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Impacts of Extreme Events on Community Livelihoods: El Niño Effects and Management of Seaweed Farms in the South Coast of Kenya

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ABSTRACT

Seaweed farming is a vital economic activity for coastal communities in the Western Indian Ocean, with growing potential in food, bio-stimulants, pharmaceuticals and environmental management. Some farmed species, such as*Eucheuma denticulatum* and *Kappaphycus alvarezii*, are known to be sensitive to extreme weather events such as El Niño rains, with direct implications for production and livelihoods. This study assessed the impacts of the November–December 2023 El Niño event on seaweed farms in three villages (Kibuyuni, Tumbe and Bati-Mwazaro) along the south coast of Kenya. The assessment focused on changes in production, labour requirements and farm management practices. Data were collected through face-to-face interviews with 99 seaweed farmers and analysed using quantitative and qualitative approaches. Production was found to have increased steadily from September to November 2023 but declined sharply in December 2023 and January 2024, during and immediately after the El Niño. Farmers in Kibuyuni demonstrated faster recovery and maintained more active ropes in the water, resulting in higher post-El Niño harvests, whereas Bati-Mwazaro and Tumbe reported lower yields. Additionally, farm labour shortages were a major constraint across all villages (reported by 98% of respondents in Kibuyuni, 94% in Bati-Mwazaro and 87% in Tumbe). Kibuyuni farmers had a greater proportion of ropes deployed at sea, whereas Bati-Mwazaro and Tumbe farmers retained most of their ropes at home, indicating reduced active farm area and slower recovery. These findings show how a single extreme rainfall event can disrupt seaweed value chains, delay recovery over multiple cropping cycles and exacerbate vulnerability in already marginalized coastal villages. The study highlights priority adaptation and management options, including integrated early warning and farming calendars, spatial planning to reduce exposure to flood plumes, strengthened farmer organizations and input supply systems and development of policy instruments for insurance and emergency support to buffer future El Niño shocks.

1 | Introduction

The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual climate variability in the tropics and has significant impacts on multiple sectors, especially agriculture and water resources (Dell et al. 2014; Woli et al. 2011; Palmer et al. 2023). Smallholder agriculture and hydropower production are particularly sensitive to ENSO-related anomalies, despite the partial predictability of ENSO phases months in advance (Adiku et al. 2007; Schaeffer et al. 2012). In Eastern Africa, seasonal

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rainfall patterns are shaped primarily by the Intertropical Convergence Zone (ITCZ), resulting in distinct spatio-temporal regimes. Countries such as Ethiopia, Sudan, South Sudan and southern Tanzania typically experience a single main rainy season, whereas Kenya, Uganda, Somalia, Burundi, Rwanda, northern Tanzania and southern Ethiopia experience two main wet seasons: March–July (long rains) and October–December (short rains). Variability in the onset, duration and intensity of these seasons has major implications for food security, public health, energy production and economic stability (Hashizume et al. 2012; Ferrer et al. 2019; Adloff et al. 2022). Prolonged rainfall deficits disrupt agricultural output, hydropower generation and groundwater recharge, whereas extreme rainfall and flooding can damage infrastructure, crops and coastal ecosystems.

Seaweeds are strongly influenced by environmental variables such as temperature, salinity, light, water motion and nutrient availability, which together affect their physiology, growth, reproduction and distribution (Breeman 1988, 1990; Steen 2004). Empirical and modelling studies show that shifts in oceanographic conditions associated with climate variability and change, including ENSO events and sea-level anomalies, can alter seaweed biogeography, community structure and productivity (Harley et al. 2012). For example, the 1997–1998 El Niño contributed to local disappearance or decline of giant kelp populations in parts of the northeast Pacific through anomalous warming and altered nutrient regimes (Edwards 2004; Grove et al. 2002). Further, recent experiments in controlled environments have shown that farming of eucheumatoids in fluctuating salinity but with corresponding high nutrient levels increases growth and production due to increased intake of nutrients (e.g., nitrates and ammonia) at low salinities, and it varies with species even though the optimal salinity for such growth was not established in the studies (Narvarte et al. 2022; Gacura et al. 2025; Narvarte and Roleda 2025).

To sustain productivity, seaweed farming systems require suitable water quality, including relatively stable salinity, low-to-moderate turbidity and adequate light penetration. In the Western Indian Ocean (WIO) region, however, there is limited empirical information on how climate change and human-induced disturbances affect seaweed resources and farms, constraining evidence-based management (Chan et al. 2006; Coelho et al. 2025). These stressors have contributed to production declines or farm abandonment in several locations. In East Africa, particularly Tanzania and Kenya, climate-related impacts on *Kappaphycus alvarezii* and *Eucheuma denticulatum* farms have been widely documented, often linked to elevated temperatures, ice–ice disease, epiphyte proliferation and hypersalinity or desiccation stress in shallow intertidal areas (Msuya 2011; Wakibia et al. 2011; Kimathi et al. 2018; Mirera et al. 2020). Extreme seawater temperatures of 36–38°C recorded in Zanzibar and Songo Songo in 2008, for instance, were associated with severe die-offs of *K. alvarezii* due to ice–ice disease (Msuya 2011). In response, farmers have increasingly shifted to cultivating *E. denticulatum*, perceived as more tolerant to thermal and disease stress and relocated farms from shallow intertidal zones to deeper, better-flushed sites in an effort to stabilize environmental conditions (Msuya 2006; Msuya et al. 2014). Despite these adaptations and resilience of *E. denticulatum* as documented in other studies (Gacura et al. 2025), production has remained vulnerable to climate-related variability and episodic stress events as described in Rusekwa et al. (2020).

Although the effects of elevated temperature on farmed eucheumatoids are relatively well documented, and several technical and spatial mitigation measures have been proposed, much less is known about how extreme rainfall events and El Niño-driven flood pulses affect small-scale seaweed farms other than results or experiments conducted in controlled environments (Narvarte et al. 2022; Gacura et al. 2025; Narvarte and Roleda 2025). Pathways of concern include enhanced river discharge, siltation, reduced salinity, high turbidity, nutrient pulses and increased hydrodynamic stress, all of which can influence growth, disease dynamics, stability of farm structures and seed availability. For coastal households whose livelihoods depend concurrently on seaweed farming, capture fisheries and rain-fed agriculture, such multi-hazard exposure may intensify socio-economic vulnerability and undermine national and regional blue economy ambitions. However, there is limited empirical evidence on the effects of El Niño events on seaweed farms in the WIO, and few policy or financial instruments exist to cushion farmers from periodic climate-induced crop losses.

The November–December 2023 El Niño event in Kenya was characterized by intense and prolonged rainfall, widespread flooding, siltation and strong winds, with major impacts on infrastructure, agriculture and coastal ecosystems. Yet, farm-level evidence on how this event affected seaweed farming systems, management responses and recovery trajectories along Kenya's south coast is lacking.

