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Comparative assessment of the performance and economic feasibility of seaweed cultivation at different depths along the Kenyan coast

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ABSTRACT

In recent decades, seaweed farmers in East Africa have faced declines in production and income, largely attributed to varying environmental conditions. Subtidal farming, promoted for its relatively more stable environmental conditions, has been proposed as a potential mitigation strategy, although empirical evidence remains limited. This pilot study assessed the technical feasibility and economic viability of cultivating three red seaweed species (*Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gracilaria salicornia*) at three depths (0.5 m, 2 m, 4 m) in coastal Kenya, using different cultivation techniques: off-bottom, long-line, and bamboo raft. Seaweed was grown at three sites at the south coast of Kenya (Kibuyuni, Kijiweni, and Mwazaro) in one single cultivation cycle during the SEM season over a 45-day period, after which survival, growth and biomass were evaluated. Regardless of treatment and location, *K. alvarezii* exhibited the highest RGR (i.e. 2.5 ± 1.5% day^{-1}) and biomass production among the three species examined, followed by *E. denticulatum* and *G. salicornia* (i.e. 1.3 ± 0.5% day^{-1} and 0.75 ± 1.3% day^{-1}, respectively). Survival decreased significantly at 4 m compared to 0.5 m for all three species. Site-specific variations were evident, with seaweed growth in Kibuyuni consistently exhibiting lower growth rates and biomass than Kijiweni and Mwazaro, indicating underlying environmental differences, despite the absence of strong differences in measured environmental parameters. Off-bottom farming at 0.5 m depth yielded the highest eucheumatoid biomass per rope (0.75 kg DW). Subsequent economic assessments revealed that, under current market conditions (USD 0.50 kg^{-1} DW), profitability is attained solely by off-bottom farming in its present form, with break-even occurring after 29 cultivation cycles (approximately 3.7 years). In contrast, deeper water cultivation systems require substantial optimization before they can be recommended as viable options. Together, these results provide a practical evidence base for future scientists, aquaculture practitioners and policymakers seeking to design sustainable seaweed farming strategies in East Africa.

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1. Introduction

Seaweed farming has emerged as an essential livelihood activity along tropical coastal regions, particularly within the Indian Ocean basin (Eggertsen and Halling, 2021). In this region, seaweed cultivation primarily focuses on economically significant species such as *Eucheuma spp*. and *Kappaphycus spp*. (Hayashi et al., 2017; Ripanda and Mtenga, 2024). These species are valued for their biomolecule production including carrageenans, natural linear sulfated polysaccharides, which are widely utilized in food, cosmetics, and pharmaceuticals (Mahardika et al., 2019). In Africa, coastal communities in regions such as Zanzibar and coastal Kenya have embraced seaweed farming, particularly focusing on cultivating red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Lukwambe and Bwathondi, 2024; Mirera at. al., 2020; Wakibia et al., 2006a; Wekesa, 2022). In Kenya, the farming of these species has been promoted as a viable alternative or supplement to traditional fishing practices in coastal communities, especially relevant considering the challenges associated with declining fish stocks. Regional fisheries-Catch per-unit effort (CPUE) across the Indian Ocean has dropped by approximately 78% since 1950, with more than 80% losses reported in small scale sectors (Zeller et al., 2023). As such, seaweed cultivation by these coastal communities provides a new source of income, which enhances food security and supporting livelihoods of the coastal communities, as well as contributing to local economic development through both domestic and export markets (Mantri et al., 2019). In addition, seaweed farming plays a vital role in supporting women and marginalized groups by creating employment opportunities along the coastal region (Kimanga et al., 2025; Largo et al., 2020; Ripanda and Mtenga, 2024). In Zanzibar, women account for 80%–90% of seaweed farmers, according to surveys (Msuya, 2012), 78–88% on mainland Tanzania (The Nature Conservancy, 2023), and nearly 90% in Kenya's coastal communities (African Centre for Technology Studies ACTS, 2022).

Traditionally, commercial cultivation of eucheumatoids has been supported by the use of conventional culture techniques such as off-bottom lines, floating rafts, long lines, fixed long lines, and single or multiple-raft long lines (Hurtado et al., 2008; Hurtado and Agbayani, 2002). The off-bottom method, commonly used in intertidal zones in this region and other developing countries (Juanich, 1988), involves tying seaweed to lines fixed to wooden stakes anchored in the seafloor. Using this technique, the seaweed is able to grow while being submerged during high tide but also results in periodic aerial exposure during low tide, as exposure to air is an inherent feature of intertidal off-bottom farming and cannot be avoided (Msuya et al., 2007). The method, favoured for its simplicity, accessibility at low tides and cost-effectiveness, is typically applied at depths ranging from 0.3 to 2 m (Forbord et al., 2020; Kimathi et al., 2018; Msuya et al., 2007). Seaweed farming operations are conducted year-round, leveraging the relatively stable tropical marine conditions in the western Indian Ocean, with typical harvesting cycles lasting about six weeks (i.e. approximately 45 days; Holeh et al., 2025).

Despite a growth in seaweed production along the Kenyan coast from less than 1 metric ton in 2008–45 tons of dried seaweed in 2017 and 109 metric tons in 2024 (Mirera et al., 2020; pers. comm. Mirera), profitability remains low due to socio-economic and infrastructural limitations, including weak market access, price fluctuations, limited value addition and inadequate drying and storage facilities (Kimanga et al., 2025; Mirera et al., 2020). Similar challenges are observed regionally in Zanzibar and mainland Tanzania (Msuya, 2012). For instance, Tanzanian female seaweed farmers report low incomes and restricted resource access (Msuya and Porter, 2014). Additionally, the industry also faces environmental challenges which threaten its profitability, such as the occurrence of diseases and epiphyte infestations (e.g. Msuya, 2011a; Msuya et al., 2022a, Tsiresy, 2016). For example, production of *Kappaphycus* has declined significantly in Tanzania from 2016 onwards because of these threats (Msuya, 2011a; Msuya et al., 2022a). These are suggested to have been exacerbated by increasing water temperatures (Msuya and Porter, 2014). Limitations of the off-bottom method are increasingly evident in the face of climate change with rising sea temperatures and erratic tidal patterns (Matoju et al., 2022). While global sea surface temperatures (SSTs) are increasing overall, the Indian Ocean is one of the fastest and largest warming ocean basins globally (Bindoff et al., 2022; Blunden and Arndt, 2019). Dalpadado et al. (2021) reported an average increase in SST of 0.4–0.5 °C in a 22-year study period (during 1998–2019) for this basin. Projections indicate that sea surface temperatures in the region could increase by an additional 1.5°C to 2.0°C by 2100 under high-emission scenarios (Tilmes et al., 2020). While such data is presented for the entire Indian Ocean, temperature extremes will predominantly manifest in tidal pools and shallow intertidal coastal zones, where seaweed farming is currently taking place. These warming trends could exacerbate stress on seaweed farms, leading to increased outbreaks of diseases and reduced biomass production (Veenhof et al., 2024). In Tanzania, farmers have already been reported to halt production of *E. denticulatum* during the hot season for the last decade, and resume their activities in the rainy season, when temperatures fall below 30 °C (Largo et al., 2020). In addition, high temperatures were found to weaken seaweed thalli in force, making them more susceptible to bacterial infections, which by consequence reduce seaweed growth and biomass yields (Largo et al., 2020). For example, the prevalence of ice-ice disease affecting *E. denticulatum* in Zanzibar was found to peak significantly during the hot-dry season in February and March (Largo, et al., 2020). In addition, anthropogenic nutrient inputs might pose an additional challenge to coastal ecosystems (Nyenje et al., 2010), especially near the coastal communities where sewage management is currently absent (pers. obs.).

To address these challenges, subtidal ("deep-water") cultivation techniques have been explored globally, involving cultivating seaweed in water depths ranging from 2 to 20 m in subtidal zones (at the water's surface), where the water column provides more stable environmental conditions compared to intertidal, shallow systems (e.g. absence of desiccation stress, less pronounced temperature changes, etc.), e.g. in Malaysia (Husin et al., 2024), South Korea (Kim et al., 2022) and Tanzania (Msuya, 2011a; Msuya, 2015). While terminology surrounding "deep water" is inherently subjective and shaped by cultural and regional practices – with some contexts considering offshore systems deeper than 10 m as "deep" – in this study we adopt the East African standard, using 2–5 m as the threshold for deeper conditions relative to current nearshore practices. Accordingly, we use the terms "deeper-water" or "subtidal cultivation" throughout the manuscript.

Deeper water, subtidal cultivation requires sophisticated equipment, including motorized boats, to access farms located in relatively deeper, but more stable environments, in contrast to shallow-water cultivation, where farmers access the farms by walking during low tides. In Zanzibar, "deeper-water" or subtidal cultivation (2–3 m at low tide) has been proposed by Msuya et al. (2014) to address the problem of die-offs, especially for *K. striatum*.

Subtidal farming, at greater depths, has been suggested to reduce competition with other fast-growing macroalgae and epiphytes that thrive in nutrient-rich, intertidal environments (Wu et al., 2023). As such, subtidal farming holds potential for scaling up production, which can increase economic benefits for coastal communities. By reducing dependence on shallow intertidal zones, this method could potentially mitigate the impact of climate change while continuing to support livelihoods.

Given the challenges faced by intertidal water farming and the potential of farming at greater depths, this study aimed to compare their effectiveness along the Kenyan coast for three seaweed species, the commercially relevant eucheumatoids *K. alvarezii* and *E. denticulatum*, as well as the promising species *Gracilaria salicornia*, which is currently not farmed commercially but occurs naturally in the region and has been recognized as a potential source of agar and other bioproducts (Buriyo and Kivaisi, 2003; Msuya and Neori, 2002). In this study, we use the term “deeper water” to refer specifically to cultivation at 2–4 m depth in nearshore Kenyan waters, and we do not target truly offshore (>10–20 m) systems. Specifically, we aimed to (i) compare survival, relative growth rate and biomass across depths and cultivation methods, (ii) relate these patterns to *in situ* environmental conditions, and (iii) evaluate the short-term economic feasibility of these systems under current local market conditions. To our knowledge, no previous peer-reviewed study from the Kenyan coast or the wider Western Indian Ocean has experimentally compared shallow intertidal off-bottom farming with subtidal (2–4 m) cultivation while simultaneously quantifying seaweed performance and short-term economic returns under artisanal farming conditions. The selected sites – Kibuyuni, Kijiweni, and Mwazaro – were chosen based on their established seaweed farming activities and their ecologically contrasting settings: Kibuyuni is a more exposed tidal reef site, while Kijiweni and Mwazaro are more sheltered lagoon systems. These differences provided a basis to assess how environmental setting influences seaweed performance. By integrating biological and economic data in this pilot-scale study, we provide a first empirical assessment of the trade-offs between intertidal and subtidal cultivation under artisanal conditions along the Kenyan coast. These findings are directly relevant for local farmers, policymakers, and researchers, as they inform sustainable site selection and future research priorities in the region.

