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Floating raft culture of Gracilaria verrucosa for optimum yield performance on the coast of Cox's Bazar, Bangladesh

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Abstract

The present study was meant to describe the very first description of *Gracilaria verrucosa* culture using a floating raft culture method on the coast of Cox's Bazar, Bangladesh. The effects of different factors such as rope materials, culture type, raft shape, seeding intensity, harvesting phase, and water depth on the biomass production of seaweed were evaluated during a 90-day culture period. Different water quality variables such as temperature, pH, DO, salinity, TDS, transparency, alkalinity, ammonia, nitrite, nitrate, and silica were measured at every 15-day interval throughout the culture period. The seasonal appearance of epiphytic algae and cost-benefit analysis of seaweed culture was also performed. We found the range of biomass production (3.03–13.37 kg/m^2) and DGR (3.08–4.72% d^{-1}) to be satisfactory in the floating raft culture method. A total of eight epiphytic algal species were recorded, which resulted in major challenges for the growth of *Gracilaria*. The cost-benefit analysis showed about a $1051 profit for a six-month culture period in 20 rafts. Our research concluded that farming *G. verrucosa* in the floating raft method, when certain critical factors are considered, can become a profitable sector for large-scale seaweed production in our coastal area.

Introduction

The macrophytic plant group of seaweed is one of the most important groups in the oceanic environment, having a lack of roots, leaves, stems, blooms, and seeds[1–2]. Seaweed's versatile application has made this category extremely popular in recent years. As a result of its storehouse of many essential macro and micronutrients, this faunal group has become quite popular as a food item in nations such as Korea, Japan, and China. Additionally, this marine fauna is a source of diverse bioactive compounds such as saponin, terpenoid, phenol, flavonoid, and prominent natural antioxidant compounds[3–4]. Bangladesh's 710-kilometer coastlines as well as the Indian Ocean's Bay of Bengal are home to an extensive source of seaweed. Around 193 algal species have been discovered along Bangladesh's shoreline, including 51 Green (Chlorophyta), 54 Brown (Phaeophyta), and 88 Red (Rhodophyta) algae[5]. Among them, gracilariales are commonly employed for agar production, with around 100 different species of *Gracilaria* being used around the world. This red seaweed's agar and agarose are noted for their high quality, containing almost 31% of agar, and are used in food, medicine, and biotechnology applications[6]. This plant is regarded as a viable candidate for culturing in many parts of the earth because of its geographical range and prompt growth rates[7].

Seaweed has been cultivated for centuries in Japan, China, Korea, and other Asian countries. In the United States, seaweed farming has been practiced since the late 19th century. *Gracilaria* was not also being cultivated even in the late 90s. However, this scenario has been changed by the growing demand for agar[8]. In the case of Bangladesh, seaweed farms are springing up gradually as a result of increased demand for raw seaweed and its derivatives, as well as the necessity for fisher communities to seek alternative or additional incomes. Consequently, wild raw materials are not always adequate to sustain a successful entity in the face of rising seaweed demand. Therefore, it is important for seaweed producers to be able to cultivate seaweed to keep up with rising requirements. Growing seaweed will also reduce pressure on natural stocks and help to have a continuous supply of seaweed all year round. Furthermore, unlike other types of mariculture, like shellfish or fish farming, seaweed cultivation requires less investment and may even be expanded in conjunction with such cultures, enhancing profitability without the need for new complex infrastructure[9]. To execute culture on a commercial scale, it is required to create a simple and easy cultivation system with a suitable cost-benefit ratio, as well as an understanding of the physicochemical parameters of water, production, and yield of economically important species.

The world aquaculture production of *Gracilaria* spp. has increased dramatically, up from 0.055 MT in 2000 to 3.455 MT in 2018[10] though culturing seaweed is still in its early stages in Bangladesh. There have been a limited number of experiments on seaweed cultivation in Bangladesh, with all of them focusing on optimizing different factors and the adoption of the different culture methods depending on ecological characteristics at possible sites[11–13]. All of these experiments were conducted only between the intertidal zones. However, the main drawbacks of these approaches were crop loss owing to crop breaking from the base, especially during bad weather. No studies have been conducted on the possibility of floating raft culture beyond the intertidal zone in Bangladesh. Therefore, the purpose of this study was to optimize the influence of various critical parameters like rope materials, culture type, raft shape, seeding intensity, harvesting phase, and water depth on the biomass yield of seaweed in a floating raft culture method to investigate the possibility of large-scale seaweed production in the Cox's Bazar region. Furthermore, the cost-benefit analysis and presence of epiphytes during the seaweed culture period were also evaluated. The present study will provide new insights into *G. verrucosa* culture in a floating raft method which will not only enhance its production scale but will also help to protect seaweed biodiversity by reducing harvest demand on natural resources.

