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EXPERIMENTAL CULTIVATION OF SEAWEED ON THE COAST OF COX'S BAZAR, BANGLADESH: IDENTIFYING THE EFFECTS OF ENVIRONMENTAL PARAMETERS ON SEAWEED GROWTH

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ABSTRACT. The current study was carried out at Rezu Khal to determine the ideal area for seaweed farming. Additionally, this investigation uncovered species of commercially productive and lucrative seaweed. Temperature, salinity, pH, dissolved oxygen (DO), conductivity, and Formazin Nephelometric Units (FNU) of surface water ranged from 20.9 to 26.2°C, 24 to 26.2‰, 6.45 to 8.5, 92 to 105%, 33,256 to 64,267 µS/cm, and 11.1 to 42.8, respectively. Phosphate-phosphorus concentrations in surface water were 2.6–7.6 mg/L, 0.04–0.12 mg/L for nitrate-nitrogen, 0.002–0.04 mg/L for nitrite-nitrogen, 0.15–0.83 mg/L for silica, and 0.13–0.28 mg/L for ammonia. Three seaweed species (*Gracilaria lemaneiformis*, *Hypnea musciformes*, and *Sargassum oligocystum*) were cultivated in the selected areas. Two methods (net and long-line) were used for the culture. In this study, 15–20 kg of *G. lemaneiformis* were harvested every 15 days using the net method. *H. musciformes* gained 4 to 12 kg every 15 days. Although *S. oligocystum* thrived nicely, it was challenging to maintain its viability. The findings of this study indicate that seaweed farming is feasible and coastal residents may participate in seasonal income-generating endeavours in coastal waters.

Keywords: culture; effects; physicochemical parameters; seaweed; Rezu Khal.

INTRODUCTION

Seaweed is a multicellular macroscopic sea alga with no actual roots, stems, flowers, or leaves that are essential to the aquatic environment (Aasim *et al.*, 2018; Bhuyan, 2023; Bhuyan *et al.*, 2023; Salehi *et al.*, 2019). Tropical, subtropical, and temperate regions have the greatest abundance of seaweed (Barrientos *et al.*, 2021). They grow on rocks, coral, shells, sand, mud, and other plant bodies (Nedumaran, 2017). They often live below the high-water line, adhering to rocks or other hard surfaces, up to a depth of 118 m, in oceans, rivers, lakes, and other bodies of water where 0.1% photosynthetic light is available (Maberly, 2014; Pereira, 2015). Based on their natural colouring or pigmentation, they are typically classified as red (Rhodophyceae), brown (Phaeophyceae), or green (Chlorophyceae) seaweed (Rashad and El-Chaghaby, 2020; Yalçn *et al.*, 2021).

Seaweed grows from November to March in Bangladesh, depending on turbidity, salinity, and temperature (Aziz and Alfasane, 2020; Sarker *et al.*, 2021). By familiarising poor farmers with cost-effective technologies, seaweed culture can be introduced in places appropriate for its development (Siddiqui *et al.*, 2019). Seaweed can be grown by utilising natural materials, such as bamboo and rope (Bokhtiar *et al.*, 2022; Islam *et al.*, 2021). Seaweed culture can be a good sector for coastal villages in Bangladesh because it involves little input, yields high returns, and employs a large number of people. From Cox's Bazar to the Sundarbans (few locations), there are excellent locations for seaweed cultivation (Hossain *et al.*, 2021; Siddiqui *et al.*, 2019).

Seaweed is a versatile raw material used to make fertilisers, cosmetics, commercial gums, and compounds for the food, drug, and cosmetic sectors (Pati *et al.*, 2016; Pradhan *et al.*, 2022). Furthermore, the seaweed microbiome promotes seaweed growth and health by releasing development- and morphogenesis-promoting factors (Ghaderiardakani *et al.*, 2019), even under abiotic stress (Ghaderiardakani *et al.*, 2020; Hmani *et al.*, 2023). For a long time, seaweed has been a staple diet in many other countries. Green seaweed, such as *Enteromorpha* sp., *Ulva* sp., *Caulerpa* sp., and *Codium* sp., are used solely as food sources (Dhargalkar, 2015; Pérez-Lloréns, 2019). These are frequently served as fresh salads or as cooked veggies with rice (Shafiuddin, 2019). Fish curry and beef meals, as well as soups and accompaniments, are made using *Porphyra* (Nori), *Laminaria* (Kombu), and *Undaria* (Wakame) (Khan and Satam, 2003). Additionally, seaweed is used in commercially produced burgers, juices, sandwiches, chocolate, ice cream, cakes, salads, biscuits, and chips (Sarkar *et al.*, 2016). Seaweed can provide nutrients that are required for body growth. It might also be a lucrative source of foreign income. In addition to harvesting seafood, cultivating seaweed can provide an alternate source of income. It can be a profitable sector, especially for women (Makame and Shackleton, 2021; Msuya and Hurtado, 2017; Shafiuddin, 2019). It is possible to build a massive industry with endless potential. If industrial entrepreneurs from similar disciplines join forces with the government, they may be able to open the door to a new world in the blue economy, thus enriching the national economy. Increasing the production of non-traditional marine resources requires the employment of contemporary technology (Siddiqui *et al.*, 2019).