2. Material & methods

2.1. Study location and community selection

The experiment was conducted along the south coast of Kenya, specifically focusing on three distinct sites, each associated with a specific seaweed farming community: Kibuyuni (KB; situated at −4.6396783 S, 39.34161 E), Kijiweni (KJ; −4.649, 39.368) and Mwazaro (M; −4.592185, 39.39400833), as illustrated in Fig. 1. The selection of these communities was based on their experience in seaweed farming (Holeh et al., 2025). The chosen sites feature relatively clear water, a moderate tidal range and gentle water currents. Kibuyuni is a more exposed tidal reef flat site influenced by a fringing reef, whereas Kijiweni and Mwazaro are more sheltered lagoon systems with sandy or sandy–mud substrates. The sandy substratum was colonized by seagrasses, as well as macroalgae such as *Gracilaria* spp. and *Turbinaria* spp.

2.2. Seaweed origin

Three seaweed species, namely *Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva et al., 1996 (commonly known as ‘cottonii’), *Eucheuma denticulatum* (N.L. Burman) (Collins and Hervey), (1917) (‘spinosum’) and *Gracilaria salicornia* (C.Agardh) E.Y. Dawson, (1954) were selected for the study. Cultivated stocks of *K. alvarezii* and *E. denticulatum* were obtained from existing commercial seaweed farms in Kibuyuni, Kijiweni and Mwazaro. Smaller branches of the thalli, used as planting stock, were obtained by cutting them with a sharp knife, cleaning them of silt, as well as associated epiphytes and animals when present. In contrast, *G. salicornia* was collected from wild populations occurring in natural beds near the cultivation sites, as this species is not yet farmed in Kenya. All seaweed fragments underwent a thorough inspection for health, size, and signs of diseases or pests and were subsequently weighed to determine their initial biomass, which consistently ranged between 20 and 30 g wet weight (WW). As thallus length differs strongly between the species, thallus length was not recorded separately.

2.3. Experimental design and set up of the growth experiment

Three distinct cultivation methods were employed: stake-to-stake (also known as off-bottom, the traditional seaweed farming practice), bamboo raft (floating), and the long line method (floating) at three specified locations. The first two locations, i.e. Kibuyuni (location 1) and Mwazaro (location 2), cultivated seaweed using both the stake-to-stake and long-line methods. Meanwhile, location 3 (Kijiweni) employed the stake-to-stake and the bamboo raft method, as illustrated in Fig. 2 below. The cultivation process took place at three different depths at low tide, encompassing intertidal, shallow waters (0.5 m; current practice), subtidal, at deeper waters (2 and 4 m depth). In intertidal waters (i.e., 0.5 m), seaweed experienced periodic aerial exposure during low tides and during manual harvesting activities by the farmers. Over the experimental period, aerial exposure occurred on 15 days, with a maximum duration of 20 min on day 15 of the experiment. Exposure durations were moreover generally intermittent, corresponding to natural tidal patterns. In contrast, for the subtidal treatments at 2 m and 4 m, the thalli remained continuously submerged throughout the study at the surface and depth of cultivation does by consequence not reflect a change in the vertical position of the specimens. This reinforces that differences among subtidal treatments reflect differences in site water-

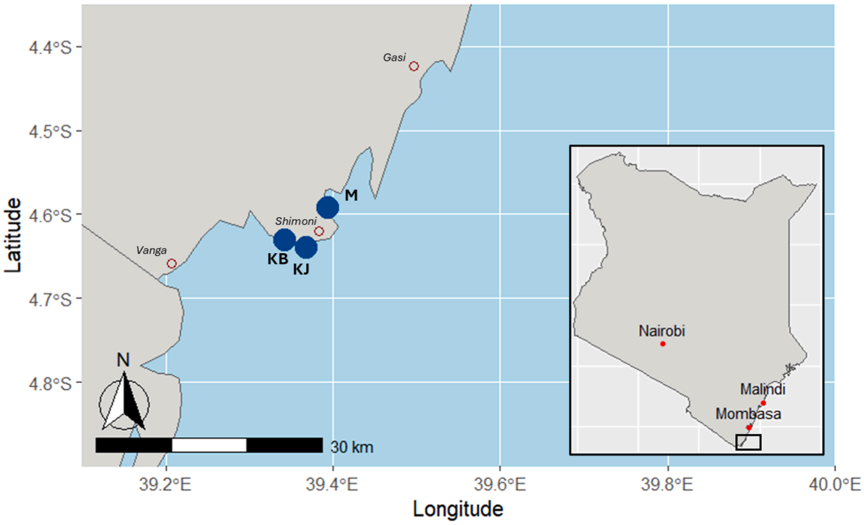

Fig. 1. Map of the south coast of Kenya showing the locations of the three study communities, marked with blue circles: Kibuyuni (KB), Kijiweni (KJ), and Mwazaro (M). Seaweed cultivation trials of three species were conducted at each site at three different depths (0.5 m, 2 m, and 4 m at low tide). The sites are situated within Msambweni sub-county, Kwale County. Empty, red circles indicate major towns in the vicinity of the study sites, while three major Kenyan cities, Malindi, Nairobi and Mombasa, being highlighted by a red dot on the map of Kenya.

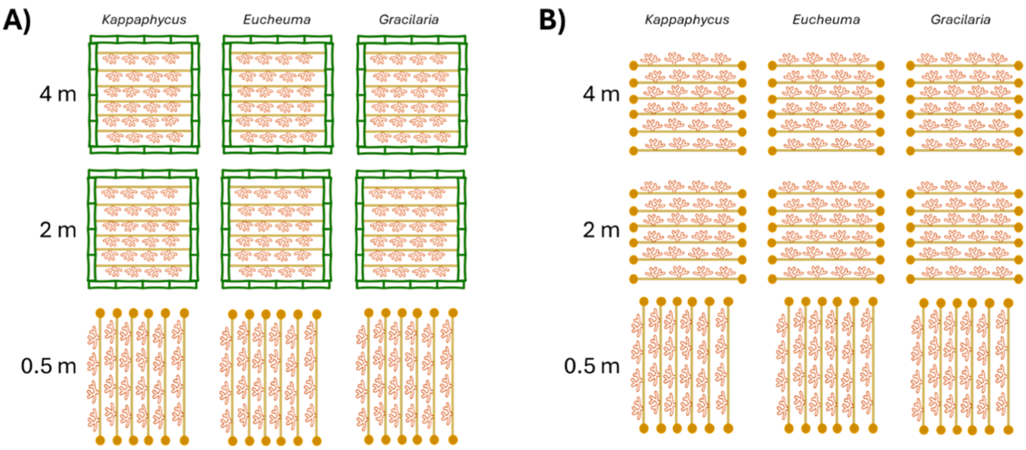

Fig. 2. Diagram illustrating the experimental setup. Three coastal communities (Kibuyuni, Kijiweni, and Mwazaro) implemented seaweed cultivation using three distinct farming methods (stake-to-stake, long-line, and bamboo raft) at three depth levels (0.5 meters, 2 meters, and 4 meters). Kijiweni employed stake-to-stake and the bamboo raft methods (A), while Kibuyuni and Mwazaro utilized stake-to-stake and long-line methods (B). The stake-to-stake (off-bottom) method was exclusively implemented at 0.5 m (intertidal, shallow water), while the bamboo raft and long-line methods were used at deeper levels (2 m and 4 m).

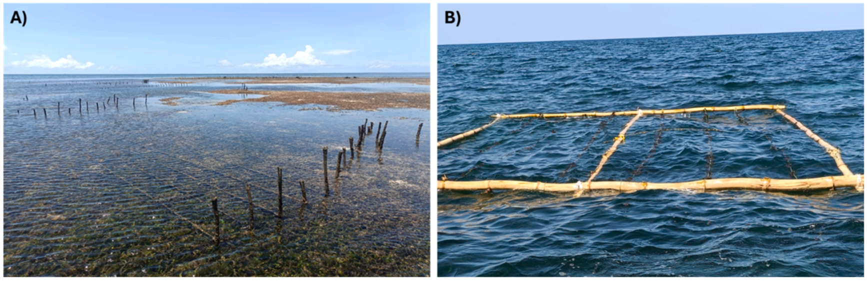

Fig. 3. Photographs illustrating two different seaweed cultivation methods employed in the study: (A) Stake-to-stake method, implemented in three coastal locations (Kibuyuni, Kijiweni, and Mwazaro) using 1.5 m stakes driven into the seabed to support cultivation ropes; (B) Bamboo raft method used in Kijiweni at depths of 2 m and 4 m during low tide, with six ropes attached to each raft, each 6 m long.

column context rather than line submergence depth.

The stake-to-stake culture method, currently the standard practice of seaweed cultivation along Kenya's coastline, was implemented in all three study sites, while the long-line method was used in Kibuyuni and Mwazaro. For both methods, 18 polypropylene ropes (FAIRB30100 polypropylene rope, 10 mm in diameter, with a 1425 kg breaking strain) served as the main lines for seedling attachment per site. The ropes measured 11 m long (10 m for seedling tying and 1 m rope used to wind the rope to stakes at both ends) for the off-bottom and long-line cultivation methods and 6 m for the bamboo raft method (5 m for seedling tying and 1 m for winding rope up to raft). Tie-ties made from raffia were prepared by winding them around this rope, creating double-loop knots at both ends, and inserting them into the rope at 15 cm intervals to securely hold the seaweed seedlings. Each tie-tie was attached at the strongest point of the seedlings to avoid damage. For the off-bottom and long-line systems, this spacing resulted in 50 seedlings per 10 m rope, i.e. 900 seedlings per plot (18 ropes; 300 specimens per species) at each site and depth. For the bamboo raft method, each 5 m seedling section carried 25 seedlings per rope, corresponding to 450 specimens per plot (18 ropes; 150 seedlings per species).

