the Western world due to their marketing and perception as ‘superfood’, increased interest in healthier diets and lifestyles as well as on more sustainable food sources and production (Mahadevan, 2015; Mendis & Kim, 2011; FAO, 2018). As a result, a wide variety of seaweed-based or containing products is now more easily available to European consumers, from the traditional sushi to salads, breads pasta, chips and drinks (Bouga & Combet, 2015).

In Ireland, there is renewed interest in seaweed that once formed part of the traditional diet. Recipe books promoting the use of 'sea vegetables' or 'marine vegetables' in home cooking are becoming more popular. Consumer health and nutrition are becoming increasingly influential in the food industry; thus, seaweed is gaining in popularity (Lee, 2008).

*Ulva* species is commonly known as sea lettuce (due to their thin and bright green fronds) and it has been shown to be acceptable to consumers when baked into breads (*Ascophyllum nodosum* up to 5% w/w) (Edwards et al., 2012; Hall et al., 2010). Along with *Ulva* species, the other seaweeds like *Enteromorpha* sp., *Caulerpa* sp., *Codium* sp., *Monostroma* sp., *Sargassum* sp., *Hydroclathrus* sp., *Laminaria* sp., *Undaria* sp., *Macrocystis* sp., *Porphyra* sp., *Gracilaria* sp., *Eucheuma* sp., *Laurencia* sp. and *Acanthophora* sp. are used in the preparation of soup, salad and curry (Kolanjinathan et al., 2014).

In addition to direct human consumption, seaweeds are also processed into food additives or food supplements (McHugh, 2003; FAO, 2018). Japanese kelp (*Laminaria japonica*) was one of the earliest raw materials for producing monosodium glutamate, which is widely used as a flavor enhancer for umami taste (Milinovic et al., 2021). Agar extracted from Gracilaria and other agarophytes, 12 carrageenan extracted from *Kappaphycus/Eucheuma* and other carrageenophytes, and alginate extracted from *Laminaria/Saccharina* and other brown seaweeds are seaweed-based hydrocolloids widely used as food additives to enhance the quality of a variety of foods. Additionally, seaweed extracts, such as iodine, fucoidan, fucoxanthin and phlorotannins, are used as food supplements for health benefits. Some of the seaweed is also taken in dried form (Pati et al., 2016).

However, seaweed, a late addition to the bioprospecting of scaling for the welfare of the humankind, are highlighted as having the potential for human consumption (Demunshi & Chugh, 2010). Despite increasing global demand, consumer awareness and acceptance of seaweed in Bangladesh remain limited due to unfamiliarity, cultural dietary preferences, and lack of market promotion.

## 3. Livestock feeds

Seaweed has been a traditional part of the livestock diet, and they have historical usage in agriculture (Evans & Critchley, 2014). Seaweeds have been seen a renewed interest as feed ingredients since the 1960s, when Norway started producing seaweed meal from kelp (McHugh, 2002).

Seaweed can be used to prepare seaweed meals as supplementary to the daily ration of the cattle, poultry and other farm animals. The nutritional value attributed to macroalgae along with their non-animal nature makes them particularly appropriate to be used in animal feed as nutraceuticals (combination of nutritional and pharmaceuticals components of feeds that bring health benefits & prevention to some diseases) (Pomin, 2012; Laudadio et al., 2015).

Thus, seaweeds are valuable alternative feeds for livestock, mostly as sources of valuable nutraceuticals, notably chelated micro-minerals, the availability of which is higher than that of inorganic ones; complex carbohydrates with prebiotic activities; and pigments and polyunsaturated fatty acids beneficial to consumer health (Evans & Critchley, 2014). Soluble *Ascophyllum nodosum* extracts obtained from alkaline hydrolysis is used as feed additives. Seaweed is used as a binding agent in shrimp feeds (Williams et al., 2009; Allen et al., 2001).

The main genera and species used as animal feed are *Ascophyllum nodosum, Laminaria species, Lithothamnion* sp., *Macrocystis pyrifera, Sargassum* sp., *Palmaria palmate* and *Ulva* sp. (Makkar et al., 2016).

Information on the application of green seaweed in ruminant feed is scarce. Red seaweed has received more attention, as demonstrated before, in bovine feed than in other ruminant feed

(Mišurcová, 2012). Cows and sheep produce methane, a greenhouse gas that is 28 times more powerful than carbon dioxide, and it has a significant impact on the climate due to its global warming potential (GWP). Most cow methane comes from burps (90%) rather than farts (10%) and is the largest direct contributor to GHG emissions in beef and dairy production (Stocker, 2014; Caro et al., 2016). Changes in ruminant diets can affect the rumen microbiome and their digestive capacity that alter methanogenic activity and gas production, which ultimately reduces methane emissions (Abbott et al., 2020; Carberry et al., 2012; Huws et al., 2018).

