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ORIGINAL ARTICLE

Integration of Nile tilapia (*Oreochromis niloticus*) and vegetables (*Amaranthus hybridus* and *Brassica rapa pekinensis*) for improved production, water use efficiency and nutrient recycling

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Abstract

Sustainable agriculture intensification is an urgent challenge in developing countries including Tanzania. One potential solution is to adopt farming systems that increase farm production by optimizing resource use efficiency, and integrated aquaculture system, which involves farming of fish and crops, is an example of such systems. This study investigated the impact of Integrated agriculture and aquaculture (IAA) farming on water use efficiency, fish and vegetable production and overall system profitability, and how these parameters are affected by fish stocking densities. *Oreochromis niloticus* (2.5 g average initial weight) were cultured at low stocking density (five fish m^{-3}, LSD), medium stocking density (eight fish m^{-3}, MSD), and high stocking density (12 fish m^{-3}, HSD) for 205 days. *Brassica rapa pekinensis* and *Amaranthus hybridus* cultivated adjacent to the fish tanks were irrigated with; (i) fish tank water, without any fertilizer inputs; (ii) fish tank water, partially fertilized; (iii) tap water, fully fertilized (farmers' practice); and (iv) tap water without any fertilizer inputs. Although the use of tank water from the high fish stocking density resulted in significantly higher vegetable yield, high fish stocking resulted in lower fish growth, profitability and water use efficiency compared to the other fish stocking densities, probably because of low survival rates (28%) at high stocking densities. The integration of fish at a medium stocking density with vegetables resulted in significantly higher net income than when fish and vegetables were grown separately.

KEYWORDS
fish and vegetable yield, integrated agriculture and aquaculture (IAA), tilapia stocking density, water use efficiency, sustainable intensification

1 | INTRODUCTION

The United Nation estimates that global population reached 7.7 billion in 2019 and it is projected to be 8.6 billion in 2030 and 9.7 billion in 2050 (UN, 2019). This growing population will lead to increased food demand. An increased and more sufficient food production is thus a major issue to meet the demand from a growing population (Bessada & Werner, 2015). The availability of fresh water is probably one of the most limiting factors for increased food production. Globally, agriculture consumes over 65% of the available fresh water, making it one of the most important water-consuming activities (Brauman et al., 2013).

On average, Tanzania is considered to have abundant water resources, which is estimated at 2200 m^3/capita/year (Mutayoba et al., 2001; NORPLAN, 2000). However, new opportunities in agriculture and increasing demand of water for irrigation and hydropower generation, coupled with long dry seasons and years of below average rainfall, have contributed to periods of water scarcity (Van Koppen et al., 2016). According to Yanda et al. (2015), about one third of the country is between arid and semi-arid and experiences less than 800 mm rainfall, while the remaining two thirds being found in highlands and coastal areas have more than 1000 mm precipitation. Water resource use conflicts have been reported to be a critical problem in some areas of Tanzania (Mulokozi , Mmanda, et al., 2020). For example, Ntilicha et al. (2012) reported that water use conflicts were a serious problem between farmers in the Hai district in Kilimanjaro region due to human population increase and water scarcity. Similarly, Mbonile (2005) reported water conflicts in the Pangani river basin, which were mainly caused by rapid population dynamics of both human and livestock, which in turn increased the demands for water. Thus, food production systems should preferably be designed for an efficient use of water in order to meet future challenges of water scarcity and food insecurity (Mancosu et al., 2015).

Integrated agriculture and aquaculture (IAA) provide a potential for sustained food production while minimizing water use (Ali & Talukder, 2008; Dugan et al., 2006). This is because when fish is introduced as one of the production components in the existing agriculture system, it adds an activity that does not compete for water (Rajabu & Mahoo, 2008). For example, integration of tilapia and vegetable, which is the most common type of IAA systems in Tanzania (Mulokozi et al., 2021; Respikius et al., 2020), offers a way to improve fish pond water quality and protect the environment from eutrophication. This is because water is used for both fish culture and vegetables irrigation, where the vegetable uses excess nutrient from the fishponds for increased growth (Ahmed et al., 2014; Limbu et al., 2017). The pond water also serves as a buffer against periods of droughts (Dey et al., 2010), which could be expected to increase with future climate change.

Chemical fertilizers are recognized for their ability to increase plant growth and production, thus improving global food security (Yousaf et al., 2016). However, excess fertilizers can have negative impacts on the environment. For example, environmental harmful gases such CH_4 and CO_2 which are by-products from synthetic fertilizers manufacturing can lead to air pollution (Savci, 2012). These fertilizers, when disposed in aquatic ecosystem, can cause water pollution and lead to water eutrophication (Khan et al., 2018). When applied to the soil continuously, they can degrade soil health and quality, and consequently lead to soil pollution (Savci, 2012). An increased adoption of integrated aquaculture systems can help to reduce these negative effects from chemical fertilizers on the environment by using nutrient rich fish pond water to irrigate crops and thereby decreasing the use of synthetic fertilizers and outputs of excessive nutrient from the fishpond (Da et al., 2015; Dey et al., 2010).

Within an IAA system, water use efficiency and productivity can be maximized by optimizing the fish stocking density to increase the fish yield (Ridha, 2005), lower production cost and increase the profit (Russel et al., 2008). The fish stocking density also influences the amount of nutrients present in the pond water that can be used for irrigating and fertilizing the crops. Ridha (2005) recommended high fish stocking densities in areas with limited water, land and man power. However, with increased stocking densities, there is also an increased risk for poor water quality that, in turn, could cause poor fish growth and low survival rates (Pouey et al., 2011; Sen et al., 2010). Recommended optimum stocking densities for tilapia vary widely depending on the culture system used. For example, M'balaka et al. (2012) recommended a tilapia stocking density of five fish m^{-3} in hapas and 250 fish m^{-3} in cages (Costa et al., 2017), while Shoko et al. (2016) reported better yield for tilapia in a polyculture with catfish in earthen ponds, reared at a stoking density of nine fish m^{-2}. In this regard, determining the optimum stocking density of fish in tilapia-vegetable integration systems is of high importance because it greatly influences the water quality, fish growth and also the extent to which the integrated crops will benefit from nutrients dissolved in the fish pond water, thus improving the overall farm water use efficiency, productivity and profitability.