This study addresses this gap by (i) quantifying changes in seaweed production, farm status and labour use before, during and immediately after the 2023 El Niño event in three key farming villages (Kibuyuni, Tumbe and Bati-Mwazaro); (ii) assessing farmers' perceptions of environmental stressors, diseases, pests and management challenges associated with the event; and (iii) identifying adaptation practices and policy-relevant measures to enhance the resilience of seaweed-based livelihoods within a climate-smart blue economy framework. By combining meteorological records with farmer-level observations and management indicators, we provide one of the first systematic assessments of El Niño impacts on seaweed aquaculture in coastal Kenya, generating actionable insights for site selection, seasonal planning, risk transfer mechanisms and coordinated response interventions.

2 | Methodology

2.1 | Study Area

The study was conducted in three established seaweed farming villages of Kibuyuni, Tumbe and Bati-Mwazaro, located in Kwale County along the south coast of Kenya (Figure 1). The region experiences a tropical monsoon climate, with long rains occurring between March and July and short rains between October and December. Local livelihoods depend heavily on marine resources (artisanal fisheries, mariculture, tourism and conservation initiatives) and rain-fed agriculture, rendering communities highly sensitive to climate extremes. Seaweed farming has emerged as an important livelihood activity supporting many households

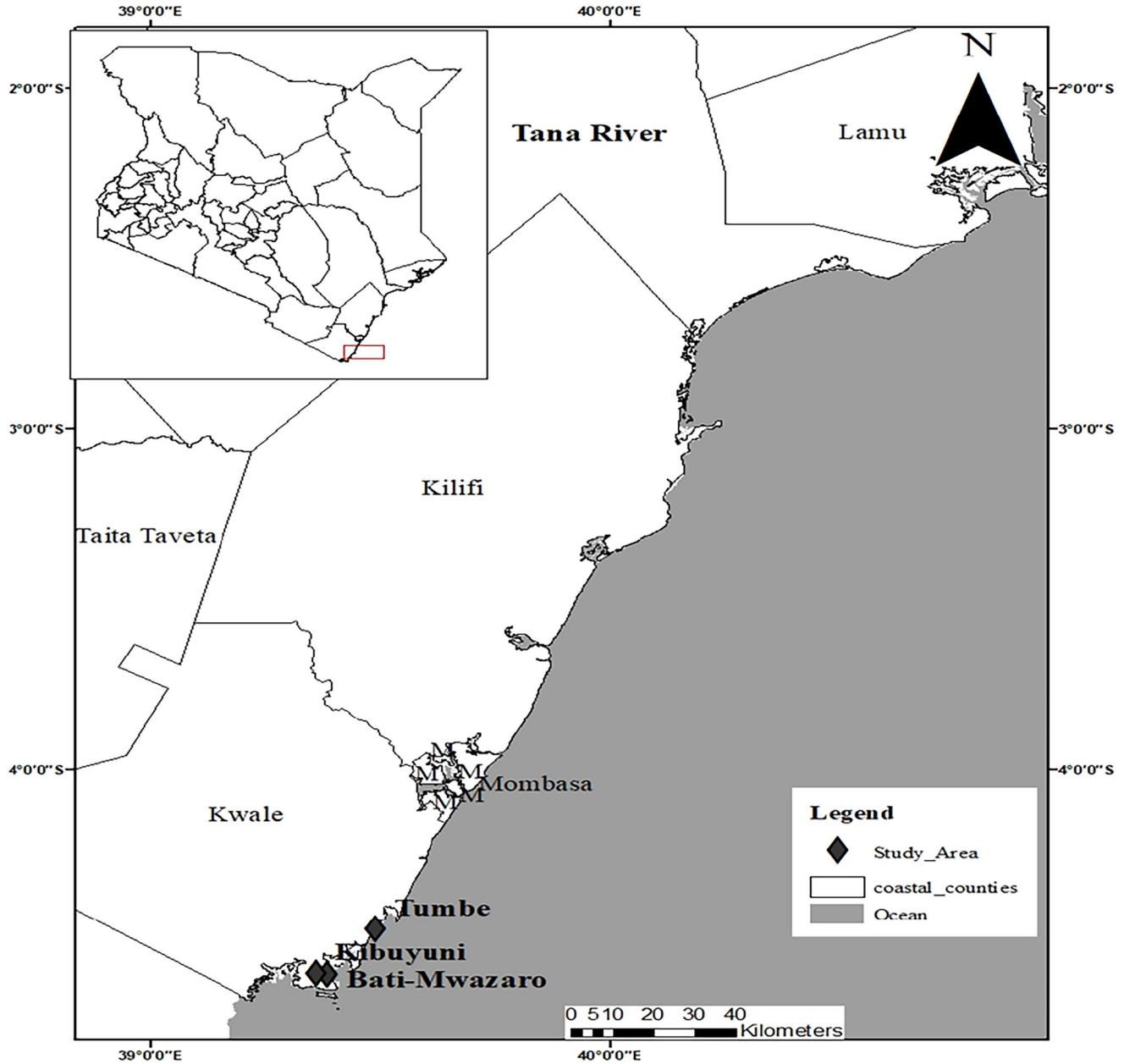


FIGURE 1 | Map of interviewed seaweed farming communities in Kwale County, Kenya.

on Kenya's south coast. This strong dependency on ocean-based activities and rainfall-dependent agriculture increases the vulnerability of these communities to environmental changes such as El Niño events, which can disrupt both terrestrial and marine production systems.

Kibuyuni is a relatively sheltered site with no major river discharging directly into the farming grounds, offering comparatively stable salinity and turbidity conditions under normal circumstances. In contrast, Tumbe and Bati-Mwazaro are more strongly influenced by flood plumes and sediment-laden run-off from nearby river systems, particularly the Ramisi and Congo rivers, increasing their exposure to freshwater pulses, elevated turbidity and hydrodynamic stress during periods of intense rainfall and flooding.

2.2 | Sampling Design and Data Collection

The study employed a descriptive research design with a mixed-methods approach, integrating both quantitative and qualitative data collection techniques. Qualitative components were used to capture farmers' experiences and perceptions of the impacts of the 2023 El Niño event, whereas quantitative components focused on production trends, labour availability and farm management practices. All participants were informed about the purpose of the study and the intended use of the data and provided informed consent prior to the interviews.

A total of 99 seaweed farmers were interviewed across the three study villages (Kibuyuni, Tumbe and Bati-Mwazaro) using a structured questionnaire (Supporting Information S1). Data

collection was conducted using the KoboCollect toolbox. Farmers were interviewed at their farming sites during low-tide periods when seaweed farming activities (planting, routine management and harvesting) typically take place, allowing direct observation and recording of farm status, infrastructure and management practices. The sample targeted active seaweed farmers available at the time of the survey in each village, aiming to capture a broad representation of operational farms and post-El Niño conditions.