In the stake-to-stake method, the ropes were secured to 36 stakes, each measuring 1.5 m, cut from locally available hardwoods such as mango (*Mangifera indica*) and cashew nut tree (*Anacardium occidentale*), which are commonly used by the coastal communities. These stakes were cleaned and rinsed with seawater, before being installed in the seabed. In the long-line method, the 11 m ropes were stretched between anchors and floaters. The floaters (i.e. plastic jerrycans, 10 L) at both ends ensured the setup remained stable and suspended in water depths of 2 and 4 m, ensuring the seaweed remained fully submerged during the experiment. The anchors, concrete cubes weighing 20 kg each, were strategically placed in the substratum to secure the lines, with two anchors used for every line. For the bamboo raft method, 24 bamboo stakes (6 m × 6 m) were sourced from the Kibuyuni area and used to construct six bamboo rafts deployed at Kijiweni. Each raft was fitted with six equal-length ropes as described above. Three rafts were installed at 2 m depth and three at 4 m depth to cultivate the three seaweed species. The system was anchored to a single concrete weight of 50 kg on the seafloor using four mooring ropes (FAI RB30100 Polypropylene rope, 20 mm in diameter, with a 2400 kg breaking strain). Extra meters were utilized to secure the rope to the anchor on the seafloor, while the remaining length held the floating raft in position. This setup ensured stability, aiming to prevent drifting during tidal movements and strong currents, and provided a stable environment for seaweed cultivation. Similarly, mooring ropes anchored the long-line ropes with seaweed to two concrete weights on the seafloor.

Ropes containing seaweed were identified with numbered knots (1–6) at the beginning and end of each line, allowing individual ropes to be tracked throughout the experiment. A total of 18 ropes (i.e. 6 replicates per species) were deployed at each site and depth, with each 10 m rope holding 50 seedlings, resulting in 900 seedlings per plot (corresponding to 300 specimens per species) for off-bottom and long-line methods. For the bamboo raft method, each 5 m rope held 25 seedlings (also spaced 15 cm apart, resulting in 450 seedlings per plot (corresponding to 150 specimens per species). The bamboo rafts, with the attached ropes, were transported to the cultivation sites using a boat, with an estimated travel time of 5 min from shore to farm. The planting process began at Kijiweni on 26th of March 2024, followed by Kibuyuni and Mwazaro on 27th of March 2024, and the cultivation experiment ran for 45 days from initial planting to final harvest at all sites (cf. current practices). These cultivation dates fall within the Southeast monsoon, also known as the “long rains” season in Kenya (from March to May), which is generally associated with improved seaweed growth conditions (Wakibia et al., 2006).

2.4. Seaweed harvest and biomass determination

Harvesting was conducted at each site approximately one and a half months (45 days) after ‘planting’, coinciding with low tide to facilitate easier access. The harvesting began in Kijiweni on 11th of May 2024 (46th day post-planting), followed by Kibuyuni on the 12th May 2024 (48th day) and Mwazaro on the 13th of May 2024 (48th day). Harvesting in subtidal areas utilized speedboats, while sites with seaweed cultivated using the stake-to-stake method were reached by foot.

After harvesting, the number of remaining seedlings along the entire length of each rope was recorded to assess seedling losses during the cultivation period (i.e. thalli missing as a result of breakage, drifting or grazing). Additionally, the weight of each seaweed rope was measured using a spring balance. First, the rope with seaweed was measured and after taking off the seaweed, the empty rope was weighed as well. The harvested seaweed was carefully detached from the ropes to prevent damage and then sorted. The weight of the empty rope was subtracted from the total weight to get the net wet weight of the seaweed. As such, survival rate and average wet weight per seedling could be estimated. Finally, following common practice in eucheumatoid seaweed farming studies in the region (e.g. Doty, 1987; Wakibia et al., 2006a), relative, daily growth rates (RGR, in % day^{-1}),

could be calculated as the change in seaweed biomass throughout the experiment.

$$RGR = \frac{WW_2 - WW_1}{WW_1 \quad (t_2 - t_1)} * 100 \tag{1}$$

With WW_2 and WW_1 representing the final and initial wet weight of the seedlings (in kilograms) measured during the experiment, and t_1 and t_2 representing the first and final day (i.e. day of harvesting) of the experiment, respectively (in days).

For dry weight (DW) determination, harvested thalli were rinsed with clean seawater to remove debris and epiphytes, and subsequently sun-dried on elevated drying racks following the standard practice of local farmers. Samples were turned at least twice daily and dried for 3–4 days until they appeared visibly dry and brittle. The resulting dry biomass (DW) was then recorded and used for subsequent yield and economic analyses.

2.5. Measurement of environmental variables

At each farming site, environmental parameters were recorded at all depths (i.e. 0.5 m, 2 m, and 4 m), both at the start and at the end of the cultivation experiment, as well as halfway through the experiment (i.e. on day 22 for KB; on day 23 for KJ, M), providing a coarse, spot-sampling characterization rather than continuous monitoring. Salinity and water temperature were measured *in situ* using a calibrated marine waterproof salinity tester (Hanna Instruments, H1–98319) and digital thermometer (Hanna Instruments, HI98501), respectively. Secchi depth, a proxy of turbidity was estimated using a creamy-white stone disk with a diameter of 20 centimeters. In case Secchi depth recordings were bottom-limited (i.e. when true Secchi depth exceeds water depth), data readings were censored for statistical analysis. Conductivity was recorded at the start of the experiment on each site using a WTW Conductivity 315i conductivity meter (Weilheim, Germany). Additionally, water samples were taken at the surface using 1.5 L PET bottles at each site and depth. The bottles were rinsed with seawater at the respective sampling depths before filling to ensure the integrity of the samples. Once collected, the bottles were securely sealed and transported for further processing on land. Environmental variables were analyzed from these water samples on each site, including pH, alkalinity and the nutrients nitrate (NO_3^-), phosphate (PO_4^{3-}), and ammonia (NH_3/NH_4^+). These were determined using Hanna Instrument Marine Checker® kits (i.e., HI780 for pH, marine; HI772 for alkalinity, marine; HI781 for nitrate, low range, marine; HI774 for phosphate, ultra-low range, marine; and HI700 for ammonia, low range, marine), following the manufacturer's protocols.

For each site and depth, one sample of 10 mL was taken out of the PET bottles and put in an AAS-tube (Corning™, TP10–02) for total metal concentration analysis. To determine dissolved metal concentrations, water samples were first sent through a 0.45 µm PES filter (0.45µm, Acrodisc; Supor 450; Type: polyethersulfon membrane; not acid-washed) that was pre-rinsed with approximately 2 mL of sample before transfer into the 10 mL AAS-tubes. Afterwards, 100 µL HNO_3 (AAS30, Normatom, 83872.270, VWR) was added to all AAS-tubes in order to prevent the metal-ions from precipitating. Samples were stored at 4 °C until analysis and transported to Ghent University, Belgium. Metal (i.e., Ag, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se Zn) and phosphorus concentrations were measured using inductive coupled plasma-optical emission spectroscopy (ICP-OES) (iCAP 7000 series, Thermo Scientific). Limits of Detection (LOD) and Quantification (LOQ) are reported in Supplementary Table S1. If measured metal concentrations were in between LOD and LOQ, the value was set to the average of corresponding LOD and LOQ value for statistical analysis. For total organic carbon (TOC) measurements, non-filtered water samples were taken and stored in 12 mL glass tubes (VWR, 391–0145). Non-purgeable organic carbon (NPOC) was measured using a TOC-L analyzer set-up (Shimadzu). For each type of measurement, procedure blanks (at each site) as well as laboratory blanks were included using ultrapure water (Rephile Purist UV, RS2200QUV). Finally, meteorological data, including daytime and nighttime air temperatures, were obtained from the Ministry of Environment and Forestry, Kenya Meteorological Department website, specific to Kwale County. Tide information for the sampling sites was sourced from the Kenya Marine and Fisheries Research Institute's (KMFRI) tide table.

2.6. Data processing and statistical analysis

Calculated relative growth rates (RGR), biomass yields, and survival rates (SR) were calculated and are expressed as mean ± standard deviation throughout the manuscript. For all analyses, individual ropes were treated as the experimental replicates, with $n = 6$ ropes per species per depth and site. Statistical comparisons of survival, RGR and biomass across depths and sites were therefore based on rope-level means. Data cleaning and initial calculations were performed in Excel, followed by statistical analyses in R v4.2.2, using RStudio v.2023.03.0 + 386. Data were checked for outliers and tested for normality and homogeneity of variance using the Shapiro-Wilk test (stats package v4.4.1) and Levene's test (car package v3.1.3), respectively, prior to any other analysis. When applicable, analysis of variance (ANOVA) was used to assess the effects of location and depth on RGR, biomass yield, and survival rate, with post hoc Tukey's HSD tests applied for pairwise comparisons. When assumptions were violated, non-parametric Kruskal-Wallis and post hoc Dunn’s tests (stats package) were conducted. Bonferroni adjustments were applied for multiple comparisons, with significance set at $p < 0.05$. Spearman’s correlation analyses (stats package v4.4.1) were performed to evaluate relationships between the measured environmental variables and seaweed key metrics (RGR, biomass yield, and survival rate), with thresholds set at $p < 0.05$ for statistical significance. Measures of variance were reported as standard deviations in the text and tables, and data was visualized in boxplots for survival, RGR and individual biomass. Graphs were generated using the ggplot2 package v.3.4.0 and ggpubr package 0.6.0.

2.7. Economic feasibility assessment

To assess the economic feasibility and viability of each farming method, we compared costs as well as eucheumatoid biomass yields (i.e. average yield of *K. alvarezii* and *E. denticulatum*), associated with each method. Therefore, we based ourselves on the model farm scenario proposed by Mirera et al. (2020), which was set to reflect current seaweed cultivation practices along the Kenyan coast. A model farm consists of 15,000 seaweed fragments ("seedlings") cultivated on either 300 ropes (for both off-bottom and longline methods, each rope holding 50 seedlings) or 600 ropes (for the bamboo raft method, each rope holding 25 seedlings). This standardized setup enabled a comparative analysis across the three farming methods under consistent production conditions, as well as comparison with the previous regional economic assessment, performed by Mirera et al. (2020).