The objective of this study was to assess the water use efficiency, growth performance, yields and economic benefits from an integrated production of tilapia (*Oreochromis niloticus*), Chinese cabbage (*Brassica rapa pekinensis*) and amaranth (*Amaranthus hybridus*), and assess how these parameters were affected by different fish stocking densities. Specifically, the study aimed at answering the following questions: (i) What is the effect of fish stocking density (low, medium and high) on fish growth performance and yield?; (ii) What is the influence of fish stocking density on water quality and on vegetable yield in an integrated tilapia-vegetable system?; (iii) How does the integrated production of fish and vegetable affect the water use efficiency (kg food produced m^{-3} water) and productivity (net income m^{-3} water)?; (iv) How does fish tank water irrigation and fertilization regimes affect soil nutrient concentration?; and (v) What is the yield and economic profitability of fish and vegetables when farmed in integrated or non-integrated systems? It was hypothesized that higher water use efficiency, growth performance, yields and economic benefits of both the fish and vegetables will be attained from a tilapia (*Oreochromis niloticus*), Chinese cabbage (*Brassica rapa pekinensis*) and amaranth (*Amaranthus hybridus*) integrated system than from a non-integrated system.

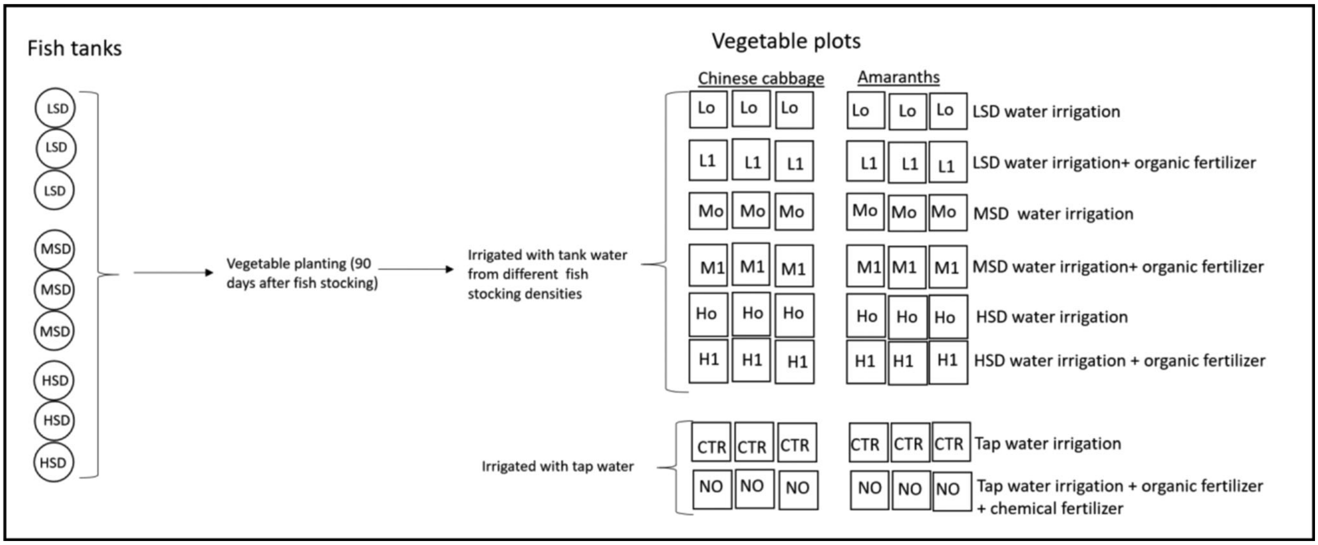

FIGURE 1 Schematic representation of the study design

2 | MATERIALS AND METHODS

2.1 | Study design

The present study involved three stages as follows: (1) a fish stocking experiment, where fish were cultured at three different stocking densities (low, medium and high) for 205 days; (2) a vegetable experiment (90 days after fish stocking), where vegetables (Chinese cabbage and amaranth) were irrigated with (i) tap water and fertilized with both organic and synthetic fertilizers, hereafter referred to as non-IAA vegetables, (ii) tank water from fish cultured at different stocking densities with and without organic manure fertilization, hereafter referred to as IAA vegetables, and (iii) tap water without any fertilizer input, hereafter referred to as control vegetables; (3) analysis of water use efficiency, growth performance, yields and economic benefits of fish and vegetables when practiced in an integrated system compared to a non-integrated system. A schematic representation of the experimental setup is shown in Figure 1.

2.1.1 | Fish experiment

The experiment was conducted at the Institute of Marine Sciences, Mariculture Center Pangani in Tanzania, using nine 1 m^3 tanks for 205 days in 2019. Sex reversed Nile tilapia (*Oreochromis niloticus*) fingerlings at 2.3–2.6 g were obtained from a commercial hatchery. Fish were cultured at three different stocking densities; low (five fish m^{-3}, LSD), medium (eight fish m^{-3}, MSD) and high (12 fish m^{-3}, HSD) in three replicates. Fish were fed on a formulated diet containing 350 g/kg protein dietary inclusion, served at 5% body weight split into two portions, one given in the morning (around 9.00) and another given in the afternoon (around 3.30). The feeding rate was reduced to 3% when the average weight of the fish reached over 120 g. The composition and proximate analysis of the experimental diet is shown in Table 1. The

TABLE 1 Ingredient and proximate composition (g/kg dry matter [DM]) of the experimental diet

Ingredient	g/kg
Shrimp meal	80
Fish meal	350
Cassava flour (binder)	20
Sunflower seedcake	70
Maize flour	480
Proximate composition of feeds	
Dry matter (DM)	896 ± 4.9
Ash	104 ± 1.4
Crude protein (CP)	353 ± 2.2
Crude fibre (CF)	53 ± 0.6
Ether extract (EE)	92 ± 0.1
Nitrogen free extract (NFE)	293 ± 3.6

Note: NFE = DM – (Ash + CP + CF + EE).

feed ingredients were purchased from a local market and ground into powder using a hammer mill (3 mm mesh size) at a milling factory. The resulting powder were weighed and mixed thoroughly, and then blended using water to form a dough. The dough was made into pellets using a meat mincer. The produced pellets were solar dried under shade for 2 to 3 days until no further changes in weight. The resulting pellets were stored in a dry room with proper ventilation until use. The diets were fed by hand to the fish by dispensing it at the surface of each fish tank. There was no exchange of fish tank water during the first 90 days to allow considerable accumulation of nutrients for vegetable irrigation (Section 2.1.2). Water was only added to compensate for loss through evaporation and irrigation (Limbu et al., 2017). After the end of vegetable cultivation, fish tank water was exchanged once per month. There was no aeration in the tanks. The experiment was designed to reflect the common practices done by fish farmers in the country, who

FIGURE 2 (a) Fish tanks and vegetable plot preparation and (b) Chinese cabbage and amaranth vegetables two weeks after sowing

normally do not practice water aeration in their aquaculture operations due to lack of reliable electricity and to minimize operation costs.