The questionnaire captured: (i) demographic characteristics (sex, age group, village, county, sub-county and membership in community groups or cooperatives); (ii) the number of active planting lines or ropes currently deployed in the sea and those stored at home as unused capacity; (iii) overall farm condition and management status (poor, fair, good and excellent); (iv) production levels (wet weight) before (September–November 2023), during (December 2023) and after (January 2024) the El Niño event; (v) labour use and organization for planting and harvesting (including number of labourers involved, lines handled per low tide and perceived labour sufficiency); (vi) key challenges affecting production (e.g., diseases, epiphytes, grazing, environmental stressors, access to inputs, training, labour, logistics, markets, prices and conflicts); (vii) farmers' perceptions of the influence of environmental variables (temperature, salinity, turbidity, currents and light) on seaweed growth, health and survival; (viii) methods used to manage or control diseases, pests and epiphytes; (ix) practices for assessing seaweed quality during growth and at harvest; and (x) priority training, extension support and resource needs to improve seaweed farming practices. The questionnaire also included items on the number of labourers engaged after the El Niño rains and farmers' projections of labour requirements and expected harvests for the subsequent low-tide period.

Daily precipitation, air temperature, relative humidity, solar radiation and wind speed data for August 2023 to January 2024 were obtained from the Ramisi meteorological station, the nearest official station to the study area. Monthly summaries were computed and grouped into three periods: pre-El Niño (August–October 2023), peak El Niño (November–December 2023) and immediate post-El Niño (January 2024). These data were used to contextualize observed farm-level patterns in seaweed production and management.

2.3 | Data Analysis

Interview data were cleaned and analysed using both quantitative and qualitative approaches. Quantitative analyses began with descriptive statistics (mean ± SD) for continuous variables such as numbers of ropes in the farm and at home, ropes ready for harvest, projected harvest (kg wet weight), anticipated harvest in the next low-tide season and ropes planned for planting (Table 5). Categorical variables, including gender and age-group representation (Figure 2a,b), farm-condition categories (Table 1), main challenges (Table 2), perceived environmental impacts (Table 3), control methods (Table 4) and training/resource needs (Figure 6), were summarized as frequencies and percentages; multiple-response items were coded as binary indicators (present/absent), so percentages may exceed 100%.

Group comparisons were matched to data type and distributional assumptions ($\alpha = 0.05$; 95% CIs).

Seaweed production (Figure 4) was analysed using a two-factor ANOVA with site (three villages) and period (pre-, peak- and post-El Niño) as fixed factors and their interaction, based on log-transformed seasonal production (kg wet weight); where assumptions were not met, an aligned-ranks ANOVA or site-stratified Kruskal–Wallis tests were used. Farm characteristics (Table 5) were treated as contextual indicators of farming intensity and recovery potential and are presented descriptively (mean ± SD) by site; given the small sample sizes and high dispersion, no formal between-site hypothesis tests are reported for these variables.

Associations between categorical variables (e.g., farm condition × site; challenge type × site; perceived extent of environmental impact × site) were evaluated using χ^2 tests of independence (or Fisher's exact tests when expected cell counts were <5). Farmers' perceptions of how strongly environmental variables affect seaweed growth and production were coded into four ordered categories ('significantly affect', 'moderately affect', 'slightly affect', 'not sure') and summarized as site-specific and overall percentages (Table 3).

Meteorological observations from the Ramisi station (August 2023–January 2024) were aggregated to monthly means for precipitation, temperature, relative humidity, solar radiation and wind speed and visualized as single-parameter boxplots (Figure 3). Differences in each environmental variable among pre-, peak- and post-El Niño periods were tested using Kruskal–Wallis tests followed, where appropriate, by Dunn–Holm post hoc comparisons; precipitation period comparisons were additionally verified in GraphPad Prism (version 10.6.1). Qualitative, open-ended responses were analysed thematically to identify convergent narratives on environmental change, operational challenges, coping strategies and priority support needs related to El Niño recovery. All data handling, statistical analyses and visualization were conducted in R (version 4.2.2) via RStudio (2023.03), primarily using the base stats functions, the ordinal package for cumulative-link models and ggplot2 and patchwork for graphics; figures were exported as high-resolution PNG files.

3 | Results

3.1 | Demographics

Of the 99 farmers interviewed, 48.5% were from Kibuyuni, 33.3% from Bati-Mwazaro and 18.2% from Tumbe. Women constituted approximately 70% of respondents, reflecting the central role of women's groups in seaweed farming (Figure 2a), whereas about 40% of respondents were youth (Figure 2b). These patterns reinforce the importance of seaweed farming for gender-inclusive and youth-engaged livelihoods on Kenya's south coast.

3.2 | Overview of Kenya's El Niño Phenomenon of 2023

Kenya's 2023 El Niño manifested strongly during the short-rains season (October–December), bringing sustained precipitation,