Results

Water quality variables. The cultivation of seaweed requires appropriate physicochemical conditions. The range values of different water quality variables during the 90 days culture period of Chowfoldondi of Cox's Bazar are described in Table 1. Additionally, correlations among different water quality parameters are analyzed and presented in Fig. 1.

Table 1
Different water quality variables of the culture site during the experimental period.

No.	Parameters	Range	References				
			9	13	14	15	16
01	Temperature (°C)	24.1–32	27–30	21.9–22.1	20–34	30.3–31.1	26–31.9
02	pH	7.1–7.6	7.1–8.3	7.9–8.1	7–8	7.6–8.04	8.1–8.3
03	DO (ppm)	6.11–7.93	-	7.1–7.3	-	5.89–7.45	4.51–7.32
04	Salinity (ppt)	30–36	30–36	31.7–32.3	5–35	32.9–35.0	30–35
05	Alkalinity (mg/L)	125–145	-	-	-	-	-
06	Ammonia (mg/L)	0.27–0.61	-	-	-	< 5	-
07	Nitrite (mg/L)	0.02–0.07	-	0.33–0.55	-	0.01–1.90	-
08	Nitrate (mg/L)	0.14–0.34	-	0.43–0.83	0.0-1.45	< 0.07	-
09	Phosphate (mg/L)	0.07–0.11	-	-	-	< 0.03	-
10	TDS (mg/L)	13.21–18.31	-	-	-	-	-
11	Silica (mg/L)	0.36–0.51	-	-	-	-	-
12	Transparency (cm)	40–50	30.2	73.1–75.9	21	-	-

Effect of rope material. In this regard, we used four different treatments, where T_1 = nylon rope, T_2 = plastic rope, T_3 = coir rope, and T_4 = jute rope. In this study, we observed that the plastic rope yielded higher production than the other three treatments. In the case of nylon rope and plastic rope, we found that plastic rope (13.02 ± 0.08 kg/m^2, 4.66 ± 0.01% d^{-1}) is more yielding than nylon rope (12.60 ± 0.06 kg/m^2, 4.62 ± 0.01% d^{-1}) whereas coir rope and jute rope yielded insignificant in terms of comparison. After all, coir rope and jute rope showed significantly ($p < 0.05$) lower production than nylon and plastic rope (Fig. 2 and Table 2).

Effect of culture type. Here, we performed two treatments, T_1 (long line) and T_2 (square net) to find out their impact on the production of *G. verrucosa.* In the case of $T_{2,}$ we found distinctively higher production and a higher percent of the daily growth rate than T_1. Production and percent of the daily growth rate of

T_1 and T_2 are 12.87 ± 0.87 kg/m^2, 4.64 ± 0.07% d^{-1} and 13.17 ± 0.67 kg/m^2, 4.67 ± 0.06% d^{-1}. The outcome of the two methods is shown in Fig. 2 and Table 2.

Effect of raft shape. In this case, we used two different raft shapes, T_1 (triangular) and T_2 (rectangular), to assess the effect of yield performance on the raft shape of our cultivated species. It was found that a rectangular-shaped raft was more productive than a triangular-shaped raft (Fig. 2 and Table 2).

Effect of seeding intensity. In this experiment, we used seeding intensity as a variable. Three treatments were in this experiment with the seeding intensities of 50, 100, and 150 seeds/m^2. It was found that, T_2 (100 seeds/m^2) shows significantly ($p < 0.05$) higher production (13.06 ± 0.29 kg/m^2) and reasonable percent daily growth rate (4.66 ± 0.02% d^{-1}) than the other two treatments (T_1 = production 13.06 ± 0.29 kg/m^2 and % DGR = 4.72 ± 0.05% d^{-1}; T_2 = production 13.06 ± 0.29 kg/m^2 and % DGR = 4.72 ± 0.05% d^{-1}) (Fig. 2 and Table 2).

Table 2
One-way ANOVA and T- test results testing the effects of different parameters on the biomass production (kg/m^2) and daily growth rate (% day^{-1}) of *G. verrucosa* in floating raft culture method.

Source of variation	d.f.	M.S.	S.S.	F	P value
Rope materials					
Biomass production (kg/m^2)	11	4.18	12.54	35.91	0.00
DGR (% d^{-1})	11	0.108	0.036	30.521	0.00
Culture type					
Biomass production (kg/m^2)	5			0.243	0.648
DGR (% d^{-1})	5			0.269	0.631
Raft shape					
Biomass production (kg/m^2)	5			1.135	0.347
DGR (% d^{-1})	5			1.910	0.239
Seedling intensity					
Biomass production (kg/m^2)	8	6.919	13.838	45.053	0.00
DGR (% d^{-1})	8	0.171	0.085	62.478	0.00
Harvesting phase					
Biomass production (kg/m^2)	11	5.560	16.680	23.564	0.00
DGR (% d^{-1})	11	0.049	0.146	22.953	0.00
Water depth					
Biomass production (kg/m^2)	8	136.436	272.871	807.722	0.00
DGR (% d^{-1})	8	16.76	33.53	1343.94	0.00

Effect of harvesting phase. Four treatments were used (T_1 = 15 days, T_2 = 30 days, T_3 = 45 days, and T_4 = 90 days) to evaluate the production performance of *G. verrucosa* depending on different harvesting phases. The study showed an increase in production and a percent daily growth rate in T_1 and T_2, whereas they declined in T_3 and T_4. The result indicated that the cultured seaweed harvested at a 30-day interval showed higher ($p < 0.05$) production compared to other treatments (Fig. 2 and Table 2).