Global aquaculture production of seaweed was reported to more than triple from 1995 to 2012, reaching 23.8 million tonnes per year, with China and Indonesia accounting for 81% of global production (FAO, 2014; Kotta *et al.*, 2021). Due to environmental concerns, seaweed production in Europe is entirely dependent on the collection of natural stocks and has declined by about one-third from 2000 to 2012 to around 230,000 tonnes per year (Thomas *et al.*, 2019). In the coming years, cultivation is likely to play a significant role in closing the growing gap between supply and demand. As research programmes and companies build the capacity to grow and process algal biomass, algal production has gained momentum (Ligtvoet *et al.*, 2019; Sandquist *et al.*, 2017). There are still many economic, political, and logistical challenges to overcome, many of which are region specific. Among these is the identification of suitable coastal areas that allow effective cultivation without interfering with current shipping operations (Jackson, 2018; Prutzer, 2019).

Farmers on the shore of Cox's Bazar frequently cultivate seaweed using off-bottom net and long-line methods (Akhtar *et al.*, 2022; Banik *et al.*, 2023; Farhaduzzaman et al., 2023). Seaweed produced by the floating raft culture method has shown great success in producing seaweed (Sobuj *et al.*, 2023; Yahya *et al.*, 2020). Different environmental parameters affect seaweed growth. The development and composition of seaweed are influenced by salinity, and optimum salinity can promote growth (Kraan, 2018). According to Tresnati *et al.* (2021), *Gracilaria changii* growth is greatly impacted by excessive salinity. The measurement range for the pH water value of *Eucheuma cottonii* seaweed farming is 6.4–6.5 (Rahman *et al.*, 2019). Bui *et al.* (2018) reported that a pH range of 6–9 is ideal for growing seaweed. Nurdin *et al.* (2020) stated that 3–7 mg/L of DO is the optimal range for seaweed cultivation. The water's temperature fluctuates between 28 and 31°C. The production of *E. cottonii* is very good at temperatures between 27 and 30°C (Aslan, 1991). Water that is too warm is thought to cause seaweed to become unhealthily pale in colour (Sulu *et al.*, 2004). In the meantime, the typical current velocity at seaweed cultivation sites is 1.5–10 cm/s. Current velocities of about 10 cm/s are adequate to support seaweed cultivation potential in nutrient-rich areas (Mustafa *et al.*, 2017).

The natural abundance of seaweed has been documented in Bangladesh's south-eastern region, and natural seaweed growth on St. Martin's Island (SMI) is massive (Bhattacharjee and Islam, 2014; Islam *et al.*, 2020, 2021). Within the coastal areas of Bangladesh, there are 138 seaweed species, 18 of which are commercially important (BFRI, 2019). Experiential seaweed cultivation is practical research aimed at developing a sustainable and profitable seaweed-growing method. The present study aimed to identify ideal locations for the cultivation of commercially important seaweed species. It also aimed to develop a sustainable and profitable culture technology for seaweed cultivation.

MATERIALS AND METHODS

Study area

The present experimental seaweed culture was conducted in Rezu Khal along Cox's Bazar coast (*Figure 1*). This culture area is very close to the coast, where the salinity remains 23–30 ppt. As a result, saline water enters the Khal. Near the cultivation site, there are several mangrove trees. Resort, in the east, dumps waste into the Khal every day. Hatchery in the west regularly discharges eutrophicated or chemically mixed water into the Khal. At the culture site, the soil is largely sandy, but the Khal bank is mostly muddy. As a result, the sedimentation rate is significant, and the water transparency is low. During both high and low tides, water movement is strong.

Selected seaweed species for culture

Three seaweed species were selected for culture: *Gracilaria lemaneiformis*, *Hypnea musciformes*, and *Sargassum oligocystum* (*Figure 2, A-C*). *G. lemaneiformis* and *H. musciformes* are red seaweed and have huge economic value. *S. oligocystum*, which is brown seaweed. These species are extremely valuable in terms of economics. These species can be used to make agar and carrageenan.

Experimental setup

In November, the infrastructure was built. Planting was completed in December. Bamboo was obtained from local residents. Ropes, knives, and other items were bought from a local market. The bamboo was cut and prepared for seaweed cultivation. The experimental plots were identified using identification leaflets. These identification plates helped identify the plot. A signboard was erected with project information. The experimental setup is detailed below.

Culture methods

Two culture methods (e.g., net and long-line) were applied (*Figure 3 - A, B*). *G. lemaneiformis* seed was planted using both the net and long-line methods. For the net method, 5 experiment plots (5 m × 5 m) were established for culture. For long-line culture, 5 ropes of 20 m long were used (5 × 2 ropes in two plots). *H. musciformes* and *S. oligocystum* were planted using the net method (4 m × 4 m). Two experimental plots were set for each species. Coir rope, jute rope, and bamboo mats were used as culture materials. For the net method, the net was fixed with a bamboo pillar in four corners, and another 4-bamboo pillar was placed in the middle of each side. This extra pillar was used so that the net could withstand strong currents. Another bamboo pillar was used in the middle of the net to create a strong structure. The rope was used to tighten the net with a bamboo pillar. In the long-line method, two bamboo pillars were used in each corner of the rope. Here, an extra bamboo pillar was used in the middle of the rope (*Figure 3 – A, B*).

Monitoring of parameters

Water quality parameters were measured to identify their effects on seaweed growth. Different parameters (temperature, salinity, pH, DO, conductivity) were analysed using a multiparameter (YSI Pro DSS, Made in USA). The sediment temperature and pH were measured with a thermometer and a Soil pH Tester (Takemura Electric Works Ltd., Tokyo, Japan). Nutrients were determined with a colorimeter (Nutrient Auto Analyzer, HACH, DR 900., Colorado, USA).