Several in vivo studies have evaluated the effects of a specific seaweed, *Asparagopsis spp.*, on methane emissions and productivity of sheep, beef and dairy cows (Vijn et al., 2020). 20 seaweed species have been tested in a study and found that they reduce methane production in test-tube samples from cow stomachs by anything from 0 to 50%. But it required high amounts of seaweed (20% by weight of the sample) which was likely to present digestion issues for animals. It is found in another test that *Asparagopsis taxiformis* reduces methane production by more than 99% in the lab, and unlike other seaweeds where the effect diminishes at low doses, this species works at doses of less than 2% (Kinley et al., 2016). *Sargassum spp.* could be introduced at up to 30% in the diets of growing sheep and goats without depressing intake, growth performance and diet digestibility (Marín et al., 2009). In the context of Bangladesh, where livestock production is an important component of the agricultural economy, the incorporation of locally available seaweeds as feed additives could offer a sustainable strategy to improve productivity while mitigating greenhouse gas emissions, although further research on feasibility and farmer acceptance is required.

Seaweed builds resistance to disease by ensuring a complete balance of micronutrients. They also assist in decreasing the rate of mastitis and cow fever (Krishnan & Narayana, 2010). It also improves fat level and iodine content in milk and in yield of milk products. It has been established that seaweed meals increase fertility and birth rate of animals and improve yolk color in eggs (Laudadio et al., 2015). Seaweed has been used in poultry to improve animal immune status, to decrease microbial load in digestive tract, and for their beneficial effect on quality of poultry meat and eggs (Abudabos et al., 2013; Chuanfeng & Yingting, 2013).

Historically, high corn prices led to the search for new feed capable of providing the required nutrients for livestock and other animals, to maintain productivity and lower the feed costs (Morais et al., 2020). Green seaweed *Enteromorpha prolifera* fed to broilers at inclusion rates ranging from 2% to 4% provided best nutrient availability and high apparent metabolizable energy, which may be attributed to a high level of amylase in the duodenum. It had a positive effect on feed intake, feed conversion ratio and average daily gain while reducing abdominal and subcutaneous fat thickness, thus improving breast meat quality (Chuanfeng & Yingting, 2013; Sun et al., 2010).

Research was done with green algae from the genus Ulva, with the inclusion of 1-3% of this seaweed, resulting in improved egg production and quality, increasing the weight, shell thickness, yolk color and reduced yolk cholesterol (Morais et al., 2020). Whereas brown seaweed like *Sargassum spp.*, at a 3–6% dietary level tested to give benefits to the egg quality, decreasing yolk cholesterol, triglycerides and increased in ω-6 fatty acids, carotene and lutein plus zeaxanthin contents. There is data of poultry being fed with boiled seaweed, which resulted in improvement of the high-density lipoprotein, which is beneficial for human health (Al-Harthi & El-Deek, 2012).

Animal feed plays a vital role in the global food security, and it is conceived to ensure the sustainable production of safe and affordable animal proteins. Seaweed is close to becoming popular, due to their suitability as potential feedstuff production, as well as supplements for other feed items. However, seaweed evidenced their potential to be further explored as an animal feed additive/supplement.

## 4. Nutritional values

Seaweeds are nothing but the wealth of Ocean and can be said as the marine living resources. It is a good source of proteins, carbohydrates, minerals, vitamins, fibers and other phytochemicals (MacArtain et al., 2007).

### *4.1. Protein content:*

Protein content varies among different genera and in different species of the same genus depending on the habitat and water depth (Pati et al., 2016). Generally, red and green seaweed has higher protein content than brown seaweed (Holdt & Kraan, 2011; Kolanjinathan et al., 2014; Murata & Nakazoe, 2001). The amino acid score of the proteins in some red seaweed such as *Porphyra* spp. and *Undaria* spp. was recorded 91 and 100, respectively, the same as that in animal-derived foods. Red seaweed contains the highest protein content, which is comparable in quantitative terms to legumes at 30 - 40% of dry matter Murata & Nakazoe, 2001). Therefore, most of the edible red seaweed can be considered as a good source of protein to be included in the diet. In addition, the blue-green alga, *Spirulina*, is well known for its very high protein content, which is close to 70% of the dry matter. In general, seaweed protein is rich in glycine, arginine, alanine, and glutamic acid, and contains all essential amino acids, the levels of which are comparable to those of the requirements of dietary proteins.

### *4.2. Carbohydrate content:*

Seaweed contains a large amount of carbohydrates as structural, storage, and functional polysaccharides, and the total carbohydrate content may range from 20% to 76% of dry weight depending on the species (Holdt & Kraan, 2011). Chlorophyceae members generally have high carbohydrate content (Chakraborty & Santra, 2008; Parthiban et al., 2013) than Rhodophyceae and Phaeophyceae, but this may also vary according to the species and type of habitat. For example, the maximum carbohydrate content was recorded in the green seaweed *E. intestinalis* was 28.58 % and the minimum was 10.63% in brown seaweed of *Dictyota dichotoma* (Parthiban et al., 2013). In green seaweed, *U. lactuca* (35.27%) and *E. intestinalis* (30.58%) also contain higher carbohydrate content, while the lowest value 14.34% of dry matter recorded in red alga *Gelidiella acerosa* (Chakraborty & Santra, 2008).

