Original Article

Economic viability of seaweed and sea cucumber culture using integrated multitrophic aquaculture systems in Zanzibar, Tanzania

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Abstract

The viability of co-culturing seaweed and sea cucumbers in Zanzibar, Tanzania, was assessed using integrated multitrophic aquaculture (IMTA) systems with oyster and recirculating aquaculture systems with milkfish. Seaweed production was affected by the ice-ice disease, resulting in specific growth rates of 1.32 to -1.96 % d^{-1}. Nitrogen content in the seaweed thallus and inorganic nutrient in the water indicated that seaweed could potentially be used as a biofilter. An economic analysis showed the economic viability of IMTA systems, co-culturing seaweed *Kappaphycus alvarezii*, sea cucumber *Holothuria scabra* and oyster *Pinctada margaritifera*, achieving a maximum benefit-cost ratio of 1.61 over one year. Interviews with local farmers on Zanzibar showed willingness to accept new aquaculture systems, but also highlighted constraints, including a lack of infrastructure, funds and expertise.

Keywords: aquaculture, integrated polyculture, cost-benefit ratio, RAS, social viability, questionnaire

Introduction

Due to the projected rise of global human population (United Nations, 2019) and the subsequent increased demand for fisheries products (FAO, 2020), many more wild fish stocks will be overexploited or depleted in a few years. Aquaculture, playing a vital role to meet the ever increasing demand for food, has however developed a controversial reputation, due to high density operations, environmental degradation and water pollution (Hall *et al.*, 2011; Ahmed and Turchini, 2021). Major changes are necessary to control aquaculture production – more resilient and innovative practices need to be developed if this sector is to become the most efficient and responsible food production system of the future (Soto, 2009; Troell *et al.*, 2009; Ahmed *et al.*, 2019).

There are several promising systems that address the issue of effluent from aquaculture operations. Recirculating aquaculture systems (RAS) as one possible solution, are based on the recirculation of water with various kinds of filters, such as biofilters, solid filters or protein skimmers (Badiola *et al.*, 2012; van Rijn, 2013). This way, water can be recycled and the amount of fresh water needed and waste water produced greatly reduced. Instead of conventional biofilters with bacteria, biofilters can also comprise of different animals or plants used to filter the water. However, RAS is expensive and technologically challenging and therefore not appropriate for aquaculture in many developing countries (Badiola *et al.*, 2018; Engle *et al.*, 2020). For aquaculture systems to work in developing countries they need to be low-tech and low-cost, which can easily be built in spite of the lack of infrastructure and high expertise. Another solution could be Integrated Multitrophic Aquaculture (IMTA), a sustainable aquaculture practice through co-culturing of species from different trophic levels. In IMTA, faeces, uneaten food materials, and nutrients from higher trophic species such as finfish or shrimps become food for lower trophic species such as detritivores or filter feeders. Dissolved inorganic nutrients can be taken up by plants or algae, acting as biofilters (Chopin *et al.*, 2001; Troell *et al.*, 2003; Neori *et al.*, 2004; Ren *et al.*, 2012). IMTA not only aims to promote an ecologically sustainable and social approach (Ertör and Ortega-Cerdà, 2015), but it also can provide economic stability for aquaculture producers by providing farmers with a more diversified set of crops compared to monoculture (Knowler *et al.*, 2020).

Recent literature shows many good examples of IMTA practices in tropical countries (Putro *et al.*, 2015; Ahmed and Glaser, 2016; Felaco *et al.*, 2020; Franchini *et al.*, 2020; Putro *et al.*, 2020), including seaweed (Largo *et al.*, 2016; Shpigel *et al.*, 2018). In Tanzania the focus has been on the combination of sea cucumbers with seaweed (Namukose *et al.*, 2016; Kunzmann *et al.*, 2018; Fabiani *et al.*, 2023; Kunzmann *et al.*, 2023). Few of these studies integrated filter feeders such as bivalves, and economic aspects were not considered in many of them.

Seaweed farming is gaining worldwide popularity, reaching a global production of 13.5 million tonnes in 2020 (Buschmann *et al.*, 2017; FAO, 2022). The seaweed culture cycle is relatively short compared to other aquaculture species, and farming techniques are low cost. As the global market for seaweed has expanded the economic returns from seaweed aquaculture have risen (García-Poza *et al.,* 2020).

Aquaculture on Zanzibar includes the farming of fish, mud crabs, pearl oysters, sea cucumbers, seaweed and sponges (Msuya *et al.*, 2016; Charisiadou *et al.*, 2022). In Tanzania seaweed farming began in 1989, initially focused on two macroalgae species, *Eucheuma denticulatum* (spinosum) and *Kappaphycus spp* (cottonii) (Msuya *et al.*, 2007; Msuya, 2020). The industry is the third largest sector in terms of value, contributing 7.6 % to the GDP of Zanzibar in 2011 (Msuya and Hurtado, 2017). Seaweed farming faced multiple challenges in the past decades (Msuya and Porter, 2014), including the ice-ice disease, which is caused by infestation of microbes and facilitated mainly by high temperatures (Ward *et al.*, 2022). There have been attempts to overcome this issue by moving the seaweed farms into deeper waters (Msuya, 2020).

In Tanzania, sea cucumber fishing is an important economic and subsistence activity for local communities and is extensively practiced (Eriksson *et al.*, 2012). Aquaculture production of sea cucumbers has primarily focused on the most valuable species *Holothuria scabra*, which are sold and exported mainly to China for high prices.

Shellfish farming for pearl production in Zanzibar started in 2004, with an estimated production in 2012 of about 1,000 pearls, valued at 10 to 20 US$ each (Mmochi, 2015). The potential of pearl oysters for bioremediation has been positively evaluated and pearl production could be a viable economic activity for coastal communities in East Africa (Southgate *et al.*, 2006; Ishengoma *et al.*, 2011).

Finfish production in Tanzania is mainly focused on the species milkfish *Chanos chanos* and flathead grey mullet *Mugil cephalus*. Traditionally wild-caught fingerlings are reared in larger earthen ponds, connected to the sea, or in smaller earthen ponds directly in the mangroves until market size and then sold mainly on local markets (Msuya *et al.*, 2016).

The success of sustainable aquaculture systems can contribute to farmers' food security and income, but requires the development and testing of new sustainable aquaculture systems. Most systems used, are outdated and can have severe impacts on the surrounding environments. This study therefore aims to compare biomass production and economic viability of different land-based IMTA approaches, including the cultivation of seaweed *Kappaphycus alvarezii* and sea cucumbers *H. scabra* with pearl oysters *Pinctada margaritifera* or milkfish *C. chanos*.