Effect of water depth. To investigate the effect of depth on the production of seaweed, three treatments (T_1 = water surface, T_2 = 25 cm depth, and T_3 = 50 cm depth) were set at our experimental site. Production in terms of depth in our study greatly varied. The results showed that the growth performance of *G. verrucosa* on the water surface is more highly productive ($p < 0.05$) than at 25 cm and 50 cm depth. Treatment 2 resulted in very lower production during the study period, whereas treatment 3 ended up with no production at all as the seedlings died after a few days of their plantation (Fig. 2 and Table 2).

Seasonal appearance of epiphytic algae. A total of eight algal species were recorded as epiphytes in *G. verrucosa* culture (Table 3). Among them, six species were Chlorophyta, and two species were Rhodophyta. *Ulva intestinalis, Ulva compressa*, and *Ulva reticulate* were found in all three months of the culture period. The dominance of green epiphytic algae was observed throughout the entire culture period. The highest amount of epiphytic algae (eight) was identified in March, while the lowest number (three) was documented in January.

Table 3
Monthly occurrence of epiphytic algae during the culture period.

Epiphytic algae	Months (2022)		
	January	February	March
Ulva intestinalis	+	+	+
Ulva compressa	+	+	+
Ulva reticulata	+	+	+
Cladophora fascicularis	-	+	+
Chetomorpha sp.	-	-	+
Acanthophora spicifera	-	-	+
Polysiphonia sp.	-	-	+
Total	3	4	8

Cost-benefit analysis of seaweed culture. A cost-benefit analysis showed about a \$ 258.00 profit for a three-month culture period in 20 rafts (Table 4). The profit will be about \$ 1051 when the culture continues with the same structure for six months. Four times the profit can be earned for a three-month extension of the culture period as long as the operation materials are the same.

Cost-benefit analysis of seaweed culture for 20 rafts (5m x 5m) in a three-month culture period			
Input materials	**Price in USD***	**Economic return**	**Price in USD***
Bamboo (40 pieces)	137.93	Final fresh weight (kg)	1,300
Plastic drams (100 pieces)	114.94	Final dry weight (kg)	210
Rope (60 kg)	103.45	Price per kg	4.02
Protective net (20 kg)	45.98	Total sale	844.20
Anchor (4 pieces)	137.93	Total profit	258.00
Maintenance cost	45.97		
Total cost	586.20		
Cost-benefit analysis of seaweed culture for 20 rafts (5m x 5m) in a six-month culture period			
Input materials	**Price in USD***	**Economic return**	**Price in USD***
Previous expenditure	586.20	Total sale	1688.40
Extra maintenance cost	51.20	Total profit	1051.00
Total cost	637.40		
*Exchange rate 1 USD = 87.0 Bangladeshi Taka (BDT).			

Table 4. Estimation of the cost-benefit relationship of *G. verrucosa* culture in a floating raft for a six-month culture period.

Discussion

Seaweed is used in a variety of ways, including as a food source, as a fertilizer, and as a source of animal feed. It is also widely used in the production of biofuels, cosmetics, and pharmaceuticals. Given its relevance, the cultivation of seaweed has become a major concern in many countries in the past few years. *G. verrucosa* is common seaweed species that is a valuable raw ingredient for agar manufacturing and can adapt to a broad array of environmental parameters[14]. The research initiatives taken to date on seaweed culture in Bangladesh were limited to the intertidal zones of the Cox's Bazar coast[11,12,13]. As the demand for seaweed increases gradually in the domestic market it needs an extension of seaweed culture beyond the intertidal zone by adopting some new culture method. Additionally, there are always some aspects that influence seaweed production profitably to a significant extent. Considering all these, in our present study we observe the yield performance of *G. verrucosa* in a floating raft method and evaluate the influence of different parameters like rope materials, culture type, raft shape, seeding intensity, harvesting phase, and water depth on the yield performance of seaweed.