2.1.2 | Vegetable experiment

Vegetable cultivation was done during the dry season, 90 days after the stocking of fish to allow considerable nutrient accumulation in the tank water and also to prevent the influence of rainfall on the growth of vegetables. Irrigation (5 L per m^2) was done once a day in the evening around 4.00. The vegetables grown in the experiments included Chinese cabbage (*B. rapa pekinensis*) and amaranth (*A. hybridus*). Seeds were purchased from a local agricultural supplier. The reason for selecting the Chinese cabbage and amaranth was due to the fact that they are commonly preferred vegetables in Tanzania (Mulokozi et al., 2021). Water from replicate fish tanks with the same fish stocking density was mixed before being irrigated to the IAA vegetable plots following the design outlined below:

CTR (control): Vegetables irrigated with tap water, no fertilization at all;
Lo: Vegetables irrigated with water from fish cultured at LSD, no fertilizer applied;
L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized;
Mo: Vegetables irrigated with water from fish cultured at MSD, no fertilizer applied;
M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized;
Ho: Vegetables irrigated with water from fish cultured at HSD, no fertilizer applied;
H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized;
NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices.

2.1.3 | Vegetable planting and harvesting

The plot size for both Chinese cabbage and amaranth was 2 m^2 (Figure 2), separated by 0.7 and 1 m within and between rows, respectively. Three replicates were applied in each treatment for both Chinese cabbage and amaranths. Before sowing, L1, M1, H1 and NO vegetable plots were fertilized with broiler manure at a rate of 10 kg m^{-2}, a fertilization practice commonly used by farmers in the study area. This was done 1 week before sowing to give room for mineralization (Dada et al., 2017). For Chinese cabbage, three seeds were sown per point in several points per plot, which were then thinned to one plant per point after 2 weeks. Plant to plant distance was 0.5 and 0.3 m between and within rows, respectively. For the amaranth, sowing was done by mixing 1 kg of sand with 10 g of amaranth seeds and then broadcasted at a rate of 1 g of seeds per m^2 to obtain uniform stands (Baitilwake et al., 2012). The first harvest was done 2 weeks after thinning for the Chinese cabbage and 3 weeks after sowing for the amaranth. This was done in order to remove matured leaves for sale and give space to the young leaves to grow to marketable size. After the first harvest, a booster chemical fertilizer (urea) was applied at 1 g per m^2 only on the NO vegetable treatment. No additional chemical fertilizer was applied on the other treatments, which were only irrigated with the water from the fish tanks (Lo, L1, Mo, M1, Ho, H1) and tap water (CTR) until the final harvest, which was done after 35 days.

2.2 | Soil and water nutrient analyses

Soil samples from vegetable plots were collected before and after the experiment. Triplicate soil samples were taken to a depth of 0.2 m from each plot. The collected samples were packed in plastic bags and sent to the laboratory at the Department of Botany, University of Dar es Salaam for analysis. Soil samples were analyzed for pH, organic matter, nitrate (NO_3), total nitrogen (TN) and total phosphate (TP). Water samples from the fish tanks were collected twice a month and analyzed for TN, TP, nitrite (NO_2), NO_3 and ammonia (NH_4). The analyses were done using standard methods (Koroleff, 1970a, 1970b, 1976; Morris & Riley, 1963). Dissolved oxygen (DO), temperature and pH were measured twice a day in the morning and evening around 9.00 and 4.00, respectively. DO and temperature measurements were taken using a multiprobe kit (model Ecosense DO 200A China), and water pH was measured using a pH meter (model Combo H198129, Hanna Instruments Inc, Woonsocket, Rhode Island, USA).

2.3 | Proximate analysis

The proximate analyses of the ingredients and experimental diet were done according to AOAC (1990), at the Department of Animal, Aquaculture and Range Sciences, Sokoine University of Agriculture. Dry matter was determined by oven (E 115, WTB binder 7200, Tuttlingen, Germany) drying to constant weight at 105°C for 12 h. Crude protein was quantified using standard Kjeldahl nitrogen method using a 2200 Kjeltec auto-distillation unit (Foss, Tecator, Sweden). Lipid as ether extract was quantified using petroleum ether (ST 243 SoxtecTM, Hilleroed, Denmark). Crude fibre content was measured using an ANKOM 200 fibre analyzer (ANKOM, New York, USA). Ash content was determined by incineration of the fresh sample using furnace at 550°C for 3 h.

2.4 | Water use efficiency

The consumptive water use (CWU) of both fish and vegetables was estimated by measuring the amount of water supplied to the fish tanks and the amount used for irrigating vegetables (Abdul-Rahman et al., 2011; Boyd, 2005). The water inputs included regular water additions and precipitation. Since fish culture extended from dry to rain season, a rain gauge (model: Pluviometre x1, France) was installed near the fish tanks to measure the amount of rain that went into fish tanks (Yoo & Boyd, 1992). The main outflow included only the water used for vegetable irrigation and intentional discharges.

From the CWU, the water use efficiency (WUE) and water productivity (WP) were calculated based on the method by Abdul-Rahman et al. (2011) as follows:

WUE (kg/m^3) = total yield/CWU, for both tilapia and vegetables as wet weight.

WP (USD/m^3) = WUE × market price (USD/kg) for both tilapia and vegetables.