Materials and methods

Study site and species collection

Research was conducted in 2022 at the KOICA-RGoZ Mariculture Hatchery Zanzibar, Tanzania (6°07'01.0"S 39°12'42.0"E). Seaweed (*K. alvarezii*) was collected from a small group of local farmers in Muungoni (6°19'11.7"S 39°24'43.2"E). Sea cucumbers (*H. scabra*) were collected from a farmer in Unguja Ukuu (6°19'01.3"S 39°22'16.4"E) and pearl oysters (*P. margaritifera*) from the farms in Nyamanzi (6°16'03.5"S 39°14'55.9"E). The milkfish (*C. chanos*) were taken from brackish water ponds near Bumbwini (5°56'42.6"S 39°12'09.4"E). All animals were kept in a separate tank without any sediment and feed, to ensure an empty gut when weighing, before stocking. Marine sand/sediment was taken during low tide from near Fukuchani (5°50'09.5"S 39°17'01.7"E) and the bottom of the tanks was covered with 5 cm of this, acting as the source of organic nutrients for the sea cucumbers.

Experimental design

Two distinct experimental designs were developed for the co-culture trials. One system (IMTA) combined seaweed, sea cucumbers and sea oysters in one tank, while in another system (RAS), seaweed, sea cucumbers and milkfish were integrated in separate tanks. Both experiments were conducted simultaneously from October to December/January 2022/2023. The IMTA systems ran for 90 days, with two cycles of 45 days each, whereas the RAS system ran for 70 days with one cycle only.

The IMTA system consisted of four treatments (A, B, C and D) with four replicates each (4x4), i.e., 16 tanks. Because of logistic restraints, of the 16 tanks, seven were 490 liter fiberglass tanks, three 500 liter fiberglass tanks and six 1000 liter plastic tanks. Nylon ropes were tied on two sides over the tanks, on which 50 g of fresh seaweed fronds were tied at 20 cm intervals and suspended 20 cm below the surface; sea oysters were suspended in a rectangular cage. Figure 1 shows the setup of tanks at the hatchery for all treatments with their respective replicates. All four treatments had discrete stocking densities (g m^{-2}), the ratio of seaweed, sea cucumbers and pearl oysters were 1:0:0, 1:1:1, 2:1:1 and 1:2:2 for treatments A, B, C and D, respectively. Treatment A was stocked only with seaweed at a density of 200 g m^{-2}. In treatment B all three species were stocked at 200 g m^{-2}. Treatment C was stocked with 400 g m^{-2} seaweed and both sea cucumbers and pearl oysters at 200 g m^{-2}, while treatment D was stocked with 200 g m^{-2} seaweed and 400 g m^{-2} sea cucumbers and pearl oysters.

The RAS, labelled treatment E, consisted of one 1000 liter tank for fish, one 1800 liter tank for sea cucumbers and one 500 liter tank for seaweed, which were set up in a row, shown graphically in Figure 2. The tanks were connected by two U-shaped water pipes each and due to height difference and gravitational force, water flowed from the fish through the sea cucumber to the seaweed tank. A submersal pump (DC Runner 2.2 Aqua Medic) in the seaweed tank pumped the water back to the fish tank at a rate of 1200 L h^{-1}. Seaweed fronds were suspended the same way as in the IMTA at 795 g m^{-2} initial stocking density. Sea cucumbers had an initial stocking density of 105.85 g m^{-2} and milkfish, in two batches, on day 0 and day 39, were stocked at a density of 2013.33 g m^{-3}. The fish were fed every day with 4 % bodyweight day^{-1} of Koudijs Tilapia broodstock feed 3.0 mm (Vietnam), containing minimum 36.0 % crude protein. In addition to the system containing seaweed, a control

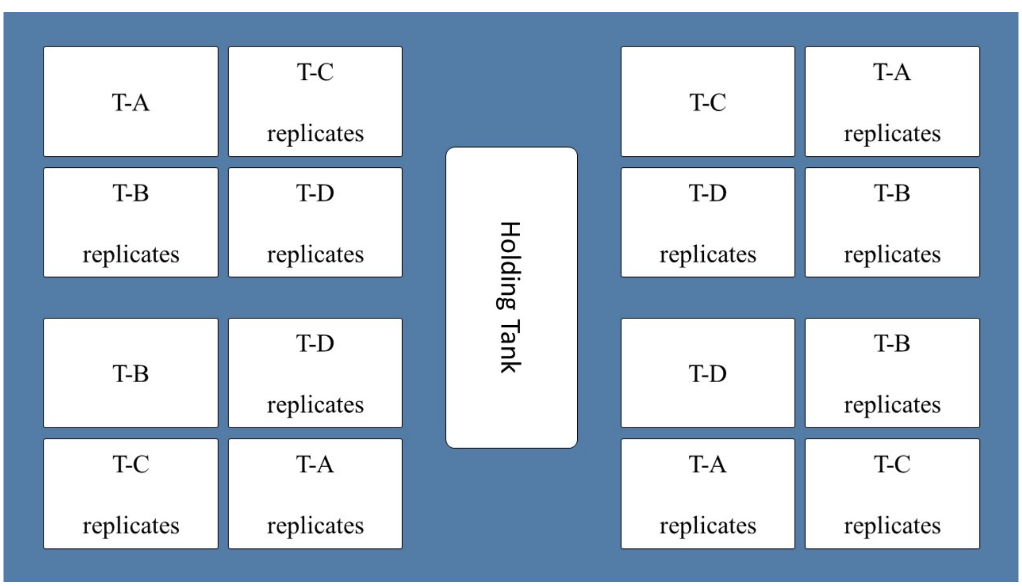

Figure 1. Layout of all tanks for treatments A (1:0:0 – seaweed, sea cucumbers and pearl oysters), B (1:1:1), C (2:1:1) and D (1:2:2) with each of the 4 replicates. The holding tank in the middle was used to keep stock of seaweed. Seven tanks were round 490 litre fiberglass tanks (0.7 m x 0.7 m x 1 m), three square 500 liter fiberglass tanks (1 m x 1 m x 0.5 m) and six square 1000 liter plastic tanks (1 m x 1 m x 1 m).