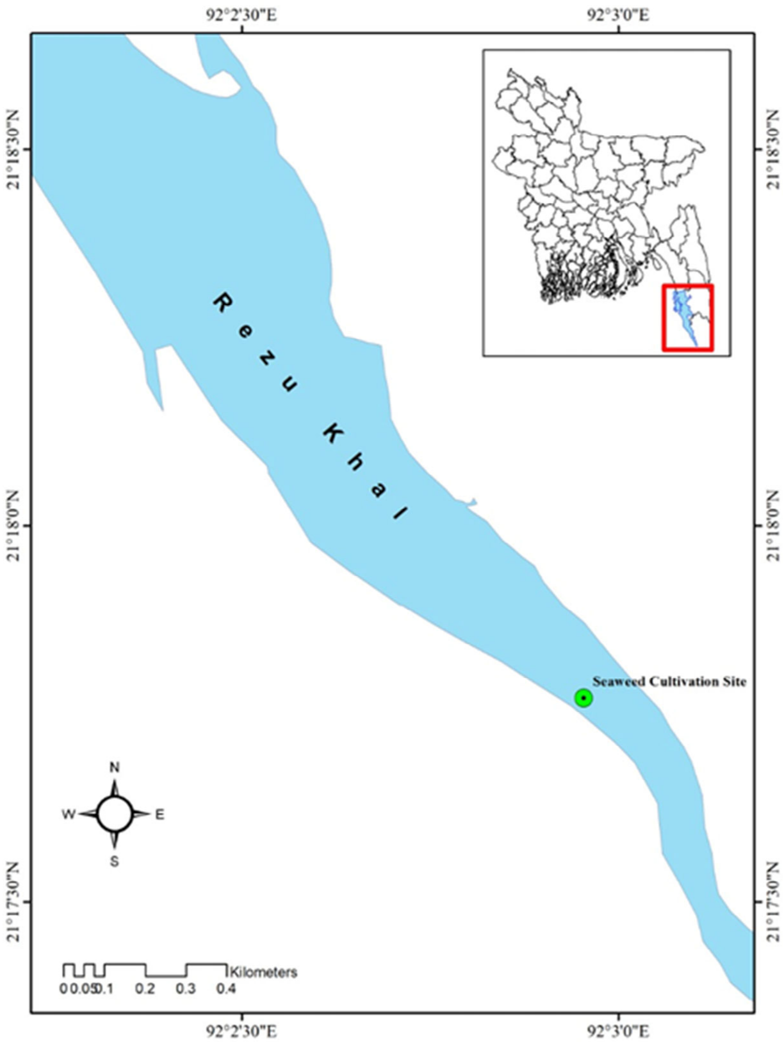

Figure 1 – Rezu Khal along Cox's Bazar coast

Figure 2 – (A) *Gracilaria lemaneiformis,*
(B) *Hypnea musciformes* and (C) *Sargassum oligocystum*

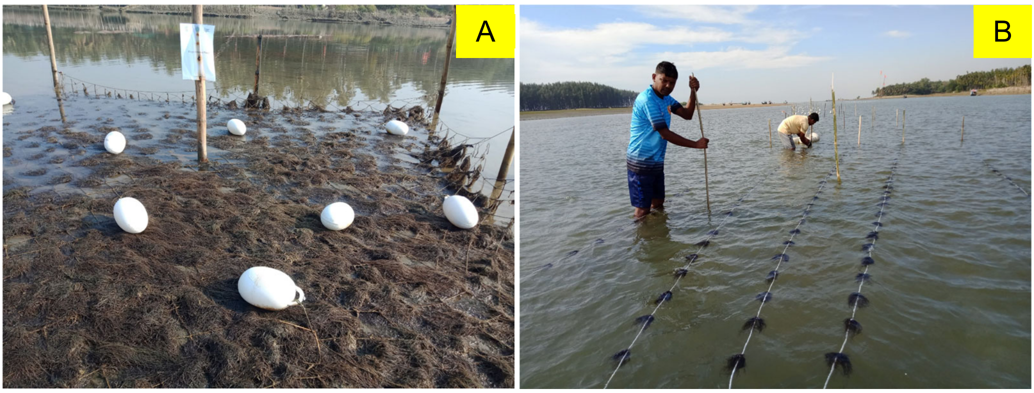

Figure 3 – (A) Net Method and (B) Long-line Method

RESULTS AND DISCUSSION

In addition to being a source of nourishment, feed, and medication, seaweed is also a source of bioactive compounds that have nutritious and biological benefits (Lomartire *et al.*, 2021; Yu-Qing *et al.*, 2016). Seaweed cultivation has become increasingly popular around the world in recent years. For Bangladesh's food, cosmetics, medicines, and fertiliser values in local and worldwide markets, seaweed cultivation has immense promise (Aktar *et al.*, 2020; Shaika *et al.*, 2022).

Growth of seaweed

Hypnea musciformis

In the present study, the production was 11 kg after 15 days of cultivation from 2 plots (each plot 4 × 4 m). This production increased to 13 kg in the next 15 days. The maximum production (22 kg) was recorded on the 45th day of cultivation. The seaweed was harvested every 15 days (*Table 1*). The high seaweed production found in this study could be due to favourable water factors at the culture site. Islam *et al.* (2021) reported that Cox's Bazar coast is suitable for seaweed cultivation due to favourable environmental conditions. *H. musciformis* is tolerant of a variety of temperatures, salinities, and light levels (Durako and Dawes, 1980). On Cox's Bazar coast, Islam *et al.* (2021) found that the biomass yield of *H. musciformis* was much higher than that of *E. intestinalis* and *P. tetrastromatica*. On

SMI, Islam *et al.* (2017) found that the daily growth rate (DGR) of *Hypnea* sp. (3.21±0.01% day^{-1}) was much higher than that of Inani (0.41±0.06% day^{-1}).

