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The potential of three culture techniques to mitigate environmental challenges and enhance yields of Eucheumoids (Rhodophyta; Gigartinales) in deep water on the Kenyan Coast

Alex G. Kimathi[1,*], Joseph G. Wakibia[2], Moses K. Gichua[2], David Mirera[1]

[1]Kenya Marine and Fisheries Research Institute, P.O. Box 81651, Mombasa, Kenya

[2]Jomo Kenyatta University of Agriculture and Technology, P.O. Box 62000-00200, Nairobi, Kenya

*Corresponding author: kimathi_alex@yahoo.com, (+254) 0 721 400063

Abstract

Relocation of seaweed farms from shallow to deeper waters has been recommended to remedy seasonal infestation of seaweeds by ice-ice disease and epiphytes. However, data supporting the best culture technique for farmers' adoption is scarce. In the present study, the production potentials of one shallow, fixed off-bottom (FB) and two deep water techniques; modified off-bottom (MB) and floating raft (FR) techniques were evaluated by comparing the yields of *Eucheuma denticulatum* and *Kappaphycus alvarezii* while monitoring the environmental factors. Each of the cultivation techniques was set at a low tide water depth of 1 m. Experiments were established at Mkwiro and Kibuyuni in the South Coast and data were collected fortnightly for nine months. The net yield (dw ha^{-1} yr^{-1}) was significantly higher at Mkwiro (32.4 t) than at Kibuyuni with 22.8 t ($p <$ 0.05). The net yield (dw ha^{-1} yr^{-1}) of 30.2 t in the FR was significantly higher than 20.4 t and 10.9 t in MB and FB respectively ($p \leq$ 0.05). The net yield (t dw ha^{-1} year^{-1}) of *E. denticulatum* (30 t) was significantly higher than 12 t for *K. alvarezii* (p < 0.05). Although the FR was the best in mitigating environmental challenges of seaweeds, the three techniques can be adopted to improve seaweed production in deep water.

Keywords: South Coast, cultivation technique, ice-ice disease, net yield, *Eucheuma denticulatum*, *Kappaphycus alvarezii*,

Introduction

There are three basic types of seaweed; red (rhodophytes), brown (bryophytes) and green (chlorophytes). These versatile marine plants have diverse economic importance. While the brown and green seaweeds are used directly as food (Paull and Chen, 2009), red seaweeds are sources of anti-oxidants/microbial agents (Gupta and Abu-Ghannam, 2011) and phycocolloids - agar, carrageenan and alginate are used as industrial binding agents (McHugh, 2003). The red seaweeds; *Eucheuma denticulatum* Collins and Hervey, and *Kappaphycus alvarezii* (Doty) Doty ex Silva are the main sources of kappa and iota carrageenans respectively that have gained a high demand in food, cosmetic and pharmaceutical industries (Wakibia *et al.*, 2006; Anis *et al.*, 2017). To meet the global demand for carrageenans, *K. alvarezii and E. denticulatum* (carragenophytes) are commercially cultivated in countries with tropical coastlines, with Asian countries such as Indonesia leading in production (FAO, 2018). Aquatic cultivation of carragenophytes in Indonesia enhanced the increase in seaweed output from less than 4 million tonnes in 2010 to over 11 million tonnes in 2016 (FAO, 2018). Away from giant seaweed producers in Asia, cultivation of carragenophytes has spread to the Western Indian Ocean (WIO) countries of Mozambique, Madagascar, Tanzania and Kenya in the recent past (Wakibia *et al*., 2011; Msuya *et al*., 2014; Msuya and Hurtado, 2017). In 2020, annual productions of carrageenophytes in Tanzania and Madagascar were 102,960 and 53,370 tonnes (fw), respectively. However, in Kenya, the production of eucheumoids is still low, standing at approximately 1,000 tonnes (fw) in 2020 (Msuya *et al.,* 2022).

Seaweed cultivation in Kenya shares similar challenges experienced in other WIO countries. Reported challenges include poor gate price of harvested seaweeds that demotivates farmers' over-reliance on the same strain (*E. denticulatum* and *K. alvarezii*) that is exposed to inbreeding and the perennial use of one culture technique i.e., off-bottom (Hurtado *et al*., 2015). Moreover, the location of farms is limited to shallow beds within the sub-littoral zone where water depth hardly exceeds 0.5 m at low tide because the majority of the farmers are women with inadequate swimming capabilities to expand their farms to deeper areas (Kimathi *et al.,* 2018). This farming behaviour has resulted in some farms being located in areas without water at low tide thus exposing seaweed cuttings directly to hot air and water temperatures above 33°C (Msuya *et al.,* 2014). For instance, in 2008, a water temperature range of 36-38°C recorded in January and February in Zanzibar and Songo Songo was reported to increase die-offs of *K. alvarezii* due to severe ice-ice disease attacks (Msuya, 2010). The ice-ice disease has been described as an unhealthy condition of seaweeds manifested by the degeneration of seaweed thalli by rotting and turning to a pale white colour similar to ice (Wakibia *et al*., 2006). However, it has been shown from various studies that the conducive season of seaweed is during the cold season (June-September) and also during short rains (October-November) when temperatures are 25-30°C, while low growths are recorded during the hot season (December -February) when temperatures are above 30°C (Msuya, 2010). Through prudent use of this information, farmers have maximized their production and inspired their colleagues thus increasing in number at Kibuyuni, Mkwiro, Gazi, Funzi and Nyumba Sita villages in the South Coast of Kenya. Just like in Tanzanian seaweed farming, women farmers on the southern coast of Kenya are today well recognized in the community setups because of their economic contributions to the households (Msuya and Hurtado, 2017; Mirera *et al*., 2020).