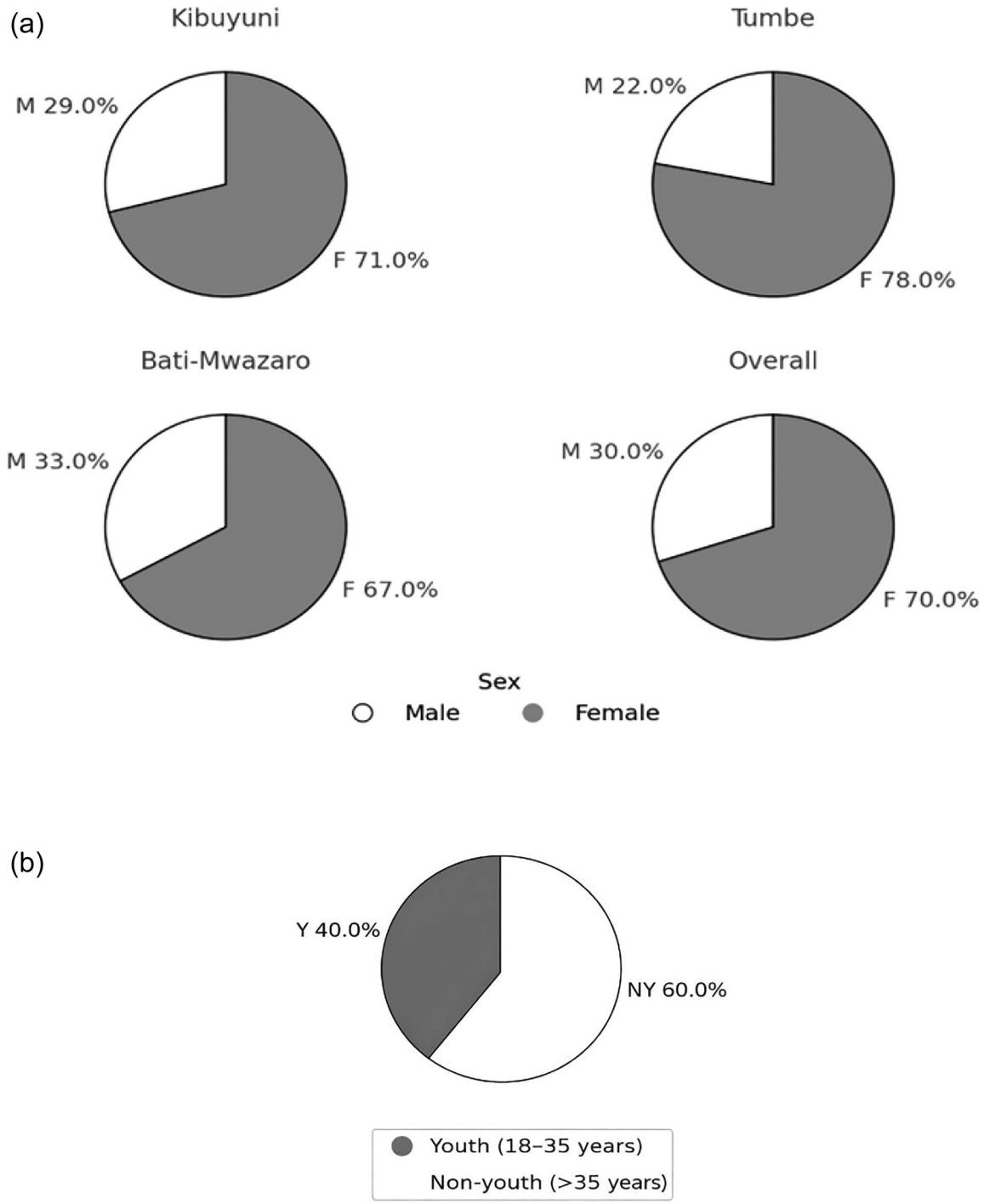


FIGURE 2 | (a) Gender representation in seaweed farmer's community groups during interviews. (b) Youth and non-youth representation in seaweed farmer's community groups during interviews.

TABLE 1 | Description of the seaweed farm management conditions after the El Niño event of 2023 in three villages in Kwale County, south coast, Kenya.

Description of farm condition	Bati-Mwazaro (%)	Kibuyuni (%)	Tumbe (%)
Excellent	0	6	0
Good	35	36	11
Fair	19	36	6
Poor	45	21	83

TABLE 2 | Classification of challenges facing seaweed farms and farmers perception on intensity in the different villages.

Seaweed farm challenges	Bati-Mwazaro (%)	Kibuyuni (%)	Tumbe (%)
Diseases	71	77	94
Epiphytes	19	19	17
Environmental conditions/temperature	77	83	83
Lack of resources/training	52	57	50
Market fluctuations	29	30	11
Labour-related issues	39	77	44
Transportation of ready seaweed	57	17	50
Fish feeding on seaweeds	29	0	50
Farm waste	14	16	0
Conflict with fishermen	0	33	0
Influx of sea urchins	0	17	0
Theft	0	17	0

TABLE 3 | Farmers perceptions on the extent to which environmental variables affect growth and production of seaweeds.

Extent of impact of environmental variables on farms	Bati-Mwazaro (%)	Kibuyuni (%)	Tumbe (%)	Aggregate (%)
Significantly affect	67	49	76	60
Moderately affect	23	28	18	24
Slightly affect	7	21	6	14
Not sure	3	2	0	2

TABLE 4 | Methods used by seaweed farmers to control pests, epiphytes and diseases in the three villages of Bati-Mwazaro, Kibuyuni and Tumbe in south coast Kenya.

Control methods	Bati-Mwazaro (%)	Kibuyuni (%)	Tumbe (%)
Natural/Traditional methods	27	28	29
No specific method	43	50	47
Hand removal	47	41	53
Avoiding planting during bad conditions	3	17	12

high river discharge, siltation and flooding that affected coastal livelihoods, including seaweed farming. At Ramisi, rainfall was modest in August–September (means 0.14 and 0.08, respectively), then rose in October (0.34) and peaked in November–December (both 0.66), remaining elevated into January 2024 (0.60) (Figure 3a). Variability was also greatest in October–November (large box-plot spread), consistent with intermittent, intense events typical of El Niño short rains.

Air temperature showed a steady warming from late winter into the peak rains and early 2024: 25.5°C (Aug) → 26.1–26.6°C (Sep–Oct) → 26.4°C (Nov) → 28.1°C (Dec) → 28.8°C (Jan) (Figure 3b). Relative humidity tracked the rainfall cycle, remaining high throughout (92%–98%) and peaking in November (98%) (Figure 3c).

Solar radiation declined as cloud cover increased, falling from 220 to 230 in Aug–Oct to 168 in November and 147 in December, with a partial rebound in January (2024) (Figure 3d). Wind speed was modest (0.7–0.9 m s^{-1}), dipping during the peak rains (lowest in November, 0.72 m s^{-1}) and slightly higher pre- and post-peak (0.81–0.86 m s^{-1}). Gustiness was greatest in September (2.92 m s^{-1}) and January (2.72 m s^{-1}), and lowest in November (2.11 m s^{-1}). Mean wind direction shifted from southerly–south-southwesterly before the peak (Aug–Oct: 171°–180°) to more southwesterly in November (206°), then veered toward south-easterly in December–January (150°–145°), matching seasonal monsoonal transitions (Figure 3e).

Together, these anomalies—sharp increases in rainfall and humidity, suppressed radiation, reduced gust and generally mod-