2.5 | Growth performance, yield and economic benefit

Fish body weights were collected monthly using a weighing balance (model: Boeco 43, Hamburg, Germany) throughout the experiment to assess fish growth performance (specific growth rate, feed conversion ratio and survival rates), yield and economic benefits. The harvested fish were weighed to obtain the yield and then valued according to prevailing local market price converted to USD (USD 1 = TZS 2297.6). Farm net income and benefit cost ratio analyses were used to compare the different treatments and systems. Production costs involved fixed costs (fish tanks and equipment for vegetables) and variable costs (fish seeds, feeds, manure, labour and transportation).

Fish growth performance was calculated using the following formulas:

$$\text{Specific growth rate(SGR, \% per day)} = \left(\frac{\text{Ln W2} - \text{Ln W1}}{\text{T}}\right) \times 100,$$

where: Ln is natural logarithm, W1 is mean initial weight (g), W2 is mean final weight (g) and T is number of days of the experiment.

$$\text{Feed conversion ratio (FCR)} = \frac{\text{Feed intake (Amount of feed fed to fish, g)}}{\text{Live weight gain (g)}},$$

$$\text{Survival rate (SR, \%)} = \frac{\text{Number of fish harvested}}{\text{Number of fish stocked}} \times 100,$$

$$\text{Yield (kg/ha)} = \frac{\text{Total weight of the harvest fish (kg)}}{\text{Area of the fish tank (ha)}}.$$

Vegetable sampling was carried out between 8 and 10 AM. Chinese cabbage was sampled by uprooting three plants from each plot. Amaranth sampling was done by uprooting plants from three different locations (0.3 × 0.3 m per location) in each individual plot. The above ground parts of the samples were labelled accordingly and then cleaned with a wet towel to remove the sediments. The weights of the fresh samples were measured using a weighing balance (Boeco, model 43, Hamburg, Germany) to obtain the yield.

Yield (kg/ha) and economic outputs (USD) were first estimated for both fish and vegetable separately and then in integration. Net income was calculated as follows:

$$\text{Net income (USD)} = \text{Total revenue} - \text{Total cost},$$

$$\text{Total revenue (USD)} = \text{Total quantity of output} \times \text{Unit price of output},$$

$$\text{Total cost (USD)} = \text{Fixed costs} + \text{Variable costs},$$

$$\text{Benefit cost ratio (BCR)} = \frac{\text{Total revenue}}{\text{Total costs}}.$$

2.6 | Statistical analysis

Before analysis, data were tested for homogeneity of variance and normal distribution using Levene's and Kolmogornov–Smirnov tests, respectively. When homogeneity of variances was confirmed, analysis of variance was used to test for significant differences in growth performance, water use efficiency, yield and economic returns between treatments. Percentage data on fish survival was first arcsine transformed before statistical analysis (Zar, 1999). When significant differences were detected, the Tukey post hoc test was performed to determine specific significant differences among treatments. Results are presented as means with standard errors. Statistical analysis was

TABLE 2 Growth performance and yield of tilapia cultured under different stocking densities (mean ± SE)

	LSD	MSD	HSD
Initial weight (g)	2.65 ± 0.14	2.54 ± 0.37	2.32 ± 0.24
Final weight (g)	268 ± 8.6^a	254 ± 3.6^a	180 ± 9.6^b
Weight gain (g)	266 ± 8.4^a	252 ± 3.4^a	178 ± 9.4^b
Specific growth rate (% day^{-1})	2.25 ± 0.03^a	2.23 ± 0.08^a	2.12 ± 0.0^a
Feed intake (feed fed to fish, g fish^{-1})	2561 ± 6^b	3022 ± 25^a	2577 ± 45^b
Feed conversion ratio	2.01 ± 0.05^a	1.95 ± 0.02^a	5.23 ± 0.08^b
Yieldkg/tank	1.34 ± 0.42^a	1.69 ± 0.16^a	0.6 ± 0.09^b
Tons/ha	11.87 ± 373^a	14.99 ± 1.39^a	5.31 ± 0.79^b
Survival (%)	100 ± 0.0^a	83.2 ± 1.76^b	28.4 ± 2.43^c

Note: Numbers with different superscripts in the same row are significantly different ($p < 0.05$).
Abbreviations: HSD, high fish stocking density; LSD, low fish stocking density; MSD, medium fish stocking density.

TABLE 3 Financial analysis (mean ± SE) in USD per tank with different fish stocking densities

	LSD	MSD	HSD
Total cost	3.46 ± 0.13^b	4.09 ± 0.04^a	4.07 ± 0.07^a
Revenue	4.67 ± 0.16^a	5.90 ± 0.56^a	2.10 ± 0.30^b
Net income	1.23 ± 0.17^b	1.84 ± 0.58^a	−2.0 ± 0.32^c
BCR	1.33 ± 0.07^a	1.45 ± 0.13^a	0.53 ± 0.09^b

Note: Numbers with different superscripts in the same row are significantly different ($p < 0.05$). Fish were valued at a local market price of 3.48 USD/kg.
Abbreviations: BCR, benefit cost ratio; HSD, high fish stocking density; LSD, low fish stocking density; MSD, medium fish stocking density.

conducted using a statistical package for the social sciences, SPSS (SPSS Inc, version 20, Chicago, USA).

3 | RESULTS

3.1 | Fish growth performance, yield, survival and economic profitability

The fish final weights (Table 2) differed significantly among fish cultured at the different stocking densities ($p < 0.05$). The fish cultured in LSD and MSD exhibited significantly higher final weights than those cultured in HSD ($p < 0.05$). There were no significant differences in final weights between fish cultured in MSD and LSD ($p > 0.05$). Similarly, there were no significant differences in FCR between LSD and MSD, but the FCR from the two treatments were significantly superior to the FCR from HSD. The survival rate for the fish cultured at LSD was significantly higher than those cultured in MSD and HSD ($p < 0.05$). The survival of 28% for the fish cultured in HSD was the lowest among treatments ($p < 0.05$).

There was a significant difference in the total cost for fish production ($p < 0.05$) among the treatments (Table 3). The fish reared at MSD and HSD had a comparable total cost ($p > 0.05$), but they had a statistically higher cost than those cultured in LSD ($p < 0.05$). The fish cultured in MSD resulted in the highest revenue, but the revenue was not significantly different from the fish cultured in LSD ($p > 0.05$). The net income from MSD was significantly higher than that of all other treatments ($p < 0.05$). Fish rearing at HSD resulted in a negative net income. There were no statistical differences in the BCR between MSD and LSD ($p > 0.05$), but the two treatments had significantly higher BCR than that from HSD ($p < 0.05$).