Relocation of seaweed farms from shallow sites to deep sites where the water quality is relatively stable for their growth has been recommended as a remedy to curb ice-ice disease (Msuya *et al*., 2014). Lack of adequate data on the best culture technique for seaweeds in deep water sites could compound the challenges of seaweed farmers in Kenya. With a focus on encouraging farmers to relocate their seaweed farms from shallow to deep sites to curb the ice-ice disease and epiphyte challenges, a study to compare the net yield of seaweeds *E. denticulatum* and *K. alvarezii* using different culture techniques in deep water was therefore critical. In the present study, we discuss the results of an experiment in which three culture techniques, fixed off-bottom (FB), modified off-bottom (MB) and floating raft (FR) were deployed at sites with low tide water of 1 m deep and monitored concurrently by measuring the net yield of seaweeds and environmental variables for nine months (September 2015 to May 2016) at Kibuyuni and Mkwiro. The study was key in providing information to inform decision-making and formulation of appropriate policies to increase seaweed production and consequently protect a livelihood that ensures food security for the marginalized coastal communities in the WIO region.

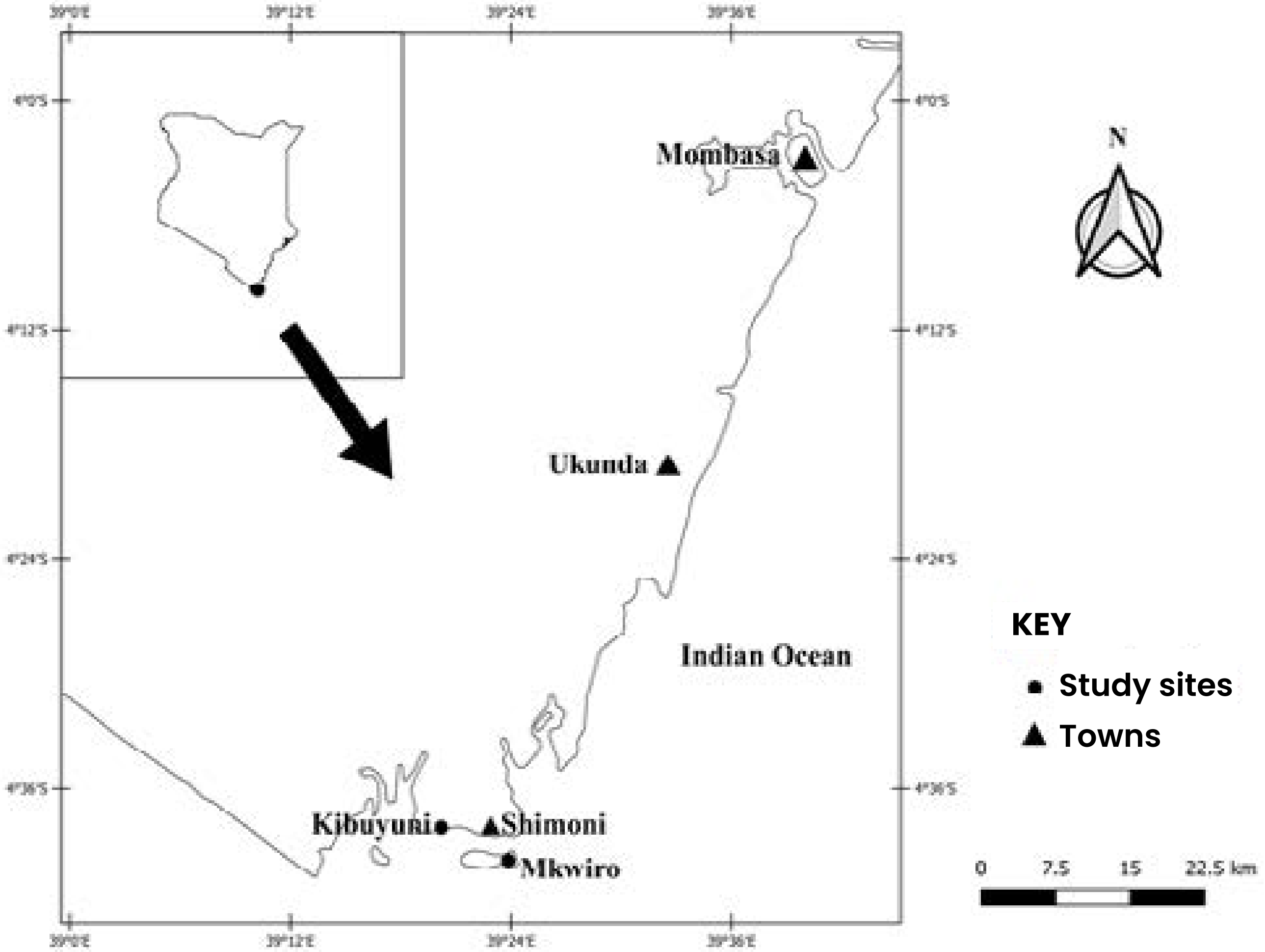

Figure 1. Map of the Kenya coast showing the location of the two study sites at Kibuyuni and Mkwiro (Source: Authors)**.**

Materials and methods

Study sites

The sites of study are shown in figure I below. The study was conducted at the villages in Shimoni; Kibuyuni (4° 38′ 17.77″ S, 39° 20′ 26.11″ E) and Mkwiro (4° 39′ 53.31″ S, 39° 24′ 5.27″ E). Kibuyuni is located about two km South of Shimoni town while Mkwiro is situated at the southern Mkwiro-Wasini Island.