Cost analysis included both material and labor inputs required for initial setup and harvesting, based on the input of the current field experiment. More specifically, input and capital costs were based on local prices at the time of the study and treated as fixed in the base scenario, with infrastructure costs accounted for as upfront investments in the first cultivation cycle; seedstock losses are implicitly captured through the observed survival and yield data. Labor requirements were estimated based on direct observations during the current experiment. The number of working hours was recorded for each activity including system installation, seedling preparation and planting, routine maintenance, and harvesting. These labor inputs were first standardized per rope and then multiplied by 300 or 600 to reflect the full model farm. Wage estimates were derived from prevailing hourly local rates at the area, as recorded during field operations (pers. obs.), and applied proportionally to the estimated total labor hours per model farm.

The economic performance of each farming method was evaluated over two key phases: (i) the initial cultivation cycle, which includes full infrastructure and setup costs, and (ii) subsequent cultivation cycles, where infrastructure is considered a sunk cost and only variable/recurrent costs are considered. This distinction was made to evaluate both short-term feasibility and long-term profitability. Revenue estimates were based on a market selling price of USD 0.50 per kilogram of wet or dry seaweed, which reflects the average price the studied communities received in 2024. As no biochemical quality metrics (e.g., carrageenan/agar yield, gel strength) were measured in the current study, potential quality premiums were not included. Economic indicators used to assess performance included: net income per cultivation cycle (USD), cost per seedling and per cultivation rope (USD), break-even yield (kg DW) and break-even price (USD kg^{-1} DW), and the number of cultivation cycles required to reach break-even. Return on Investment (ROI) was calculated as:

ROI (%) = (Income-operational cost)/Operational cost) * 100%

Finally, a sensitivity analysis was conducted, following the approach of Wakibia et al. (2011), to evaluate financial resilience of each method under two hypothetical but realistic scenarios: (i) a 20% reduction in farm gate price, and (ii) a 20% increase in operating costs.

3. Results

3.1. Environmental differences between cultivation sites and depths

Supplementary Table S2 provides an overview of the measured environmental parameters for the sampled locations at the three depth levels: intertidal (0.5 m) and subtidal (2.0 and 4.0 m), averaged over the three sampling timepoints (at start, during and harvest time of the experiment). Across all sites and depths, water temperatures were relatively stable, ranging between 28.55 ± 0.1 °C and 30.3 ± 2 °C throughout the cultivation experiment. There were also no major differences in salinity among study sites or depths, with the highest recorded salinity of 35.7 ± 2.0 PSU (Mwazaro, 0.5 m depth), averaged over time. Additionally, pH levels ranged from 8.3 ± 0.2 (Mwazaro, 2.0 m) to 8.4 ± 0.3 (Kijiweni, 2.0 m).

Regarding nutrient concentrations, nitrate was the most abundant nutrient, with mean (±SD) concentrations ranging from 1.28 ± 0.82 mg L^{-1} (Mwazaro, 0.5 m) to 4.05 ± 0.51 mg L^{-1} (Mwazaro, 2.0 m). Phosphate concentrations ranged from 0.02 ± 0.01 mg L^{-1} (Mwazaro, 4.0 m) to 0.11 ± 0.08 mg L^{-1} (Kibuyuni, 2.0 m). Ammonia concentrations were generally low, with a notably higher level at Kibuyuni at 0.5 m depth (0.14 ± 0.08 mg L^{-1}) compared to 2.0 m and 4.0 m depth. No significant differences in ammonia concentrations were found between the different depths at the other sites (Tukey HSD, $p > 0.05$).

Total organic carbon (TOC) concentrations across the sampling locations exhibited slight variations, with a mean (±SD) ranging from 1.98 ± 0.4 mg L^{-1} (Mwazaro, 4.0 m) to 5.3 ± 5.0 mg L^{-1} (Kibuyuni, 0.5 m). Among the metals that were analyzed, total and dissolved silver (Ag), arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), nickel (Ni), lead (Pb), and selenium (Se) concentrations were consistently below the LOD and were therefore excluded from statistical analysis and interpretation.

There were few correlations (Spearman) between the measured environmental parameters, as depicted in Fig. 4. Principle component analysis was used to visualize and investigate the clustering of our data, based on the measured environmental parameters (Figs. 4C, 4D). The PCA results based on dimension (Dim) 1 and 2, capturing 29.7% and 20.8% of the variance respectively, revealed no distinct clustering patterns, indicating that these components do not effectively summarize the major sources of variation in the dataset. This suggests that the measured environmental parameters do not exhibit strong spatial structuring at the investigated depths (0.5 m, 2 m, and 4 m) or across the selected coastal communities (Kibuyuni, Kijiweni, and Mwazaro). The first principal component (Dim 1) is mostly associated with nutrient concentrations, while water temperature is mostly associated with the second dimension. These results correspond to the correlation analyses presented in Fig. 4A.

3.2. Effect of deeper, subtidal cultivation on survival rate

There were no significant differences in survival rate across sites for the three species (Kruskal Wallis, $p > 0.05$), except for a significantly lower survival rate of *K. alvarezii* at Kibuyuni compared to Kijiweni (Dunn's test, adj. $p < 0.05$) (Table S3). Regardless of cultivation site, survival at 0.5 m depth was significantly higher compared to subtidal water cultivation at 4 m depth for all species (Dunn's test, adj. $p < 0.05$). In addition, for *K. alvarezii*, there was also a significant difference in survival rate between 2 and 4 m depths (Dunn's test, adj. $p < 0.05$), although this was not the case at the other sites (Fig. 5). *Kappaphycus alvarezii* recorded the highest survival at 97.7 ± 0.8% in Mwazaro at a depth of 0.5 m (off-bottom method), while survival dropped to 24.70 ± 17.20% at 2.0 m in the same location (long-line method). For *E. denticulatum*, there was no significant difference in survival between cultivation at 0.5 and 2 m (Dunn's test, adj. $p > 0.05$), but similar to *K. alvarezii*, there was a significant difference in survival rate between 2 and 4 m depths (Dunn's test, adj. $p < 0.05$). For *G. salicornia*, survival significantly decreased with increasing cultivation depth at all sites (Dunn's test, adj. $p < 0.05$), except between 2 and 4 m at Kijiweni (Fig. 5). *Gracilaria salicornia* exhibited the lowest survival rates, ranging from 78.0 ± 24.2% at a depth of 0.5 m in Mwazaro (off-bottom) to 0% in Mwazaro and Kibuyuni at a depth of 4.0 m (long-line method).

3.3. Effect of subtidal cultivation on relative growth rate and biomass yield

Average individual fresh weight and relative growth rates (RGR) of *K. alvarezii*, *E. denticulatum*, and *G. salicornia* at harvest are summarized in Supplementary Table 3. Regardless of species, we found a significant difference in relative growth rate between cultivation sites and depths

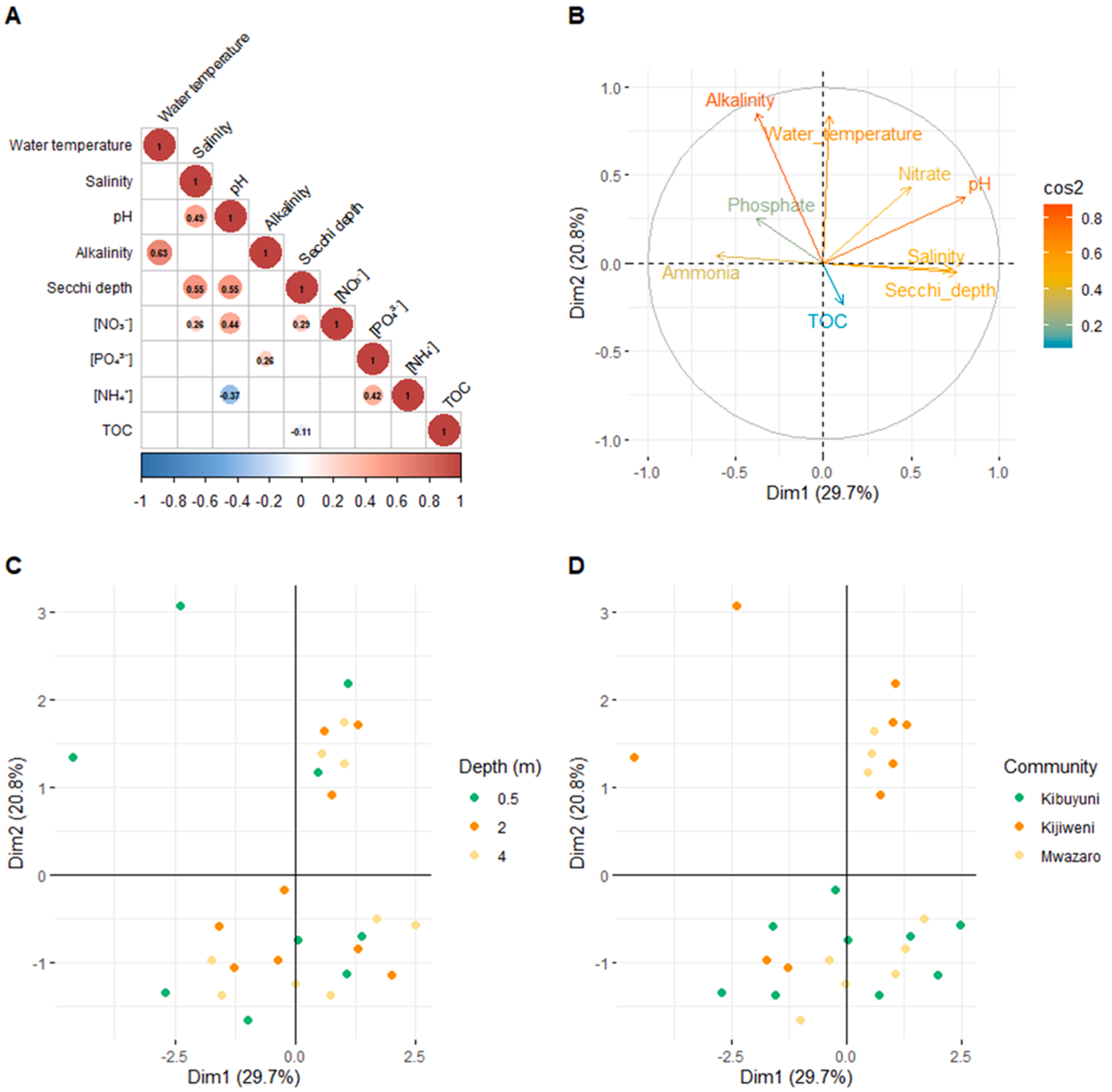

Fig. 4.. Graphs depicting relationships between environmental parameters. A) Correlation plot visualising correlations (Spearman rank correlation) between the different environmental variables. The circles' colour represents correlation strength, while the numbers inside each box indicate the corresponding correlation value. Only significant correlations are reported ($p < 0.05$), while insignificant correlations are left blank. B) Correlation circle of associated PCA (see C, D). Vectors are the loadings on PC1 (x-axis) and PC2 (y-axis). The quality of representation of the variables (taxa) is indicated by the squared cosine (cos2). A high cos2 value indicates a good representation of the parameter on the principal component. In this case the parameter is positioned close the circumference of the correlation circle. A low cos2 indicates the variable is not well represented by the PCs and will be positioned close to the centre of the circle. Vector length indicates the strength of the relationship and the angle between two vectors gives the degree of correlation (adjacent = highly correlated parameters, orthogonal (90°) = uncorrelated parameters, and opposite (180°) = negatively correlated parameters). C, D) PCA plots focusing on clustering patterns for sampling depth and location, respectively. Single points refer to an individual sample taken at a specific time, location and depth, as indicated in the legend.