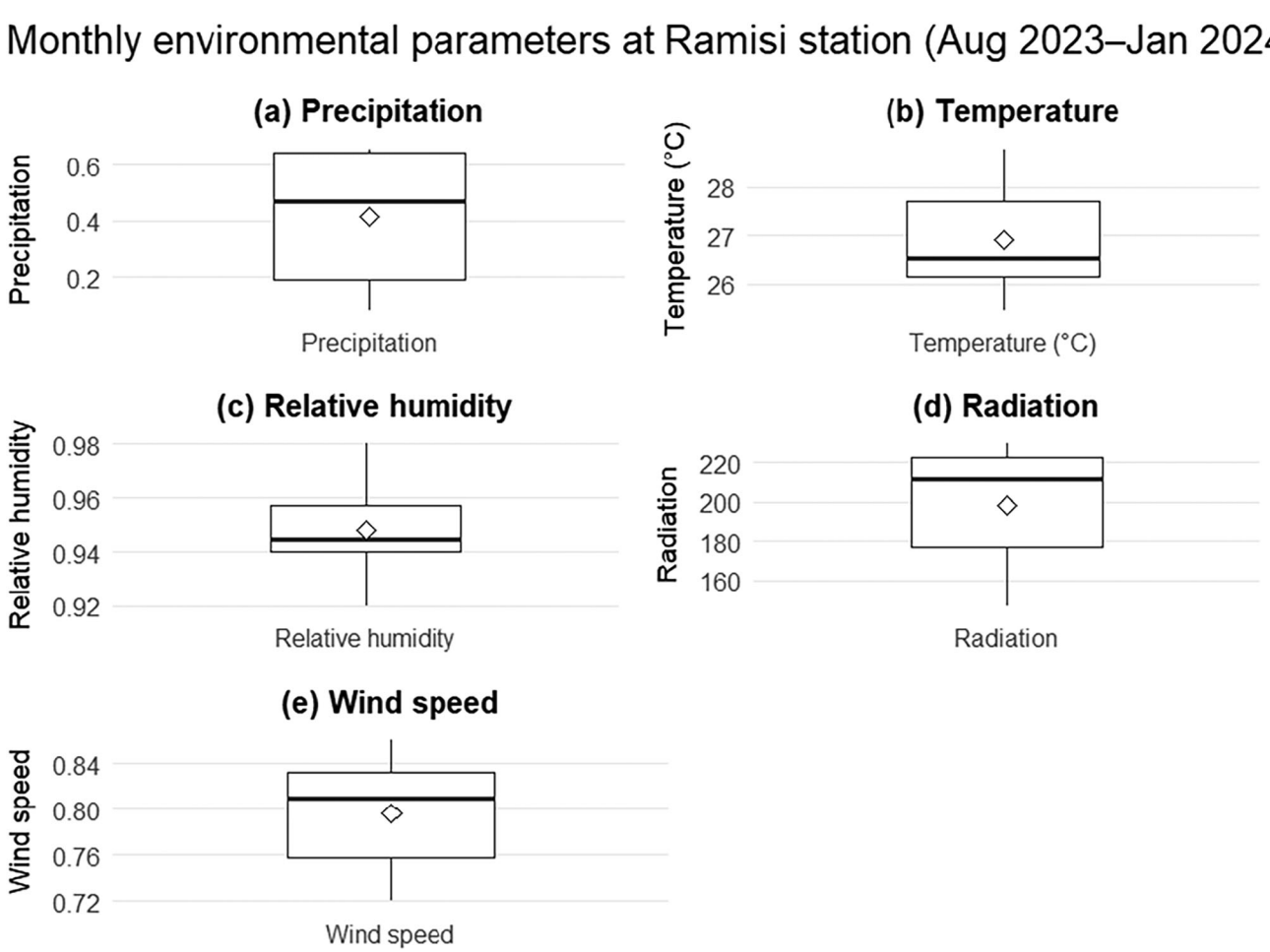


FIGURE 3 | Monthly environmental parameters at Ramisi station (Aug 2023–Jan 2024). Boxplots summarize variability across months for (a) precipitation, (b) temperature (°C), (c) relative humidity, (d) solar radiation and (e) wind speed. Boxes show the interquartile range (Q1–Q3) with the median as the central line; whiskers indicate the minimum and maximum; the marker denotes the mean. Values reflect monthly averages recorded at the Ramisi weather station in Kwale County, Kenya.

erate winds—align with widespread reports of flooding, high freshwater inflows, siltation, organic and inorganic nutrient loads and turbidity at Tumbe and Bati-Mwazaro. In the short run, increased intake of nutrients will enhance seaweed growth, whereas other conductions will overall reduce light availability, increase sedimentation and impose physical stress on the seaweed plants.

3.3 | Status of Seaweed Farms After the El Niño Event

The El Niño rains had a clear impact on seaweed farms in Kibuyuni, Tumbe and Bati-Mwazaro. Farmers reported a sharp decline in seaweed production between December 2023 and January 2024. Field observations revealed damage to farming facilities and structures, increased detachment of seaweed ropes and reduced active farming efforts, largely attributed to poor environmental conditions, including high sedimentation/siltation and turbid water at farm sites. A substantial number of planting ropes was kept at home rather than deployed in the sea.

Significant disparities in farm management among villages were observed (Table 1). Kibuyuni exhibited the best farm conditions, with 6% of farms classified as 'excellent' and 36% as 'good', whereas 21% were categorized as 'poor'. Tumbe had the highest proportion of poorly managed farms (83%), with only 11% classified as 'good'. In Bati-Mwazaro, 35% of farms were rated 'good' and 45% 'poor'.

Farmers across all three sites reported multiple challenges, most frequently poor environmental conditions (83%), diseases (94%) and lack of resources (57%) (Table 2). The number and combination of reported challenges varied by site, with Tumbe reporting the fewest distinct challenges, Bati-Mwazaro an intermediate number and Kibuyuni the highest. Overall, 60% of respondents indicated that environmental conditions had a significant effect on seaweed growth and production on Kenya's south coast (Table 3).

Farmers employed a range of practices to manage pests, epiphytes and diseases, including hand removal, temporarily avoiding planting during unfavourable conditions and various traditional methods, whereas a considerable proportion reported using no specific control method (Table 4).

TABLE 5 | characteristics by site (mean ± SD).

Site	Ropes in farm	Ropes at home	Ropes ready for harvest	Projected harvest (kg)	Anticipated harvest in low season (kg)	Ropes to be planted this season
Kibuyuni	132.4 ± 116.7	106.1 ± 97.9	29.6 ± 41.1	718.7 ± 1621.4	54.9 ± 90.1	65.6 ± 119.8
Tumbe	53.4 ± 53.1	137.2 ± 82.7	43.4 ± 140.1	336.1 ± 428.7	144.7 ± 207.4	82.8 ± 165.2
Bati-Mwazaro	28.0 ± 25.4	200.9 ± 175.2	5.6 ± 11.4	211.7 ± 492.5	60.8 ± 102.7	31.5 ± 73.8

Note: Values shown are mean ± SD per site. Variables include: ropes planted in farm during visit; ropes at home not planted; ropes ready for harvest in the working season; projected harvested quantity in this season (low tide, kg); ropes anticipated for harvest in the next low tide season; and ropes to be planted this season by labourers.

3.4 | Effects of El Niño on Farm Characteristics and Labour Requirements

Total seaweed production was higher during the pre-El Niño period (September–November 2023) and declined markedly during and immediately after the El Niño period (December 2023–January 2024) across the three villages (Figure 4). This decline corresponded with the period of intense rainfall, flooding and reported farm damage.

Farm characteristics differed markedly across sites (Table 5). Kibuyuni showed the greatest level of active deployment, with the highest mean number of ropes in the sea (132.4 ± 116.7) and the largest projected wet-weight harvest per farm (718.7 ± 1621.4 kg). Stocks kept at home were moderate (106.1 ± 97.9 ropes), and the number of ropes ready for harvest averaged 29.6 ± 41.1. Tumbe had fewer ropes deployed (53.4 ± 53.1) but more ropes held at home (137.2 ± 82.7) and the highest mean number of ropes ready for harvest (43.4 ± 140.1), indicating substantial within-site variability. Tumbe also reported the greatest anticipated harvest in the next low-tide season (144.7 ± 207.4 kg) and the highest intention to (re)plant (82.8 ± 165.2 ropes). Bati-Mwazaro exhibited the lowest deployment (28.0 ± 25.4) and readiness for harvest (5.6 ± 11.4), alongside the highest average number of ropes retained at home (200.9 ± 175.2), pointing to a more constrained production phase with limited short-term harvest potential (projected harvest: 211.7 ± 492.5 kg; intended planting: 31.5 ± 73.8 ropes).