The two farming sites are about 5 km apart and have intertidal zones that share similar characteristics. Both sites have a narrow (20 m) belt of mangrove species on the shore and an exposed rocky flat of about 100 m wide running parallel to the shore. A high diversity of thermal-tolerant seaweed species such as *Gracilaria spp* are common. Between the rocky flat and the sub-tidal zones of each site is a wide and shallow (0.2 m - 1.5 m deep) seagrass bed comprising species including *Thalassodendron ciliatum* (Forskal) Hartog 1970, *Thalassia hemphrichii* (Ehrenberg) Ascherson 1871, *Syringodium spp, Cymodocea spp, Hophila spp.*, among others. All the seaweed farms at both sites are located within this area. Although a depth of 1.0 m could be accessed by farmers at low tide, their farms hardly exceeded 0.5 m water depth at low tide. From the seagrass beds of each site is a narrow coral biotope running parallel to the beach, with water depths ranging from 0.5 m - 2 m at low tide. The availability of commercial farms at these sites assured ideal sources of seaweeds for stocking the anticipated experiments. In addition, the availability of local farmers (both male and female) with prior knowledge of the basic seaweed farming protocols, would enhance the capacity of the individuals to be hired in providing the necessary support to the project with minimum supervision. The farming communities provided free space and protection for experimental setups during the study period. To implement the experimental design, the field activities were coordinated by the researcher. Rotational criteria designed by the seaweed group leaders provided 2 men and 3 women during each sampling period to participate in the activities of setting up field experiments, especially the preparation of the ropes and seed stocking. This strategy ensured that the maximum number of different farmers benefited from the training and also developed confidence working in deep water (1 m) at low tide.

Seaweed and planting materials

Two rhodophytes; *E. denticulatum* and *K. alvarezii* used in the present study were similar to those imported from Zanzibar for culture trials in Kenya in 2001 (Wakibia *et al.*, 2006). The species were distinguished by the branching pattern of the thalli, with *E. denticulatum* having spinose branchlets while *K. alvarezii* has smooth thalli. The first stock of fresh, young and clean seedlings of *E. denticulatum* and *K. alvarezii* were bought from farmers at Kibuyuni and Mkwiro to set the first month's experiment. All the other monthly experiments were stocked with seaweeds harvested from the previous month's experiments. The farming materials which included polypropylene ropes, tie-ties, bamboo, mangrove poles, tape measures, *pangas* (machetes), knives, metallic rings, spring balance, Plaster of Paris (POP) and tennis balls were purchased locally. The refractometer and thermometers were provided by the laboratory at KMFRI.

Experimental design

An experimental design that ensured that the seaweed growth for that particular month of the year was measured during the spring tides was emphasized in the present study. A completely randomized design (CRD) was adopted, in which five replicates of seaweed-stocked ropes for each species were randomly planted in three different culture techniques namely; fixed off-bottom (FB) method, modified off-bottom (MB) method and floating raft (FR) method during spring tide at water depths of 1 m. Each of the cultivation techniques was located at a distance of 50 m away from the other. The sampling unit was the seaweed-stocked rope with 25 cuttings and an initial known stocking density. After 30 days of growth, each of the seaweed-stocked ropes was harvested and weighed. The farm layouts of all the cultivation techniques were modifications of techniques described by Msuya and Hurtado (2017). However, the MB technique was adopted from Kimathi *et al.* (2018). The water temperature, salinity, diffusion factor, ice-ice disease symptoms, herbivory, epiphytes and plant loss were monitored every month. This farming procedure was replicated at Mkwiro and Kibuyuni for nine months.

Cultivation techniques

Fixed off-bottom (FB) technique

In figure 2, the FB technique during planting (D1) and during harvesting (D30) after 30 days is presented. In the FB technique, two opposite rows of six mangrove posts (0.76 m height), were fastened to the sea bottom perpendicular to the beach. The distance between the rows was 5 m (rope length) and 0.5 m between posts in each row. The polypropylene ropes used to culture seaweeds were 8 mm thick. Twenty-five thin and short raffia strings (tie-ties) were fixed at intervals of 0.2 m along the length of a 5.0 m polypropylene rope. Twenty-five seaweed cuttings of each species were then attached to different ropes using tie-ties. Each seaweed cutting was 50 - 80 g and five replicates ropes were stocked for each species and each technique. Similar initial weight of each stocked rope was maintained and recorded before being taken to the water for growth in the respective cultivation technique. For the FB system, the stocked ropes of both species were randomly tied to opposite ends of short mangrove posts by suspending

Figure 2. The fixed off-bottom technique during planting (D1) and during harvesting (D30) after 30 days (Source: Usi Mohammed).

them in water at a depth of 0.3 m above the substrate. The stocked ropes were then left for about 30 days to grow.

The structural setup of the FR during planting (D1) and harvesting (D30) after 30 days is shown in figure 3. The FR technique consisted of a floating 4 m x 5 m bamboo device anchored to the bottom of a 5 m deep lagoon by a polypropylene rope (0.01 m diameter). The anchoring device was a 100 kg rectangular block constructed of cement, concrete and sand in different proportions. The same set of stocked polypropylene ropes (as those in FB) for both species were each weighed and stretched along the length of the bamboo raft. The distance between stocked ropes was approximately 18 - 20 cm with each raft having a total of 10 stocked ropes. The experiment was repeated after 30 days (monthly).

