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The performance of the seaweed *Ulva reticulata* as a biofilter in a low-tech, low-cost, gravity generated water flow regime in Zanzibar, Tanzania

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Abstract

In most land-based mariculture, seaweeds have been cultured using expensive ponds and electrical pumps to aerate the seaweeds, methods that can be expensive and not applicable to areas where electricity is lacking. In this study, a low-tech, low-cost, gravity-generated water flow regime was used in earthen ponds in Zanzibar, Tanzania. The seaweed *Ulva reticulata* was cultured suspended in 2 m^{-2} fishnet cages (units) in channels located at the outflow of fishponds as treatment and at the channel leading water to the fishponds as control, in a fish-seaweed integrated system.

The seaweed grew at an average of 4.0% per day at the treatment (fishpond outflow channel) with a biomass yield averaging 46 g m^{-2} day^{-1}, compared with 2.5% and 27 g m^{-2} day^{-1} at the control (fishpond inflow channel). Likewise, the seaweed removed a significant amount of areal total ammonia nitrogen (TAN) averaging 6.5 g N m^{-2} day^{-1} with 65% removal efficiency and 0.3 g P m^{-2} day^{-1} of soluble reactive phosphate (SRP) with 33% efficiency, from a TAN load of 10.6 g m^{-2} day^{-1} and phosphate load of 0.7 g m^{-2} day^{-1}. In the control, only 1.9 g N m^{-2} day^{-1} (44% efficiency) TAN and 0.3 g P m^{-2} day^{-1} (33% efficiency) SRP were removed from TAN and phosphate loads of 4.8 and 0.8 g m^{-2} day^{-1}, respectively. Through its photosynthetic activity, the seaweed significantly ($p<0.001$) raised the oxygen concentration and pH of the fishpond outflow water (from 5.6 to 13.4 mg l^{-1} and 7.8 to 8.4, respectively). It is therefore concluded that seaweeds can be cultured in fishpond outflow channels, in a low-tech, low energy, gravity-generated water flow regime and function as effective biofilters of fishpond effluent water.
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Keywords: Seaweed biofilters; *Ulva reticulata*; Gravity generated water flow regime; Nutrient removal

1. Introduction

Land-based mariculture operations involve feeding of the fish using formulated feeds; the main source of potentially polluting waste discharge is feed derived. Such operations, whether semi-intensive or intensive, thus release organic materials mainly as unconsumed feed, but also as undigested feed residues and fish inorganic nutrient excretions. Effluent water from fish or shrimp ponds are a concern considering that fish for example incorporate only about 30–40% of the nitrogen that they ingest and the rest is excreted in dissolved forms (Porter et al., 1987), although this depends on feed quality and management. Ammonium and suspended solids are known to be the most significant polluting components of fishpond effluents (Tovar et al.,

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2000). If released directly to the sea, the organic and nutrient loads cause eutrophication of the marine environment, which affects the naturally growing marine organisms. In addition, a mariculture operation itself can be affected by upstream impact of environmental degradation. Qian et al. (1996) reported on the collapse of a prawn industry in China for reasons attributed to outbreak of pathogenic bacteria caused by increased nutrient load. Thus, it is crucial to treat mariculture fishpond effluent water before it is released back to the sea or recirculated.