### *4.3. Fatty acid content:*

Seaweed has very little lipid content, ranging from 1% to 5% of dry matter. The percentage of lipid found 2.82±0.24 and 2.94±0.45 in green and brown seaweeds, respectively (Mohammadi et al., 2013). Seaweed synthesizes higher amounts of polyunsaturated fatty acids (PUFAs) especially under the cool climates, and PUFAs in seaweed contain substantial amount of omega-3 fatty acids as the major component. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are the two important fatty acids of marine origin belonging to omega-3 fatty acids that are responsible for several health benefits in the human body. The major PUFA in most seaweed is EPA and the content of which can be even closer to 30% of the total fatty acid content. Though the red seaweed is rich in EPA and omega-6 fatty acids (such as arachidonic acid) as a whole, all seaweeds are a balanced source of omega-3 and omega-6 fatty acids (Rajapakse & Kim, 2011). The amount of phospholipids in seaweed is about 4-10% of the total lipid. Moreover, phospholipids in the diet act as an emulsifier and ease the digestion and absorption of fatty acids enhancing the nutritive value of the food. Therefore, seaweed is a good source of health-promoting PUFA compared to the other foods derived from plant and animal sources, which may add to their efficacy as a part of a balanced diet.

### *4.4. Vitamins and minerals content:*

Seaweed contains both water- and fat- soluble vitamins. They are also an excellent source of vitamins such as A, B1, B12, C, D and E, riboflavin, niacin, pantothenic acid, folic acid as well as minerals such as I, Ca, P, Na and K in significant amount in different species of algae (Pati et al., 2016; MacArtain et al., 2007; Teas et al., 2009; Pereira, 2011). Nori has large amounts of vitamins A and C (MacArtain et al., 2007; Teas et al., 2009). High vitamin E content helps to protect PUFA in seaweed and to maintain their nutritional benefits (Rajapakse & Kim, 2011).

Red and brown seaweeds are rich in carotenes (provitamin A) and vitamin C, and their amounts may range from 20 to 170 ppm and 500 to 3,000 ppm, respectively. Vitamin C, which is of interest for its stress combating mechanism. It strengthens the defense system, traps free radicals, and helps to regenerate vitamin E, and the importance of carotene lies on its antioxidant properties (Chakraborty & Santra, 2008; Rajapakse & Kim, 2011). The concentration of vitamins B1, B12, pantothenic acid, folic and folinic acids are generally higher in green and red than in browns (Kilinç et al., 2013).

The minerals like sodium, calcium, magnesium, potassium, chlorine, sulphur, phosphorus and micronutrients such as iron, zinc, copper, selenium, molybdenum, fluoride, manganese, boron, nickel and cobalt are plenty in different species of seaweed (Kolanjinathan et al., 2014). Apart from that, it is a good source of iodine; generally highest in brown seaweed (1,500–8,000 ppm) (Pati et al., 2016; Kilinç et al., 2013; Kolanjinathan et al., 2014; Rajapakse & Kim, 2011). Iodine amount in the seaweed remains comparatively high than that in the land plants. Since animal- and plant-derived foods are very low in iodine, seaweed can be considered as the best inexpensive food to fulfill the iodine requirement of human (Rajapakse & Kim, 2011).

Presence of minerals with values about ten times higher than found in traditional vegetables, such as iron in *Himanthalia elongata* (Sea spaghetti) in comparison with that of *Lens esculenta* (lentils), or in the case of calcium present in *Undaria pinnatifida* (Wakame) and *Chondrus crispus* (Irish Moss), in comparison with milk. The presence of proteins containing all essential amino acids, constituting a type of protein of high biological value, comparable in quality to the egg; presence of vitamins in significant quantities, in particular the presence of B12 (*Porphyra* spp.), absent in higher plants. *Palmaria palmata* and *Himanthalia elongata* are rich in potassium and, together with the algae of the genus *Porphyra* and *Laminaria*, have a ratio of sodium/potassium considered optimal for human health (Pereira, 2011).

With high nutritional value due to the presence of important macro - and micronutrients including vitamin B12, omega-3 and omega-6 fatty acids, selenium, iodine and dietary fiber, seaweeds are also studied as a source of several bioactive compounds with potential health benefits (Holdt & Kraan, 2011; Teas et al., 2009; Aguilera-Morales et al., 2005; Gil et al., 2015; Brown et al., 2014; Gómez-Ordóñez et al., 2010). Among the marine organisms, seaweed represents one of the richest sources of natural antioxidants and antimicrobials (Morais et al., 2020).

In general, it is accepted that green and red algae have higher nutritional value than brown algae due to low protein and high mineral content. However, brown algae have a higher and diversified content on bioactive molecules with high commercial interest (Mišurcová, 2012). In conclusion, seaweed is of nutritional interest as they are low calorie food, but rich in vitamins, minerals and dietary fibers, and can be considered as the good source of food for human consumption.