In all seaweed farming villages, there was a lack of sufficient labour available to participate in seaweed farming, according to 96% of farmers. Kibuyuni showed a high requirement for labour, according to 98% of the farmers, although not significantly different from Tumbe (87%) and Bati-Mwazaro (92%) (Figure 5). Further, during the study, Kibuyuni village had 40% more labour deployed in the farms compared to the other two villages.

Taken together, these patterns suggest that Kibuyuni was the most actively farming and currently productive site, Tumbe was in a rebuilding phase with substantial at-home stocks and strong replanting intentions, and Bati-Mwazaro faced the greatest constraints.

3.5 | Post-El Niño Recovery Capacity and Anticipated Production

Indicators of short-term recovery capacity also varied by site (Table 5). In Kibuyuni, the average number of ropes deployed exceeded the number kept at home (132.4 vs. 106.1), consistent with active restoration of farmed area. In Tumbe and Bati-Mwazaro, the reverse pattern was observed—more ropes were retained at home than deployed (Tumbe: 137.2 vs. 53.4; Bati-Mwazaro: 200.9 vs. 28.0)—signalling a cautious approach to replanting following El Niño-related losses.

Readiness and near-term harvest expectations reflected these differences. Tumbe had the highest mean number of ropes ready for harvest (43.4 ± 140.1) and the largest anticipated harvest during the next low-tide season (144.7 ± 207.4 kg), albeit with very wide dispersion. Kibuyuni combined substantial active deploy-

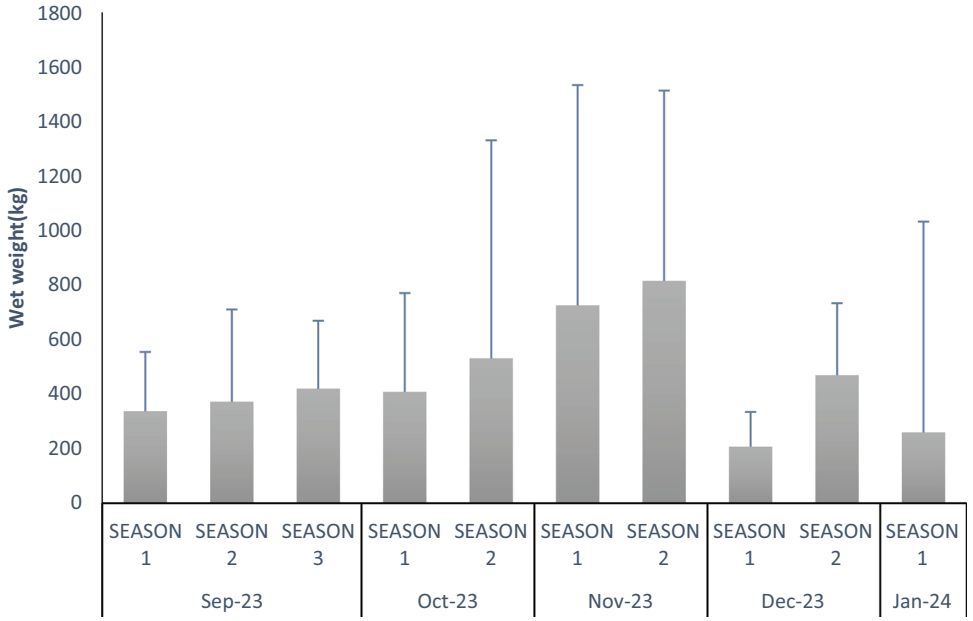


FIGURE 4 | Average seaweed production (wet weight) per season before, during and post-El Niño rains in three villages, Kwale County, South Coast, Kenya.

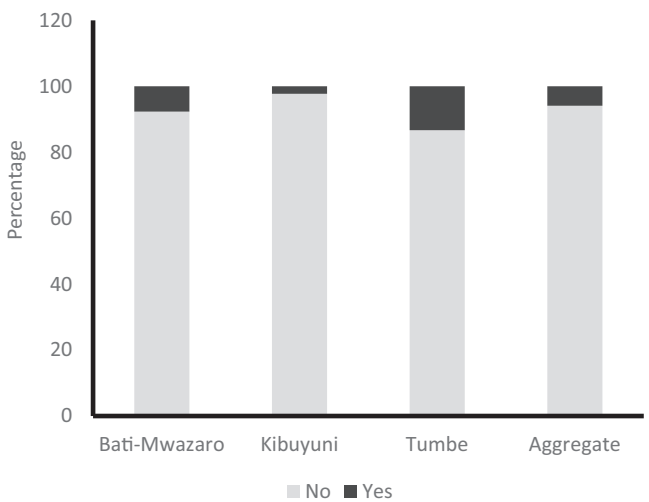


FIGURE 5 | Sufficiency of labour required for the seaweed farms post-El Niño period of 2023 in the three farming villages (Tumbe, Bati-Mwazaro and Kibuyuni).

ment with a high projected near-term wet-weight production (718.7 ± 1621.4 kg per farm), exceeding the averages for Bati-Mwazaro (211.7 ± 492.5 kg) and Tumbe (336.1 ± 428.7 kg). The large standard deviations indicate heterogeneous recovery stages within each site.

Consistent with questionnaire responses, most farmers reported constraints that may slow recovery—particularly labour availability (Figure 5) and access to inputs (e.g., ropes, floats and stakes), the need for farm inputs, training on improved farming techniques, suitability site assessment, control of diseases and epiphytes and financial support among others (Figure 6). These support needs underpin the observed differences in replanting intentions (Table 5) and should be considered in the design of site-specific recovery interventions.

4 | Discussion

4.1 | Influence of Environmental Variables on Seaweed Production

Farmers faced major difficulties accessing farms during the 2023 El Niño event due to flooding, elevated river discharge and unsafe working conditions. This constrained routine management, reduced effective farming days and contributed to substantial crop losses. Heavy rainfall and associated flooding increased discharge from rivers such as the Ramisi and Congo, driving turbid, silt, low-salinity water across exposed farming areas, particularly Tumbe and Bati-Mwazaro. These freshwater pulses, sediment inputs and hydrodynamic disturbances are consistent with mechanisms known to reduce eucheumatoid growth, increase thallus breakage and elevate disease susceptibility. Experimental and field studies highlight the sensitivity of carrageenophytes to reduced salinity, high turbidity and physical stress, which can trigger ice–ice disease, necrosis and crop loss (Ask and Azanza 2002; Wakibia et al. 2006; Pereira et al. 2017). The findings of controlled growth experiments for eucheumatoids by Narvarte et al. (2022) and Narvarte and Roleda (2025) indicated that fluctuating salinity that corresponds with high nutrient levels increases seaweed growth due to increased intake of nutrients as salinity decreases, although the optimal and critical salinity levels were not established. Although salinity, nutrient loads and turbidity were not directly measured in this study, farmers' observations of large volumes of flood-discoloured water, silt deposits, strong currents and widespread detachment align with established environmental stress pathways impacting growth and survival of seaweeds.