Most works on the use of seaweeds to treat effluent water from land-based mariculture has used integrated systems with seaweeds of the genera *Ulva* and *Gracilaria* with finfish such as *Sparus aurata.* Vandermeulen and Gordin (1990) reported some of the first mariculture experiments with *Ulva lactuca* in an integrated system of finfish, *S. aurata*, and the seaweed in Israel. They found that *Ulva* efficiently removed up to 85% of total ammonia nitrogen (TAN) from fishpond effluent water. The authors described the use of *Ulva* as a viable cost-effective way of removing nutrients in situ. High growth rates, high yields and reduced C/N ratios were subsequently reported by Neori et al. (1991) who cultivated *U. lactuca* using fishpond effluent water in outdoor tanks in Israel. Shpigel et al. (1993) reported removal efficiencies by *U. lactuca* of over 90% from TAN concentrations of 2 g m^{-2} day^{-1} and stocking densities of 1 kg m^{-2}. Jimenez del Rio et al. (1996) obtained dissolved inorganic nitrogen (DIN) removal rate of 2.2 g DIN m^{-2} day^{-1} during the summer and 1.1 g DIN m^{-2} day^{-1} during winter by the seaweed biofilter *Ulva rigida*. Working with a 3.3 m^3 system of fish, shellfish and seaweed, Neori et al. (2000) found that *U. lactuca* removed 67% of its TAN input. In a three-stage seaweed system connected to an intensive fishpond, Schuenhoff et al. (2003) obtained TAN removal efficiencies of 70% by *U. lactuca* and Neori et al. (2003) obtained areal removal rates of up to 2.9 g m^{-2} day^{-1} with removal efficiencies of 85–90% in a novel three-stage system of *U. lactuca*. All these works have used costly ponds and expensive aeration systems not suitable for non-electrified areas in developing countries.

The present work examined a low-tech, low-cost system using gravity generated water flow to cultivate the seaweed biofilter *Ulva reticulata* in earthen ponds in Tanzania. Some low cost regimes may involve the use of minimum electricity to pump water from the sea and the rest of the system operates by other means of water flow such as gravity. The regime presented here does not require the minimum electricity as the water is filled in the reservoir pond by gravity and thus energy use here is very low. In addition, water flow by gravity in this regime creates a high enough velocity to reduce the diffusive boundary layer (DBL) between seaweed thalli and ambient water and thus enhance the performance of the biofilter. The seaweed *Ulva* was selected for the study because it has been used elsewhere and proved to be an effective biofilter.

2. Materials and methods

2.1. Study site

The research work was conducted at Makoba Bay, located on the North West Coast of Unguja Island (Zanzibar), Tanzania (Fig. 1). The study site at Makoba contains a reservoir pond (40,000 m^2) that collects water at high spring tide and the water is then released to six smaller (260 m^2) low-density fishponds (Fig. 2a and b). The seaweed *U. reticulata* was cultivated in fishpond outflow channels (1 m wide and 20 cm deep) using fishpond effluent water in a fish-seaweed integrated system.

2.2. Experimental design

U. reticulata was collected from wild stocks at Chwaka Bay, on the East Coast of Zanzibar (Fig. 1). The experimental seaweed was kept overnight in aerated 300 l plastic containers filled with seawater, at room temperature and transported to the experimental site the next morning as was described in Msuya and Neori (2002).

The seaweed was cultivated in channels located at the fishpond outflow in a fish-seaweed integrated system. Water flowed continuously through the seaweed and then to the sea in a water flow-through model. Rectangular (1 m × 2 m) cages (units) made of fishnet material (1.5 mm) were constructed and used for this study. Six such units (three units in two replicates) were placed in a series at the fishpond outflow channels, at positions marked A and B in Fig. 2b. Two control units, also placed in series, were positioned at the reservoir to fishponds channel (fishpond inflow channel, C in Fig. 2b). The seaweed was stocked at a stocking density of 1 kg m^{-2} as was recommended by Neori et al. (1991). Water flowed continuously through the biofilters, at an average velocity of 1.12 cm s^{-1}. From this velocity, water flow was calculated as the product of the velocity and the cross section area the flow is crossing through as follows:

$$0.0112 \text{ m s}^{-1} \times 0.0846 \text{ m}^2 \times 3600 \text{ s h}^{-1} = 3.411 \text{ m}^3 \text{ h}^{-1}$$