3.2 | The effect of fish tank water on vegetable yield

The vegetable yield (as the sum of the first and second harvests) for both Chinese cabbage and amaranth is presented in Figure 3. For Chinese cabbage, the yields from M1 and H1, which received partial fertilization and irrigated with fish tank water, were 9% ($p > 0.05$) and 23% ($p < 0.05$) higher than that from NO, respectively. The yield from Mo, which were only fertilized using tank water from MSD, were similar to that obtained from NO ($p > 0.05$), which was fully fertilized and irrigated with tap water. For the amaranths, the yield from Ho and H1 was 40% ($p > 0.05$) and 60% ($p < 0.05$) higher than the yield from NO, respectively. The vegetable yield from H1 was statistically higher ($p < 0.05$) than from the other treatments, for both Chinese cabbage and amaranth.

3.3 | Profitability of integrated farming

The use of fish tank water from different tilapia stocking densities for vegetable irrigation under various fertilization regimes had a significant impact on the net income from vegetables (Table 4). The net income from IAA vegetables which were irrigated with water from medium and high tilapia stocking densities were significantly higher ($p < 0.05$) than that from NO (non-IAA Chinese cabbage) that received synthetic fertilizers and were irrigated with tap water. Similar results

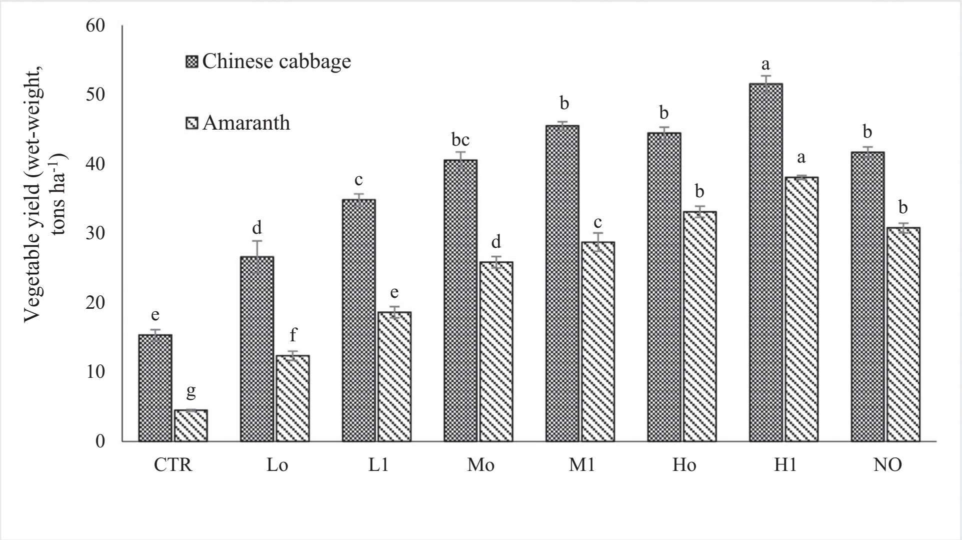

FIGURE 3 Vegetable yield (wet-weight, tons ha^{-1}) under different irrigation and fertilization regimes. Within each vegetable group (Chinese cabbage or amaranth), bars with different letters are significantly different, $p < 0.05$ (bars represent means ± SE). CTR (control): Vegetables irrigated with tap water, no fertilization at all. Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied. 1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized. Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied. M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized. Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied. H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized. NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices

TABLE 4 The effect of different irrigation and fertilization regimes on the total cost (TC), revenue (RV) and net return (Net) from vegetable farming (mean ± SE)

	Chinese cabbage			Amaranth		
Treatments	TC	RV	Net	TC	RV	Net
CTR	6.1	6.0 ± 0.3^{e}	-0.9 ± 0.0^{f}	6.1	1.8 ± 0.1^{g}	-4.5 ± 0.0^{e}
Lo	4.6	10.5 ± 0.3^{d}	5.9 ± 0.3^{e}	4.6	4.8 ± 0.4^{f}	0.3 ± 0.0^{d}
L1	6.8	13.7 ± 0.9^{c}	6.9 ± 0.9^{d}	6.8	7.3 ± 0.2^{e}	0.6 ± 0.0^{d}
Mo	4.6	15.9 ± 0.3^{bc}	11.3 ± 0.3^{b}	4.6	10.1 ± 3.1^{cd}	5.5 ± 0.0^{b}
M1	6.8	17.8 ± 0.5^{b}	11.1 ± 4.4^{b}	6.8	11.2 ± 3.3^{d}	4.5 ± 0.3^{c}
Ho	4.6	17.4 ± 0.2^{b}	12.8 ± 2.4^{a}	4.6	13.0 ± 5.2^{b}	8.4 ± 0.5^{a}
H1	6.8	20.2 ± 0.3^{a}	13.4 ± 3.4^{a}	6.8	14.9 ± 3.1^{a}	8.2 ± 0.3^{a}
NO	8.3	16.3 ± 0.5^{b}	8.1 ± 0.5^{c}	8.3	12.6 ± 0.3^{c}	4.3 ± 0.0^{c}

Note: Numbers with different superscripts in the same column are significantly different ($p < 0.05$). Values are in USD/ha × 103.
CTR (control): Vegetables irrigated with tap water, no fertilization at all.
Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied.
L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized.
Mo: Vegetables irrigated with water from fish cultured at MSD, no fertilizer applied.
M1: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), partially fertilized.
Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied.
H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized.
NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices.

were obtained from the amaranth vegetables. For both Chinese cabbage and amaranth, the control (CTR) vegetables that were irrigated with tap water without fertilization had a negative net income.