In our experiment, different water quality variables showed lower fluctuations throughout the culture period due to the low rainfall and surface runoff. The water temperature fluctuated from 24.1–32°C, which is within the recommended temperature range (30.3–31.3°C) for *G. dura* culture[15]. However, other researchers described the optimum temperature range as 21°C in the case of *G. pacifica*[17]. The value of pH altered between 7.1 and 7.6, which is almost similar to the described optimum growth level for *Gracilaria* culture (Table 1). The dissolved oxygen value varies between 6.11 and 7.93 ppm, which is within the suggested DO range for *Gracilaria* culture by another author[13]. Salinity is a crucial factor for *Gracilaria*'s culture as the growth of *Gracilaria* is largely limited by the adequacy of salinity, despite the presence of other nutrients such as phosphate[14]. During our experiment, the salinity in the culture area was found to be between 30 and 36 ppt (Table 1). This range is between the optimum salinity levels described for the culture of *Gracilaria* [9,13–16]. The levels of nitrate (mg/L) and nitrite (mg/L) were found to be at a satisfactory level throughout the experimental period. According to other scholars, nitrate improved the biological activity of several *Gracilaria* species[18]. The Secchi disc transparency level in the culture site was about 40–50 cm and was mostly above the value (21 cm and 30.2 cm) given by some authors[9,14], but below those ranges (2.12-5 m and 73.1–75.9 cm) described by other authors[8,13]. A low level of transparency in culture sites could be caused by an increase in turbidity as a result of a muddy bottom, wind action, or navigation.

Concerning the effect of rope materials, plastic rope showed the highest yield performance and %DGR followed by nylon, coir, and jute rope. Another scholar also observed maximum biomass yield in *G. dura* culture by polypropylene net method[16] and lower growth rate in *G. edulis* culture by coir rope method[19]. Coir and jute ropes are biodegradable and can't sustain a longer period in saline water. These types of ropes are environmentally friendly and aren't able to sustain more than two months in the culture system. The use of coir and jute rope in the seaweed culture caused extra maintenance costs. But if the raw materials are the farmer's own it will minimize the input materials cost. Apart from specific and geographical differences, it was revealed that cultivating method has a significant impact on red algae yield and daily growth rate[18]. In our present investigation, we found distinctively higher production and a higher percent of daily growth rate in the case of the square net than in the long line method. Our present findings collaborated well with the cultivation of *G. dura* at the Gulf of Mannar[16] and the cultivation of *G. edulis* at Mandapam coast[20] by the square net method. Once the plants are fully developed, the horizontally positioned square net will provide support while also reducing frond damage and ejecting caused by wave action and tidal currents. The expanded surface area also helps to facilitate the formation of new shoots in the case of square net methods. However, because of seedling loss owing to strong water currents and wave action, the long line approach yielded lesser biomass. A similar lower growth rate was also reported in the long line rope method by some other scholar's[21]. In our experiment, we found both production and % DGR was higher in square shape raft than in triangular shape raft. A contradictory finding has been observed earlier in the case of *G. edulis* culture[22]. This is because we didn't perform cluster management to arrange the triangular rafts. As a result, each triangular raft receives individual drag pressures and loss of fragile fronds of seaweed. However, for the cultivation of seaweed square-shaped raft was also applied and found satisfactory yield performance which is correlated to our present findings[18,23].

Seeding intensity is considered a critical factor for the cultivation of seaweed. The appropriate seeding intensity and seeding distance will enable more water movement that will help to distribute nutrients and advance the propagation, which results in an improvement in growth rates[24]. In our present experiment, we found that 100 seeds (500gm) initial seeding per square meter showed the highest yield performance and %DGR compared to others. In our study, the cultivation of *G. verrucosa* with an initial 500gm seaweed seed per square meter was supposed to be appropriate. These results mean all the thalli parts received enough sunlight and got enough space to grow. Limited scientific research findings are available in this regard in the literature. Though, Mantri et al.[22] and Islam et al.[11] used 1 kg fresh weight for seeding in the case of *G. edulis* and *Hypnea* sp. culture which is much higher than our current experiment. These variations might be caused by differences in species, location, or culture type. Another factor that has been shown to influence seaweed farming production is the harvesting phase. Harvesting crops on time provides excellent crop quality and profit margin. In this investigation, we observed that harvesting seaweed 30 days after sowing provided the best production output. Seaweed harvested 15 and 45 days after seeding has lower production efficiency. This might be because of the decaying of the bunch of seaweed ropes after 30 days, resulting in a reduction in seaweed production. Our research correlates with the findings of Bokhtiar et al.[13] in the case of *G. tenuistipitata* and Padhi et al.[25] in the case of *G. verrucosa*. Moreover, the harvesting phase is influenced primarily and foremost by the rate of growth and the period whenever the seaweeds achieve the maximum economic value, such as a high polysaccharide substance or specific flavor qualities[26]. During the 90-days culture period, we found that the seaweed culture at the surface level of the water column had the maximum output and % DGR (12.44 ± 0.48 kg/m^2, 4.65 ± 0.04% d^{-1}), while the depths of 25 cm and 50 cm had very lower output and nil, respectively. At the water surface level, seaweed was highly exposed to sunlight which helped in the photosynthesis process, as well as the comparatively higher water circulation than the other depth carried a higher amount of nutrients assimilated by the seaweed. Additionally, a lower transparency level at the culture site during the experimental period resulted in lower sunlight penetration at 25 cm and 50 cm depth. Though, other scholars such as Mensi et al.[8] cultured *G. gracilis* at 3.75m depth, Yang et al.[27] cultured *G. lemaneiformis* at 0.5–1.5 m depth, and Ben Said et al.[28] cultured *G. gracilis* at 0.5 m depth.