Modified off-bottom (MB) technique

The structural setup of the MB technique presented in figure 4 employed the principles of both the fixed off-bottom and floating raft methods but differed in the structural design (Fig. 4). Unlike in the FB where the ropes were suspended in water using short (0.76 m) wooden posts, in the MB

Figure 3. The floating raft technique (FR) during planting (D1) and during harvesting (D30) after 30 days (Source: Alex Kimathi).

technique, longer mangrove poles (5.0 m), equivalent to the highest tidal depth at the site were used and a floating mechanism that ensured the cultivated seaweeds ascended and descended with the tidal direction along the height of the supporting poles was designed. One-end sharpened long poles were slowly dipped in the water and vertically pressed deep into the soft sediments for stability. A circular metallic ring prepared locally was then inserted on the long pole from the top and settled on the bottom to rest on a small wooden material fixed by nails on the long pole at 0.30 m from the bottom. Another wooden material was fixed on the other end (top) of the long pole to prevent the ring from being pushed out of the pole at high tide. At the end of the exercise, two opposite rows, each with ten poles were constructed and the distance between rows was 5 m. The initial weight of each polypropylene rope stocked with seaweed cuttings (as those in the FB and FR techniques) was taken and later tied to the circular metallic rings on the pole for growth. Three - 5 L empty plastic bottles were tightly cocked and tied to the middle of each seaweed-stocked rope at equal intervals using thin nylon ropes. The empty plastic bottles provided buoyancy to the stocked rope so that it could rise and fall with tidal direction. The seaweeds were then cultured for 30 days. Figure 4 shows the structural setup of the MB technique during planting and harvesting of the seaweeds.

Young, healthy thalli were selected from every harvest of each cultivation technique and served as new transplants for the next month's stocking. This procedure was repeated for all techniques at the two sites and experiments were conducted for nine months from September 2015 to May 2016 to obtain growth data for yield and productivity analysis.

After a culture period of 30 days, the final weight of each rope in each culture system was averaged to the number of cuttings present. The net yield of the seaweeds for each rope was then calculated as the difference between the final weight and initial weight per unit area under cultivation according to the formula described by Wakibia *et al.* (2011).

$$\text{Net yield (kg wet wt m}^{-2}\text{ 30 d}^{-1}\text{)} = \frac{W_f - W}{A}$$

Where W_f is the weight of harvesting after 30 days (kg); W_i is the initial weight (kg) and is the area under cultivation (m²)

Biotic factors

After every fortnight, the number of missing cuttings and those with signs of ice-ice disease, epiphytes and grazing were recorded from each stocked rope. During analysis, the number of missing cuttings in each rope was computed as a percentage of the original number of cuttings on the planting day while those with ice-ice disease, epiphytes and those grazed upon were computed as a percentage of the total number of cuttings present during the sampling day.

Specific grazers were identified by swimming gently over the seaweed lines at mid-tide. During the monitoring, the *in situ* grazing behaviour of the prevailing fish species was mastered to aid future identifications. For example, the fish-bitten thalli were differentiated from those with urchin bites by exhibiting the 'nipping' nature as described by Ateweberhan *et al.* (2015).

Abiotic factors

During the sampling period, daily salinity and water and air temperatures were recorded at midday. The seawater salinity was measured fortnightly using a refractometer (Atago, Japan) while the temperatures were measured using a clinical mercury thermometer. The monthly temperature ranges were recorded usinga maximum/minimum thermometer fixed on the bottom of a selected wooden peg. Water motion was measured fortnightly by monitoring the rate of dissolution of spherical Plaster of Paris (POP) balls according to a modified clod card method (Wakibia *et al.*, 2006). To prepare the balls, a mixture of water and POP (1:1) was poured into tennis ball moulds of 5 cm diameter. A stick (15 cm long, 0.5 cm diameter) was

Figure 4. The modified off-bottom (MB) technique during planting (D1) and during harvesting (D30) after 30 days (Source: Abdalla Darusi).

then inserted into the wet POP mixture of each ball. After two days of hardening in air, the tennis ball moulds were removed using a sharp blade and the rough surfaces smoothed with sandpaper. The initial weight of each smoothened ball was measured using an electronic top-loading balance (Satorius model). The diffusion index factor (DIF) was measured by the deployment of 3 sets of POP balls at each of the three experimental setups in the two sites. A thin string (usually a tie-tie) was used to attach the hanging POP ball to the polypropylene ropes stocked with seaweed cuttings. The POP balls were left in the water column and retrieved after 24 hrs. Upon retrieval, the POP balls were rinsed with fresh water, dried in the oven at 40°C and weighed to a constant weight. The final weight was compared with the average final weight of five control POP balls left for 24 hours in a 20-litre motionless bucket of seawater of equal salinity placed in the laboratory. Seawater samples for determination of nitrate and phosphate levels were collected 20 cm below the surface seawater at each site fortnightly using five 125 mL high-density polyethylene bottles. The samples were fixed immediately using mercuric chloride, labelled and stored in a cooler box at 40°C before being transported to the KMFRI laboratory for analysis. The samples were analyzed using the modified automated method of Parsons *et al*. (1984) as applied in the Technicon Auto Analyzer II system.

Data analysis

All data were analyzed using MS Excel and SPSS software (version 26.0). ANOVA was conducted to test the individual main factor effect on net yields and the interaction effects of subjects and net yields. To confirm the suitability of the ANOVA test, the homogeneity of variance was tested by conducting Levene's test (Levene, 1960). A post hoc pairwise comparison test using Turkey HSD was conducted to determine significant differences between the means of the three culture techniques. Two sample t-test was used to determine significant differences in net yield between sites and species. The Pearson product-moment correlation coefficient test was conducted to establish the relationships between net yield and environmental factors.