Hoq *et al.* (2016) discovered the highest DGR of 3.21±0.01% day^{-1} on the 60th day at SMI and the lowest DGR of 0.41±0.11% day^{-1} on the 15th day at Inani. SMI produced much more biomass of *Hypnea* sp. (11.05±0.10 kg fresh wt. m^{-2}) than Bakkhali and Inani. Bakkhali and Inani may be appropriate places for seaweed cultivation, adding a new dimension to Bangladesh's mariculture prospects (Hoq *et al.*, 2016).

During a 60-day culture period, Zafar (2007) used two types of culture systems and discovered growth rates of 1.06 and 0.95 cm day^{-1} for *Hypnea* sp. in SMI.

The growth of *H. musciformis* after 25 days of cultivation on long-line ropes in the bay of Krusadai Island, India, obtained a four-fold rise in biomass, which is consistent with the findings of Rao and Subbaramaiah (1986). In SMI, growth rates of 1.06 and 0.95 cm day^{-1} were recorded for *Hypnea* sp. after 60 days of farming using two methods (net and suspended rope, respectively) (Zafar, 2007). From July through January, a suitable season for *H. musciformis* cultivation was reported in the Gulf of Mannar, India, with a peak between August and September (Reddy *et al.*, 2006). The growth rate was 2440 g (fresh weight) m^{-2} for *Padina boergesenii* after 90 days of cultivation on the Mandapam coast (Ganesan *et al.*, 1999).

Table 1 – Growth of *Hypnea musciformes* in net method cultured in Rezu Khal

Net Method (4/4m)							
Time (Day)	**0th**	**15th**	**30th**	**45th**	**60th**	**75th**	**90th**
Experimental plot	**Growth (kg)**						
1	4	5	7	10	12	10	11
2	4	6	6	12	12	11	10

Table 2 – Growth of *Gracilaria lemaneiformis* in net method cultured in Rezu Khal

Net Method (5x5m)							
Time (Day)	**0th**	**15th**	**30th**	**45th**	**60th**	**75th**	**90th**
Experimental plot	**Growth (kg)**						
1	7	18	20	20	20	15	16
2	7	15	20	20	19	16	15
3	7	15	19	20	18	15	15
4	7	16	18	19	16	16	15
5	7	16	19	20	18	15	15

Table 3 – Growth of *Gracilaria lemaneiformis* in long-line method cultured in Rezu Khal

Long-line Method (10m/5 rope)							
Time (Day)	**0th**	**15th**	**30th**	**45th**	**60th**	**75th**	**90th**
Experimental plot	**Growth (kg)**						
1	5	8	10	12	12	7	8
2	5	7	9	12	13	4	5

H. musciformis produced the lowest biomass production in January and the largest biomass yield in August (Ganesan *et al.*, 2006). An enhanced seedling concentration increased the biomass output. The DGR of the 10 g fwm^{-1} initial seedling density was higher (7.6–10.9%) and differed substantially from the DGR of the other seedling densities (Ganesan *et al.*, 2006). Summer and autumn were the peak seasons for *H. musciformis* development along the Moroccan Atlantic coast. The species remained productive virtually all year, with the highest levels (52–77%) in October and the lowest levels (0–2%) in April and June in 1997 and February and April (3–10%) in 1998 (Aziza *et al.*, 2008).

The red alga *H. musciformis* dry weight levels in Florida's Atlantic and Gulf of Mexico coastal sites were lowest in late winter and early spring, increased throughout the summer, and peaked in the fall (Durako and Dawes, 1980). In July and November, *H. musciformis* reached two doublings per day maxima of 0.12 and 0.09, respectively. In July, *H. cornutu* reached the highest specific growth rate (SGR) of 0.19 doublings day^{-1}, the highest recorded (Friedlander and Zelikovitch, 1984).

Gracilaria lemaneiformis

In this study, 15–20 kg of *G. lemaneiformis* were harvested every 15 days using the net and long-line method (*Table 2* and *Table 3*). *Gracilaria tenuistipitata* is an important seaweed species that can adapt to a high range of conditions and is a valuable raw material for making agar (Yarnpakdee *et al.*, 2015). *Gracilaria* can withstand an extensive range of environmental conditions (Abreu *et al.*, 2011; Raikar *et al.*, 2001). An ideal atmosphere can promote the growth rate of algae by improving nutrient uptake (Hoq *et al.*, 2016). Another element that influences the production of seaweed farming is harvesting time. Timely harvesting ensures a high-quality harvest and a high market value. Temperature, salinity, and light influence the growth and spread of *Gracilaria* spp. (Raikar *et al.*, 2001). *Gracilaria* spp. are mainly grown in calm seas, especially in the water of the Gulf of Mannar, India (Reddy *et al.*, 2006). Bokhtiar *et al.* (2022) reported that different physicochemical parameters (e.g., salinity, temperature, transparency, pH, and DO) were suitable for the cultivation of *G. tenuistipitata* on Cox's Bazar coast.

Sargassum oligocystum

Sargassum oligocystum is a dominant species in marine ecology and plays an important ecological role. Compared to kelp, *Sargassum* has essential and non-essential amino acids, essential fatty acids, and minerals (Redmond *et al.*, 2014). *Sargassum* also includes phycocolloids, bioactive chemicals, and polyphenols, all of which can be used in nutraceuticals and medicine (Álvarez-Viñas *et al.*, 2019). Holdfast regeneration of the cut fronds allows for several harvests, allowing a seeded line to be produced for two to four years. The first year's harvest occurs between December and January, whereas the second year's harvest occurs between October and January (Redmond *et al.*, 2014).