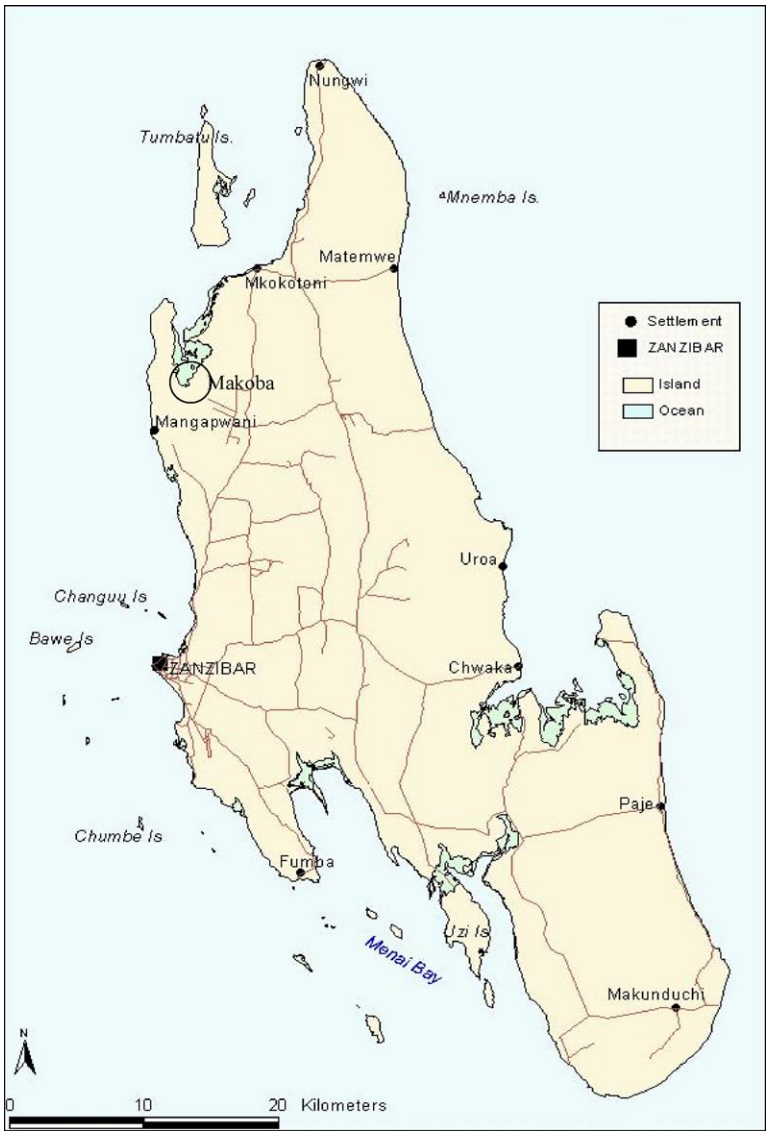


Fig. 1. Map of Unguja (Zanzibar) Island showing the Makoba Bay study site.

TAN concentration was on the average 10.6 μM in the fishpond outflow channels and 4.8 μM in the fishpond inflow channels, whereas soluble reactive phosphate (SRP) averaged 0.7 and 0.8 μM, respectively. The experiments were conducted for 6 weeks in August–October 2004.

2.3. Sample collection and analysis

2.3.1. Seaweed growth rate and biomass yield

The seaweed was harvested once a week, squeezed to remove excess water according to Fujita (1985) and placed in plastic bags. To obtain fresh drained weight, the seaweed was weighed on a mechanical scale. 2 kg of the harvested biomass were restocked to each unit for the continuation of the study. Biomass yield (fresh weight) was calculated as the difference between the initial and final weights and expressed in units of g m^{-2} day^{-1}. Specific growth rate (SGR, %) was calculated as: $SGR = 100 \times [\ln(w_t / w_0)] / t$ according to Rosenberg et al. (1984), where w_0 is the initial biomass and w_t is the biomass at t culture days.