## 5. Industrial uses

Seaweed based products that have known and clinically documented bioactivity have potential to become value-added functional products and many investigators foresee a future where seaweed is grown for high value functional product markets such as cosmeceuticals, nutraceuticals, pharmaceuticals, and functional foods, animal feed additives, and fertilizers (Evans & Critchley, 2014; Balboa et al., 2015; Hafting et al., 2015; Humaya & Kim, 2015).

### *5.1. Medicinal use:*

Microalgae have been explored for their therapeutic potential during the last 50 years or so, but only a few marine algae so far have been investigated (Jha & Zi-Rong, 2004; Blunt et al., 2015). A few academic researchers have surveyed local seaweed flora from the perspective of potential utility in the health industry by broadly screening specific extracts with established bioassays (Cornish et al., 2015). In vitro and animal studies suggest the potential for human health promotion that may include anticancer, anticoagulant, gut health promotion, antimicrobial, antiviral, antifungal, anti-allergic, antifouling and antioxidant activities, and prevention of metabolic syndrome like atherosclerosis, cardiovascular disorder and ageing processes (Holdt & Kraan, 2011; Murphy et al., 2014; Pooja, 2014; Teas et al., 2009; Yuvaraj & Arul, 2014).

Use of seaweed can help in reduction of plasma cholesterol, which may reduce the risk of cardiovascular disease (Jiménez-Escrig & Sánchez-Muniz, 2000; Cornish et al., 2015). Reduction of the risk of cardiovascular diseases by consuming seaweed is suggested due to its modifying effects on the gastrointestinal tract such as emulsification of bile acid and interfering with lipid micelle formation, dilution of lipase concentration, binding with cholesterol, and slowing down of lipid absorption (Rajapakse & Kim, 2011).

Methanol extracts of the seaweeds *Undaria pinnatifida* and *Ulva linza* have a better inflammatory activity while tested against mouse ear edema and erythema. Edema was strongly dormant and the greatest suppression of erythema resulted by these two seaweeds (Khan et al., 2008).

Infected rats (diabetes) have been treated with aqueous of *Ulva fasciata*. Aqueous extract of it has shown a significant decrease in blood glucose and glycosylated hemoglobin level in diabetic rats as compared to other standard medicine (Abirami & Kowsalya, 2013). Thus, seaweed can be a good option for diabetic treatment.

Seaweeds are the most prominent source of iodine (Pati et al., 2016; Kilinç et al., 2013; Kolanjinathan et al., 2014; Rajapakse & Kim, 2011). T4 and T3 have been found as the main organically bound iodine compounds in several brown seaweeds, notably *Laminaria species* and *Sargassum species*. Seaweeds are used in medicine for the treatment of iodine deficiency (goitre, Basedow’s disease and hyperthyroidism), for intestinal disorders, as vermifuges, and as hypocholesterolemic and hypoglycemic agents (El Gamal, 2010). Seaweeds are also a good source of melatonin; as a dietary supplement, it is often used for the short-term treatment of insomnia and interestingly daytime harvested sea weeds possess more amount of melatonin.

Medicinal effects of seaweed have been seen for thousands of years but further research will help specify the uses of it.

### *5.2. Chemicals:*

Three types of hydrocolloids are extracted from seaweed, such as alginate, carrageenan and agar. In the baking industries, hydrocolloids are of increasing importance in bread making with the objectives to improve dough handling properties, increase the quality of fresh bread, extend the shelf life of stored bread and increase the nutrient content of the final products (Arufe et al., 2018; Xiren, 2013; Menezes et al., 2015).

Agar or “agar-agar” which is well known in Southeast Asia is used as a solid substrate for the growth of bacteria and fungi. It is commonly used as in inert carrier of nutrients in Biotechnology and Microbiology. No modern microbiological laboratory in the world can survive without agar, and no reasonable alternative has been found even in with today’s technological advances (Krishnamurthy, 2005; Subbaramaiah, 2004). This can also be used in cakes, chocolates, candies, jellies, jams, juices, coffee, wafers, liquors, salad dressing etc. As a stabilizer, it is being used in sauces, a solidifying agent, emulsifier and laxative. In the manufacture of photographic film, paint, batteries, graphite, glue etc. the seaweeds are in use (Pati et al., 2016). Cofrades et al. (2013) reported the quality of bread has improved by the addition of both green seaweed *Ulva lactuca*, and 2.5% of powdered Laminaria [118]. Oh et al. (2020) used seaweed flour to enrich cookies and concluded the possibility of developing bakery products using seaweed (Oh et al., 2020). Major seaweeds genera which are being used for agar production includes *Ahnfeltiopsis, Gelidium, Gelidiella, Gracilaria, Pterocladiella* and *Pterocladia*. The highest quality of agar and its derivative called agarose comes from red algae belonging to family Gelidiaceae.

Alginate derived from brown seaweed is used to improve the quality of paper texture. It is being used as a potential ingredient in frozen foods, stabilizer in ice creams, and reactive base in reactive dye printing of textiles. It is also widely used in many pharmaceutical industries as a stabilizer. It acts as an emulsifier for many food products in food industries such as an additive in instant food drinks, to keep food particle liquid in the mixture. It also helps as natural latex creaming and thickening of rubber (Subbaramaiah, 2004). Funoran (a natural polysaccharide), obtained from red seaweed *Gloeopeltis* used in textile and paper-making industry (Gade et al., 2013).