In all stages of cultivation, biofouling and predatory organisms can cause problems. Other algae and invertebrates can adhere to *Sargassum* and the culture lines, vying for space and resources (Redmond *et al.*, 2014). *Sargassum* sp. peaks between November and April, when ocean temperatures are at their lowest (22–25°C). A temperature of 24°C is nearly optimal for the development of *Sargassum* embryos in culture tests. The timing of these different life history events is thought to be synchronised for maximal reproduction and resettlement, as well as providing ideal conditions for embryo growth (De Wreede, 1976). In the present study, there was a challenge to survival. It survived, and growth was good. There is huge potential for this species culture commercially.

Effects of physicochemical parameters on seaweed growth

External and internal variables in seaweed cultivation have a significant impact on the growth rate of seaweed (Gultom *et al.*, 2019). Water quality is one of these crucial variables. In seaweed cultivation, optimal water quality factors are critical (Rusdi *et al.*, 2017; Warnadi *et al.*, 2017). DO levels and fluctuations in water temperature have a significant impact on the productivity rate of organic seaweed cultivation. Variations in temperature and DO caused by weather conditions or other natural factors are positively related to the cultivation rate and productivity of *E. cottonii* (Rahman *et al.*, 2019). This is quite similar to the present study.

Temperature is crucial for seaweed growth (Eggert, 2012). In the present study, a temperature between 20 and 26°C was best for seaweed production. For this reason, seaweed production was high in the winter season (*Table 1*). The temperature of the water at the surface is influenced by precipitation, evaporation, moisture, air temperature, wind speed, and sunlight (Monteith, 1981). As a result, seasonal variations in surface temperatures are common (Morain, 1999). The water temperature for seaweed farming is between 27 and 30°C, with daily temperature fluctuations no more than 4°C. Temperature has both direct and indirect effects on photosynthesis in water (Sulistiawati *et al.*, 2020). Temperature has a direct effect on photosynthesis because it regulates enzyme processes. The maximal rate of photosynthetic activity can rise with temperature, whereas changing the hydrological structure of the water column has an indirect effect on the distribution of phytoplankton (Carey *et al.*, 2012).

Although the effect varies from species to species, temperature acts as a potential environmental variable that affects seaweed production. The colour of seaweed is said to turn pale and harmful when the water temperature is too high (Burdames and Ngangi, 2014). In Nuniachara, Cox's Bazar Sadar, Bokhtiar *et al.* (2022) recorded a temperature of 22°C. Uddin (2019) measured temperatures ranging from 24.0 to 31.5°C at the Salimpur coast algae farming site. Temperatures of 28-31°C were reported by Rahman et al. (2019) at an Indonesian *E. cottonii* cultivation site. At seaweed culture sites in Sulawesi Province, Indonesia, Sulistiawati *et al.* (2020) found an average temperature of 30.5°C. Islam *et al.* (2017) recorded temperatures from 23.8 to 25.6°C at SMI, 21.7 to 24.1°C at

Bakkhali, and 22.1 to 25.5°C at Inani. Because of the ideal temperature range, *Hypnea* sp. grew well at SMI (Islam *et al.*, 2017). At SMI, Bakkhali, and Inani, Hoq *et al.* (2016) measured temperatures of 23–25, 25–28, and 23–25°C, respectively. Guist *et al.* (1982) discovered that maintaining the water temperature at 18–24°C boosted the biomass of *H. musciformis* by 20%. Ding *et al.* (2013) discovered that *Hypnea* grows rapidly at temperatures between 15 and 25°C (*Table 4*).

Temperatures varied between 20.9 and 26.2°C, which is ideal for culturing seaweed species *G. arcuata* and *G. taxtorii* from Japan, which grow best at 20°C. Different seaweed (*G. venniculophylla*, *G. incwvata*, *G. foliifera*, *G. corticate*) from Japan and India had optimum growth rates at 25°C, while *G. edulis* and *G. lichenoides* (from India and Malaysia) had optimal growth at 30°C. *Gracilaria venniculophylla* can tolerate high temperatures (up to 35°C), although the growth was highest when the temperature was between 18–24°C with continuous water flow and additional N and P (Guist *et al.*, 1982; Raikar *et al.*, 2001).

The salinity of the water varied according to depth; it was more variable at the surface than at the bottom. Because the waters of the research area are combined with freshwater from rivers during the measurement process, the recorded values reveal fairly different results. It plays a crucial role in the survival of aquatic organisms. The salinity levels vary spatiotemporally due to evaporation, sea ice freezing, precipitation, and freshwater inflow from upstream (Tomascik, 1997). Salinity plays a significant role in seaweed growth, and it has been reported that too high and too low salinity affect production. Fluctuations in salinity are caused by a variety of variables, one of which is season (Bricheno *et al.*, 2021).

Salinity is an important determinant of osmotic balance; it is a prudent and potential factor for seaweed cultivation. According to Burdames and Ngangi (2014), the optimal salinity for *E. cottonii* growth is between 28 and 33 g/L. In field trials, seaweed grows best at hypohaline salinities (Van Ginneken, 2018). In Nuniachara, Cox's Bazar Sadar, Bokhtiar *et al.* (2022) found an average value of 32‰. In the seaweed-growing area on the coast of Salimpur, Uddin (2019) found a salinity between 6 and 21‰. Rahman *et al.* (2019) found a salinity of 30–36‰ at an Indonesian *E. cottonii* production site. The salinity of seaweed culture sites in Sulawesi Province, Indonesia, ranged from 29.22 to 32.33‰ (Sulistiawati *et al.*, 2020). At SMI, Bakkhali, and Inani, salinities ranged from 31.1 to 32.5, 27.1 to 29.9, and 29.5 to 30.5‰, respectively (Islam *et al.*, 2017). At SMI, Bakkhali and Inani, Hoq *et al.* (2016) recorded salinities of 31–32, 27–29, and 29–30‰, respectively. Zafar (2007) recorded less *Hypnea* sp. production at <24‰ and high production at >30‰ at SMI. The summer biomass yield of *H. musciformis* was reduced by the high salinity of water on the Florida coast (Durako and Dawes, 1980). In the current study, salinity in the Rezu Khal ranged from 24 to 26.2‰, and algal growth was good at this salinity. Therefore, this study showed that a critical variable for the best biomass yield in Rezu Khal was constant and moderate salinity. All *Gracilaria* spp. have different growth rates depending on salinity, although most of them reach their maximum growth rates at a standard salinity of 35‰ (Raikar *et al.*, 2001).