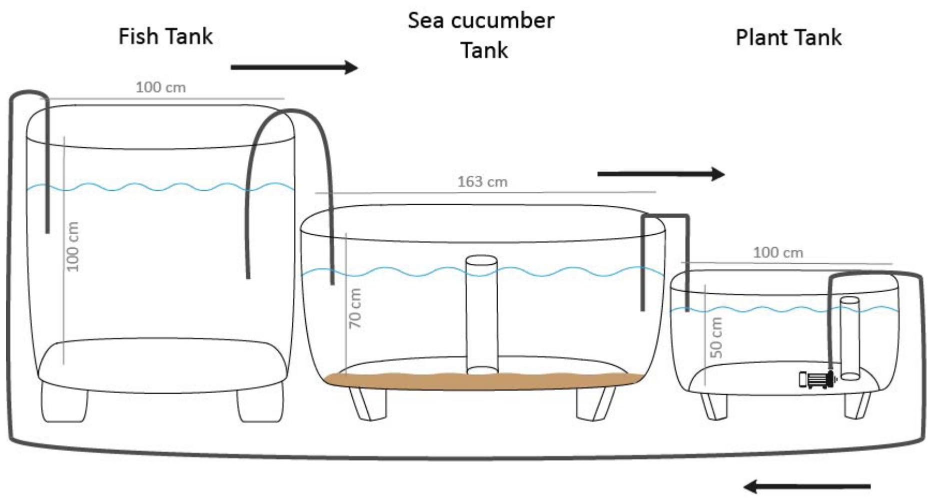

Figure 2. Sketch of the experimental RAS set-up with squared fish (1000 liter plastic, 1 m x 1 m x 1 m), sea cucumber (1600 liter fiberglass, 1.63 m x 1.63 m x 0.5 m) and seaweed (500 liter fiberglass, 1 m x 1 m x 0.5 m) tanks. The arrows indicate the water flow and the grey lines indicate water pipes and hoses.

system was constructed, which did not include any seaweed or artificial biofilter and therefore required regular water changes.

Growth of all species was monitored three times during the entire experimental period (initial, half way and at the end). Specific growth rates (SGRs), measuring the percentage increase in fish weight per day, were calculated by using the formula according to (Dawes *et al.*, 1993):

$$SGR = \frac{(ln(W_d) - ln(W_0))}{d} * 100$$

Where SGR indicates the specific growth rate (% d^{-1}); W_0: Weight at day 0, W_d: Weight at day d.

Water parameter measurements and N content

Temperature, salinity, pH, and DO, were measured at 14-day intervals in the IMTA system and twice a week in the RAS using a YSI ProQuatro Multiparameter sensor (USA) and measurements taken between 09h00 and 12h00. Water samples of 11 ml were taken three times a week from the milkfish and seaweed tank of the RAS, and stored frozen at -20 °C. During the analysis, the samples were thawed and inorganic nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}) were analysed with spectrophotometry using a Microplate reader infinite 200Pro (TECAN, Austria) following the procedure of Strickland and Parsons (1972). The data were graphically and statistically processed using the statistical software RStudio and R version 4.0.5.

Seaweed samples from the IMTA were collected on the first and last day of each cycle (Day 0 and 45), dried in an oven at 60 °C for 24 hours, and then stored at room temperature. 1 to 2 mg of the ground and homogenized samples from each treatment were put in pre-combusted (500 °C, 3 hours) tin cups and then the nitrogen content (%) of dry weight was determined by using an EURO EA 3000 CN elemental analyser, following a similar approach to Kennedy *et al.* (2005). The data were transformed logarithmically (Logan, 2011), and checked for normality with the Shapiro-Wilk test and for homogeneity of variance with the Levene-Test. A t-test was applied to determine the differences in nitrogen between batch one and batch two of seaweed and a two-way ANOVA was carried out to determine the effect of stocking density on different days.

Economic viability and questionnaire on farmers' perception

Buying and selling records (species-wise) were maintained to perform the financial analysis. Seaweed was collected directly from farmers, at a price of 0.43 US$ per kg wet weight (1 kg = 1000 TZS). Sea cucumbers and sea oysters were also collected from farmers and the costs per individual were 0.19 US$ (450 TZS) and 0.2 US$ (470 TZS), respectively. The price of milkfish per kilogram was 0.84 US$ (2000 TZS). According to Msuya (personal communication), in December 2022, the price of a kilogram of dry seaweed (*Kappaphycus*) in Zanzibar was 0.86-0.95 US$ per kg (2000-2200 TZS), and full-grown milkfish was sold for 2.15 US$ per kg (5000 TZS). Gutted sea cucumber price was approximately 15.07 US$ per kg (35,000 TZS/kg, according to ministry of fisheries, Zanzibar) and sea oyster were sold at current market price of 10.55 US$ per kg (24500 TZS/kg).

For the estimation of total costs, the following components were considered per square meter: variable costs, such as human labour, transportation, feed, ropes, pipes and species, as well as fixed costs, including tanks and pumps. Estimation of total production, gross return (sales value of total production), and benefit-cost ratio (BCR) were used to examine the economic performance of the treatments (Rahman *et al.*, 2017; Magondu *et al.*, 2022). BCR is used to compare the ratio of benefits, in this case the gross return, and the costs and is calculated as follows:

$$BCR = \frac{|PV\ [Benefits]|}{|PV\ [Cost]|}$$

Where PV is the Present Value, being the current value of the sum of benefits or costs in this case. The annual estimates of variable costs (including tank repairing costs), return, and BCR value were used to approximate the long-term profit analysis. Whereas fixed costs were considered an initial investment and not annualized.

For the questionnaire survey, interviews were conducted with a total of 30 farmers at six sites (Muungoni (n = 2, 6°19'11.7"S 39°24'43.2"E), Jambiani (n = 11, 6°19'15.1"S 39°32'54.9"E), Uzi (n = 4, 6°20'23.5"S 39°23'03.4"E), Unguja Ukuu (n = 6, 6°19'01.3"S 39°22'16.4"E), Nyamanzi (n = 2, 6°16'03.5"S 39°14'55.9"E), and Fukuchani (n = 5, 5°50'09.5"S 39°17'01.7"E)) between October and December 2022, with the support of a local translator in Swahili. To understand the socio-economic profile of the farmers, constraints of different culture systems, seasonal influences, weather, and market situations, the coastal farmers were interviewed at all six-sites, using a combination of focus groups and individual interviews. All interviews were semi-structured and open-ended questionnaires, where the interviewers not only asked questions, but encouraged farmers to provide opinions and recommendations. In order to include both sexes and a range of age groups, the interviewees were chosen at random from among the farmers who were willing and able to participate (Charisiadou *et al.*, 2022). To preserve uniformity among respondents, the survey's interviews with each respondent lasted between 20 and 30 minutes (Fröcklin *et al.*, 2012). The focus of discussion topics included problems and conflicts related to mariculture practices. Data were processed with MS Excel and frequency statistics were analysed using IMB SPSS (version 29.0.1.0).