2.4. Water quality

Water samples were collected at the fishpond outflow channels and outflow of the seaweed units. Sampling was done once a week at 08:30 and 14:30 h. After

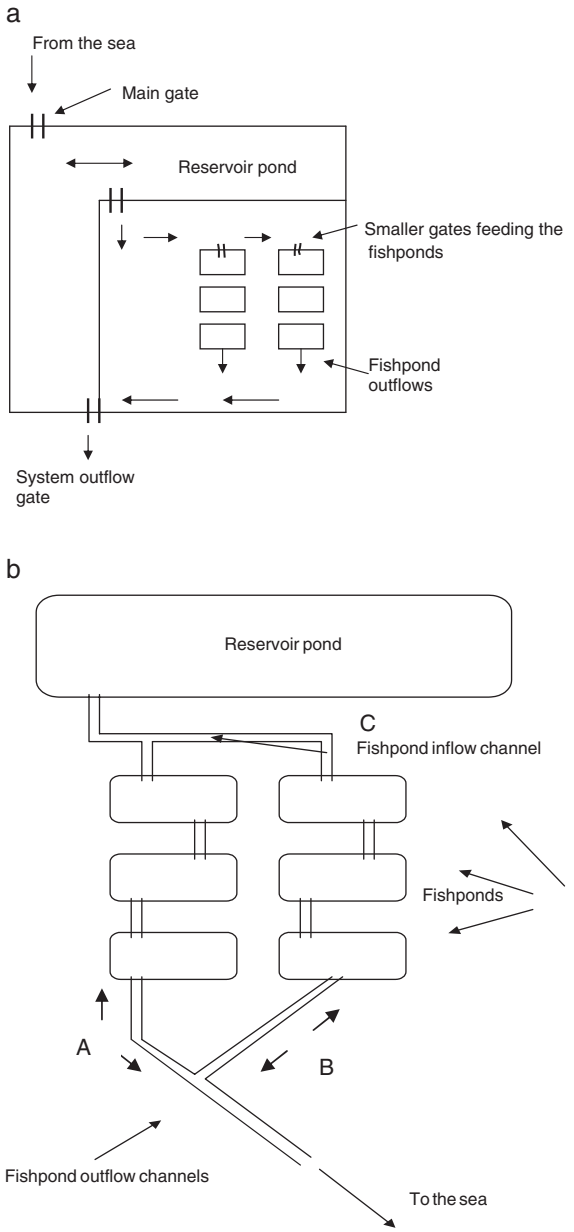


Fig. 2. (a) A presentation of the water flow in the integrated system at Makoba, Zanzibar. (b) The integrated system showing seaweed units placed at positions A and B as treatments and C as control (modified from Msuya and Neori, 2002).

collection, the water was filtered through GF/C Whatmann filter papers. Nutrient analysis for TAN and SRP was done by using a spectrophotometer and methods of Parsons et al. (1984). Total oxidised nitrogen (ToxN) was not analysed due to problems with the nitrate column. For the treatment, biofiltration rate and efficiency was calculated from the difference in nutrient concentrations between the outflows of fishponds and outflows of the seaweed units (after Krom et al., 1985). The rate and efficiency for the control were calculated as the difference in nutrient concentrations between the outflow from the reservoir and that from the seaweed control unit.

Oxygen concentration (mg l^{-1}), saturation (%) and temperature (°C) of the water were measured by using an oxygen meter (OxyGuard Handy Gamma, Denmark). Water velocity in the fishpond outflow channels was measured by using pieces of leaves and a stopwatch. The pH of the water was measured using a pH-meter (HANNA Instruments, Canada, Model No. HI 8014), whereas salinity was measured using a hand refractometer (Bellingham and Stanley Eclipse UK, 45-83). Oxygen, water temperature, pH and salinity measurements were recorded every other day.

2.5. Data analysis

Data were analysed by analysis of variance (ANOVA) to determine whether there were significant differences in the results of the measured parameters between the treatment and the control. Data that were measured as percentage (biofiltration efficiency) and that were out of the range of 30–70% were arcsine transformed to ensure normality before statistical tests were performed on them. The data were analysed by using SPSS and Excel 2000.

3. Results

3.1. Water quality

The temperature of the water averaged 28.5±1.3 at the outflow of fishponds and 29.3±1.4 at the outflow of the seaweed units, with no significant difference between the fishpond outflow and seaweed outflow (ANOVA, $F=0.37$, df 34, $P>0.05$). The temperature range was 26.2–31.4 °C at the fishpond outflow and 26.8–31.6 °C at the outflow of the seaweed units. The temperature variation was less than 3 °C on any day.