(Kruskal Wallis, $p < 0.05$; Fig. 5). Regardless of treatment and location, *K. alvarezii* exhibited the highest RGR (i.e. 2.5 ± 1.5% day^{-1}) and biomass production among the three species examined, followed by *E. denticulatum* and *G. salicornia* (i.e. 1.3 ± 0.5% day^{-1} and 0.75 ± 1.3% day^{-1}, respectively). For all species, RGRs and biomass yields at Kibuyuni were significantly lower compared to Kijiweni and Mwazaro (Dunn's, adj. $p < 0.05$). There was no significant difference in RGR for *K. alvarezii* between the different cultivation depths (Dunn's, adj. $p > 0.05$). In contrast, RGR of *E. denticulatum* was significantly lower at 4 m cultivation depth compared to 0.5 m in Mwazaro and Kijiweni (Dunn's, adj. $p < 0.05$), but not in Kibuyuni (Fig. 5). We also found a significant higher RGR for *G. salicornia* grown at 0.5 m compared to subtidal waters (Dunn's, adj. $p < 0.05$), but this pattern was only observed in Kijiweni (Fig. 5).

In terms of average harvested biomass per individual, we also found a significant effect of location for *K. alvarezii* and *E. denticulatum* (Kruskal Wallis, $p < 0.05$) and cultivation depth for *G. salicornia* and *E. denticulatum* (Kruskal Wallis, $p < 0.05$). Regardless of depth, biomass yields at Kibuyuni were significantly lower compared to the other two sites (Dunn's, adj. $p < 0.05$; Suppl. Figure 1). There was no significant difference in average thallus biomass for *K. alvarezii* between the different cultivation depths in Mwazaro and Kijiweni (Dunn's, adj. $p > 0.05$). Individual *G. salicornia* biomass was not significantly higher when cultivated in water column of 0.5 m deep compared to 2 m, except for Kijiweni where no *Gracilaria* was left at harvest (Dunn's, adj. $p < 0.05$). There was no difference in individual biomass when cultivating *E. denticulatum* in water columns of 0.5 and 2 m deep across all sites, but individual biomass at 0.5 m was significantly higher compared to the 4 m treatment (Dunn's, adj. $p < 0.05$; Suppl. Figure 1).

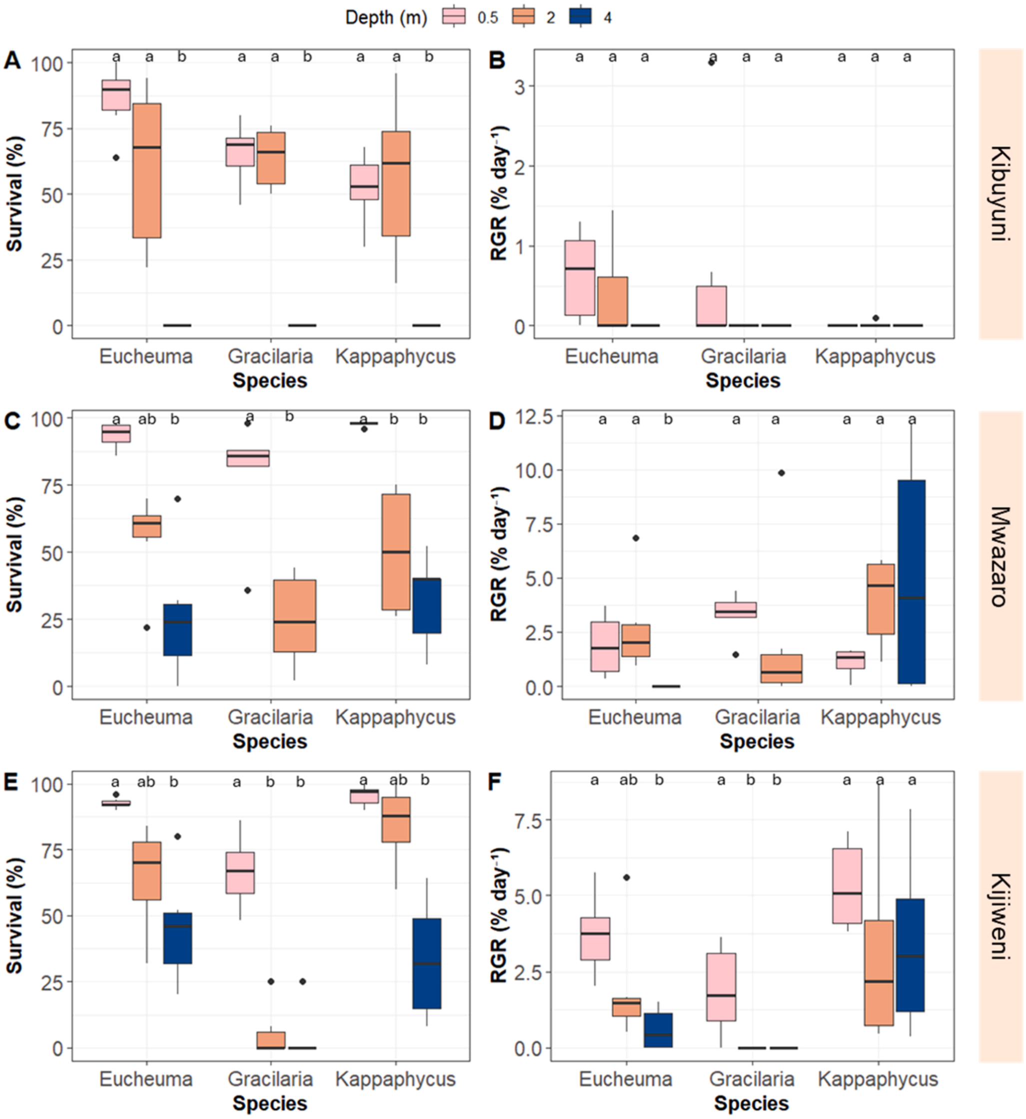

Fig. 5. Boxplots illustrating (A, C, E) variation in survival rates (%) of *Eucheuma denticulatum*, *Gracilaria salicornia* and *Kappaphycus alvarezii* and (B, D, F) respective relative growth rates (RGR, as % day^{-1}) after harvest at different depths (0.5, 2 and 4 m) at the different cultivation sites *Kibuyuni*, *Mwazaro* and *Kijiweni*. Each box represents the interquartile range (IQR, 25th to 75th percentile), with the horizontal line inside the box indicating the median (50th percentile). Whiskers extend to the lowest and highest values within 1.5 × IQR, and outliers beyond this range are shown as individual dots. Different letters represent statistically significant differences (per species) (Dunn's test, adjusted $p < 0.05$).

3.4. Correlation between environmental factors and seaweed growth and survival

To elucidate the influence of environmental conditions on seaweed growth (growth rate and biomass yield) and survival, we searched for correlations between the measured environmental parameters and the studied indicators of seaweed performance. Among the variables assessed, water temperature exhibited a statistically significant positive correlation with the RGR of *K. alvarezii* (Spearman's $\rho = 0.68$, $p < 0.05$), but not with other seaweed performance metrics. No significant correlations were observed between these metrics and other environmental factors such as pH, salinity, total organic carbon (TOC), or nutrient concentrations, with the exception of dissolved phosphorus (P). Specifically, a significant positive correlation was identified between dissolved phosphorus concentrations and the RGR of *K. alvarezii* (Spearman's $\rho = 0.71$, $p < 0.05$). In addition, the RGR of *G. salicornia* demonstrated significant positive correlations with concentrations of dissolved iron (Fe) and zinc (Zn) (Spearman's $\rho = 0.82$ and 0.71, respectively; $p < 0.05$).

3.5. Economic assessment of the different farming models

To compare the economic performance of the different farming models, we constructed a simple cost–benefit model for a standardised "model farm" of 15,000 eucheumatoid seedling fragments. For the stake-to-stake (off-bottom) and long-line methods this corresponds to 300 ropes with 50 seedlings per 5–10 m rope, whereas the bamboo raft method consists of 600 ropes with 25 seedlings per 5 m rope. Input and capital costs (stakes, ropes, raft frames, anchors, tie-ties and boat hire) were based on local market prices and wages in Kwale County at the time of the study and are treated as fixed in the base scenario. Infrastructure costs are accounted for as upfront capital investments incurred in the first cultivation cycle; subsequent cycles only include operational costs (labour and transport). The farm-gate selling price of dried seaweed is set at USD 0.50 kg^{-1} dry weight, reflecting the prevailing price reported by farmers and buyers in the study communities during the study period. Seedstock losses are implicitly incorporated through the experimentally observed survival and yield data, which form the basis for all revenue and profitability calculations. No discounting is applied, and prices are assumed to remain constant across cultivation cycles in the base scenario.

Supplementary Table S5 and S6 summarize the estimated farming costs and labor requirements to set up and harvest a model farm of 15,000 eucheumatoid seaweed fragments, cultivated on 300 ropes (off-bottom and long line methods) or 600 ropes (bamboo raft method), containing 50 and 25 seedlings per rope, respectively. The polypropylene ropes were identified as a major cost component, which accounted for approximately 87.3% of total material costs in the off-bottom method (USD 1666.65 out of USD 1909.05), 37.4% in the bamboo raft method (USD 1665 out of USD 4451.9), and 33.1% in the long line method (USD 1666.65 out of USD 5034.05) (Table S5), reaffirming their critical role in production setup.