Results

Water quality

Water temperatures ranged from 24.1 °C to 27.5 °C in the RAS system, and from 27.9 °C to 30.1 °C in the IMTA systems, with lower temperatures in the beginning, progressively getting warmer. Average salinity was 30.2 ± 1.1 (± SD) ppt and 31.5 ± 1.1 ppt and average pH 8.2 ± 0.2 and 7.9 ± 0.4 for the IMTA and RAS

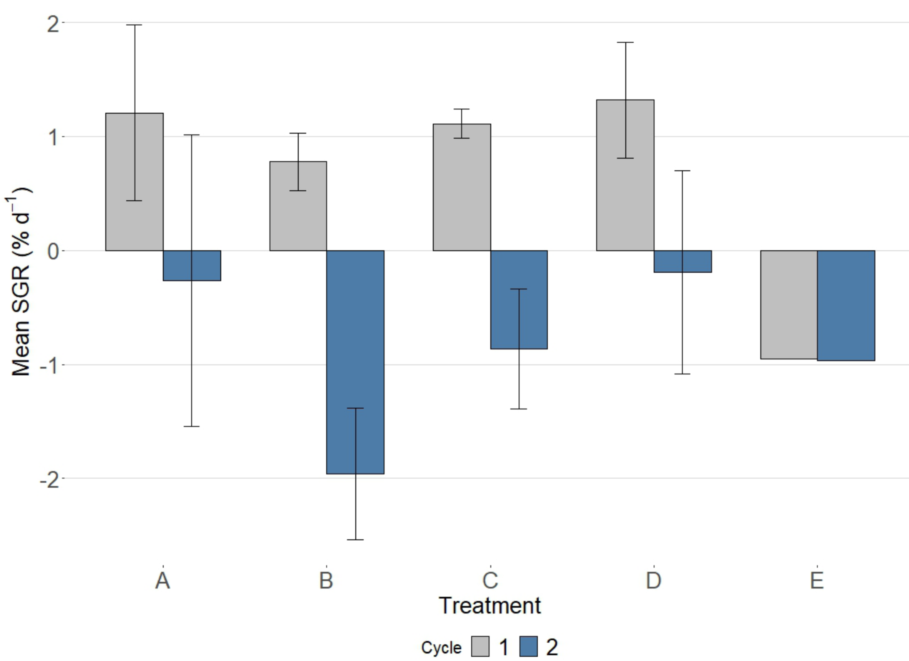

Figure 3. Seaweed specific growth rate (SGR, % d^{-1}) in two cycle periods (45 days for treatment A-D; 35 days for treatment E). Treatments A-D represent ratios 1:0:0, 1:1:1, 2:1:1, and 1:2:2, respectively of seaweed, sea cucumbers and pearly oyster. Treatment E represents seaweed, sea cucumbers and milkfish. Grey indicates the first growth period, blue the second one. Data are in mean values ± standard deviation, n = 4 for treatments A-D, treatment E is only one data point per cycle.

designs, respectively. Dissolved oxygen decreased in all tanks over time, ranging from 4.6 ± 0.05 mg L^{-1} to 3.7 ± 0.07 mg L^{-1} in the IMTA and 4.6 ± 0.72 mg L^{-1} to 4.2 ± 0.34 mg $^{-1}$ in the RAS, respectively for the first and second half, but never below critical values.

Growth and survival

Seaweed performance varied greatly between the first and second culture cycle, as seen in Figure 3. SGR in the first cycle was positive for treatments A to D and above 1 for A (SGR 1.21 ± 0.77 % d^{-1}), C (SGR 1.11 ± 0.13 % d^{-1}) and D (SGR 1.32 ± 0.51 % d^{-1}). In the second growth cycle, all treatments experienced severe seaweed loss, due to the sudden occurrence of ice-ice disease (Ward *et al.*, 2022). In treatment E ice-ice also occurred in the first growth cycle, resulting in SGRs of -0.95 % d^{-1} and -0.97 % d^{-1}, respectively.

Sea cucumber survival was 94.9 % in treatments A to D, and 100 % in treatment E. During the first cycle, treatment D showed the greatest weight loss (SGR -0.3 ± 0.22 % d^{-1}), while treatment C the least weight loss (SGR -0.03 ± 0.2 % d^{-1}). Specific growth rates in treatments B and D were also negative during the second cycle, with B experiencing even higher losses (SGR -0.89 ± 0.47 % d^{-1}). Treatment C showed positive growth in the second cycle (SGR of 0.35 ± 0.06 % d^{-1}). SGR of sea cucumbers in treatment E were 0.94 % d^{-1} and 0.01 % d^{-1} for the first and second half, respectively (Fig. 4).

The survival rate of the **sea oysters** in the IMTA was 97.22 %. Dead sea oysters were only found in treatment D, which also showed the highest SGR (0.11 ± 0.04 % d^{-1}). Survival rate of the first batch of **milkfish** was 9 %, because of this they were restocked on day 42 of the RAS experiment. The second batch had a survival rate of 100 % and an SGR of 0.42 ± 0.2 % d^{-1} over the 28 days left until the end of the experiment.

Nitrogen uptake and biofiltration by seaweed

Thallus nitrogen content in seaweed showed no significant difference in different stocking densities and on different days among the treatment tanks ($p > 0.05$), but there was a significant difference between cycles one and two ($p < 0.05$) (Fig. 5A, B). Assimilation rate was the highest in Treatment D in both culturing cycles.

In the RAS systems, there were no significant differences in the NH_4^+, NO_3^-, NO_2^- and PO_4^{3-} concentrations between the seaweed and control system. NH_4^+ in the seaweed system peaked at around 1.0 mg L^{-1}, in the control at 0.7 mg L^{-1} at day 7, after which it decreased in both systems to around 0.2 mg L^{-1} on day 20 (Fig. 5C). A second and third peak was only observable in the