Seaweed has a good water-binding capacity. It increases texture; improves fat replacement, product yields and helps with analogue seafood binding. It is used in dairy products e.g. chocolate milk, frozen desserts, UHT milks, flans, puddings, low-fat cheese and cheese analogue. It also provides cocoa suspension, milk stability, emulsion stability and for milk gelling. Its other uses include- cold milk powders, diet powder mixes and nutritional beverage mixes. In toothpaste, it provides structure without masking flavors, resistant to enzymatic breakdown. In pet foods, it binds water, provides structure and prevents fat separation in canned, retorted products. Its wider use includes controlled release products, e.g. air freshener gels (Gade et al., 2013; Dhargalkar & Pereira, 2005).

#### *5.2.1. Cosmetics:*

An astonishing similarity between human skin tissue and algal cellular structure has helped to solve numerous cosmetic and dietetic problems. In recent years, the application of seaweed-derived ingredients in cosmetic products has increased particularly soaps, shampoos, powders, body creams or lotions and sprays. Mineral-rich seawater is used in a range of therapies, including hydrotherapy, massage and a variety of marine mud and algae treatments. It is said to be useful in various ways, including relief of rheumatic pain or the removal of cellulite (Gade et al., 2013; Jesumani et al., 2019).

*Hypnea musciformis* extract could be a potential key player for its skin soothing, collagen protecting and cell turnover capability. Green seaweed such as *Ulva* spp. with high content of polysaccharide, an active ingredient in cosmetic formulations, plays significant cosmetic roles as hair conditioners, moisturizers, collagen synthesis, anti-aging, and wound-healing agents (Dhargalkar & Pereira, 2005; Pereira, 2018; Venkatesan et al., 2017).

#### *5.2.2. Bioplastics:*

Packaging materials, especially plastic, are somehow affecting our planet. About 150 million tonnes of plastics already exist in the ocean that is equivalent to dumping 8 million tonnes each year and 15 tonnes in every minute, which estimates more plastics in the ocean than fish by 2050 in terms of weight (Crawford & Quinn, 2016). Thus, alternative packaging materials need to introduce seaweed-based polysaccharide can be used as edible bio-plastic packaging materials to open an avenue of new plastics economy (Khalil et al., 2017). Agar-based bio-plastic film possesses flexible characteristics like low moisture content and heat-sealable, which makes it an excellent option for food packaging industry (Hii et al., 2016). Developing seaweed and cellulose composite film not only maximizes the performance of food packaging, and biomedical applications, but also creates a huge potential for bio-economy growth (Khalil et al., 2017). However, these seaweed ingredients must meet industrial and technical specifications and consumer safety regulations before large-scale production and uses.

### ***5.3. Agro-Fertilizers:***

An adequate amount of potassium, nitrogen, growth-promoting hormones, micronutrients, humic acids etc. present in seaweeds make it as excellent source of fertilizer. Unlike chemical fertilizer, fertilizers derived from seaweeds (*Fucus, Laminaria, Ascophyllum, Sargassum* etc.) are biodegradable, non-toxic, non-polluting and non-hazardous to human, animals and birds (Dhargalkar & Pereira, 2005).

Many studies have demonstrated the benefits of seaweed in enhancing plant growth and productivity. Added to this, they are known to be promising soil conditioners, protect the plants under abiotic and biotic stress and increase plant resistance against pets and diseases.

Seaweed extracts are used in different ways like seed treatment, foliar spray and soil application for plant protection and for plant growth promotion and better productivity. Seaweed extract is more useful than chemical fertilizer because of its bio-decomposable, non-toxic and eco-friendly property. Usage of seaweed increases agricultural crops through enhancement of plant growth, seedling growth, both root hair and secondary root development. It can also improve nutrient incorporation, fruit setting, resistance properties against pests and diseases, improving stress management (drought, salinity and temperature) (Gade et al., 2013; Dhargalkar & Pereira, 2005; Raghunandan et al., 2019; Mukherjee & Patel, 2020).

The concept of spraying fertilizer on plants is gaining importance because the nutrients do not leach down into the soil but are available to the plant through leaf openings such as lenticels, hydathods and stomata. Leaves absorb nutrients within 10 to 15 minutes of its application.

Many brands of seaweed liquid fertilizers like Maxicrop (UK), Kelpak 66 (South Africa), Seagrow (New Zealand), Algifert (Norway), Plantozyme, Shaktizyme (India) etc. are available in the market and many firms in India are coming forward to prepare seaweed bio-fertilizers (Dhargalkar & Pereira, 2005).

An experiment was conducted on a farmer's field near Bhavnagar (Gujarat, India) to study the effect of foliar applications of *Kappaphycus alvarezii* and *Gracilaria edulis* on growth and yield response of wheat variant 'GW 496'. It was found that yield of grain was increased significantly by 19.74% and 13.16% for plants receiving 7.5% and 5.0% concentrations of *K. alvarezii* and *G. edulis* respectively, over control. The increase in yield was attributed to increases in the number of spikes, spike weight, spike length and 100 seed weight as well as increased nutrient contents in grains also reported (Raghunandan et al., 2019; Mukherjee & Patel, 2020; Shah et al., 2013; Thirumaran et al., 2009).