In terms of setup costs, the stake-to-stake (off-bottom) method stands out as the most affordable option, with a total implementation cost of USD 1956.65 (comprising USD 1909.05 for materials and USD 47.60 for labor). Including harvest-associated costs, the total cost per rope in this method is approximately USD 5.56, and the cost per seedling is around USD 0.13. Both the bamboo raft and long line methods incur significantly higher costs, totaling USD 4541.39 (USD 4451.90 in materials and USD 89.49 in labor) and USD 5125.64 (USD 5034.05 in materials and USD 91.59 in labor), respectively. Despite similar seedling output, the cost per 5-meter rope is USD 7.57 and per seedling USD 0.30 using the bamboo raft method. For the long line method, the cost per seedling is USD 0.34 and per 10-meter rope is USD 17.08. These higher expenses at subtidal water sites are primarily driven by raft construction materials, anchoring infrastructure, and transport logistics (Table S5).

The economic performance of the different seaweed farming methods based on experimental data is summarized in Table 1. The analysis compares production yields, costs, revenues, and profitability indicators for each method. All methods assume a standard selling price of USD 0.50 kg^{-1} dry weight, reflecting prevailing market conditions in local communities. The off-bottom method achieved the highest output per rope (0.75 kg DW) and one of the highest total farm yields (223.6 kg DW), resulting in a total income of USD 111.8 per cycle. In contrast, the bamboo raft and long line methods yielded 210.5 kg DW and 150 kg DW per cycle, generating total incomes of USD 105.2 and USD 75.0, respectively. Despite this, all three methods incurred net losses after the first cultivation cycle due to high initial setup costs (Table 1). Under current prices and yields, only the off-bottom method generated positive net returns, becoming profitable from the second cultivation cycle onward. From the second cultivation cycle onward, when infrastructure costs are significantly reduced, only the off-bottom method becomes economically viable, generating a profit of USD 64.2 per cycle. Both the bamboo raft and long line methods remain unprofitable, with continued losses of USD 584.2 and USD 676.6 per cycle, respectively. The break-even analysis underscores these differences. For the first cultivation cycle, the off-bottom method would require a break-even price of USD 8.8 kg^{-1}, $^{-1}$, compared to 20.5 and 34.2 USD kg^{-1} for the bamboo raft and long line methods, respectively. Although all of these values are far above the current farm-gate price (USD 0.50 kg^{-1}), they illustrate the relatively better economic performance of the off-bottom method. Finally, the off-bottom method is projected to reach break-even status after approximately 29 cultivation cycles (3.7 years), which represents a long and potentially risky payback period for smallholder farmers exposed to storms, disease outbreaks and price fluctuations. By contrast, under the tested yields and prices, both the bamboo raft and long line methods do not reach break-even, highlighting limited financial viability in these circumstances.

Table 1

Economic performance comparison of the different farming methods for eucheumatoids, based on a 300 rope (off-bottom & long-line method) or a 600 rope (bamboo raft method) model farm scenario. NA: Not applicable.

Variables	Off-Bottom	Bamboo Raft	Long Line
Total yield per rope (kg WW)	4.10	1.93	2.75
Total yield per rope (kg DW)	0.75	0.35	0.5
Yield per model farm (kg DW)	223.6	210.5	150
Selling price per kg DW (USD kg^{-1})	0.5	0.5	0.5
Total income from one cultivation cycle (USD)	111.8	105.2	75
Total Costs (USD) 1st cultivation	1956.65	4312.81	5125.64
Profit after 1st cultivation (USD)	-1844.86	-4207.56	-5050.66
Operational Costs (USD) 2nd cultivation (i.e. labor, transport (boat) costs)	47.6	689.49	751.59
Profit – 2nd cultivation onwards (USD)	64.2	-584.2	-676.6
Break-even price (USD kg^{-1} DW)	8.8	20.5	34.2
Break-even yield (kg DW)	3913.3	8625.6	10,251.3
ROI (%) from 2nd Cycle	134.87	-85.34	-90.02
Number of cultivation cycles required to reach break-even (#)	29	NA	NA
Payback period (Years)	3.73	NA	NA

Supplementary table 7 presents a sensitivity analysis of return on investment (ROI) and payback periods for the different farming methods, under varying economic scenarios. The economic indicators (ROI and payback period) for all cultivation methods were sensitive to changes in farm gate price and operational costs. In the event of a 20% decrease in farm gate price, the ROI for the off-bottom method declined from 134.87% to 87.9%, while the payback period extended from 3.73 to 6.03 years (equivalent to 46.8 cultivation cycles). Similarly, a 20% increase in operational costs caused the ROI of the off-bottom method to decrease to 95.73%, with a corresponding increase in the payback period to 4.61 years (or 35.8 cycles). In contrast, both bamboo raft and longline methods remain financially unviable and continued to incur losses in other scenarios.

4. Discussion

4.1. Effect of subtidal water cultivation on seaweed growth and survival

In the current study, we evaluated seaweed growth and survival of three red algae at three different water depths in three different sites along the south Kenyan coast. The three cultivated species *K. alvarezii*, *E. denticulatum*, and *G. salicornia* naturally occur in intertidal, shallow tropical waters and are typically farmed at depths of 0.5–2 m to maintain continuous submersion and minimize stress from tidal exposure (Du et al., 2023; Goh et al., 2023). For the bamboo raft and long-line systems, culture ropes were suspended near the water surface at all sites, so that the 2 and 4 m treatments represent different total water-column depths rather than different vertical positions of the thalli themselves. In other words, for these systems “depth” mainly reflects differences in water-column characteristics and exposure (e.g. hydrodynamics, tidal regime, absence of aerial exposure) compared to the intertidal off-bottom plots.

It is important to note that cultivation method and depth were not fully independent in this artisanal field setting, which may confound depth-related effects. Off-bottom farming was applied exclusively in the intertidal/very shallow treatment (0.5 m), whereas floating long-line and bamboo-raft systems were deployed only at subtidal depths (2–4 m), reflecting realistic method–depth combinations used by seaweed farmers around the globe. To minimize methodological variation, we used the same materials whenever possible (e.g., ropes, tie-ties); however, some system-specific differences were unavoidable. For example, floating bamboo poles in the raft system may subtly modify water flow and potentially influence growth or survival. Nonetheless, both subtidal systems yielded comparable results, suggesting that any system-specific effects on performance were likely minimal. Future studies employing a fully factorial design with standardized cultivation gear across depth strata would enable the quantification of depth effects independently of cultivation method.

The results of this study indicate that “the depth” of the water column significantly affected the survival and performance of *K. alvarezii, E. denticulatum,* and *G. salicornia*, with cultivation at subtidal, deeper waters resulting in lower survival across all species. These patterns confirm that moving farms from intertidal/off-bottom settings into deeper, permanently submerged sites does not automatically improve performance. Subtidal ("deeper-water") cultivation of eucheumatoids has been recorded in several countries, such as Brazil, India, Indonesia and Tanzania (Hayashi et al., 2017; Msuya, 2011b), but these reports are usually anecdotal and not detailed in peer reviewed literature. To date, no peer reviewed studies have systematically compared seaweed performance across different depths, although some reports are available in the grey literature. For example, Msuya (2010) describes the evaluation of "deeper-water" floating lines to cultivate *K. alvarezii* in water depths of 2.5–6 m, depending on the tide, in Tanzania. Using the new technique, she reported the die-off problem to be reduced to a minimum and that farmers were able to harvest *K. alvarezii* throughout the year and regardless of the tide. In addition, the floating lines technique were reported to be more productive (0.35 kg per meter line per year) compared to the off-bottom method (Msuya et al., 2007). Yahya et al. (2020) compared intertidal off-bottom lines and "deeper-water", subtidal floating rafts with tubular nets (at a depth of 4–5 m during high tide and 1–2 m during low spring tide) in Zanzibar, Tanzania, and found no significant differences in *E. denticulatum* growth between subtidal and intertidal farms, with an average daily growth rate of 3.42 ± 0.18% and 3.01 ± 0.27% per day, respectively. The results of Yahya et al., (2020) are in sharp contrast with these findings. Rodine et al. (2026) cultivated *Gracilaria salicornia* in the Toliara region (southwestern Madagascar) using a 20 m long-line system installed approximately 4 m above the seabed, with tidal fluctuations causing depth variations between 2.5 and 5.5 m; however, growth performance was not compared with cultivation at shallower depths.

Environmental analysis did not reveal a major difference in nutrient concentrations, water temperature, salinity or turbidity across the different depths. Moreover, as the algae were cultivated near the water surface in the bamboo raft and long-line methods, light limitation likely is not responsible for the lower performance observed when cultivating the seaweed in a water column of 4 m deep. While there was no direct quantification of epiphytic growth in this study, visual observations indicated that seaweed cultivated at greater depths did not appear to have noticeably higher epiphyte loads. This suggests that the observed differences in seaweed survival are likely attributable to other factors, such as biotic interactions (e.g., herbivory) or physical stressors (e.g., wave exposure). The decline in performance at increased depths might be attributed to heightened water movement, which is known to adversely affect seaweed attachment and growth (Doty et al., 1987; Glenn and Doty, 1992). However, changes in water current or wave action were not measured in this study and therefore cannot be ruled out as contributing factors when interpreting the results. Stronger currents at greater depths and/or increased grazing by herbivores may have influenced survival rates factors that have also been reported to affect seaweed farming in other coastal regions of East Africa (Flores et al., 2015; Halley, 2024; Kasim and Asnani, 2013). For example, herbivorous fish activity was reported to decrease total production of *E. denticulatum* up to 60% in Indonesia (Kasim and Asnani, 2013). Yahya et al. (2020) also suggested higher herbivory prevalence in the Tanzanian "deeper-water" farms compared to the off-bottom system.

In Kenyan and Tanzanian waters, *K. alvarezii* has also been reported to be a food source for rabbitfish (*Siganus* spp.) and linked with for poor growth rates and yields (Msuya, 2021; Nyamora et al., 2018). In the plots of Kibuyuni, characterized by the lowest yields overall in the current study, we indeed observed signs of grazing by fish and sea urchins at the time of harvest, with individuals of the latter still being attached to the ropes and thalli. Kasim and Mustafa (2017), conducting research in Southeast Sulawesi, Indonesia, observed that *E. denticulatum* cultivated in floating cages exhibited higher growth rates and better thallus morphology compared to those grown using long-lines, as the seaweed in the cages were protected from herbivory. Implementing protective measures could help mitigate these challenges.