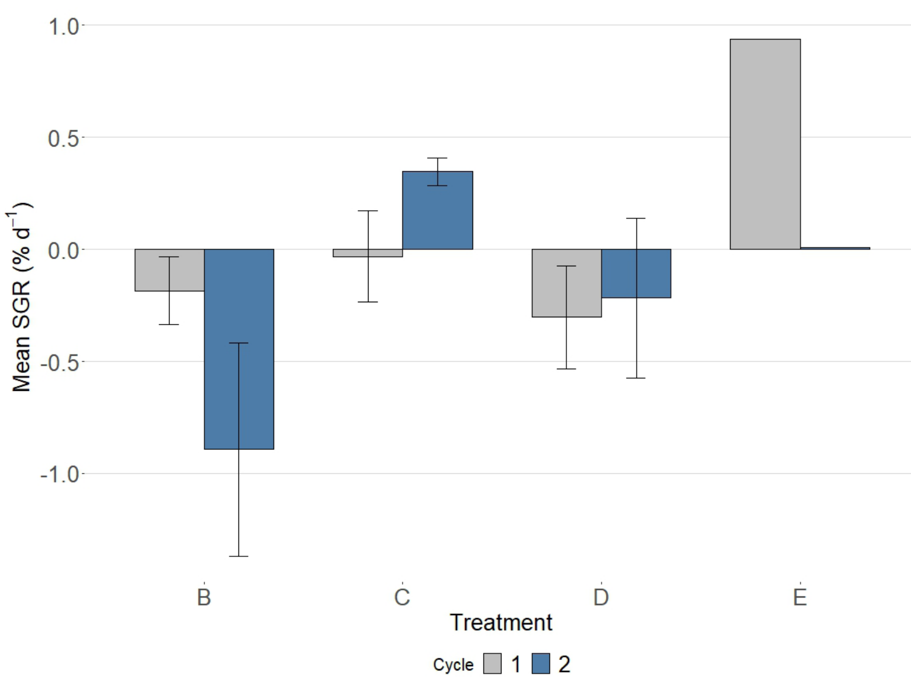

Figure 4. Sea cucumber specific growth rate (SGR, % d^{-1}) in two cycle periods (45 days for treatments A-D; 35 days for treatment E). Treatments B-D represent ratios 1:1:1, 2:1:1, and 1:2:2, respectively of seaweed, sea cucumbers and pearl oyster. Treatment E represents seaweed, sea cucumbers and milkfish. Grey indicates the first growth period, blue the second one. Data are in mean values ± standard deviation, n = 4 for treatments B-D, treatment E is only one data point per cycle.

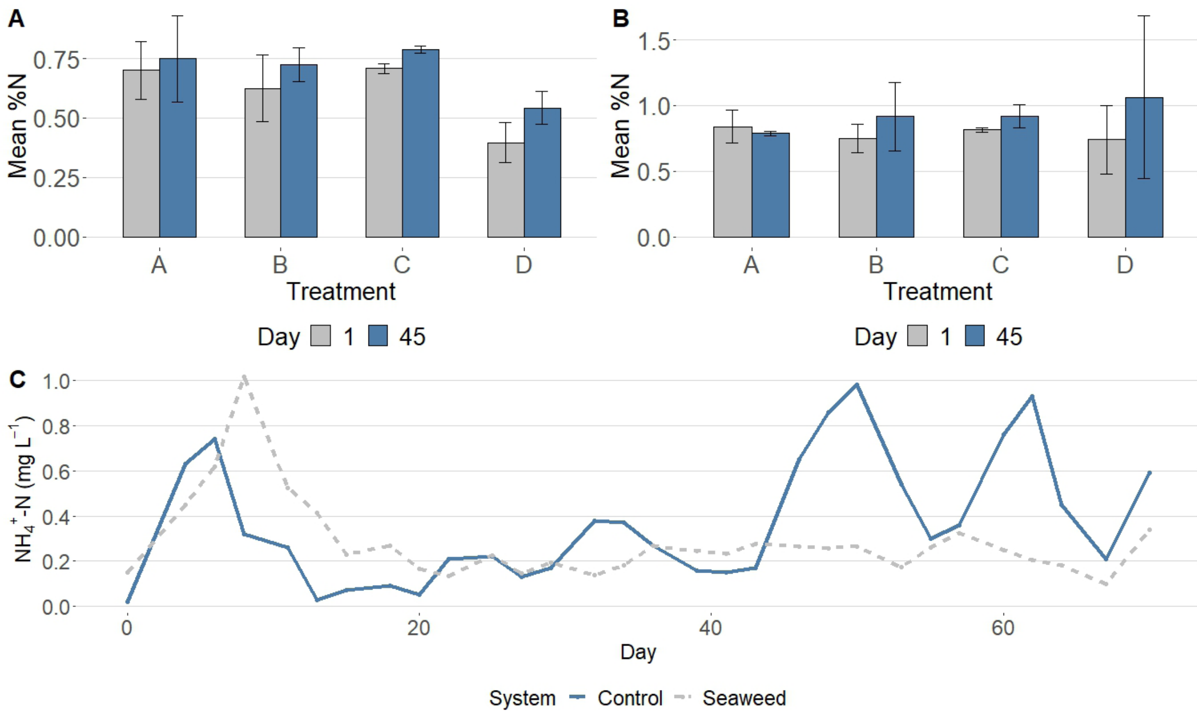

Figure 5. Nitrogen content in the seaweed thallus on day 0 and 45 in cycle one (**A**) and two (**B**). Treatments A-D represent ratios 1:0:0, 1:1:1, 2:1:1, and 1:2:2, respectively of seaweed, sea cucumbers and pearl oyster. Data are in mean values ± standard deviation, n = 2 for each treatment. (**C**) Average NH_4^+-N concentration (mg L^{-1}) in all three systems over the 70 days. The blue line is from water samples of the control system, the grey line from the seaweed system, n = 30 for control and seaweed system, respectively.

control on day 50 and 62, not in the seaweed system. Nitrite concentration peaked in the seaweed system shortly after the ammonium peak and stayed low afterwards, while the control experienced a strong increase in the last 10 days of the experiment. Nitrate levels fluctuated around 0.6 and 3 mg L^{-1} in both systems, and after day 50 it increased to 4.5 mg L^{-1} in the seaweed system. Phosphate concentrations stayed relatively low for the first 45 days of the experiment, not exceeding 0.2 mg L^{-1}. After day 50 it started to increase in both systems, with maximums reaching 0.5 mg L^{-1} in both on day 70.

Economic viability

In the IMTA systems, treatment D had the highest total yield for all species (635.36 g m^{-2}) and highest gross return (US$ 6.96 per m^2), while treatment B had the lowest yield (299 g m^{-2}) and gross return (US$ 3.15 per m^2). Treatment A demonstrated especially poor economic performance. After analysing cost, return, and BCR values on an annual basis, it was discovered that treatment C and D were economically viable with treatment D being slightly more viable (Table 1). In the RAS, economic feasibility was not satisfactory due to the loss of milkfish in the first batch (survival rate 9 %). This also makes an annualization difficult to perform, as the possible growth over the entire experiment duration is unknown.