Species of *Ascophyllum, Ecklonia* and *Fucus* have a suitable content of nitrogen and potassium but are much lower in phosphorus than traditional animal manures and the typical N:P:K ratios in chemical fertilizers (Gade et al., 2013; Dhargalkar & Pereira, 2005). All these explain seaweed worldwide use as manure along the coastal areas.

Seaweed fertilizer therefore provides valuable nutrients to every plant that needs to grow and thrive well. Farmers throughout the world are switching over to organic fertilizers where seaweed fertilizer can be a good choice.

### *5.4. Miscellaneous usage:*

The unexploited and remaining unused seaweed biomass can be utilized to produce biogas through anaerobic digestion to methane. The biogas is a reasonably clean burning and eco-friendly fuel, which can be used for cooking, heating or electricity generation (Dhargalkar & Pereira, 2005). Moreover, carbon sequestration in seaweed biomass may mitigate global warming and ocean acidification (Chung et al., 2013; Duarte et al., 2017).

Seaweed can enhance growth and immune system of fishes by reducing the feed cost as it contains many nutrients and bioactive compounds. Different studies indicate that the seaweed supplementary feed for growth performance of fish was higher and more effective than commercial feed. Seaweed powder from *Ulva spp.* and *Hypnea musiformis* has been used as a supplement of feed to observe the effect on growth and immune system of Tilapia (*Oreochromis niloticus*) and found that average weight gain (WG) of Red Tilapia (*Orechromis sp*) and *O. niloticus* increased up to 15% and 30%. The growth was significantly increased with the increased supplement rate of fishmeal by seaweed powder and as part of immune response gradual increase of RBC found which help preventing anemia (Nur et al., 2020). 1% seaweed *Sargassum whitti* for *Mugil cephalus* showed a significantly increasing WBC which indicated the good sign of immunity and prevent the fish from invasive bacteria and virus (Kanimozhi et al., 2013). In another study for *Catla catla*, seaweeds *Chlorodesmis fastigiata*, *Padina tetrastomatica* and *Stoechospermum marginatum* showed WG 13.38g/month, 11.56 g/month, 9.05g/month respectively that are higher than the control (6.48g/month) (Kotnala et al., 2010). All other parameters regarding growth such as specific growth rate (SGR), feed conversion ratio (FCR) etc. and parameters of blood for immune response such as mean corpuscle volume (MCV), hemoglobin, hematocrit etc. showed higher results in seaweed treated feed than the commercial feed (Razia, 2018).

In modern times, seaweed is used in the treatment of sewage and some agricultural and domestic wastes to reduce nitrogen and phosphorus containing compounds. Seaweed extracts nutrients from the water, mitigating coastal eutrophication, purifying surrounding water and maintains ecosystem health (Pati et al., 2016; Dhargalkar & Pereira, 2005; Xiao et al., 2017). Thus, seaweed can be employed as water disinfectant in aquaculture and to treat wastewater.

## Potentials in Bangladesh

Seaweed farming is highly developed in many Southeast Asian countries. However, the seaweed industry in Bangladesh is an initial stage and its people are still not aware of the seaweed production techniques and its potentials for diversified uses.

### 1. Production Scenario of Seaweeds

Bangladesh has 710 km coastline and 47,201 km2 of coastal area; this coastal area with sandy and muddy beaches, estuaries and mangrove swamps can provided suitable substrates and habitats for various seaweeds farming (Ahmad, 2019; Ahmed & Taparhudee, 2005). Salinity of 20-34 ppt, pH 7.5-8.5 and temperature 20-30°C is required for seaweed growth and October to April in Bangladesh provides the favorable condition for seaweed production, but highest abundance occur from January to March (Sarkar et al., 2016; Satpati et al., 2012). At present, the BFRI (Bangladesh Fisheries Research Institute) and the BARI (Bangladesh Agricultural Research Institute) and WorldFish through its Enhanced Coastal Fisheries in Bangladesh (EcoFish) are trying to culture seaweeds in Cox’s Bazar coastal waters, mostly around the Moheshkhali Channel (Sarkar et al., 2016).

Although seaweed is available throughout the southern coast, the seaweed species are found mostly in marine waters of Cox’s Bazar. Great abundance of natural seaweed resource is reported from St. Martins’ Island (DoF, 2014). Good growth for the green, red and brown seaweed has been reported in the Sunbarbans mangrove forests, on the pneumatophores (Laudadio et al., 2015; Ahmed & Taparhudee, 2005).

Natural production of seaweeds and regular statistics on production of seaweed is yet to be developed in Bangladesh. Hossain et al. (2020) reported, 300 households are engaged with seaweed farming that is practiced in Nuniarchara, Inany beach and Rezu khal areas. From those culture plots, the fishers harvested 390 MT of wet seaweed (equivalent to 59 MT dry weight) annually (Erlandson et al., 2015). However, as per Sarker et al. (2016) approximately, 5,000 MT seaweed biomass is annually available throughout the Bangladeshi coast from October to April (Sarkar et al., 2016).