Epiphyte growth has been documented in several other cultivated seaweeds, which are perhaps linked to significant changes in salinity, temperature, and nutrient levels[18,29]. In our experiment, the dominance of *Ulva* species was observed throughout the culture period as they are locally available on many shores. They are also stress-tolerant as well as functionally resilient and have been shown to endure a wide range of temperature and irradiance levels[29]. These fouling algae directly compete with the *Gracilaria* for space in the culture unit. Additionally, the cost-benefit analyses were used to compare the commercial feasibility of these floating raft methods on the coast of Bangladesh. The daily growth rate observed in this floating raft method is about 4.69% d^{-1}. Parallel growth was stated in the case of other cultivated *Gracilaria* spp. such as *G. verrucosa* (8.96% d^{-1})[25], *G. edulis* (7.4% d^{-1})[18], *G. gracilis* (5% d^{-1})[30], and *G. birdiae* (4.4% d^{-}

[1])[9]. It was stated that large-scale commercial cultivation of *Gracilaria* is possible when the growth rate was more than 5% per day[30]. Our findings reveal that seaweed farming can become a promising sector for large-scale seaweed production in our coastal area.

Considering all of these aspects into account, our research indicated that *G. verrucosa* species may be cultivated using the floating raft method in our coastal region, especially on the Chowfoldondi coast of Cox's Bazar. However, for better yield performance, certain important aspects such as seeding intensity, raft shape, rope materials, culture type, harvesting phase, and water depth need to be considered, as we found that these parameters have a significant influence on the yield performance of *G. verrucosa*. Further research could be performed on the biochemical composition, agar content, and gel strength of cultured seaweed at altered locations along the Cox's Bazar coast.

Methods

Study area. An experimental seaweed culture site was designed in the sheltered intertidal zones of Chowfoldondi (21.503248, 91.994117) of Cox's Bazar district (Fig. 3), along the Bay of Bengal's north-eastern coast. The study area is on the Bakkhali River (the second largest river in the district), which has moderate wave action and is directly connected to the Bay of Bengal. This area is considered a biologically diverse ecosystem, having intertidal mudflats with various salt marshes, seagrasses, cord grasses, seaweeds, and also some mangrove vegetation. Additionally, this place is a safe habitat for numerous types of fish, reptiles, oysters, mussels, crabs, snails, shrimp, and so on. The yearly average rainfall and temperature follow at 3770 mm and 25.6°C, respectively, in the Cox's Bazar district. This tropical climatic area's wind speed average is about 8.3 miles per hour. The study was performed for a period of 90 days from January 2022 to March 2022.

Seed collection. Young, wild *G. verrucosa* seed was initially collected from the intertidal zones of the Nuniachara coast (21.474700, 91.964450) of Cox's Bazar Sadar. This sand flat site is a natural bed of seaweed with some other seagrass, salt marsh, and mangrove vegetation. Permission to collect seaweed samples and their culture practices was obtained from the local government in accordance with local and national legislation. The botanical identification of seaweed species was checked and confirmed through the published literature[5,31]. Dr. Md. Enamul Hoq, Former Director of BFRI, validated the botanical identification of seaweed species as the voucher specimen has already been placed at BFRI herbarium [BFRI (MFTS-RS-18/19–038). A fresh sample was collected in an open box with adequate seawater and an aeration facility and then immediately transferred to the cultivation site to keep the fresh quality.

Experimental culture raft setup. Several bamboo poles (7.0–10.0 cm diameter) made into a square (5 m x 5 m) frames were prepared to provide the seaweed culture layout. The four corners of the raft were steadied tightly between and among themselves to keep the raft shape intact. Two more bamboos were fastened tightly at the opposite end to make the structure stronger. Four recycled plastic drams were attached to the structure's four corners, ensuring that it was always floating on the water. A 1.50 cm mesh size plastic net was placed in the lower part of the frame to minimize the wave action, and crop loss caused by plant rupture from the base, especially during adverse weather. All of the rafts were rope-tied, placed in the culture site, and anchored to help stabilize the structure. The anchor of the structure was placed in such a way that it could raise and fall vertically during the tidal action. Each experiment had three replications.