4.2. Spatial differences in seaweed performance and influence of environmental conditions

The obtained RGRs of *E. denticulatum* and *K. alvarezii* at Kijiweni using the off-bottom method (i.e. 3.72 ± 1.31% day^{-1} and 5.32 ± 1.45% day^{-1}, respectively) are above the recommended value for commercial cultivation, which is 3.5% day^{-1} (Doty et al., 1987, Glenn and Doty, 1990). However, a maximum RGR of *K. alvarezii* has been reported to be up to 5.7% day^{-1} in Kenya (Kimathi et al., 2018) and 5.0% day^{-1} in Zanzibar (Msuya et al., 2014). At the other cultivation sites, obtained RGRs were below the recommended threshold. Observed variation in seaweed performance across locations suggests that site selection is a key determinant of farming success. Supplementary table 4 presents the RGRs of eucheumatoids cultivated in East Africa, aligning our findings with previously reported values in the literature. Wakibia et al. (2006a) reported variations in RGRs depending on farming site and *in situ* environmental settings. Our results are similar to Wakibia et al. (2006a), who reported eucheumatoid RGRs of 5.6% per day in a sandy flat mangrove site and 3.2% per day in tidal reef sites in Kenya (employing the off-bottom technique). In our study, *E. denticulatum* had higher RGRs in sandy flat environments, such as those observed in Kijiweni and Mwazaro (3.72 ± 1.31% day^{-1} and 1.88 ± 1.40% day^{-1} at 0.5 m depth, respectively), compared to the tidal reef site in Kibuyuni (0.64 ± 0.56% day^{-1} at 0.5 m depth). These patterns are consistent with the sheltered, lagoonal settings of Kijiweni and Mwazaro, which are likely characterized by lower hydrodynamic forcing, reduced mechanical abrasion, lower turbulence and thus more stable sedimentary conditions compared with the more exposed tidal reef environment at Kibuyuni. These trends suggest that lagoon environments provide more favorable conditions for seaweed productivity, while tidal reef environments might impose either greater physical stress, by wave-induced damage, or greater risk to predation. Yahya et al., (2020), Kimathi et al. (2018) and Msuya (2021) indeed found that herbivory by fish (e.g. rabbitfish (*Siganus* spp.) and parrotfish (Scaridae)),and invertebrates (e.g. sea urchins) can significantly reduce seaweed biomass in Zanzibar (Tanzania), particularly in areas with higher biodiversity. Kimathi et al. (2018) similarly reported a significantly higher incidence of herbivory, epiphytism and 'ice-ice' syndrome in Kibuyuni compared to Mkwiro, a sandy mudflat site. The lower productivity observed in the tidal reef site (Kibuyuni) may also reflect an ecological trade-off. Under higher stress from herbivory pressure and/or hydrodynamic forces, seaweed may invest more in the production of secondary metabolites as a defense mechanism rather than allocating energy to growth. This hypothesis warrants further investigation to assess whether differences in metabolite profiles correlate with site-specific environmental pressures. Comparable lagoon–reef contrasts have been reported in Tanzania, where more sheltered, subtidal farms showed better survival and lower disease incidence than exposed sites (Msuya, 2011a; Yahya et al., 2020), and in Malaysia, where Husin et al. (2024) also identified hydrodynamic exposure and site choice as key drivers of eucheumatoid performance.

Environmental monitoring in this study primarily served to understand whether abiotic variation affected cultivation performance. Sea water temperature (Kumar et al., 2020), water depth (Hurtado et al., 2008), salinity (Araujo et al., 2014), sedimentation levels and water motion (Doty et al., 1987; Glenn and Doty, 1992) are considered as crucial factors influencing the survival and growth of eucheumatoids. Water temperatures and salinity were relatively stable across all sites and depths and within the broad ranges considered for cultivation of eucheumatoids, which is recommended between 25 °C and 28 °C, and between 30 and 40 ppt (Ask and Azanza, 2002). Other studies reported general optimal growth within a temperature range of 21–30 °C (Glenn and Doty, 1990; Largo et al., 2020), or within a temperature range of 23–32 °C for *E. denticulatum* and a range of 22–33°C for *Kappaphycus* spp. for optimal growth (Lideman et al., 2013). Despite these optima, temperatures above 30°C have been associated with increased susceptibility to the "ice-ice" disease (Harley et al., 2012). In Tanzania, Msuya et al. (2022b) have shown that higher water temperatures (33–38 °C) during warmer months (December – February) can indeed reduce survival rates. Kimathi et al. (2018) reported weak, but significant, negative correlations between the RGRs of both eucheumatoids and environmental factors such as maximum water temperature, phosphate concentrations, prevalence of 'ice-ice' syndrome (%), herbivory (%) and epiphytic load. In our dataset, we similarly detected a positive correlation between dissolved phosphorus concentrations and RGR for *K. alvarezii* (3.4), but no strong chemical differences among depths, suggesting that physical exposure and biotic stressors, rather than basic water chemistry, dominate the spatial patterns in performance. Although *in situ* environmental parameters were recorded in this study, the resolution and frequency of measurements (e.g., spot sampling) were insufficient to detect short-term or microhabitat fluctuations that may significantly affect seaweed performance. For instance, fine-scale thermal fluctuations, water turbulence, and light variability particularly critical in intertidal, shallow waters were not captured. We therefore consider the environmental dataset as a coarse characterization of site conditions rather than a high-resolution time series, and emphasize that higher-frequency or continuous monitoring (e.g. through temperature and current loggers) will be needed in future studies to more robustly link environmental dynamics to growth and survival. This limitation reduces the explanatory power of our environmental analysis and highlights the need for higher-resolution environmental monitoring in future studies.

Notably, the seaweed planting and harvesting periods in this study occurred during the Southeast Monsoon (SEM, March–May), locally known as the *Kusi*, which is characterized by stronger southerly winds, cooler temperatures, increased rainfall, and enhanced nutrient dynamics along the Kenyan coast. These monsoonal winds significantly influence the chemical and physical properties of nearshore waters, including water temperature, turbidity, and nutrient fluxes, all of which affect seaweed performance (Kimathi et al., 2018; Wakibia et al., 2006a). The SEM has been associated with higher seaweed growth rates, averaging 4.7% day^{-1} compared to 4.0% day^{-1} during the Northeast Monsoon (NEM, December–March), of which the latter was suggested to be less favorable for photosynthesis and nutrient uptake (Wakibia et al., 2006a). In East African waters, biological responses to the SEM-particularly nutrient advection and upwelling-are stronger than those to the NEM, further supporting its role in driving marine productivity (Jebri et al., 2020). Similarly, Rodine et al. (2026) cultivated *Gracilaria salicornia* using a long-line system during the warm (January–March) and cool (June–August) season in Madagascar. After nine weeks, retention rate was found to be on average 45% (warm season) and 67% (cool season), with no significant seasonal effect ($p > 0.05$). However, specific growth rate ranged from 1.34 ± 1.03% day^{-1} (cool season) to 4.99 ± 1.34% day^{-1} (warm season). Our experiment was conducted during a single 45-day cultivation cycle within the SEM season, which is generally considered favourable for eucheumatoid growth along the Kenyan coast. Seasonal shifts in temperature, light regime, hydrodynamics and nutrient dynamics during the NEM and transitional periods may alter both biological performance and the relative advantages of intertidal versus subtidal cultivation. Our results should therefore be interpreted as a SEM "best-case" snapshot rather than a year-round average, and multi-season trials will be necessary to assess the seasonal robustness of depth-based adaptation strategies.

It is suggested that at deeper waters, temperatures are more stable and less likely to fluctuate strongly in response to rapid environmental fluctuations that are more common in shallow intertidal zones, as such potentially buffering seaweed against heat stress. However, since this study only encompassed a single cultivation cycle, the long-term consistency and seasonal resilience of subtidal farming remain unassessed. Radiarta (2013) suggest that seasonal and site-based adjustments to seaweed farming schedules could help avoid periods of extreme rainfall or salinity dilution. Finally, Glenn and Doty (1990) emphasized the influence of wind direction and water flow across farms, noting that upstream thalli consistently outperformed downstream ones, a factor not evaluated in this study but worth considering in future designs. Together with the absence of strong depth-related gradients in the measured environmental variables, these observations suggest that the modest RGR response to depth and the marked decline in survival at 4 m are more likely linked to physical stressors (e.g. hydrodynamic exposure, abrasion) and biotic interactions (e.g. grazing) than to differences in water chemistry. While this study provides preliminary insights into spatial variability and depth effects on seaweed farming performance in Kenya, future research should integrate high-resolution environmental monitoring (e.g., temperature loggers, current meters), quantify incidence and frequency of biotic stressors like herbivory and epiphyte growth, and explore seasonal variability across cultivation cycles. Such integrative approaches will be critical to improving the resilience and productivity of seaweed farming under changing climatic and ecological conditions.

4.3. Interspecies differences in seaweed performance

Supplementary table 4 summarizes the reported growth rates for *E. denticulatum* and *K. alvarezii* in Kenya and Tanzania in literature. The RGRs observed in this study showed significant variation across species, locations, depths, and cultivation methods, with *K. alvarezii* exhibiting the highest RGR, regardless of cultivation site and depth. This result is consistent with studies conducted in Malaysia and Indonesia, where *K. alvarezii* has been reported to outperform other species due to its high growth rate and adaptability to varying environmental conditions (Prasedya, 2013). Similarly, in Zanzibar and other regions of Tanzania, *E. denticulatum* is cultivated extensively, but its productivity is often lower than *K. alvarezii* due to its sensitivity to environmental fluctuations (Msuya, 2013). Also, Glenn and Doty (1992) and Azanza & Ask (2002 and Azanza, Ask, 2017) highlighted *K. alvarezii*'s superior growth performance, which has been attributed to its greater adaptability to water motion (Glenn and Doty, 1992) and its morphological plasticity (Smith, 2001). This contrasts with the findings of Kimathi et al. (2018), where *E. denticulatum* consistently outperformed *K. alvarezii* (Supplementary table 4). Similarly, Wakibia et al. (2006a) reported average RGRs of 4.7% day^{-1}, 4.3% day^{-1}, and 4.2% day^{-1} for *E. denticulatum*, green and brown *K. alvarezii* strains respectively in shallow depths, contrasting with our findings. Also, Russell (1982) reported higher growth rates for *E. denticulatum* (7.5% day^{-1}) compared to *K. striatus* (6.1% day^{-1}), indicating that growth performance may vary depending on site-specific conditions and genetic factors.