The integration of fish and vegetables had a greater impact on the net income than when they were cultivated separately (Figures 4 and 5). Among the integrated systems, the highest net income was from integration of vegetables with fish cultured at medium stocking densities ($p < 0.05$). For example, the net income from Mo + MSD fish-Chinese cabbage system was about 2.6 and 1.6 times higher than when Mo and MSD were farmed separately. A similar pattern was also noted

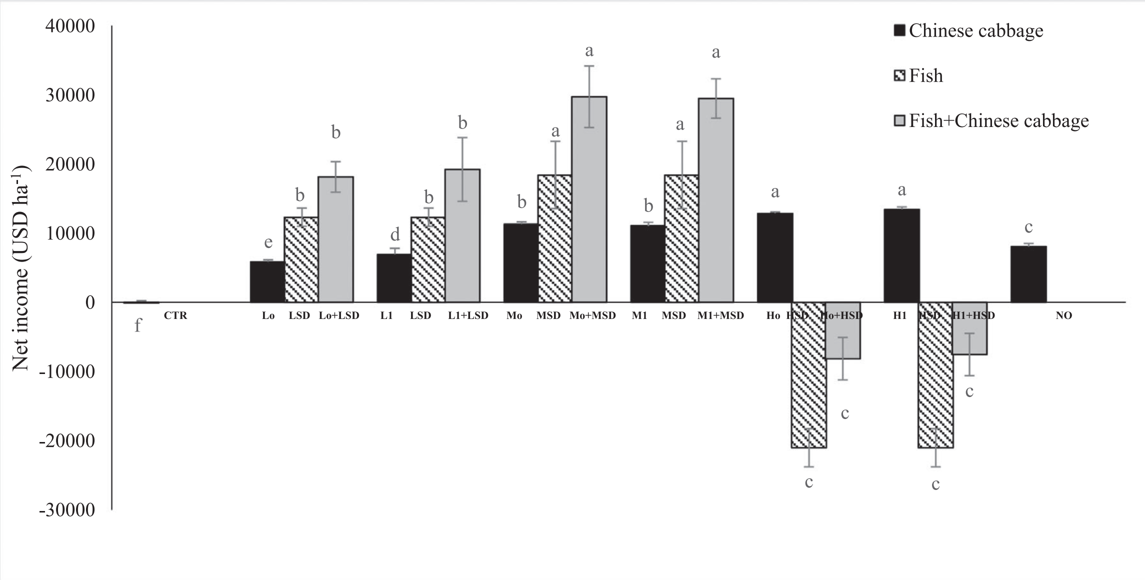

FIGURE 4 Net income (USD ha^{-1}) for fish and Chinese cabbage grown as separate systems or as an integrated system. Within each farming system, bars with different letters are significantly different, $p < 0.05$ (bars represent means ± SE). "+" sign stands for combination of two harvests. CTR (control): Vegetables irrigated with tap water, no fertilization at all. Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied. L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized. Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied. M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized. Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied. H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized. NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables , that is, farmer's practices

for the amaranth when not integrated with tilapia farming. Again, the net income from Mo + MSD was 3.7 and 5.6 times higher than that from NO for Chinese cabbage and amaranth, respectively. For both Chinese cabbage and amaranth, the integration with tilapia under high stocking densities (Ho + HSD and H1 + HSD) resulted in negative net incomes because of the low fish survival rate.

3.4 | Water use efficiency, productivity and water quality

Water productivity for vegetables irrigated with tank water from HSD was significantly higher ($p < 0.05$) than that from other vegetable treatments (Table 5). For the Chinese cabbage, the WUE (kg m^{-3}) from Mo (5.07) was 16% higher than that from L1 (4.36), ($p < 0.05$). There was no significant difference in WUE between M1 (5.69), Ho (5.56) and NO (5.21), ($p > 0.05$). The lowest WUE was exhibited by Chinese cabbage plots in the CTR (1.92), $p < 0.05$. Similar for the amaranth vegetables, the lowest ($p < 0.05$) WUE was from the CTR (1.55). The WUE did not differ significantly between Mo and M1 ($p > 0.05$), and neither between Mo and N ($p < 0.05$). H1 had the highest WUE (4.76), which was significantly higher ($p < 0.05$) than all other treatments. For the fish (Figure 6), the WUE from MSD was 27% and 186% higher than that from LSD ($p > 0.05$) and HSD ($p < 0.05$), respectively. The results for water productivity (USD m^{-3}) followed a similar pattern as that of the water use efficiency (kg m^{-3}).

Stocking densities significantly affected fish tank water quality (Tables 6 and 7). The concentrations of DO in the tank water were significantly different among different densities ($p < 0.05$). Similarly, there were significant differences in the water pH among different stocking densities ($p < 0.05$). The concentrations of NO_3, NH_4 and PO_4 in the HSD tanks were significantly higher ($p < 0.05$) than those in the MSD and LSD tanks. The concentrations of NO_2, TN, and TP in the MSD tanks were comparable to those in the HSD tanks ($p > 0.05$). There were no significant differences in water temperatures among treatments during the study period ($p > 0.05$).

3.5 | Effect of vegetable irrigation and fertilization regimes on soil nutrient concentration

The effects of different fertilization and irrigation regimes on the soil characteristics are presented in Tables 8 and 9. For both Chinese cabbage and amaranth, there were no significant differences in soil pH before and after the experiments, and nor between treatments. The concentration of NO_3 varied significantly among all the treatments ($p < 0.05$). Similarly, the concentration of TN differed significantly among the treatments except for M1, Ho, and NO which had comparable TN concentrations. Soil samples from L1, M1, H1 and NO that were initially fertilized with chicken manure had significantly higher concentration of organic matter than the CTR, Lo, Mo Ho treatments that were not fertilized with chicken manure ($p < 0.05$).