Seaweed seeding. The younger pieces of *G. verrucosa* were used for seeding with an average of 5 ± 0.4 gram of fresh weight in each knot and 5 cm size in the rope twists. No fertilizer, growth hormone, or any other chemicals were used during the culture period. Partial harvesting was done when the seaweed reached an average standard length. The partial harvesting took place by cutting off the algae hanging on the surface, allowing the base on the surface to expand further. Seaweed biomass production was measured as the fresh weight of seaweed per unit culture area (Kg m^{-2}) and was calculated using the given Eq. 3[2].

$Y = (W_n - W_0)/A$ (1)

Here, Y = seaweed biomass production; W_n = raw weight on day n; W_0 = beginning raw weight; A = culture unit's area.

Daily growth rate % was calculated using the formula given Eq. 3[3].

DGR % = $\ln (W_f / W_o) / t \times 100$ (2)

Here, W_f = final raw weight (g) at t day; W_o = initial raw weight (g); t = cultivation period (days).

Water quality variables. The culture site was studied throughout the 90 days culture period from January 2022 to March 2022. Sampling was carried out twice a month. Multiple water quality parameters such as temperature, pH, dissolved oxygen (DO), salinity, TDS (total dissolved solids), transparency, alkalinity, ammonia, nitrite, nitrate, phosphate, and silica were measured. Temperature, pH, dissolved oxygen, salinity, and TDS were all measured on the spot using HANNA HI-98194 multiparameter. Measurement of water transparency was performed with a Secchi disc. Water samples from 0-100cm depth were collected (Van Dorn water sampler) and immediately transported to the laboratory. Alkalinity, ammonia, nitrite, nitrate, phosphate, and silica in water were analyzed following the methods of HANNA (Hanna COD and Multiparameter Bench Photometer, 230V - HI83099 procedure manual).

Effect of rope material. This experiment was carried out to find out the rope material's effect on the yield performance of *G. verrucosa*. In this study, four types of rope materials (T_1 = nylon rope, T_2 = plastic rope, T_3 = coir rope: acquired from coconut husk, and T_4 = jute rope) were used. Among them, coir and jute ropes are biodegradable, while the other two are non-biodegradable. Best yield performances along with the rope materials' sustainability in saline water were observed.

Effect of culture type. In this study, different culture types, such as long line and square net methods, were used to observe the yield performance of *G. verrucosa*. Here, T_1 stands for the long line method and T_2

stands for the square net method.

Effect of raft shape. In this experiment, different shaped rafts were prepared and observed for their effect on the yield performance of *G. verrucosa*. Here, T_1 (square shape) and T_2 (triangular shape) rafts were prepared and observed for their yield performance.

Effect of seeding intensity. This experiment was conducted to observe the effect of seeding intensity on the biomass production of *G. verrucosa*. Here, T_1, T_2, and T_3 indicate 50, 100, and 150 seeds per square meter, respectively. This results in 250gm, 500gm, and 750gm initial seaweed seeds per square meter for cultivation. During harvesting, fresh seaweed samples were collected separately and washed carefully with running fresh water to remove dirt or any other impurities. The fresh sample was then weighted with the help of a digital balance.

Effect of harvesting phase. In this study, after initial seeding, harvesting was performed at four different intervals (T_1 = 15 days, T_2 = 30 days, T_3 = 45 days, and T_4 = 90 days). Here, in the case of T_1 a total of six partial harvests, in the case of T_2 a total of three partial harvests, in the case of T_3 a total of two partial harvests, and in the case of T_4 zero partial harvests were performed throughout the 90 days of the culture period. The best harvesting intervals were evaluated through the maximum yield performance of *G. verrucosa*.

Effect of water depth. In this study, several vertical culture units were placed at different water levels in the open sea. T_1 represents the first unit that was placed at the water's surface, T_2 represents the second unit that was placed below the first one at a 25cm depth from the water's surface, and T_3 represents the third unit that was placed below the second one at a 50cm depth from the water's surface. The possibility of vertical expansion of seaweed culture was evaluated through the maximum yield performance of *G. verrucosa* at each depth.

Seasonal appearance of epiphytic algae. Epiphytic algal occurrences on *G. verrucosa* and the associated culture materials were documented during the three-month (January–March 2022) cultivation period. Seaweed samples were collected, washed with clean water, and preserved in silica gel in a sample vial. Finally, seaweed samples were confirmed through microscopic examination and cross-checked against the published literature[5,31].

Cost-benefit analysis of seaweed culture. The cost-benefit analyses of *G. verrucosa* culture for 20 rafts (5m x 5m) in a six-month culture period were analyzed. The economic turnover of *G. verrucosa* culture through biomass production can be estimated. All operation and maintenance costs were considered here as input materials. Based on the local market, all prices of input materials were included and expressed in USD.

Statistical analysis. The experimental data was analyzed using standard statistical techniques. Statistical package SPSS version 20.0 (IBM Co., Chicago, IL) was used to examine the data. One way

ANOVA and T-test were used to determine the significance of each parameter among different treatments. Level of significance was set at 95% probability level.