Questionnaires for farmers' perception

In total, 30 participants in discrete age groups were interviewed, of which 60 % were females (n = 18) and 40 % males (n = 12), with all females actively engaging in seaweed culture. Interviewed people had diversified occupations (small scale business 27.8 %, fishing 26.4 %, mariculture 22.2 %, tourism 15.3 %, the rest were involved in crop and animal husbandry). This study tried to find out the principal constraints in specific aquaculture systems (Table 2). Seaweed farmers mentioned their main problems were low market prices, die-offs, and high cost of materials. Farmers of sea cucumbers suffered because of theft, the limited availability of fingerlings, and high cost of materials. Almost two-thirds of farmers agreed to accept new technologies such as IMTA, but highlighted the main obstacles in implementing such systems, including the lack of funding, security, and knowledge. The majority of participants (n=20, 66.67 %) stated concerns about the situation of the market and frequently mentioned that they are unable to directly connect with large consumers since primarily local traders purchased their products, and did not agree to pay reasonable prices. They frequently voiced specific requirements towards the government and NGOs who are involved in coastal aquaculture development such as financial support (small

Table 1. Estimation of yield, return and economic viability from all treatments per square meter cultivation area, and an annualization of these.

Culture type	Treatment	Cost (US$/m²)	Total Yield (g/m²)	Gross return (US$/m²)	BCR	Annualization		
						Total Yield (g/m²)	Gross return (US$/m²)	BCR value
Seaweed mono-culture	A	6.04	60	0.05	0.01	360	0.31	0.05
IMTA	B	13.93	300	3.15	0.23	1270	12.65	0.91
	C	13.39	430	4.06	0.30	1930	16.44	1.23
	D	17.34	640	6.96	0.40	2670	27.95	1.61
	E (RAS)	36.19	1350	3.85	0.11	6900	19.37	0.54

Note: 1 US$ = 2322 TZS (25 September 2022)
Total yield of seaweed wet weight (1 wet kg = 0.12 dry kg)
Kappaphycus alvarezii market price= 0.87 US$/ dry kg
Total yield of sea cucumber is given in live weight
(1 kg of live = 0.54 kg of gutted)
Holothuria scabra market price = 15.07 US$/ gutted kg
Pinctada margaritifera market price = 10.77 US$/ kg
Chanos chanos market price = 2.15 US$/ kg

scale credits), instrument and training facilities, security for reducing poaching, establishing a hatchery to produce fingerlings, introducing new technique (e.g., integrated aquaculture), subsidies or allowances (during rainy season aquaculture production is hampered seriously), collaboration with foreign buyers, availability of a health facility, interaction and monitoring.

Discussion

Biomass production under different culturing conditions

Seaweed cultured in the RAS got infected by the ice-ice disease shortly after the stocking and the absolute biomass therefore decreased in both 35-day intervals. The ice-ice disease causes rotting of the stems and

Table 2. Constraints regarding three farming methods mentioned by the individual farmers and their frequencies (frequency equals 100 % means that a reply appeared in all the members in a specific group).

Frequency (%)	Constraints
Seaweed farmers (n=12)	
100	Low market price of dry seaweed
75	Seaweed die-offs for ice-ice disease
66.7	High price of equipment, after covid-19, market price suddenly increased
50	Extreme weather, especially December to May, with average temperature 30-36⁰C
41.7	Serious health problems, skin diseases, pain, allergies, injured by sea urchin and other hard-shell species
41.7	Lack of support from government and non-government stakeholders
Sea cucumber farmers (n=10)	
100	Poaching is the main problem in open coastal aquaculture
70	Scarcity of fingerlings
50	Escaping, most of the farmers use fish net which have not enough capability to protect fingerling
40	Extreme weather, climate change has a great impact on this sector
40	Limited buyers, mainly China is the major importer and their purchase depends on the best quality of the products
IMTA farmers (n=8)	
100	Insufficient capital to facilitate the multi-trophic aquaculture
87.5	Theft, security maintenance more difficult in open area
62.5	Poor knowledge about multiculture, authority had less/no involvement with researchers
50	Lack of goverment support, mainly the funding and monitoring
37.5	High material cost

a significant loss of tissue. It is usually caused by environmental factors such as the warming of sea water, a decrease in salinity, low light levels (<125 µmol photon m^{-2} s^{-1}) or slow water movements (Ward *et al.*, 2022). Largo *et al.*(1995b) showed that lower temperatures (~25 °C) and salinities between 25 and 35 ‰ increased growth rates and inhibited the formation of ice-ice when culturing *K. alvarezii* under laboratory conditions. As temperatures were as high as 28 °C and the tanks were under a roof, this further facilitated the formation of ice-ice. Furthermore, the low fish feed input of 4 % bodyweight d^{-1}, as the main source of phosphate in aquaculture (Nora'aini *et al.* 2005), was most likely not sufficient. Only with the higher input of fish feed after stocking the second batch of milkfish, was the phosphate availability sufficient. With a 100 % survival of the first batch and a consistently high input of feed, phosphate levels probably would have been higher compared to what was found, which could have facilitated a better growth, as it has been shown that P can be a growth limiting factor in seaweed culture (Lapointe, 1987; Pedersen *et al.*, 2010).

As for the seaweed cultured in the IMTA design, SGRs in the first cycle were all positive, with treatment D (high sea cucumber and sea oyster stocking density) showing the best performance. However, the observed SGRs, with max. 2.3 % d^{-1}, were well below the recommended 3.5 % d^{-1} for commercial eucheumatoid farming (Doty, 1987; Wakibia *et al.*, 2006). Several factors could have limited the seaweeds growth, such as low light availability, low water movement or too little nutrient input. Additionally, because of the type of tank, the seaweed was only suspended around 20 cm from the surface, well below the recommended 0.5 to 1 m for *Kappaphycus* culture (Sahoo and Yarish, 2005; Zuldin *et al.*, 2016). Looking at the individual treatments, it is observable that seaweed growth was facilitated by the presence of sea cucumbers and sea oysters. This positive effect of sea cucumbers was also reported by Uthicke (2001) and Wolkenhauer *et al.* (2010), showing that they boost primary producers' productivity through recycling of nutrients. This is in contrast to Davis *et al.* (2011), who discovered that the survival of seaweed appeared to be little/not influenced by the presence of sea cucumbers.

In contrast, the performance in the second cycle of the present study strongly declined, with all treatments showing a decrease in absolute biomass. The more optimal water parameters in the first batch facilitated the growth, compared to the higher water temperatures in the second cycle. This led to higher environmental stress and more opportunities for pathogenic bacteria (Glenn and Doty, 1990; Ward *et al.*, 2020; Faisan *et al.*, 2021). The ice-ice disease and unwanted algae growth were noticed more severely in the second cycle. Seaweed growth and carrageenan yields are frequently hampered by the growth of epiphytes (Ask and Azanza, 2002), and infestation by the algae *Neosiphonia spp*. on grown *Kappaphycus spp.* has already been observed for seaweed farms in Tanzania (Msuya and Kyewalyanga, 2006; Vairappan *et al.*, 2008).