Osmotic balance (determined by salinity) stimulates nutrient accumulation from water, although the range of optimal salinity varies depending on the species. Phosphate (PO_4) is an important nutrient for aquatic plants and has a significant impact on primary productivity. Variations in the PO_4 concentration are generally triggered by changes in measurement time and sampling site. Furthermore, PO_4 concentration variations can be caused by an increase in organic material in the form of domestic trash (detergents), agricultural waste, or the breakdown of phosphorous rock by water movement. Effendi (2003) reported that most PO_4 comes from organic material from the land, e.g., industrial or household waste (detergents). The total PO_4 values measured show that the waters of the sampling area with total PO_4 values of 0.051–0.1 mg/L are still suitable and optimal for seaweed production (Rugebregt *et al.*, 2020).

Coastal waters with a nitrate (NO_3) value of 0.008 mg/L are ideal for aquaculture (Sulistiawati *et al.*, 2020). Excess amounts of NO_3 can result from liquid waste from agriculture and plantation activities, as well as inputs from soil and adjacent activities (Indriani and Suminarsih, 2003). The presence of biotic communities that allow NO_3 to enter water bodies leads to changes in average NO_3 concentrations. NO_3 is required more than PO_4 for the optimal growth of phytoplankton in water. Electrical storms, N-fixing organisms, and bacteria that consume ammonium (NH_4) are all potential sources of NO_3. The decomposition of plant or animal waste causes an increase in the NH_4 concentration (Effendi, 2003). PO_4 and NO_3 levels were 0.10–0.21 and 0.22–0.44 mg/L at SMI, 0.22–0.33 and 0.74–1.1 mg/L at Bakkhali, and 0.19–0.26 and 0.25–0.64 mg/L at Inani, respectively, according to Islam *et al.* (2017). In this investigation, 2.6–7.6 mg/L PO_4-P, 0.04–0.12 mg/L NO^3-N, and 0.002–0.04 mg/L NO_2-N were found at the Rezu Khal seaweed culture site (*Table 5*).

In Nuniachara, Cox's Bazar Sadar, Bokhtiar *et al.* (2022) found an average of 0.632 mg/L NO_3-N and 0.443 mg/L NO_2-N. In an algae growth site on the Salimpur coast, Uddin (2019) found 0.56 to 0.69 mg/L NO_3-N, 0.18 to 0.47 mg/L NO_2-N, and 0.90 to 1.10 mg/L PO_4-P. In the surface water of a *Kappaphycus alvarezii* and *Spinosum* sp. cultivation site in Sulawesi Province, Indonesia, Sulistiawati *et al.* (2020) found 0.008 to 0.09 mg/L PO_4. In the surface water of a seaweed culture site in Sulawesi Province, Indonesia, NO_3 levels range from 0.005 to 0.06 mg/L (Sulistiawati *et al.*, 2020). Hoq *et al.* (2016) found 0.73, 0.67, and 0.51 mg/L NO_3-N, while NO_2-N were detected ND, 0.45 and 0.23 mg/L at SMI, Bakkhali, and Inani, respectively.

DO is required for aquatic organisms for both metabolic and respiration processes. For all living creatures, DO is a limiting element. DO is a basic requirement for the survival of aquatic organisms.

Table 4 – Water quality criteria for seaweed cultivation (Source: Zafar, 2005, 2007)

Parameters	Unsuitable	Suitable	Strongly suitable
Depth (m)	<2 or >15	1-2	2-15
Wave (cm)	0.10->0.40	0.10-<0.20	0.20-0.30
Water Transparency (cm)	<30	30-100	>100
Salinity (ppt)	<4 or >37	24-37	28-34
Water Temperature (°C)	<20 or >30	20-24	24-2 S
pH	<6.5 or>8.5	6.5-<7.5	7.5-8.5
DO (mg/l)	<4 or >7	6.1-7	4-6
Alkalinity (ppm)	<45 or >130	80-120	100-130

The difference in DO content is caused by the movement and mixing of water. DO is a natural condition in open water; hence, water conditions that are weak or low in DO are uncommon (Kannel *et al.*, 2007). DO levels ranged from 5.5 to 6.2 mg/L at SMI, 4.1 to 4.9 mg/L at Bakkhali, and 5.0 to 6.1 mg/L at Inani (Islam *et al.*, 2017). DO levels in the Rezu Khal seaweed culture site varied from 92 to 105% in this study (*Table 5*).

In Nuniachara, Cox's Bazar Sadar, Bokhtiar *et al.* (2022) found an average of 7.2 mg/L. In an algae growth site on the Salimpur coast, Uddin (2019) found 3.8 to 5.8 mg/L DO. In an Indonesian *E. cottonii*-growing site, Rahman *et al.* (2019) found 5–6.5 mg/L DO. In the surface water of a *K. alvarezii* and *Spinosum* sp. culture site in Sulawesi Province, Indonesia, the DO ranges from 5.50 to 7.41 mg/L (Sulistiawati *et al.*, 2020). At SMI, Bakkhali, and Inani, Hoq *et al.* (2016) found values of 6.9–7.2, 5.8–6.8, and 6.1–7.2 mg/L, respectively. The concentration of DO in SMI was much greater than in Bakkhali and Inani. This is another reason for the increased *Hypnea* production at SMI.