In contrast, few studies have reported attempts to cultivate *G. salicornia*. However, *Gracilaria* farming trials have been evaluated its potential as a biofilter for fishpond effluents and as an alternative species for agar production value addition in Tanzania (Msuya and Neori, 2002; Msuya 2011a). *Gracilaria sp.* achieved a growth rate of 1.5% day^{-1} and showed effective nitrogen removal in an integrated land-based finfish seaweed system (Msuya and Neori, 2002; Msuya 2011a). Specific growth rates of G. salicornia cultivated on long lines in Madagascar ranged from a minimum of 1.34 ± 1.03% d^{-1} in the cool season to a maximum of 4.99 ± 1.34% d^{-1} in the warm season (Rodine et al., 2026). The poor biomass yields of *G. salicornia* in deeper waters observed in this study are consistent with research from Brazil, where subtidal cultivation (e.g., at 2.5 m) of *G. gracilis* significantly reduced growth rates and agar yield, compared to cultivation at shallower depths (Ben Said et al., 2018). Unlike the eucheumatoids, *G. salicornia* was sourced from wild stocks and has not yet been subject to cultivation optimisation in Kenya. Its lower performance and economic returns should therefore be interpreted cautiously, as they likely reflect early-stage domestication and suboptimal culture practices rather than inherent species limitations. Taken together, these interspecies differences highlight the importance of tailoring seaweed farming strategies to species-specific traits and environmental compatibility. Future research should explore selective breeding, integrated farming systems, and seasonal adjustments to further optimize species performance under Kenyan coastal conditions.

4.4. Economic assessment of seaweed farming models

The stake-to-stake method remains the most traditional form of seaweed farming along Kenya's coastline. It requires minimal tools and labor, relying on simple materials such as wooden stakes and ropes that are locally available. This is in sharp contrast to subtidal, "deep water" farming techniques which require additional investments. To assess the economic viability of the different techniques, we evaluated the financial and time inputs required at various stages of seaweed cultivation – critical factors for scaling up production. Our cost–benefit analysis is based on locally observed prices and wages in Kwale County at the time of the study and should therefore be interpreted as a time-specific, conservative snapshot. In practice, input prices (e.g. ropes, fuel, labour) and farm-gate prices can fluctuate over time, which would directly affect profitability, especially for more capital-intensive technologies. However, the relatively long payback period (29 cycles) for off-bottom farms and the persistently negative returns for bamboo raft and long-line systems highlight that even the better-performing off-bottom method is economically fragile and expose smallholder farmers to considerable financial risk. As a result, our cost–benefit analysis should be interpreted as a time-specific, conservative snapshot of farm performance under current local conditions; Supplementary Table S7 further illustrates how modest changes in farm-gate prices and operational costs can substantially alter ROI and payback periods, especially for the more capital-intensive subtidal systems. In addition, although farm-gate prices are presently determined on the basis of biomass (dry weight), it is important to note that this metric does not capture the agar or carrageenan content of the seaweed, nor does it reflect quality attributes such as gel strength. These compositional and functional properties can substantially influence profitability further along the value chain, particularly in contexts where pricing is linked to biochemical quality rather than bulk biomass. Therefore, the economic results presented here should be interpreted as reflecting biomass-based feasibility under current local pricing structures, rather than representing full value-chain profitability that might include premiums associated with higher-quality material.

The economic analysis of the current study supports the continued use of the off-bottom method for coastal communities in Kenya. From the second cultivation cycle onward, the off-bottom method becomes profitable, generating a net profit of USD 64.2 per cycle. These findings are consistent with those of Mirera et al. (2020), who reported that a model farm with 300 ropes can yield up to 1.5 tons of dry seaweed per harvest. At USD 0.25 kg^{-1}, this translates to USD 375 per harvest, echoing the viability of scaling up off-bottom farming for community economic upliftment. In comparison, the current study – using a more conservative yield estimate of 0.75 kg DW per rope – projects a total farm yield of 223.6 kg DW per cycle (also for a model farm with 300 ropes), generating USD 111.8 in gross income and USD 64.2 in net profit from the second cultivation cycle onward. While modest, this reflects real-world, present-day conditions along the Kenyan coast and confirms the potential for profitability when scaled appropriately.

Among the models tested, the off-bottom method emerged as the only financially viable option, yielding a return on investment (ROI) of 134.87% with a payback period of 3.73 years under current market conditions and inflation-adjusted input costs. These results are consistent with earlier findings by Wakibia et al. (2011), who reported that ROI for *K. alvarezii* cultivation exceeded 100% in select Kenyan pilot farms, but with payback periods of less than one year. However, our sensitivity analysis (Supplementary Table S7) shows that relatively small changes in farm-gate price or operational costs already substantially reduce ROI and lengthen the payback period for off-bottom farms, underscoring their exposure to temporal economic fluctuations. Similar results were achieved under different economic settings, as demonstrated in the sensitivity analysis.

In contrast, subtidal cultivation (i.e., bamboo raft and long-line methods) produced negative ROI values, indicating that initial investments could not be recovered under present operational and price conditions. The high capital and labor demands associated with these methods make them less accessible to small-holder farmers without external support. Importantly, the lower economic performance of the long-line system in this study reflects the combination of locally observed biomass yields and the material and operational requirements recorded under the Kenyan artisanal production context, and should therefore be interpreted as site- and assumption-specific rather than a universal limitation of long-line farming. Because these systems rely more heavily on purchased materials (e.g. raft frames, anchoring systems, boat fuel and maintenance), they are particularly sensitive to temporal changes in input prices and farm-gate price volatility, and their economic performance would likely deteriorate further under less favourable price regimes than those used in our baseline model. While our analysis assumes relatively stable market and environmental conditions, several risk factors may further affect the viability of seaweed farming. The fluctuation of farm gate prices remains a central concern. As previously observed in the Philippines and East Africa (Padilla and Lampe, 1989; Wakibia et al., 2011), price instability weakens farmer motivation and undermines the economic sustainability of seaweed production. In some cases, buyers provide inputs (e.g., ropes, tie-ties) in exchange for fixed, often suppressed prices, which limits farmer autonomy and profit potential. Empirical value-chain studies (e.g. in Malaysia) have shown that introducing standards for farm management and product quality can help align seaweed prices with labor inputs and quality, thus promoting fair compensation and sustainable industry growth (Nor et al., 2019). Establishing farmer cooperatives and linking seaweed prices to quality could help address this structural issue. Micro-credit mechanisms, collective bargaining, and market diversification may also help de-risk participation for smallholder farmers. Adoption of more capital-intensive innovations in production technologies (e.g., subtidal systems requiring anchoring infrastructure and boat access) will likely depend on targeted financial support from the government or other entities and/or risk-sharing mechanisms. In Kenya, coastal livelihood programmes such as the Kenya Marine Fisheries and Socio-Economic Development (KEMFSED) Project, implemented by the Government of Kenya with World Bank support, aim to strengthen fisheries management while expanding livelihood opportunities in coastal communities, including Kwale county (World Bank, 2020). At continental scale, the Africa Blue Economy Strategy further underscores policy support for fisheries and aquaculture value-chain development and investment in sustainable marine resources (African Union Inter-African Bureau for Animal Resources, 2019). Aligning cultivation optimization with enabling finance mechanisms will be essential to ensure that productivity gains translate into durable livelihood improvements. Beyond financial and environmental challenges, gendered access to technology is another critical constraint. Offshore systems typically require boats, diving or snorkeling and handling heavier gear equipment, tasks often culturally and physically restricted for women who form the majority of seaweed farmers in coastal Kenya. Projects like Sea PoWer in Zanzibar encountered this barrier directly: tubular-net farming, suited for deeper waters, required swimming and boat-handling skills that many women lacked, necessitating gender-sensitive training interventions (Brugere et al., 2019). Stakeholders should thus ensure that technological innovation does not widen existing inequalities. Given these findings, the off-bottom method currently remains the most appropriate entry point for expanding seaweed farming among coastal communities, despite remaining vulnerable to environmental change.

5. Conclusion

To fully harness the potential of seaweed farming along the Kenyan coast, cultivation strategies must align with both environmental conditions and socio-economic realities. This study provides the first empirical comparison of intertidal (0.5 m) and subtidal (2–4 m) cultivation methods for *Kappaphycus alvarezii*, *Eucheuma denticulatum*, and *Gracilaria salicornia* along the Kenyan coast. Results show that shallow off-bottom farming at 0.5 m depth, particularly of *K. alvarezii*, is currently the most productive, cost-effective, and accessible option for smallholder farmers—especially women and community-based cooperatives. While subtidal systems (e.g., long-line and bamboo raft at depths of 2–4 m) may offer climate resilience through more stable environmental conditions, they yielded lower survival, reduced biomass, and were economically unviable under current market conditions without external support. Growth and profitability varied significantly by site and species, underscoring the importance of site- and species-specific strategies. Notably, *E. denticulatum* performed well in the sandy mudflat of Kijiweni, where it showed strong survival and growth. Given these findings, the off-bottom method currently remains the most appropriate entry point for expanding seaweed farming among coastal communities, despite remaining vulnerable to environmental change and economic changes. Future research should expand the depth range, number of cultivation units, and trial duration—through multi-season and multi-year experiments—to robustly assess "deeper-water" cultivation as a climate adaptation strategy for smallholder seaweed farming in the Western Indian Ocean. When investigating new techniques to cultivate seaweed along the Kenyan coast, stakeholders should ensure that the employed technological innovations do not widen existing inequalities. Finally, given the variable survival and yield outcomes and the associated economic risks identified in this study, we caution against broadly promoting subtidal cultivation systems without prior site-specific testing.

Authors' contributions

All authors contributed to the conception and design of the study. Resources were provided by Jan Mees and Colin R. Janssen. Material preparation, data collection and analysis were performed by Ilias Semmouri and Gladys Mwaka Holeh. The first draft of the manuscript was written by Gladys Mwaka Holeh. Editing and reviewing of the manuscript was done by all authors. All authors read and approved the final manuscript.

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James Njiru: Writing – review & editing, Supervision, Funding acquisition. **Jana Asselman:** Writing – review & editing, Supervision, Resources. **Jan Mees:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Gladys Mwaka Holeh:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Ilias Semmouri:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Colin Janssen:** Writing – review & editing, Supervision, Resources, Funding acquisition. **David Mirera:** Writing – review & editing, Supervision.

Ethical approval

Not applicable

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aqrep.2026.103585.

Data availability

Data will be made available on request.

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Further reading

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