Table 1 shows that 4 species of Chlorophyta (green seaweed) and 10 species of Rhodophyta (red seaweed) are suitable for farming (Hossain et al., 2020). Most cultivable seaweed species in Bangladesh are *Hypnea musciformis*, *Ulva intestinalis, Ulva lactuca, Caulerpa racemosa, Gracilaria spinuligera, Gracilaria tenuistipitata, Gracilariopsis longissima* and *Catenella nipae* for the expansion of seaweed farming (World Fish Bangladesh, 2021).

**Table 1.** List of potential cultivable seaweed species in Bangladesh

| Family | Genus | Species | Common name |
|---|---|---|---|
| Caulerpaceae | *Caulerpa* | *Caulerpa racemosa* | Sea grapes |
| | | *Caulerpa sertulariodis* | Green feather |
| Ulvaceae | *Ulva* | *Ulva lactuca* | Sea lettuce |
| | | *Ulva intestinalis* | Gut weed |
| Scytosiphonaceae | *Hydroclathrus* | *Hydroclathrus clathratus* | Sponge seaweed |
| Halymeniaceae | *Halymenia* | *Halymenia durvillei* | Dragons tongue |
| Hypneaceae | *Hypnea* | *Hypnea musciformis* | Maiden hair |
| | | *Hypnea esperi* | Maiden hair |
| | | *Hypnea pannosa* | Maiden hair |
| Gracilariaceae | *Gracilaria* | *Gracilaria tenuistipitata* | Ogonori |

| | | | |
|---|---|---|---|
| | | *Gracilaria canaliculata* | Bangladesh ogonori |
| | *Gracilariopsis* | *Gracilariopsis longissima* | Dragon beard alga |
| Solieriaceae | *Kappaphycus* | *Kappaphycus alvarezii* | Cottonii/Sea moss |
| Caulacanthaceae | *Catenella* | *Catenella nipae* | Mangrove seaweed |

The USAID-funded Enhanced Coastal Fisheries in Bangladesh (EcoFish) Activity has taken a massive effort in seaweed farming in Cox's Bazar coastal water through engaging the fishing communities, mostly women for an alternative income-generating option. The activity jointly implemented by WorldFish, Chattogram Veterinary and Animal Sciences University (CVASU) and Falcon International Limited, a private entrepreneur, exports seaweeds to Southeast Asian countries. They tried three culture technologies like, i) Off bottom long line, ii) Off bottom net, and iii) Floating long line over last three years but found that floating methods gave the best and quality production of *Gracilaria* sp. Community-based seaweed farming has been seen as a good start at Cox's Bazar coast, but needs (a) capacity building and infrastructure, (b) access to suitable farming sites, (c) value addition and market linkages, and (d) industrial utilization of seaweeds (Hossain et al., 2020). However, introduction of cost-effective technology for seaweeds production could open a new avenue for community resilience and livelihoods of marginalized and poor farmers, which will help expand seaweed industry in the country.

## 2. Diversified Utilization of Seaweed

Utilization of dried seaweeds by illegal trading to Myanmar from St. Martin's Island is widely reported, and about 200 tons of seaweeds are annually smuggled to Myanmar. In recent years, few Chinese restaurants are often used seaweeds as fresh salads, cooked vegetables, in fish curry and meat dishes. Seaweeds are sometimes used as medicinal food for young women and post-pregnant females in the said island. Rotten seaweed is used there as biofertilizers for vegetable growing (Majumder, 2010).

In the approach of utilization, MFTS (Marine Fisheries and Technology Station, BFRI, Cox's Bazar) has established a seaweed-processing lab. They have experimentally prepared different types of seaweed food products such as salad, soup, pickle, cake, *chanachur*, jelly, sauce, etc. At the Fish Processing Laboratory, Bangladesh Agricultural University (BAU), Mymensingh the *Hypnea* sp. seaweed powder was used in manufacture of four value added seaweed food products; namely, seaweed jelly, soup, ice-cream, curd; two functional food products, namely, seaweed *singara, samucha/samosa*, and two cosmetic products, namely, seaweed face pack, and shampoo. For seaweed jelly, soup, ice cream and curd consumer acceptance was found as 66. 7%, 50%, 41.7% and 83.3%, respectively. For seaweed snacks like *singara* and *samucha/samosa*, 100% consumers' acceptance was found. Seaweed face pack and shampoo got 100% and 66.7% consumer's acceptance, respectively. Thus, all these products have potential to be produced commercially (Sarkar et al., 2016).