One of the most important criteria in assessing water stability is acidity or pH. Since each biota has different pH thresholds, changes in water pH affect the longevity of the biota. The input of waste from upstream into the aquatic ecosystem leads to an upsurge in pH from the river mouth to the open ocean.
The pH of marine and coastal waters is usually constant and has a narrow range, mostly between 7 and 8 (Akib *et al.*, 2015). Buffer capacity, i.e., the presence of carbonate and bicarbonate salts, influences pH (Kautsari and Ahdiansyah, 2015). In Nuniachara, Cox's Bazar Sadar, Bokhtiar *et al.* (2022) found an average pH of 8.0. In an algal growth site on the coast of Salimpur, Uddin (2019) reported a pH of 7.2–8.4. In an Indonesian *E. cottonii*-growing site, Rahman *et al.* (2019) found a pH of 6.4–6.5. The surface water pH at a seaweed-growing site in Sulawesi Province, Indonesia, ranged from 7.71 to 8.10 (Sulistiawati *et al.*, 2020). At SMI, Bakkhali, and Inani, Hoq *et al.* (2016) found a pH of 8.0–8.5, 7.4–7.5, and 7.6–8, respectively. The lower salinity could explain the significantly lower pH in Bakkhali. A concentration of 3–8 mg/L DO is required to support the seaweed cultivation industry (Tuwo *et al.*, 2020).

Table 5 – Physico-chemical parameter in the seaweed culture site on 0 -90 Days

Parameters	Day 0		Day 15		Day 30		Day 45		Day 60		Day 75		Day 90	
	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide	High tide	Low tide
Temperature (˚C)	26	26	23	21	24	22	21	21	21	21	23	24	26	24
Salinity (‰)	25	26	24	24	25	25	25	24	26	25	24	23	23	24
pH	7.95	8.0	7.5	7.6	7.7	7.8	7.6	7.5	8.25	7.9	8.1	7.8	7.9	7.5
DO (%)	92	94	95	93	98	100	95	96	99	105	100	101	98	101
Conductivity (µS/cm)	41188	33344	64267	49352	62345	48453	45299	39116	39245	33256	38225	34254	37555	34234
FNU	11.1	15.7	13.2	16.1	14.2	15.1	24.03	32.12	39.8	41.08	36.8	42.1	40.1	42.8
Phosphate-Phosphorus (PO_4-P) (mg/l)	7.6	5.68	2.58	5.12	3.60	5.20	6.56	4.25	7.28	5.68	7.1	5.2	7.5	5.4
Nitrate-nitrogen (NO_3-N) (mg/l)	0.05	0.04	0.09	0.07	0.08	0.06	0.12	0.09	0.06	0.04	0.05	0.03	0.04	0.03
Nitrite-nitrogen (NO_2-N) (mg/l)	0.012	0.005	0.041	0.003	0.03	0.002	0.03	0.02	0.02	0.01	0.01	0.02	0.03	0.01
Silicate (SiO_3) (mg/l)	0.33	1.40	0.26	0.15	0.16	0.15	0.83	0.27	0.29	0.24	0.25	0.21	0.25	0.23
Ammonia (NH_3) (mg/l)	0.26	0.25 (150 ml)	0.22	0.13	0.13	0.14	0.19	0.16	0.28	0.26	0.23	0.22	0.26	0.24

Soil quality parameters

Seaweed cultures alone tend to lower the pH of the system, whereas animal waste is acidic. A good pH balance can be achieved with care (Colt and Huguenin, 2002). The ideal pH range for seaweed cultivation is between 7.0 and 8.5 (Rosyida *et al.*, 2021). The depositional soils on SMI have pH values ranging from 5.23-6.23 (Salam, 2020). Uddin (2019) measured soil pH at a *Catenella nipae* growing site on the Salimpur coast and found it to be 5.9–6.7. Grant (1981) recorded the inter-tidal soil pH of North Inlet, South Carolina, USA, which ranged from 7.6 to 8.1. In the bottom silt taken from the lower Meghna River estuary, Islam (2016) found pH values ranging from 6.35 to 6.85. The availability of phosphorus is affected by soil pH and organic matter degradation rates. The soil pH at the culture site in this study ranged from 4.8 to 6.4 (*Table 6*). The maximum pH (6.4) was observed after 45 days of culture, whereas the lowest pH was recorded after 30 days. At the seaweed culture site, soil temperatures ranged from 21 to 26°C. The maximum temperature was recorded early in the culture period, and the minimum temperature was discovered after 15 days of seaweed culture (*Table 6*).

Multivariate analysis

Variation in water quality parameters

One-way analysis of variance (ANOVA) results (SPSS Analysis) indicates that, during the study period, temporal variation of different parameters such as temperature, salinity, pH, DO, conductivity, FNU, PO_4-P, NO_3-N, NO_2-N, SiO_3, and NH_3 was normal. There was no significant variation in these parameters in terms of month or tide. For example, temperature ($F = 2.173$ and $p = 0.270$), salinity ($F = 0.065$ and $p = 0.975$), and NO_3-N ($F = 0.431$ and $p = 0.812$) had no prevalent effect on seaweed growth since the culture was carried out in winter.