Salinity of the water was 40‰ at both the fishpond outflow and the outflows of seaweed units, with occasional days where the salinity level was different. These included the days when the reservoir was refilled where the salinity was 39‰ or when there was not enough water for release to the fishponds (about 1 week) when the salinity was 44‰. Likewise, it was raining during the last week of the experiments and the salinity dropped to 32‰ at the fishpond and seaweed outflow channels and 30‰ at the fishpond inflow channel.

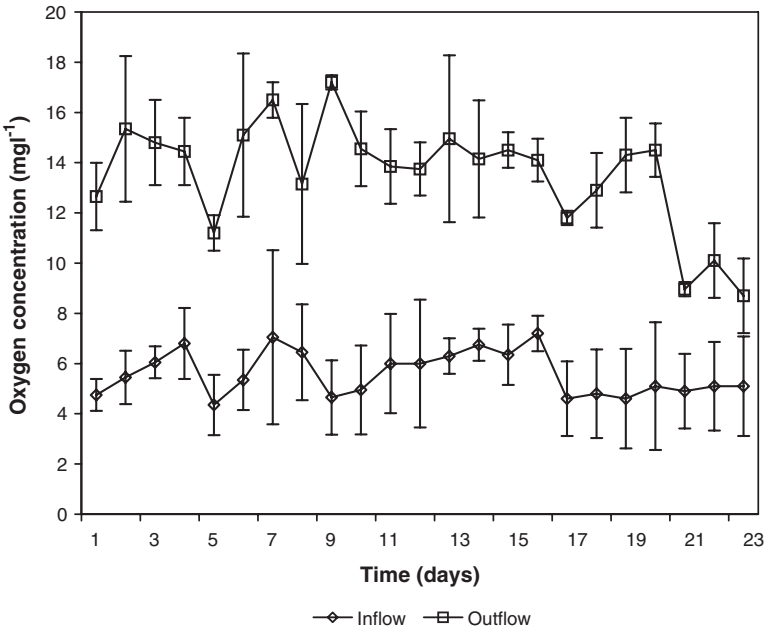


Fig. 3. Variation in oxygen concentration (average±S.D.) at the fishponds and seaweed outflow channels of the fish-seaweed integrated system, Makoba, Zanzibar, August–October 2004. The time shows sampling days, i.e., at least 3 days/week for 6 weeks.

Oxygen concentration of the water from the fishpond outflow that entered the seaweed biofilter units was between 3.5 and 7.8 mg l^{-1} and at the outflow of the seaweed biofilter units was between 10 and 17 mg l^{-1}. Average values for the entire study period were 5.6± 0.9 mg l^{-1} at the fishpond outflow channel and 13.4± 2.2 mg l^{-1} at the outflow of the seaweed units (Fig. 3). Statistically significant (F=276.9, df 22, P<0.001) difference was found between the fishpond outflow and the outflow of the seaweed biofilters. Most of the