Results and discussion

Growth conditions

The diffusion factor varied significantly over the eight months at the two sites ($p < 0.05$), with the highest (4.4 ± 0.5) being recorded in March and the lowest (2.8 ± 0.3) in January. The diffusion factor was highest in the FR technique (4.2 ± 0.2) followed by MB (3.9 ± 0.2) and lowest in FB (2.8 ± 0.1). These diffusion factors were significantly different ($p < 0.05$), However, the diffusion factors of 3.63 ± 0.1 and 3.51 ± 0.2 obtained at Mkwiro and Kibuyuni, respectively were not significantly different ($p > 0.05$). The salinity levels in the South Coast of Kenya ranged between 35.0 and 35.5 ‰, with a mean of 35.1 ± 0.3 ‰. No significant difference was observed in salinity between culture techniques and between sites ($p > 0.05$).

The air temperature, minimum and maximum water temperatures at Kibuyuni (A) and Mkwiro (B) are displayed in figure 5. The average minimum water temperature ranged between 27°C and 29.9**°**C and a mean of 28.3°C while the average maximum water temperature was 30.4°C ranging from 28.0°C to 32.7°C. Maximum water temperatures were highest in December (32.7°C) and February (32.7°C) and the lowest value was recorded in May (25°C). The minimum water temperature was neither significantly different between sites nor between techniques ($p > 0.05$). However, the maximum water temperatures did not vary significantly between the sites but did between the culture techniques ($p < 0.05$) with the FB technique having the highest, followed by MB and FR having the lowest. During the study period, the mean air temperature at the South Coast of Kenya was 27.7°C with the lowest (25°C) and highest (29.5°C) being obtained in May and January respectively. No significant difference was observed in air temperature between sites and techniques ($p > 0.05$).

The mean nitrates and phosphate concentration (μmoles L^{-1}) were 1.31 ± 0.2 and 0.746 ± 0.1 respectively at Kibuyuni while at Mkwiro, the mean nitrate and phosphate concentrations were 1.2 ± 0.1 and 0.624 ± 0.1 respectively. There were no significant variations in nutrient concentration both between sites and cultivation techniques ($p > 0.05$).

Water motion (diffusion factor) in the South Coast of Kenya has been described earlier, with higher water motion being reported at Gazi than at Mkwiro and Kibuyuni (Wakibia *et al.*, 2006). The water motion was not significantly different between the MB and FR techniques but was indeed higher than in the FB technique ($p < 0.05$). This observation could be attributed to the higher speed of surface tidal currents experienced in FR and MB techniques than at the bottom where the FB technique was positioned. Water motion in the FR technique has been associated with wave action generated by wind (Ask and Azanza, 2002). The highest water temperatures observed in this study coincided with the North East Monsoon (NEM) season while the lowest temperature aligned with South East Monsoon (SEM) season. Our observations are consistent with the findings of Obura *et al.* (2000), who reported the highest sea surface temperatures during NEM, with an average of 28.4°C, a maximum of 29°C and lowest temperatures during

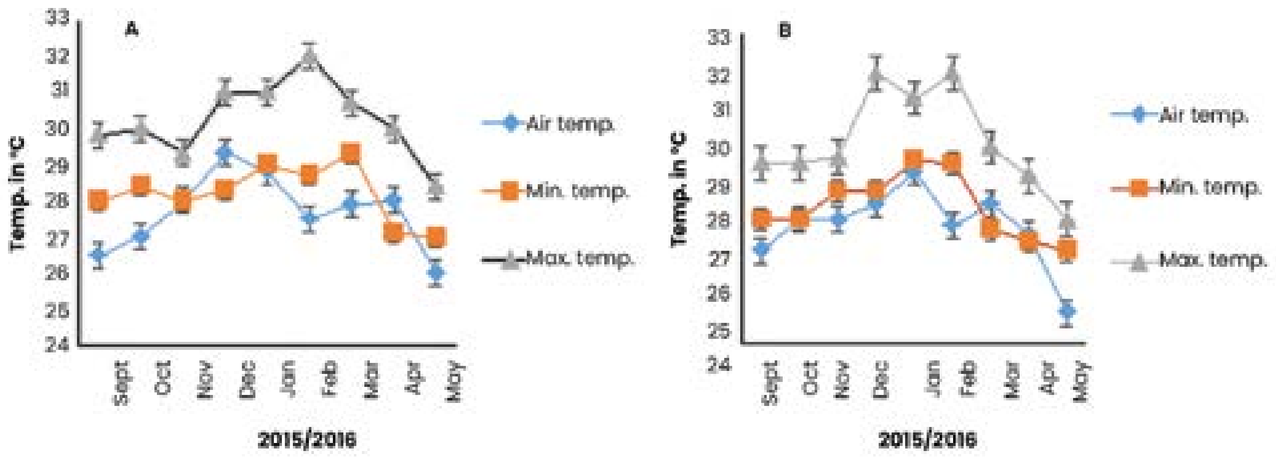

Figure 5. The air, minimum and maximum water temperatures at Kibuyuni (A) and Mkwiro (B) at the South Coast of Kenya.