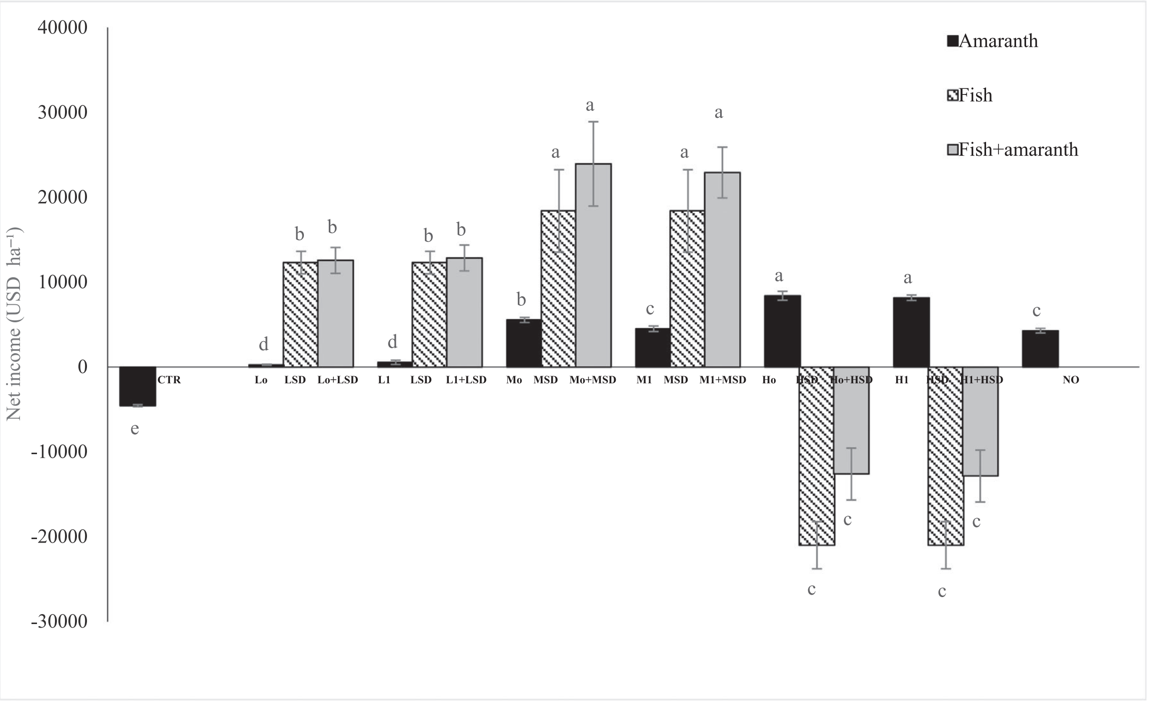

FIGURE 5 Net income (USD ha^{-1}) for fish and amaranth grown as separate systems or as an integrated system. Within each farming system, bars with different letters are significantly different, $p < 0.05$ (bars represent means ± SE). "+" sign stands for combination of two harvests. CTR (control): Vegetables irrigated with tap water, no fertilization at all. Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied. L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized. Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied. M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized. Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied. H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized. NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices

TABLE 5 Water use efficiency (WUE) and water productivity (WP) for vegetables under different irrigation and fertilization regimes (mean ± SE)

	Chinese cabbage		Amaranth	
Treatment	WUE (kg m^{-3})	WP (USD m^{-3})	WUE (kg m^{-3})	WP (USD m^{-3})
CTR	1.92 ± 0.1^{e}	0.75 ± 0.04^{e}	0.56 ± 0.04^{g}	0.22 ± 0.01^{g}
Lo	3.33 ± 0.09^{d}	1.3 ± 0.04^{d}	1.55 ± 0.14^{f}	0.61 ± 0.05^{f}
L1	4.36 ± 0.29^{c}	1.71 ± 0.11^{c}	2.33 ± 0.08^{e}	0.91 ± 0.03^{e}
Mo	5.07 ± 0.11^{bc}	1.99 ± 0.04^{bc}	3.23 ± 0.1^{cd}	1.27 ± 0.04^{cd}
M1	5.69 ± 0.15^{b}	2.23 ± 0.06^{b}	3.59 ± 0.1^{c}	1.41 ± 0.04^{c}
Ho	5.56 ± 0.08^{b}	2.18 ± 0.03^{b}	4.14 ± 0.17^{b}	1.62 ± 0.07^{b}
H1	6.44 ± 0.11^{a}	2.53 ± 0.04^{a}	4.76 ± 0.1^{a}	1.87 ± 0.04^{a}
NO	5.21 ± 0.15^{b}	2.04 ± 0.06^{b}	2.91 ± 0.09^{d}	1.14 ± 0.03^{d}

Note: Numbers with different superscript letters in the same column are significantly different ($p < 0.05$).
CTR (control): Vegetables irrigated with tap water, no fertilization at all.
Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied.
L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized.
Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied.
M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized.
Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied.
H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized.
NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices.

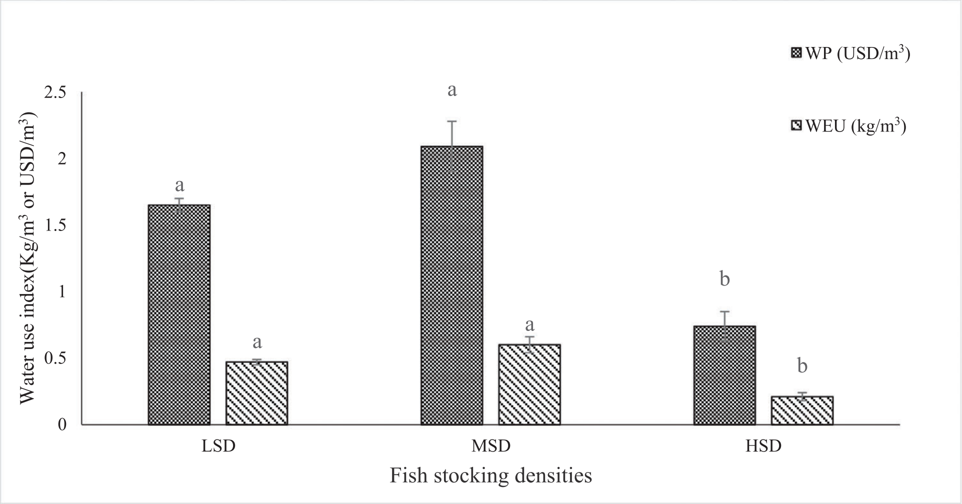

FIGURE 6 Water use efficiency (WUE) and water productivity (WP) for fish under low stocking density (LSD), medium stocking density (MSD) and high stocking density (HSD). Bars with different letters for the same water use index are significantly different, $p < 0.05$. Bars represent means ± SE.

TABLE 6 Temperature, concentration of dissolved oxygen (DO) and pH in water from tanks with fish cultured at different stocking densities (mean ± SE)

Fish stocking	Temp (°C)	DO (mg L^{-1})	pH
LSD	29.1 ± 0.5^a	6.76 ± 0.31^a	7.2 ± 0.1^b
MSD	29.1 ± 0.4^a	5.00 ± 0.41^b	7.9 ± 0.1^a
HSD	29.2 ± 0.4^a	3.87 ± 0.47^c	8.6 ± 0.2^a

Note: Numbers with different superscript letters in the same column are significantly different ($p < 0.05$).
Abbreviations: HSD, high fish stocking density; LSD, low fish stocking density; MSD, medium fish stocking density.