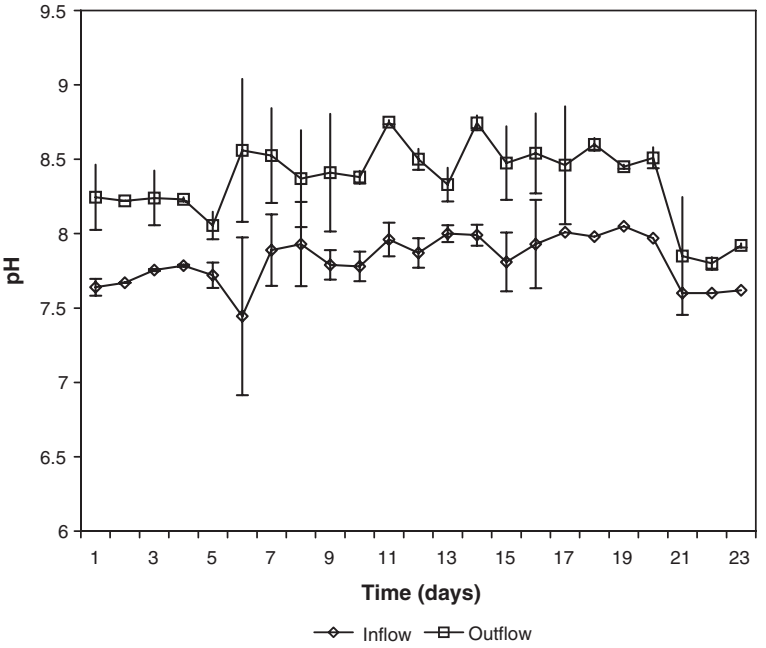


Fig. 4. Variation in pH (average±S.D.) at the fishponds and seaweed outflow channels of the fish-seaweed integrated system, Makoba, Zanzibar, August–October 2004. The time shows sampling days, i.e., at least 2 days/week for 6 weeks.

time, water at the seaweed units was supersaturated in dissolved oxygen, with an average of 213±50% saturation, while water at the fishpond outflow channel had an average oxygen level of 88±15%.

The pH of the water was raised from between 7.1 and 8.1 at the fishpond outflow channel to between 8.1 and 8.9 at the outflow of the seaweed units (Fig. 4), with statistically significant (F=90.1, df 22, P<0.001) difference between the fishpond outflow channel and the outflow from the seaweed units. pH recorded at the fishpond outflow channel averaged 7.8±0.2 and that at the outflow of the seaweed units averaged 8.4±0.3. Towards the end of the study period, it was raining and the pH dropped (Fig. 4).

3.2. Seaweed growth and biomass yield

Specific growth rate (SGR) of *U. reticulata* averaged 4.0% day^{-1} at the fishpond outflow channel and 2.5% day^{-1} at the fishpond inflow channel (Table 1), with significant difference (F=26.3, df 26, P<0.001) between the fishpond outflow channel (treatment) and the fishpond inflow channel (control). The average yield per unit area was 46 g m^{-2} day^{-1} at the fishpond outflow channel and 27 g m^{-2} day^{-1} at the fishpond inflow channel (Table 1), with statistically significant difference (F=19.7, df 26, P<0.001) between fishpond outflow and fishpond inflow channels.

3.3. Nutrient removal rates and efficiencies

Areal nutrient removal by the seaweed biofilter showed that the biofilter removed a significant amount of TAN averaging 6.5 g N m^{-2} day^{-1} at the fishpond outflow channel with 65% removal efficiency (Table 1).

Table 1
Growth rate, biomass yield, nutrient uptake rates and efficiencies of the seaweed *Ulva reticulata* cultured under a gravity generated water flow regime, Zanzibar, Tanzania: treatment=fishpond outflow channel; control=fishpond inflow channel (water flow was 3.4 m^3 h^{-1})

Parameter	Fishpond outflow channel	Fishpond inflow channel
SGR (% day^{-1})	4.0±0.7	2.5±0.4
Biomass yield (g m^{-2} day^{-1})	46±9	27±18
TAN uptake rate (g N m^{-2} day^{-1})	6.5±3.2	1.9±1.2
TAN uptake efficiency (%)	65	44
Phosphate uptake rate (g P m^{-2} day^{-1})	0.3±0.2	0.3±0.2
Phosphate uptake efficiency (%)	33	33
Nutrient load (g m^{-2} day^{-1})		
TAN	=10.6±5.2	4.8±3.2
P	=0.7±0.2	=0.8±0.0

Likewise, 0.3 g P m^{-2} day^{-1} of SRP were removed at an efficiency of 33%. The fishpond inflow channel gave areal removal rate of 1.9 g N m^{-2} day^{-1} and an efficiency of 44% for TAN and 0.3 g P m^{-2} day^{-1} (35% efficiency) for SRP. ANOVA tests showed significant differences in removal rates (F=8.29, df 10, P<0.05) and efficiencies (F=10, df 6.3, P<0.01) between the fishpond outflow channel and fishpond inflow channel.