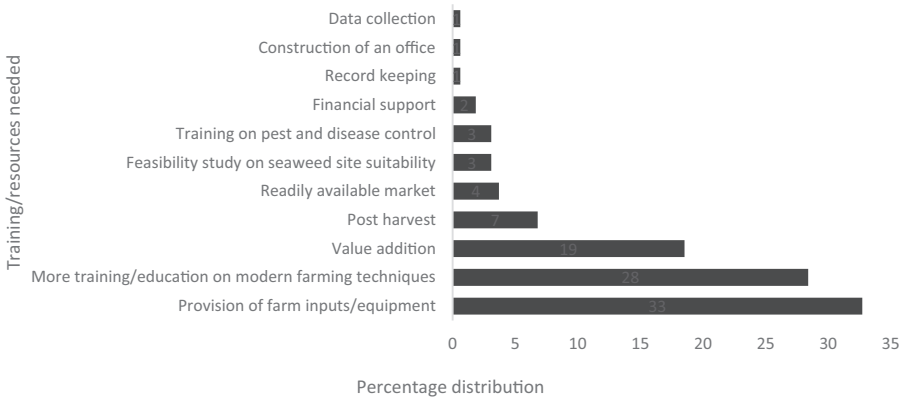


FIGURE 6 | Trainings and resources required to enhance seaweed production.

Recorded seawater temperatures during the study period remained within generally suitable ranges for tropical eucheumatoids and below the >30°C thresholds associated with severe thermal stress and disease outbreaks reported from other regions in the WIO and beyond (Msuya et al. 2014; Msuya and Porter 2014; Wakibia et al. 2006). This suggests that, for the 2023 event at these sites, extreme rainfall and flood-driven changes in water quality and hydrodynamics—rather than anomalous warming—were the primary drivers of farm damage and production decline.

Moderate wind-driven water movement and adequate light are generally beneficial for nutrient exchange and photosynthesis in seaweed farms (Ask and Azanza 2002; Wakibia et al. 2006). However, when combined with high river discharge, stronger currents and waves can detach lines, transport sediments and amplify the impacts of freshwater plumes. Recent global and regional assessments similarly conclude that extreme events—including storms, heavy rainfall and flood pulses—pose growing risks to seaweed aquaculture through mechanical damage, salinity shocks, turbidity and enhanced disease pressure (Buschmann et al. 2017; Hayashi et al. 2020; Veenhof et al. 2024). Overall, the combination of enhanced river discharge, increased siltation and turbidity, altered salinity and physical disturbance during the 2023 El Niño plausibly heightened farm vulnerability and helps explain the sharp declines and slow recovery documented in Kibuyuni, Tumbe and Bati-Mwazaro. These findings underscore the importance of integrating site exposure to flood plumes and run-off dynamics into seaweed farm planning and management along Kenya's south coast.

4.2 | Status of Seaweed Farms Post-El Niño and Management

Post-El Niño assessments revealed marked spatial variation in farm conditions. Tumbe, directly influenced by the Congo River outlet and associated run-off pathways, showed the highest proportion of poorly rated farms, reflecting strong exposure to floodwaters, sedimentation/siltation and freshwater inputs. Similar patterns—where storm events, prolonged rainfall and altered circulation damage farm structures, promote opportunistic fouling and reduce crop performance—have been documented in other eucheumatoid farming areas (Largo et al. 2017; Hayashi et al. 2020).

By contrast, Kibuyuni, with a more sheltered setting and lack of major direct river discharge into the farming grounds, exhibited relatively better farm condition scores and a faster resumption of farming activity that supports the findings. This spatial contrast supports evidence that local hydrodynamics and freshwater exposure strongly mediate farm vulnerability and enhance growth rates of eucheumatoids due to an increase in nutrient loads that are absorbed to support plant growth (Wakibia et al. 2006; Msuya et al. 2014; Gacura et al. 2025).

Across all sites, farmers reported disease, epiphytes, grazing, poor environmental conditions and limited access to farm inputs. Common management responses included hand removal of fouling organisms, avoiding planting during perceived high-risk periods and reliance on traditional practices—approaches also reported in other WIO seaweed farming systems (Msuya et al. 2014; Matoju et al. 2022). Nearly half of farmers reported no specific control strategy for epiphytes, diseases or pests, pointing to a persistent gap in technical guidance and extension. Weak farm management/maintenance and limited adaptive options under stressful conditions increase the risk of chronic productivity losses, consistent with broader analyses of climate-stressed seaweed value chains in East Africa and Asia (Valderrama et al. 2013; Buschmann et al. 2017).

Together, these patterns indicate that farm performance is governed jointly by biophysical exposure (e.g., flood plumes, sedimentation and wave energy) and management capacity, reinforcing the need for targeted support to strengthen local adaptive practices.

4.3 | Effects of El Niño on Seaweed Farming

Seaweed production declined markedly during and immediately after the 2023 El Niño event, coinciding with periods of intense rainfall, flooding, visible farm damage and reported deterioration of growing conditions. The timing and nature of these changes are consistent with El Niño-driven freshwater inputs, reduced salinity, heightened turbidity and physical disturbance as key drivers of loss, and mechanisms widely recognized as

critical stressors for Kappaphycus and Eucheuma farms (Ask and Azanza 2002; Msuya et al. 2014; Hayashi et al. 2020). Reduced yields directly affected household incomes in communities where seaweed farming is a major livelihood component, echoing evidence from carrageenophyte-farming regions that environmental shocks translate rapidly into income and food security risks (Hurtado et al. 2001; Valderrama et al. 2013; Matoju et al. 2022).

Patterns of labour engagement and recovery also varied among villages. Kibuyuni mobilized more labour for replanting and maintenance and retained sufficient seed stock to restart production, facilitating a relatively rapid recovery trajectory. In Tumbe and Bati-Mwazaro, heavier impacts from freshwater inflows and sedimentation led to a greater loss of standing crops and propagules, fewer active lines in the water and lower capacity or incentives to hire labour, resulting in slower recovery. Similar links between environmental shocks, seed scarcity, reduced labour demand and constrained re-entry into farming have been highlighted in socio-economic studies of seaweed sectors in Tanzania, India and the Philippines (Valderrama et al. 2013; Krishnan and Narayanakumar 2013; Matoju et al. 2022). Limited financial resources to purchase ropes, stakes and seedlings, combined with disease pressure and damaged infrastructure, further restricted the pace at which farmers could rebuild their farms.