Jahanara of Cox's Bazar, an Agro entrepreneur, has been involved in business of seaweed products over last 20 years. She has developed more than 110 products from seaweed so far, including desserts, balachao (local pickles), noodles, salad, drinks and smoothies, sunscreen and other cosmetics. The food items include seaweed rice wraps, seaweed papads, seaweed and fish curry, seaweed custard, seaweed milk pudding, seaweed ice cream etc. The cosmetics items vary from potato and seaweed cleanser, sunscreen, seaweed facials with coffee, tea, milk etc. She was interviewed in the newspaper (TBS News, 2021). An NGO, named COAST Trust, also developed different value-added foods and functional food products like seaweed cake, salad, pudding, *samucha*, biscuits, chop, *piyaju* and seaweed used in vegetable and noodles (TBS News, 2021).

The Mog and Rakhyine tribal communities and the people of St. Martins' Island in Cox's Bazar traditionally utilize as human food. They locally know seaweeds as 'Hejla'. Like different non-conventional food items, they take seaweeds, whereas seaweeds are almost unknown to Bangladeshi mainstream Muslim and Hindu people in general. Most of the farmed seaweeds (e.g. *Gracilaria* spp., *Ulva* spp. and *Hypnea* spp.) produced in Cox's Bazar have been used for human food by the indigenous communities and tribal peoples of CHT as fresh vegetables and steamed/cooked foods. The most common seaweeds are used in different indigenous food items in Bangladesh has been shown in Table 2 (Sarkar et al., 2016).

**Table 2.** Common seaweeds used as food among selected communities in Bangladesh

| Seaweed species | Human food use |
|---|---|
| Green seaweed (Chlorophyta) | |
| *Ulva intestinalis,*<br>*U. lactuca* | Fresh salad, vegetable, burger, role, soup, *samucha, singara, chop*, *biryani* and *polao* |
| *Caulerpa racemosa,*<br>*C. chemnitzia* | Fresh salad, vegetables with dry fish, burger, role, *chop*, *biryani* and *polao* |
| Red seaweed (Rhodophyta) | |
| *Hypnea musciformis,*<br>*H. esperi* | Fresh salad, noodles, soup, *piyaju*, tea, coffee, cake, pudding and *semai* |
| *Gracilaria tenuistipitata,*<br>*G. spinuligera,*<br>*Gracilariopsis longissimi* | Fresh salad, soup, tea, coffee, *piyaju*, cake, pudding and *semai* |
| *Catenella nipae* | Vegetable with dry fish, soup, *biryani* and *polao* |

Bangladesh Oceanographic Research Institute (BORI) has been working on three kinds of seaweed in laboratory to produce the expensive agar-agar, carrageenan, and sodium alginate (TBS News, 2021).

In Bangladesh, possible usages of seaweeds could be as follows-

- Source of food and livelihoods of the poor
- In food industry as stabilizer and/or emulsifier for many food products, such as chocolate, as additive in instant food drinks
- Medicinal ingredients
- Additives in the preparation of livestock feed, fertilizer and pesticides.
- Ingredients for bio-chemicals, pharmaceuticals and cosmetics industries.
- Adhesive for paper bags and gummed tapes, coating for food packages and milk containers etc.

Seaweed has good export potential. It could easily be a new item on the country's limited export basket and would contribute greatly to reducing poverty and persistent unemployment problem. At present, Japan, Korea, Philippines, China, India and Taiwan have been producing the seaweed commercially. On the other hand, USA, Japan, Singapore and some European countries are importing seaweed and Bangladesh could explore those markets for exports (Sahoo et al., 2002).

Bangladesh has a high potential for seaweed aquaculture development due to the favorable conditions of natural habitats along its long coastal waters. Seaweed has immense food and medicinal values, and other potential usage, the efforts in seaweed cultivation and its utilization through product and process development could help exploring new arena of investment and income for coastal population as well as fetching substantial foreign exchange.

## Conclusions and Actionable Future Research Directions

Future research should prioritize field-scale cultivation trials across Bangladesh's varied coastal zones to identify region-specific species and optimize culture methods. Scalable processing and value-addition technologies must be developed in parallel (e.g., pilot-scale biorefineries for bioactive extraction), alongside comprehensive nutritional and bioactivity profiling of indigenous seaweeds using metabolomic and genomic approaches. Controlled livestock and aquaculture feeding trials (including randomized designs) are needed to evaluate seaweed supplements for animal health, productivity, and methane mitigation. Research should also quantify the ecosystem services of cultivated seaweeds (nutrient removal, bioremediation, coastal protection) and their carbon sequestration potential to align with climate goals. To ensure relevance in Bangladesh, studies must engage smallholder farmers and coastal communities, considering diverse agro-ecological contexts (e.g., Sundarbans mangroves, Bay of Bengal reefs) and regulatory frameworks. Socio-economic surveys and market analyses will guide product development, consumer acceptance, and policy support. Life-cycle assessments and techno-economic analyses are recommended to evaluate viability and scalability. In the short term, emphasis should be on demonstrating proof-of-concept (site selection and germplasm trials); medium-term work should pilot integrated cultivation–processing models; and long-term efforts should establish an inclusive, industry-ready seaweed sector integrated into Bangladesh's Blue Economy strategy. Such interdisciplinary research will chart a path from experimental farms to a robust seaweed industry, enhancing coastal livelihoods while advancing national sustainability and climate resilience objectives.

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