4. Discussion

4.1. Water temperature

The daily variation in water temperature that did not exceed 3 °C gives conditions that are good for mariculture. A daily water temperature variation of up to 4 °C is acceptable in mariculture standards where the water does not harm the cultured organisms (see, e.g., Vandermeulen and Gordin, 1990). In addition, the high temperatures that are typical of tropical climates enhanced the growth rate and general performance of the seaweed cultured at Makoba. Species of the genus *Ulva* especially *U. lactuca* have been cultured under higher temperatures than those obtained here and found to have high growth and produced high biomass yields (Cohen and Neori, 1991; Neori et al., 2000, 2003).

4.2. Salinity of the water

The average salinity obtained here is higher than that obtained by Msuya and Neori (2002), whose part of the research was conducted during long-rains season, giving also a smaller range than that obtained by the authors. The salinity range is also higher than the salinity of seawater found in Zanzibar waters (35–37‰), showing that evaporation was taking place in the reservoir pond at Makoba. However, the salinity was favourable for *Ulva* as the seaweed is known to tolerate much higher salinity ranges (Msuya and Neori, 2002).

The interaction between temperature and salinity could be clearly seen during the study time, where both temperature and salinity showed a small range, i.e., stable values. Furthermore, because the study was undertaken during the dry season, high evaporation (due to solar irradiance heating up the water) resulted into salinities higher than that found in seawater in Zanzibar, as explained above.

4.3. Oxygen concentration

The oxygen concentration obtained here and the significant differences in concentrations between the

fishpond outflow channel and the outflow of the seaweed biofilter units depict the ability of the biofilter to oxygenate the water in the integrated system through efficient photosynthetic activity. Other workers such as Neori et al. (2000) and Schuenhoff et al. (2003) found significant similar results of oxygenation of fishpond water by seaweeds, in aerated culture regimes. Oxygen levels at night, although not measured in this study, are lower than the levels found here because of respiration of the fish and minimum photosynthesis by the seaweed. With supersaturated water at the seaweed units found in the current study, the water needs to be passed through a settling pond if it is recirculated to avoid fish toxicity (Wajisbrot et al., 1991). In the case of release back to the sea, as is done at Makoba, the water can be safely released to the sea as the oxygen levels are lowered when the high oxygen water passes through the main drainage channel and the outlet gates where it mixes with seawater before it reaches the open sea. The oxygen concentrations remained stable throughout the study period, a sign of goodwater conditions for efficient performance of the biofilter.

4.4. pH of the water

The toxicity of ammonia to aquatic organisms is attributed primarily to the unionised form (NH_3) and not to the ionised form (NH_4^+), and pH strongly controls the aqueous ammonia equilibrium of the water (Wajisbrot et al., 1991). It is, therefore, important to keep the pH of the water at levels that allow for the presence of NH_4^+ in mariculture systems. The pH of the water from fishpond outflow was restored by the seaweed biofilter, i.e., pH was increased from low fishpond outflow values to conditions that are similar to seawater. With pH values that did not exceed 9, no negative effect is expected on the photosynthesis of the seaweed (Menendez et al., 2001) that could have resulted in lower biomass yield. pH values of 9.0, or above, commonly occur in culture systems and may inhibit growth (Frost-Christensen and Sand-Jensen, 1990).

As pH increases, dissolved CO_2 levels in the water decrease and photosynthesis becomes more dependent on the use of HCO_3^- or CO_3^{-2} (Falkowski and Raven, 1996). At the gravity regime used in the current study that received high tropical irradiances, the removal of CO_2 from the water through photosynthesis by *Ulva* did not increase the pH of the water to above standards of 6–9 required for aquaculture (Howerton, 2001). *Ulva* being a HCO_3^- user (Beer and Eshel, 1983), it performed well under such a pH range as found here. pH remained stable during the entire study period, indicating good conditions that can be recommended for seaweed cultivation and release to the sea or recirculation (e.g., pH 6–9, deCastro and Guanzon, 1993).