SEM (24-26°C). The present study observed no significant variation in water nitrate and phosphate concentrations between Kibuyuni and Mkwiro. The incidence of the ice-ice disease of eucheumoids was higher in the FB culture technique than in the MB and FR techniques probably due to the presence of significantly lower water motion and higher minimum and maximum water temperature in the FB than in the MB and FR techniques. Lower water motion may have prolonged stagnation of water in the FB than in the MB and FR techniques leading to the accumulation of water pollutants such as metabolic products which exacerbated the effects of ice-ice disease on seaweeds.

The environment under which seaweeds were cultured in the FR technique appeared to have been also conducive for the growth of epiphytes. The two algae species thus seemed to favourably compete for space and nutrients without significant harm to each other. On the other hand, the epiphytic load in the FB technique may have been proliferating to occupy the space left by the lost seaweeds, thus increasing food diversity and the number of foraging herbivores. Epiphytes have been shown to provide ecological niches, food and protection for animals including grazers (Bittick *et al.*, 2010).

Growth performance

A higher incidence of ice-ice disease, herbivory and plant loss on eucheumoids occurred between December and February, a period when the highest air and water temperatures were also observed. Significant variations of the biotic factors between the three culture techniques were observed with the ice-ice disease, plant loss and herbivory being higher in FB than in the MB and the FR techniques ($p < 0.05$). Epiphytic load (%) was highest in FR and lowest in MB techniques. Further analysis showed that all the biotic factors were significantly higher in *K. alvarezii* than in *E. denticulatum* ($p < 0.05$).

The fish population observed during the nine months of the study was dominated by Siganidae (60%), Scaridae (30%), and Acanthuridae (10%). These fish were encountered more at Kibuyuni than at Mkwiro and were more abundant during high tides than at low tides. The thalli of eucheumatoid cuttings stocked in the FB ropes showed the highest signs of nipping and the lowest in MB technique at both sites. Aggregations of 10-20 individuals of the sea urchin *Tripneustus gratilla* were also observed crawling on the bottom of all the culture techniques. However, there was no clear evidence of seaweed grazing by urchins.

Net yield of seaweeds

The net yields of eucheumoids presented in figure 6 show a general trend of net yields in the FR and MB techniques with high net yields from September to January and a drop in February. This observation contrasts with that of net yields in FB where high net yields were observed from September to November and declined in December and January. The net yields of eucheumoids in FR and FB seemed to recover in March in both sites but a continuous decline was observed thereafter in the MB technique. Positive and negative growth of seaweeds were encountered in all the culture techniques during the cultivation period. The growth variation coincided with changes in the prevailing environmental conditions. For instance, the growth rate was highest during the wet season compared to the hot season. However, during the wet season, there was negative growth of seaweeds in the MB technique because the structure supporting the cultivated seaweeds was destroyed by a strong typhoon.

A statistically significant variation of eucheumoid net yields across the nine months of cultivation was observed in the three culture techniques $F(8, 448) = 60.8, p < 0.001$). The mean net yield of eucheumoids at the South Coast of Kenya was 2.3 kg wet wt m^{-2} 30 d^{-1} with FR showing its highest yield (kg wet wt m^{-2} 30 d^{-1}) in October (4.33) and both MB and FB showing their highest net yields in November (MB = 2.234, FB = 1.14). The lowest net yields (1.98 in December, 0.44 in

February, and 1.13 in January) were observed in FR, MB and FB techniques, respectively.

According to multiple comparison tests, the cultivation techniques had statistically different net yields (kg wet wt m^{-2} 30 d^{-1}) with the FR, MB and FB having 2.6 ± 0.2, 1.7 ± 0.1 and 1.0 ± 0.1, respectively ($p < 0.05$).

The mean net yield at Mkwiro was 2.7 kg wet wt m^{-2} 30 d^{-1} ranging from 0.7 to 7.7 kg wet wt m^{-2} 30 d^{-1}, with the lowest and highest being observed in December and February respectively. On the other hand, Kibuyuni had a net yield mean of 1.9 kg wet wt m^{-2} 30 d^{-1} ranging from 0.4 to 4.3 kg wet wt m^{-2} 30 d^{-1}. T-test analysis showed that the mean net yield (kg wet wt m^{-2} 30 d^{-1}) obtained at Mkwiro was significantly higher than that obtained at Kibuyuni and that the net yield (kg wet wt m^{-2} 30 d^{-1}) of *E. denticulatum* (3.0 ± 0.2) was significantly higher than that of *K. alvarezii* with 1.6 ± 0.1 ($p < 0.001$).

Correlation of eucheumoids net yields and environmental parameters

Table 1 shows the correlations between environmental parameters with the net yields of eucheumoids. Significant correlations of eucheumoids net yield with both biotic and abiotic factors were observed at $p < 0.05$ and $p < 0.01$, respectively. Among the abiotic factors, diffusion factor showed a positive correlation with the net yield of both species while air and maximum water temperature and phosphate concentration were inversely correlated with the net yields of both species ($p < 0.05$). On the other hand, all the biotic factors had negative correlations with the net yields of both eucheumoids (Table 1). However, based on the stepwise multiple regression analysis, there was no single environmental factor that could explain 50% of the variation in the eucheumoid net yield.