Correlation matrix (CM)

Correlation is a method of determining a possible two-way linear relationship between two continuous variables (Altman, 1990). The strength of the relationship can fall between −1 and +1 and the stronger the correlation, the closer the correlation coefficient comes to ±1 (Mukaka, 2012). Directly related variables give a coefficient with a positive number, while inversely related variables give a coefficient with a negative number (Hinkle *et al.*, 2003). In this study, the Spearman correlation was executed to determine the relationship between seaweed spp. and water parameters. There were some correlations between the water parameters and seaweed (*Table 7*). *G. lemaneiformis* had a positive correlation with salinity ($r = 0.154$), DO ($r = 0.579$), NO_3-N ($r = 0.569$), and NO_2-N ($r = 0.504$). *H. musciformes* also had a positive relationship with these parameters (*Table 7*).

Canonical correspondence analysis (CCA)

The Redundancy Analysis (RDA) triplot was used to describe the preferred abiotic environmental factors for seaweed and indicated the influence of the parameters (*Figure 4*).

Table 6 – pH and temperature of soil collected from culture site

Time	pH	Temperature (°C)
0 days	6.2	26
15 days	5.4	21
30 days	4.8	23
45 days	6.4	22
60 days	6.1	22
75 days	5.7	24
90 days	5.9	23

Table 7 – Correlation (Spearman correlation) among different parameters that have effects on seaweed growth

Correlations													
	Temperature	Salinity	pH	DO	Conductivity	FNU	PO_4-P	NO_3-N	NO_2-N	SiO_3	NH_3	*Gracilaria lemaneiformis*	*Hypnea musciformes*
Temperature	1												
Salinity	-.554	1											
pH	-.006	.265	1										
DO	-.290	-.113	.473	1									
Conductivity	-.078	.034	-.760*	-.197	1								
FNU	-.225	-.177	.664	.748	-.713	1							
PO_4-P	.122	.058	.727	.079	-.983**	.604	1						
NO_3-N	-.626	.302	-.727	-.293	.545	-.427	-.504	1					
NO_2-N	-.131	-.258	-.790*	-.120	.703	-.274	-.725	.569	1				
SiO_3	-.490	.227	-.318	-.376	-.188	-.034	.242	.696	.104	1			
NH_3	.121	-.057	.638	-.036	-.702	.504	.648	-.598	-.396	-.093	1		
Gracilaria lemaneiformis	-.704	.154	-.233	.579	.304	.298	-.356	.569	.504	.242	-.500	1	
Hypnea musciformes	-.797*	.651	-.054	.199	.126	.169	-.100	.611	.328	.468	-.215	.765*	1

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

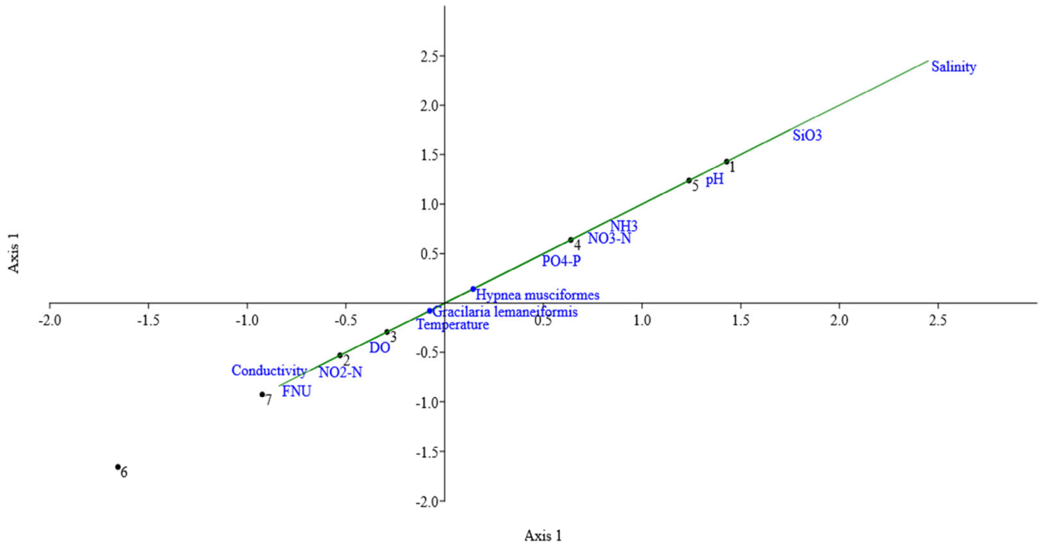

Figure 4 – (A) The redundancy analysis triplot displaying the ecological Relationship between physico-chemical parameters and seaweed growth

Based on the CCA, salinity and pH had a good impact on seaweed growth. Different nutrients (e.g., NO_2-N, PO_4-P, SiO_3) had a good role in seaweed growth.

Hence, a detailed study on the interrelations among the seaweed species and environmental factors was performed, and the triplot in the RDA was supportive by both visualising all the data points plotted in the coordinate system and identifying the interrelationships among species and environmental factors.

CONCLUSIONS

In the present study, Rezu Khal was identified as a suitable site for seaweed cultivation. The growth of *G. lemaneiformis* and *H. musciformes* was massive. *S. oligocystum* survived and grew well but was not found in sufficient numbers. If coastal people become involved in the seaweed culture in Rezu Khal, they can make money. Seaweed cultivation has great potential to contribute to the national economy. It can be a great source of income for coastal dwellers. It can be an alternative source of income for fishermen during a period when fishing is prohibited. Women can play a crucial role in the cultivation and processing of seaweed. Seaweed can change the economic structure of coastal dwellers by improving their livelihoods. The national economy can be transformed by meeting local demand and exports. A few challenges to having a good growth rate were found. A few problems were minimised, and the rest could also be minimised. To fulfil the dream of the Bule economy, seaweed can be an important component.

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