As temperatures in the two designs (RAS and IMTA) were similar and both situated underneath a roof, the occurrence of ice-ice in the first half of the RAS experiment cannot only be linked to high water temperatures and low light setting. While the water in the IMTA systems was changed regularly, the water in the RAS was only changed once during the entire 70 days, which was necessary to establish the microbial community to drive nitrification and denitrification (Keuter *et al.*, 2015). This, however, could also have enabled the bacteria responsible for the ice-ice disease to accumulate (Largo *et al.*, 1995a). As Ward *et al.* (2022) showed, the presence of ice-ice does not originate from only one stressor, but most likely a 'complex pathobiotic syndrome'. This means that both abiotic and biotic factors combined are responsible for the ice-ice disease.

Although overall water quality remained within tolerable limits in both experimental designs, parameters such as temperature, salinity, pH and DO need to be observed more tightly and adjusted if necessary. Specifically, water temperatures rose in the second half of the experiments, as the months of December and January are the hottest in Zanzibar (Muhando, 2002). As water temperature is one of the most important parameters in seaweed culture (Breeman, 1988; Wiencke and Bischof, 2012), it is necessary to adjust the temperature to the seasonal variations, to increase the possible yield.

Sea cucumber performance varied strongly between the treatments; while in the RAS they showed a high growth rate in the first 35 days, it dropped to almost zero for the second half. For the other treatments, only treatment C showed a positive growth rate in the second half. The IMTA systems had much higher stocking densities and less space available for the sea cucumbers, which could have resulted in the negative growth, as these factors have a significant impact on sea cucumber growth rates (Slater and Carton, 2007; Davis *et al.*, 2011; Namukose *et al.*, 2016). This phenomenon has been called 'aestivation', and links the limited space with low metabolic rates and a stop of feeding (Li *et al.*, 2013). Furthermore, studies showed, that the growth of sea cucumber individuals can greatly vary and is dependent on multiple environmental factors and individual genetics (Qiu *et al.*, 2014; Dumalan *et al.*, 2019). Also, depending on the type of tank and sediment, sea cucumber SGRs were found to be negative, meaning a weight loss over the time of rearing further showing that sea cucumber growth is unpredictable in tank culture (Robinson *et al.*, 2013).

Nitrogen uptake by seaweed

Even though the thallus nitrogen content did not show any significant difference between days 1 and 45 of the respective cycles, a clear trend was apparent that the seaweed took up inorganic nitrogen over time. It is well reported that *Kappaphycus* assimilates dissolved inorganic nutrients and uses them as a source of N for assimilation (Rosenberg and Ramus, 1984; Smith *et al.*, 1999; Dy and Yap, 2001; Granbom *et al.*, 2004). Looking at the treatments individually, it shows that seaweed in treatment D had the highest mean uptake of nitrogen after 45 days, originating from a higher nitrogen availability. With higher sea cucumber and oyster stocking densities the quantity of excretory products and therefore of inorganic nutrients was higher compared to the other treatments (Taylor and Rees, 1998).

Especially ammonium, excreted by sea cucumbers, but also milkfish (Mook *et al.* 2012), plays an important role in intensive aquaculture and was therefore, together with nitrite and nitrate, measured three times a week in the RAS. The build-up of ammonium right after the first stocking, observed in both the seaweed and control system, is normal in recirculating aquaculture. Removal of ammonium by nitrification takes up to 14 days, as the responsible bacterial communities first have to establish themselves in the system (Keuter *et al.*, 2015). The observed ammonium levels decreased even earlier than that, most likely due to the filtration properties of the seaweed (Neori *et al.*, 2003; Quintã *et al.*, 2015). In the first step of nitrification, ammonium is oxidized into nitrite by aerobic chemoautotrophic bacteria (Sharma and Ahlert, 1977; Camargo *et al.*, 2005). This is observable in the measured nitrite concentration, as about 5 to 10 days after the ammonium peaked, the nitrite also showed peak concentrations. Nitrite concentrations measured in the two systems are quite similar to the ones reported by Senff *et al.* (2020), and highly likely not lethal. The observed concentrations of nitrate (NO_3^--N < 5 mg L^{-1}) were well below critical limits of 10 to 20 mg L^{-1} (Spotte, 1979; Ward *et al.*, 2005). The regular water changes in the control system probably kept the nitrate levels low and stopped a built-up of nitrate, while in the seaweed system the seaweed could filter out the nitrate. Although, the nitrogen content in the seaweed thallus and the inorganic nutrient measurements in the water come from two different systems, the assimilation of ammonium and nitrate by the seaweed can be seen in both. The seaweed kept the nitrogen levels in the water low, while incorporating it in its thallus.

Economic viability and farmers' perception

IMTA can enhance production sustainability, mitigate the negative effects of intensive aquaculture operations, and generate financial gains through diverse products and faster production cycles (Knowler *et al.*, 2020). In this study, gross return and BCR were calculated and converted to annual figures to understand the experimental viability of the designs used. In comparison, seaweed monoculture had a low return, while having the same construction costs as the other IMTA systems. In the IMTA systems, the high-density treatment showed the highest return of US$ 6.96 per m^2. Whereas the RAS was found to have a comparatively low return of US$ 3.85 per m^2, while having the highest cost of US$ 36.00 per m^2 due to high initial construction and material costs. By annualizing the production of seaweed monoculture, it was shown that it is impossible to generate revenue over the long-term, while the IMTA system with high stocks of seaweed, sea cucumber, and sea oyster, generates an income of 27.95 US$ m^{-2} per year with initial costs being approximately 17.34 US$ m^{-2}, achieving a BCR of 1.61 over one year. The RAS had initial costs of 36.19 US$ m^{-2}, however, when calculating the yearly income, it was determined to be 19.37 US$ m^{-2} with a BCR of 0.54. This indicates that the system needs to continue for almost two years in order to recover its losses. A 100 % survival of milkfish could achieve a BCR above 1, although this would require further research and investment.