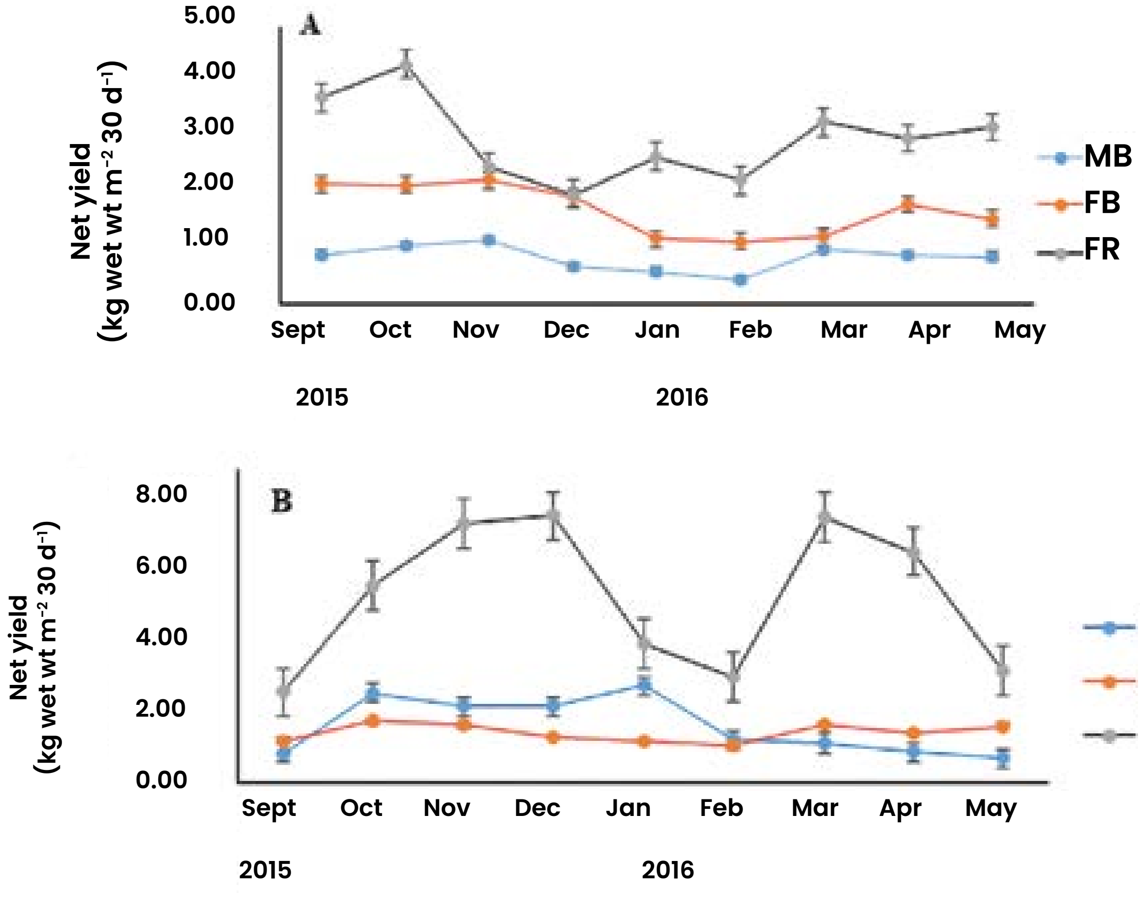

Figure 6. Monthly net yield of eucheumoids at two sites i.e., Kibuyuni (A) and Mkwiro (B) in the southern coast of Kenya, (n = 91 - 97, mean ± SEM).

Net yields

The significant relationships expressed in the correlation analysis in table 1 could suggest that the monthly variations in eucheumoid net yields in the present study were associated with monthly changes in environmental conditions including diffusion factor, water temperature, incidence of ice-ice disease, herbivory and plant loss. The monthly trends in eucheumoid net yields observed in this study, are typical of seasonal variations in eucheumoid growth rates observed in previous studies. Kimathi *et al*. (2018) observed high growth rates of eucheumoids in September and October and the lowest between December and February. Low net yield of seaweeds following the outbreak of ice-ice disease and epiphytes during regimes of abnormal increase in air and surface water temperature has been reported in Malaysia (Vairappan *et al*., 2006) and Tanzania (Msuya *et al*., 2014). In the Philippines, Hurtado and Agbayani (2002) reported that moderate to strong water movement contributed between 70-80% of seaweed productivity in southern Mindanao. In the WIO region, the negative effects of ice-ice disease and epiphytes were responsible for a drop in biomass production of *K. alvarezii* from 1,000 tonnes (dry wt) to only 13 tonnes in Tanzania while the epiphytic algae and ice-ice disease infestations seriously hampered growth of *K. alvarezii* in Kenya (Msuya and Kyewalyanga 2006; Wakibia *et al*., 2006; Msuya *et al*., 2014). In the present study, the highest net yields of eucheumoids were observed between September and January when the water temperature was lower and water motion was moderate, thus reducing the incidences of ice-ice disease, and plant loss. This observation contrasted with the lowest net yield observed in February when the highest water temperature was observed and incidences of ice-ice disease, epiphytes and plant loss were higher. In his study, Vairappan (2006) reported that cultured seaweed in the dry seasons becomes susceptible to epiphytes and that the outbreak of epiphytic filamentous red algae correlates with drastic changes in seawater temperature and salinity.

Destruction of the culture facility (MB technique) by the storm (typhoon) between April and May led to a continuous decline of eucheumoids biomass during the period and consequently impacted the mean net yield of eucheumoids negatively. However, the high biomass accumulated by plants in the MB technique in the previous months ensured that the MB technique had a better overall performance than the FB tech-

Table 1. Correlation coefficients (r) of eucheumoid net yield of two species with environmental factors and seaweed parameters in South Coast Kenya.