4.5. Seaweed growth and biomass yield

Culturing the seaweed at the outflow of fishponds resulted in higher growth rate and biomass yield than at the fishpond inflow channel, showing the benefits of using fishpond effluents to produce high seaweed biomass. The growth rate obtained here is higher than that obtained by Msuya and Neori (2002) (1.2% day^{-1}) at Makoba, probably because of a lower stocking density used here, but also the seaweed was cultured in a different season than that of those authors. These are the most probable reasons considering that nutrient concentrations at the inflow water were similar to those used by the previous workers. Other workers such as Troell et al. (1997) and Nelson et al. 2001 reported on increased seaweed production as a result of culturing the seaweeds in locations where they would receive effluent water from adjacent fishponds.

4.6. Nutrient removal rates and efficiencies

The nutrient removal rates obtained here are very high not only in this kind of culture regime and integrated system, but compared also with the aerated regimes used by other workers. The TAN removal rate obtained in this regime is higher than that of Neori et al. (2003) who used higher nutrient concentrations and aeration in their *U. lactuca* low nutrient load experiment, and obtained TAN areal removal rate of 0.5–0.9 g N m^{-2} day^{-1} and an overall removal efficiency of 90%. The higher removal rates may have been the result of a higher water flow used here, i.e., 3.4 m^3 h^{-1} compared with 1.5 m^3 h^{-1} used by those workers. Using higher nutrient concentrations and aeration on the seaweed biofilter, Cohen and Neori (1991) and Shpigel et al. (1993) obtained TAN removal efficiencies of 40–56% and biofiltration rates of up to 5.6 g m^{-2} day^{-1} in *U. lactuca*, results that are similar to those of the current study. Working with high rate ponds with much higher nutrient concentrations, Pagand et al. (2000) and Jimenez del Rio et al. (1996) obtained average removal efficiencies of about 60% for DIN and P. Therefore, the integrated system at Makoba resulted in nutrient removal rates and efficiencies that are similar to other systems

that use expensive ponds and air aeration to culture seaweeds.

4.7. Overall performance

The gravity generated water flow regime enabled the removal of a significant amount of nutrients from fishpond effluent water, produced high seaweed biomass coupled with re-aeration and restoration of the pH of fishpond water. Apart from that, the regime generated the required water movement (velocity averaging 1.12 cm s^{-1}) to reduce the DBL and thus enhance diffusion of nutrients in and out of the seaweed. The multifactorial hypothesis defining at least four major physical factors that influence site fertility (Glenn and Doty, 1981) holds strongly for water movement since the other three factors were optimal, i.e., temperature and light, and nutrients were higher than in nature. If compared to other works mentioned above that used high nutrient concentrations and aeration, the regime in this study is as efficient as some of the regimes used by other workers.

These results are, however, obtained with a total surface area of 12 m^2. If more seaweed units are place in the system, water velocity will be reduced while seaweed surface area is increased. Thus, the amount of nutrients removed and biomass production per unit area will be lower than presented here. Due to lower water velocity, fouling of the seaweed by other seaweeds or microalgae, which was not observed in this study, could occur and these factors could reduce the growth rate and efficiency of the biofilter. Likewise, maintenance of a larger surface area may be more difficult especially in cleaning the cages and sampling.

5. Conclusions

The seaweed *U. reticulata* can be cultured in fishpond outflow channels using a low-tech, low-cost, gravity generated water flow regime and function as an effective biofilter of land-based fishpond effluents. A gravity generated water flow regime like the one used at Makoba, Zanzibar, can generate enough water movement for efficient culture and function of seaweed biofilters. Pollution of the environment that determines the development of intensive culture systems can be reduced by the application of this low-tech, low-cost culture regime.

Due to short time studies that have so far been conducted, a study to cover all the four seasons of the year, i.e., long-rains, short-rains, hot-dry and cold-dry seasons would be a marked addition to the results obtained so far.

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