By conducting questionnaires on the perception of farmers, this study found that seaweed farming is largely female dominated, while men were more actively engaged in fishing, following the observations of Msuya *et al.* (2007). The fishing industry, not only in Zanzibar, but in Tanzania in general, is dominated by men (Shao *et al.*, 2003). During the survey, seaweed farmers claimed to have the lowest market price, though Msuya (2020) reported that the seaweed (dry) price has increased to approximately 1800 TZS per kg, most likely due the establishment of a processing plant in Pemba Island. In contrast, Makame *et al.* (2021) found that the seaweed price is fixed by buyers and 76.4 % of farmers are not satisfied with it. Additionally, the production of *Kappaphycus* has been significantly impaired by diseases, such as the ice-ice disease, as well as epiphyte outbreaks that are now more severe through rising sea surface temperatures associated with climate change (Msuya and Porter, 2014; Largo *et al.*, 2020).

To alleviate the above mentioned problems in the local seaweed industry, it is vital that different stakeholders should come forward in proposing solutions. One of which could be the regulation of prices of unprocessed seaweed by the local government on the basis of current instrument cost, as Jong Cleyndert *et al.* (2021) reported that weak bargaining power of farmers is the reason why they receive a low sale price. To improve the seaweed market's attractiveness, Msuya (2021) suggested value adding initiatives, such as training to process seaweed into more valuable products such as soap, shampoo, cookies, and juice. To further overcome the challenges induced by climate change and the associated rise in sea surface temperature, the SeaPoWer project, proposed a new technology for seaweed farming in deeper waters (>8m) using tubular nets (Brugere *et al.*, 2020).

Another obstacle for farmers in Zanzibar is the regular poaching of sea cucumbers due to their high market value. In this study, sea cucumber farmers frequently mentioned their main constraints being poaching and fingerling scarcity, high pressure on natural sources reducing fingerling availability and the lack of a recognized hatchery. Kunzmann *et al.* (2018) reported that fingerling production was initiated by the FAO hatchery supported by the Korean International Cooperation Agency (KOICA), but during this study they stopped the sea cucumber fingerling production (personal observation).

The pearl oyster is mainly cultured for producing half-pearl, which was initiated in Zanzibar in 2005 (Mmochi, 2015). There were two farmers found during this study, who are mainly fishermen, but they also cultured oysters to produce half pearl and make jewellery, which are sold to the local market. Farmers mentioned that the main constraints to producing half pearls are poaching, inadequate spat (Ishengoma *et al.*, 2011), an irregular and unreliable market, and lack of expertise (Charisiadou *et al.*, 2022). In Zanzibar there is a great potential for producing half pearl, as in the south pacific countries, where oyster culture is popular for forming valuable pearls due to less labour input, capital, and training requirements (Johnston *et al.*, 2020). To get a broader view of the local communities' perception of the introduction of new aquaculture practices, a more detailed survey would be necessary, as the current questionnaire only reflects the local farmers perception.

Improvements to the systems

Some improvements to the IMTA and RAS systems have already been mentioned, but this section aims to highlight them in detail and give recommendations for future systems. The biggest constraint found in this study was the appearance of the ice-ice disease and the subsequently fouling of seaweed. This reduced the economic viability of all treatments. There are already several suggestions how to overcome this disease, including a stricter control and adjustment of water parameters, such as temperature and salinity as well as light intensity (Largo, 2002; Tahiluddin and Terzi, 2021). Another potential method is to manually clean the seaweed from macroalgae epiphytes and filamentous epi-endophytes, which can cause the ice-ice disease (Largo *et al.*, 2020; Kambey *et al.*, 2021). The setup of tanks also seems to play an important role; seaweed should be able to be suspended at least 50 cm into the water column (Sahoo and Yarish, 2005; Zuldin *et al.*, 2016) and steady water movement should be maintained (Ward *et al.*, 2022). Furthermore, there are suggestions that *E. denticulatum* can withstand adverse environmental factors better, and would therefore be better suited for this type of aquaculture (Tisera and Naguit, 2009; Pang *et al.*, 2015). Kambey *et al.* (2021) showed that seaweed farms integrating various biosecurity measurements, not only achieve higher growth rates and reduced infection rates, but also increase the quality of the carrageenan yield and therefore the products value. Apart from biosecurity measurements, it would be beneficial to increase the tank size and change the tank shape, not only for seaweed, but also for the sea cucumbers (Slater and Carton, 2007; Davis *et al.*, 2011; Li *et al.*, 2013) and milkfish (Oca *et al.*, 2004; Duarte *et al.*, 2011; McLean, 2021). Large circular tanks/ponds or raceway systems would be possible solutions. In particular for the RAS, a possible solution could be the use of just one big tank, which can be divided into compartments for each species, ensuring a better dispersion of nutrients and diminish technical failures due to power failures and broken equipment, which is especially important in developing countries lacking infrastructure. Furthermore, it seemed that the sea cucumbers in the IMTA were lacking a source of nutrients, which could be overcome by artificially feeding them, either with algal extracts or sludge from fish cultures. Because of the type of tank used for the fish, the removal of sludge was not possible. This is, therefore, another possible improvement to boost the sea cucumbers growth. Overall, more testing is necessary for both types of systems to overcome the ice-ice issue and to boost growth rates. However, as this study demonstrated, sustainable tank culture of seaweed in IMTA can be economically feasible and provide farmers with a secure income. Seaweed farming has been a profitable business for local farmers over the last decades and will likely stay that way (Msuya and Kyewalyanga, 2006) and farmers are willing to adapt to new farming techniques (Lumenyela *et al.*, 2023). Improved versions of the systems used could be viable options for farmers not only on Zanzibar but in many developing tropical countries. The initial investments would need to be covered by microcredit schemes from local government or NGOs.

Conclusions

In conclusion, the study highlights the importance of developing sustainable aquaculture systems to meet the increasing demand for food, especially in developing countries, as well as the complexities and challenges that are associated with this. Both experimental designs, IMTA and RAS, show promising results to be used as low-tech and sustainable alternatives to already existing practices. However, for both designs, there are still a lot of improvements necessary, especially regarding the seaweed culturing. The prevalence of the ice-ice disease, driven by high water temperatures and inadequate nutrient input, significantly hampered seaweed growth. Only the IMTA system in the first growth cycle showed more robust growth, most likely attributed to the beneficial effects of nutrient recycling from sea cucumbers and oysters. The results of the economic analysis revealed that the IMTA system, particularly with high-density seaweed, sea cucumber, and pearl oyster stocks, was more profitable compared to RAS and monoculture systems, thus IMTA is a more practical system for Zanzibar and Tanzania in general. Equally, IMTA can be a better choice for Zanzibar given that the IMTA system achieved a higher BCR, indicating better financial viability over time. Socially, seaweed farming remains a crucial livelihood for many, particularly women, though market challenges such as low prices and disease outbreaks persist. With appropriate support and investments, these novel aquaculture practices can mitigate the impacts of environmental stressors, enhance production, and ensure long-term viability.

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