Declarations

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Author contributions statement

M.K.A.S. and M.G.M. implemented conceptualization, designed and drafted the original manuscript. M.K.A.S., M.G.M., Z.I., T.R., and S.S.S. performed field investigation, data collection, and data compilation. Z.I. and A.F.R. carried out the formal analysis. S.J.H. and S.R. performed supervision, editing, and revising of the manuscript. All authors read and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

All data generated or analyzed during this study are included in this published article.

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Figures

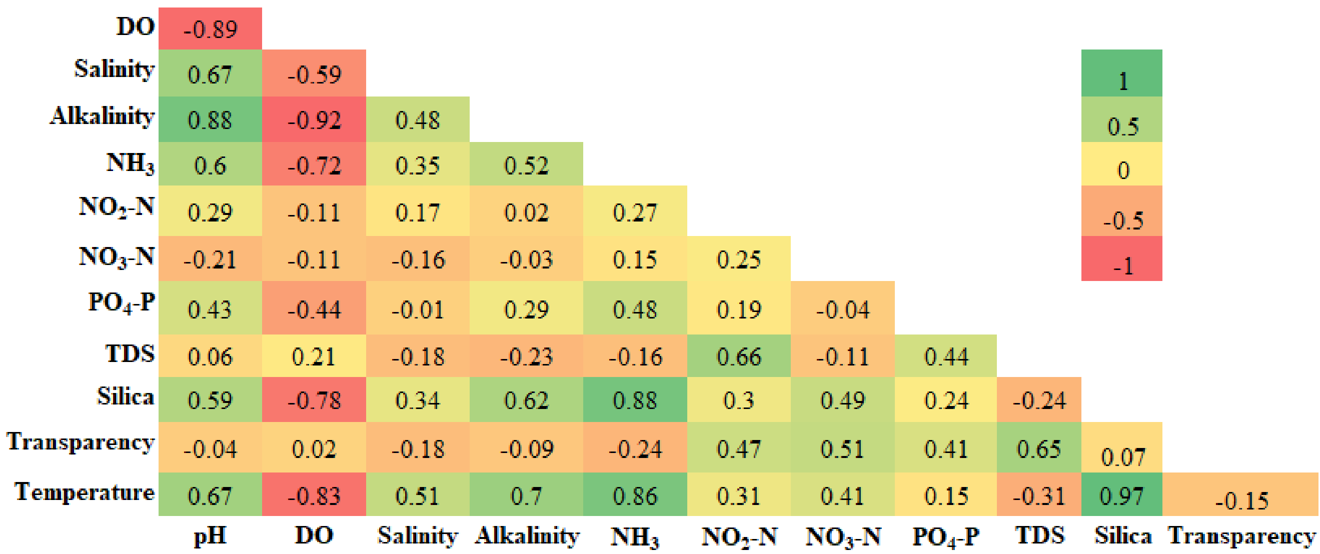

Figure 1

Correlation among the water quality parameters.