	Eucheuma denticulatum		*Kappaphycus alvarezii*	
Variable	r	p-value	r	p-value
Diffusion factor	0.247	0.001**	0.222	0.001**
Air temperature (°C)	-0.213	0.007**	-0.138	0.005**
Maximum temperature (°C)	-0.041	0.503	-0.286	0.001**
Nitrate (µM)	0.097	0.116	0.115	0.063
Phosphate (µM)	-0.229	0.001**	-0.200	0.001**
Herbivory (%)	-0.221	0.001**	-0.342	0.001**
Ice - ice disease (%)	-0.208	0.001**	-0.346	0.001**
Epiphytic load (%)	-0.271	0.001**	-0.468	0.001**
Plant loss (%)	-0.368	0.001**	-0.336	0.001**

r is significant at $p < 0.05$, where p has **, r is highly significant at $p < 0.05$

nique. The damage of seaweed farms due to typhoons in tropical regions has been reported in Argentina which resulted in the mean net yield of eucheumoids reducing from 4.27 ± 0.23 kg wet wt m^{-2} 30 d^{-1} to 0.02 ± 0.04 kg wet wt m^{-2} 30 d^{-1} (Valderrama *et al.,* 2013). In the Philippines, the challenges of typhoons are annual occurrences that negatively impact seaweed yield (Hurtado and Agbayani, 2002). The results of this study thus suggest that if mechanisms are devised to improve the stability of the MB technique in deep water to resist strong typhoons, then it could be an effective technique for seaweed cultivation in deep water. Nevertheless, the study observed that the high biomass in the MB technique could have been influenced by the position of seaweeds on the surface at all times where grazers were minimal and the water temperature was stable. Contrastingly, the permanent fixing of seaweed ropes on the sea bottom in the FB technique exposed seaweeds to many grazing hazards and subsequently to bacterial infections, ice-ice disease and plant loss.

The highest diffusion factor, lowest maximum water temperature, lowest herbivory, ice-ice disease and capacity to overcome the typhoon were attributed to the highest net yield observed in the FR technique compared to the other techniques. The interaction of the cooler environment and higher water motion could have triggered positive results. In a previous study in Kenya, Wakibia *et al*. (2006) observed significantly higher growth rates of *E. denticulatum* in comparison to *K. alvarezii* at a site where water motion was highest.

The net yields (kg wet wt m^{-2} 30 d^{-1}) of 3.0 ± 0.4 and 1.6 ± 0.1 in the present study for *E. denticulatum* and *K. alvarezii* (1.6 ± 0.1) respectively were higher than those reported in the previous study. Wakibia *et al.* (2011) reported net yields (kg wet wt m^{-2} 30 d^{-1}) of 0.57 - 0.99 for *K. alvarezii* and 0.77 for *E. denticulatum* in South Coast Kenya. When compared to net yields from other regions, the net yields of *Kappaphycus* (0.57 - 0.99 kg wet wt m^{-2} 30 d^{-1}) were lower than 4.8 kg wet wt m^{-2} 30 d^{-1} in Indonesia, 2.1 kg wet wt m^{-2} 30 d^{-1} in Hawaii and 2.8 kg wet wt m^{-2} 30 d^{-1} in the Philippines (Hurtado-Ponce *et al.*, 1996). The higher prevalence of ice-ice disease, herbivory, epiphytic load and plant loss in the *K. alvarezii* than in the *E. denticulatum* accounted for a higher mean net yield (3.0 ± 0.4 kg wet wt m^{-2} 30 d^{-1}) of the former compared to the latter (1.6 ± 0.1 kg wet wt m^{-2} 30 d^{-1}). *E. denticulatum* possesses the capacity to produce H_2O_2 during oxidative burst which is suspected to be part of its chemical defence mechanisms against epiphytic attack (Collen *et al.,* 1995). This characteristic could portray that in an environment where both species are challenged by epiphytes, *E. denticulatum* has a greater capacity to maintain a higher growth rate and biomass compared to *K. alvarezii*. In Tanzania, a drop in biomass production of *K. alvarezii* from 1,000 t (dry wt) to only 13 t (dry wt) was associated with ice-ice disease (Msuya *et al.,* 2014). In other studies, the abundance of *Kappaphycus* decreased from 62.5% to 15.9% in five months in Hawaii by a single *Tripneustes gratilla* foraging within an enclosure of 0.25 m^2 (Conklin and Smith, 2005).

Conclusion and recommendations

The study demonstrates how the exposure of seaweed species to environmental challenges may influence variations in its biomass accumulation. The abiotic factors (water motion and water temperature) and biotic factors (ice-ice disease, epiphytes and herbivory) significantly influenced the variations of euchemoid net yields between the cultivation techniques on the South Coast of Kenya. All the techniques were suitable for the production of *E. denticulatum* in deep water but the FR technique had the highest potential for commercial application since it supported the production of both *E. denticulatum* and *K. alvarezii* in deep water. The positive observations of the FR technique were associated with its ability to mitigate ice-ice disease challenges in deep water environments. On the other hand, MB was the best technique to mitigate epiphyte challenges. However, the structural design of the MB technique could not resist occasional typhoons leading to the highest loss of seaweed biomass during the SEM. Consequently, mechanisms to improve the stability of the MB technique to overcome strong destructive oceanic waves (typhoons) in deep water should be devised. The FB is a favourable seaweed cultivation technique for adoption by new farmers, especially those with limited swimming ability and low confidence in working in deep water. Further research should be conducted to determine the economic feasibility of FR and MB techniques before commercial adoption. The government of Kenya in collaboration with donor agencies should mobilize resources to promote seaweed cultivation in deep water using the floating raft technique. Such efforts would boost national seaweed production and contribute significantly to ensuring food and job security for coastal communities and the sustainable development of the Blue Economy.

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