These relationships illustrate how extreme events can simultaneously erode the biophysical foundation of production (loss of biomass and structural damage) and the social and economic capacity required for recovery (labour, capital and seed), thereby narrowing options for adaptation. Recent global reviews similarly warn that without deliberate risk management, repeated extreme events—including El Niño phases—may drive progressive disinvestment from seaweed farming in highly exposed locations (Buschmann et al. 2017; Veenhof et al. 2024; Troell et al. 2023).

4.4 | Seaweed Farming in Relation to Climate Change Impacts

The 2023 El Niño event exposed and amplified existing climate-related vulnerabilities in Kenya's south coast seaweed sector. Farm damage, loss of seed stocks and labour and input constraints resulted in reduced active farm area, more ropes stored at home instead of deployed in the sea and lower projected harvests across all sites. Kibuyuni showed signs of faster recovery, but in Tumbe and Bati-Mwazaro, farmers anticipated substantially lower production and prioritized available biomass for reseeding rather than sale. On the basis of typical cropping cycles, the interruption is estimated to delay restoration of full farm capacity and reliable dry seaweed supply by at least three production cycles (≈135 days), with direct implications for local processors and exporters that depend on continuous throughput—patterns consistent with other reports of climate shocks destabilizing carrageenan supply chains (Valderrama et al. 2013; Buschmann et al. 2017).

These findings demonstrate how a single extreme rainfall event can disrupt seaweed value chains beyond the immediate shock period, particularly where farmers lack access to formal seed systems, savings, crop insurance or emergency support. In this context, El Niño operates both as an acute hazard and as a stress test of systemic resilience in seaweed-based livelihoods, echoing broader concerns that climate-driven extremes, if unmanaged, may constrain the contribution of seaweed aquaculture to sustainable blue economies (Hayashi et al. 2020; Veenhof et al. 2024; Ross et al. 2023).

Strengthening the resilience of seaweed farming to future climate variability and extremes will require coordinated interventions. First, site selection and mariculture zoning should explicitly account for exposure to river plumes, flood pathways and local hydrodynamics, favouring more sheltered or deeper water sites where feasible, in line with recommendations for climate-smart seaweed aquaculture in the WIO and North Atlantic (Msuya et al. 2014; Veenhof et al. 2024). Second, climate- and El Niño-informed farming calendars and effective early warning systems are needed to guide planting, thinning and harvesting decisions and to minimize losses during high-risk periods, building on emerging work showing how farmers increasingly rely on (and are challenged by) shifting seasonal cues (Matoju et al. 2022; Arwati et al. 2025). Third, investment in seed security—including community/private nurseries, hatcheries (government and private) and diversified cultivars with improved tolerance to environmental stressors—would reduce dependence on standing crops and enable faster post-shock recovery (Ask and Azanza 2002; Kim et al. 2017; Hayashi et al. 2020).

Fourth, improving access to quality farming materials, extension services and practical training on farm design, disease and epiphyte management and record-keeping can enhance farm performance under variable conditions, as emphasized in regional and global assessments of seaweed sector sustainability (Msuya et al. 2014; Buschmann et al. 2017; Langton et al. 2019). Finally, integrating seaweed farming into broader climate-risk governance—through mechanisms such as emergency funds, index-based insurance pilots and explicit recognition in coastal adaptation and blue economy strategies—would help buffer households and value chains from recurring El Niño shocks and other extremes (Valderrama et al. 2013; FAO 2024; Veenhof et al. 2024).

Taken together, the evidence from Kibuyuni, Tumbe and Bati-Mwazaro shows that seaweed farming on Kenya's south coast remains viable but is highly sensitive to extreme rainfall events and associated riverine influences. Proactive, climate-risk-informed management and policy support are therefore essential to safeguard its contribution to livelihoods, gender- and youth-inclusive employment and a resilient blue economy.

5 | Conclusion

Seaweed farming remains a viable and strategically important livelihood option for coastal communities on Kenya's south coast, but the 2023 El Niño event demonstrated how quickly extreme rainfall and flood-driven disturbances can erode its benefits. Our findings show that enhanced river discharge, siltation, turbidity and altered salinity led to substantial crop losses, damaged infrastructure, loss of seed stock and reduced active farm area, with uneven impacts across sites depending on exposure and local management capacity. These short-term shocks cascaded into at least three disrupted production cycles, constraining income

generation and destabilizing local value chains in ways consistent with wider evidence on climate-sensitive seaweed sectors in the WIO and beyond (Valderrama et al. 2013; Buschmann et al. 2017; Msuya et al. 2014; Veenhof et al. 2024).

To sustain and scale seaweed farming under increasing climate variability, deliberate climate-risk-informed governance is required. Priority actions include: (i) integrating exposure to flood plumes, run-off pathways and local hydrodynamics into site selection and mariculture zoning; (ii) co-developing El Niño- and seasonally informed seaweed farming calendars and early warning systems including AI in partnership with national meteorological services in addition to sharing of data; (iii) strengthening seed security through community/private nurseries, hatcheries (government/private) and robust cultivars to reduce dependence on vulnerable standing crops; and (iv) improving access to quality farming inputs, farming technologies, extension services and practical training on farm design, health management and record-keeping. In parallel, innovative financial and policy instruments such as emergency support schemes and piloted index-based crop insurance should be explored to buffer farmers and buyers against recurrent extreme events, aligning with broader blue economy and coastal adaptation strategies (Valderrama et al. 2013; Langton et al. 2019; FAO 2024).

Targeted investments along these lines would enhance the resilience of Kenya's seaweed farming systems to future El Niño events and other climate-related extremes while safeguarding their contributions to livelihoods, gender- and youth-inclusive employment, ecosystem-compatible production and a resilient blue economy.

Author Contributions

All authors contributed to the conception and design of the study. Field investigations, data collection and curation were led by the research team based in the south coast of Kenya. Data analysis and interpretation were conducted collaboratively by the author team. The first draft of the manuscript was prepared by the lead author, with all co-authors contributing to reviewing, editing and critical revision of the text. All authors read and approved the final manuscript.

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Ethics Statement

Research approval was obtained from the Kenya Marine and Fisheries Research Institute (KMFRI) prior to fieldwork. All procedures involving human participants (seaweed farmers) complied with institutional and national research guidelines. The objectives of the study were explained to all participants in a language they understood, participation was voluntary, and written and/or verbal informed consent was obtained before each interview. Personal identifiers were not recorded, and all responses are reported in aggregated form to ensure confidentiality.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability

Analysis code used in this study is available from the corresponding author on reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Material: aff270223-sup-0001-SuppMat.pdf