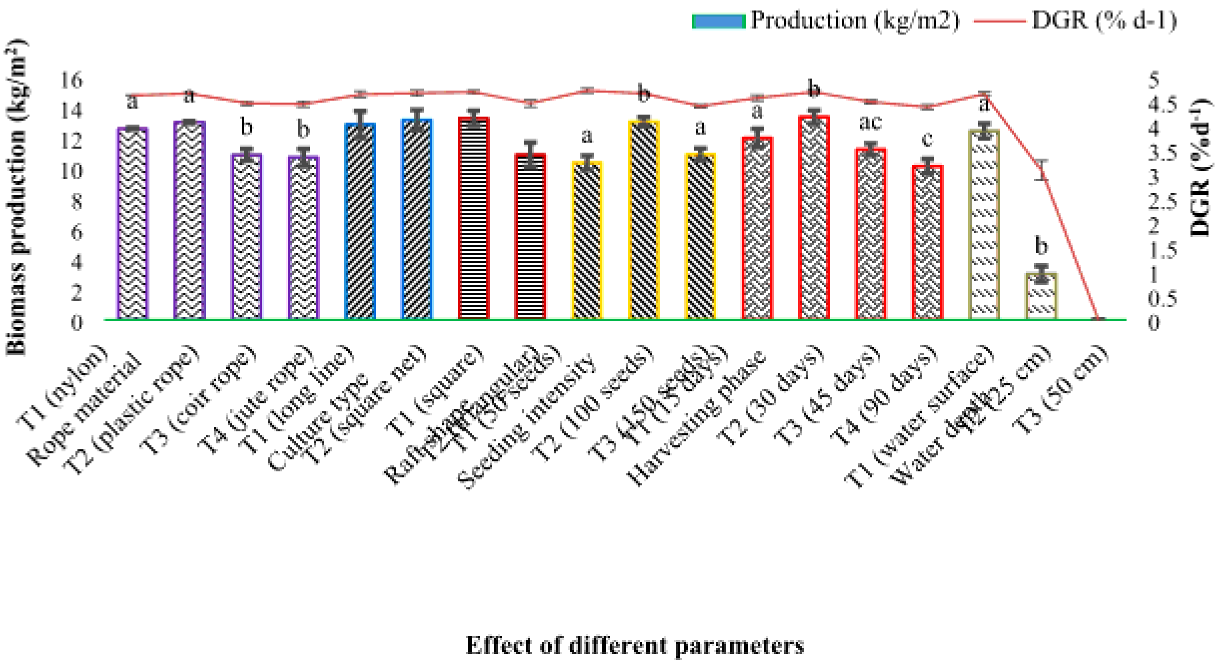

Figure 2

Effect of different parameters on the biomass production (kg/m^2) and DGR (%d^{-1}) of *G. verrucosa* in the floating raft method.

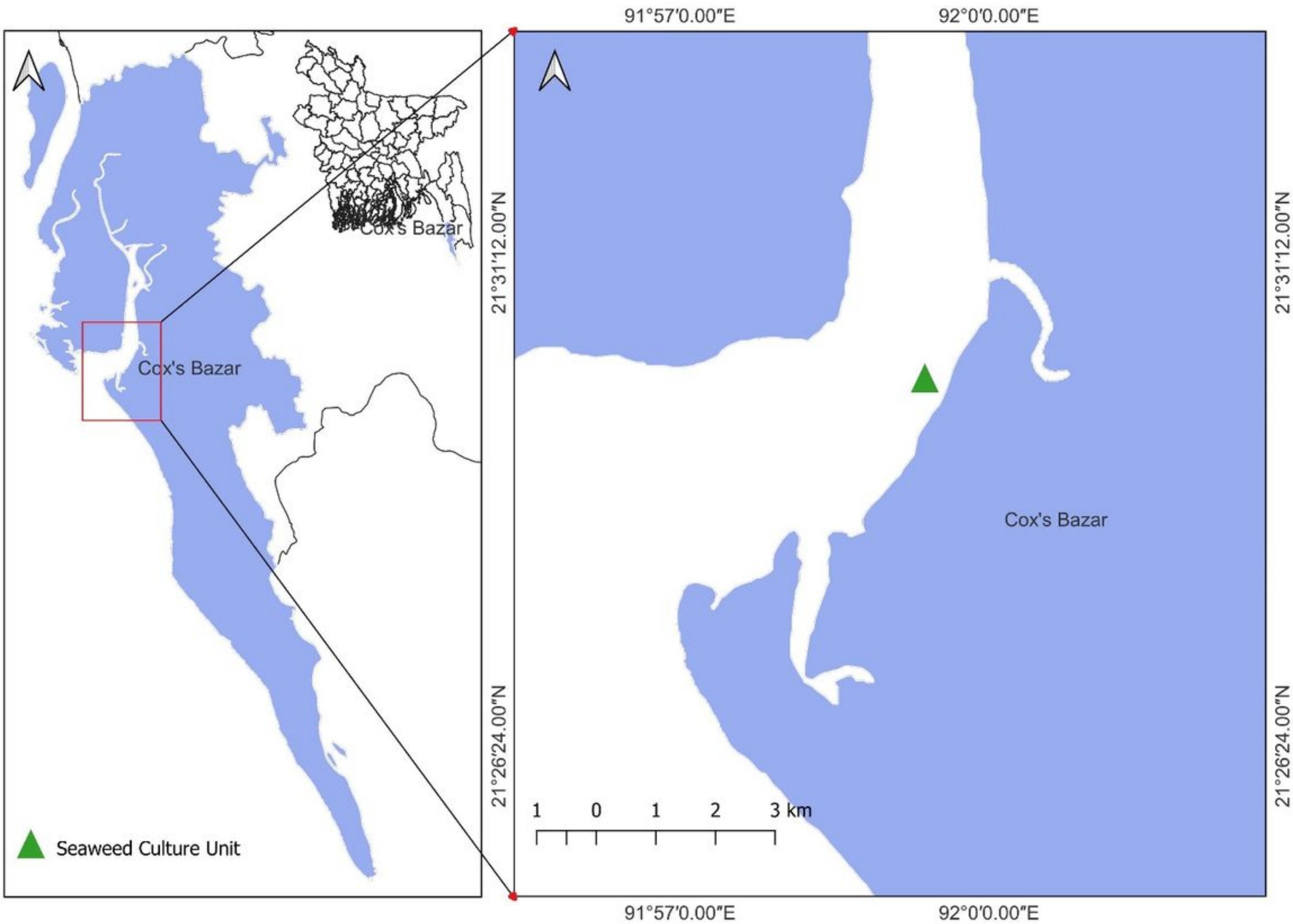

Figure 3

Location of the *G. verrucosa* culture area at Chowfoldondi, Cox's Bazar