4 | DISCUSSION

The present study assessed the impact of fish-vegetable integrated system on water use efficiency, growth performance, yields and economic benefits as affected by fish stocking densities. The results from the present study support the hypothesis set earlier that integration of fish (*O. niloticus*) and vegetables (Chinese cabbage [*B. rapa pekinensis*] and amaranth [*A. hybridus*]) leads to higher water use efficiency, growth performance, yields and economic benefits than when produced in a non-integrated system. Furthermore, the present results corroborate that benefits of fish-vegetable integrated system are more realized when fish are cultured at a medium stocking density.

Fish stocking density is one of the key parameters affecting fish growth in several ways (Garr et al., 2011; Zhu et al., 2011). The fish weight gained in the present study decreased as stocking density increased from low to high density, though there were no significant differences between LSD and MSD. In a similar study in Malawi, M'balaka et al. (2012) reported a superior weight gain in tilapia cultured at stocking rates of five and seven fish m^{-3} over those stocked at nine fish m^{-3}. This is probably due to overcrowding at high stocking densities, which cause additional stress to the fish due to insufficient space. Apart from insufficient space, low fish growth and yield in HSD can also be related to poorer water quality, including low dissolved oxygen levels and high concentration of NH_3, as indicated in the water nutrient analyses. These factors may also have contributed to the comparatively low survival rate of 28% in HSD (cf. Diana et al., 1997). Poor water quality in the high fish stocking density could be related to the decomposition of feed remains and fish feaces, which resulted in increased levels of toxic nitrogen compounds and low dissolved oxygen levels (Diana et al., 1997; M'balaka et al., 2012).

Despite fish stocking in MSD being 60% higher compared to LSD, the yield from MSD was only 30% higher than that of LSD. This is because the fish cultured in LSD had a more rapid growth and higher survival rate (100%) compared to the 83% found in MSD. The average fish yield (11 to 14 tons per ha) recorded in this study was similar to those reported previously (Mulokozi, Berg et al., 2020; Shoko et al., 2016; Toma et al., 2015), but higher than those (2–6 tons per ha) reported by other research in Tanzania (Chenyambuga et al., 2014; Limbu et al., 2017; Shoko et al., 2011). The reason for this is probably due to the fact that the present study involved the use of sex reversed tilapia cultured at high stocking densities compared to the use of mixed tilapia at lower stocking densities employed in previous studies in Tanzania.

The economic analysis showed that rearing fish at high stocking densities was not profitable. It increased the risks for financial losses and resulted in a significantly lower profitability than that recorded from medium and low stocking densities. This was due to poor fish growth and survival rates in HSD, which in turn led to a lower revenue than input costs and, consequently, a negative net income. Additionally, fish from HSD had an average weight of 200 g, which is below recommended weights for higher market prices in Tanzania. Assessing consumers preferences and perception in Morogoro region, Mgina (2015) reported that fresh tilapia with weights of at least 250 g had

TABLE 7 Water nutrient concentration (mg L^{-1}) in tap water and in water from fish tanks stocked at different stocking densities (mean ± SE)

Fish stocking	NO_2	NO_3	NH_4	PO_4	TN	TP
LSD	0.04 ± 0.0^{b}	1.84 ± 0.03^{c}	0.39 ± 0.02^{c}	0.25 ± 0.02^{c}	3.57 ± 0.03^{b}	1.49 ± 0.02^{b}
MSD	0.08 ± 0.01^{ab}	3.18 ± 0.13^{b}	0.69 ± 0.02^{b}	0.52 ± 0.05^{b}	5.26 ± 0.21^{a}	1.79 ± 0.02^{a}
HSD	0.13 ± 0.02^{a}	4.65 ± 0.16^{a}	1.05 ± 0.04^{a}	0.67 ± 0.02^{a}	6.56 ± 0.24^{a}	1.82 ± 0.03^{a}
Tap water	0.01 ± 0.0^{c}	0.08 ± 0.01^{d}	ND	0.04 ± 0.01^{d}	0.91 ± 0.02^{c}	0.77 ± 0.02^{c}

Note: Numbers with different superscript letters in the same column are significantly different ($p < 0.05$).
Abbreviations: HSD, high fish stocking density; LSD, low fish stocking density; MSD, medium fish stocking density; ND, not detected; TN, total nitrogen; TP, total phosphate.

TABLE 8 pH, organic matter and nutrient concentrations of soils from Chinese cabbage plots under different irrigation and fertilization regimes (mean ± SE)

Treatment	pH	NO_3 (mg/kg)	TN (g/kg)	TP (g/kg)	Organic matter (g/kg)
Before experiment	8.16 ± 0.1^{a}	150.5 ± 1.0^{g}	0.77 ± 0.01^{g}	0.13 ± 0.01^{f}	12.73 ± 0.19^{b}
CTR	8.19 ± 0.04^{a}	143.1 ± 1.1^{h}	0.58 ± 0.02^{h}	0.25 ± 0.01^{e}	10.91 ± 0.3^{b}
Lo	8.17 ± 0.02^{a}	172.6 ± 1.0^{f}	1.23 ± 0.01^{f}	0.32 ± 0.01^{e}	12.93 ± 0.5^{b}
L1	8.25 ± 0.04^{a}	205.6 ± 1.0^{e}	1.77 ± 0.01^{e}	0.51 ± 0.02^{cd}	33.93 ± 0.67^{a}
Mo	8.27 ± 0.07^{a}	225.5 ± 0.8^{d}	1.54 ± 0.04^{d}	0.49 ± 0.01^{d}	14.21 ± 1.12^{b}
M1	8.24 ± 0.01^{a}	242.3 ± 0.5^{c}	2.01 ± 0.04^{c}	0.63 ± 0.01^{b}	33.32 ± 0.18^{a}
Ho	8.47 ± 0.07^{a}	251.3 ± 0.7^{b}	2.1 ± 0.02^{b}	0.6 ± 0.02^{b}	13.55 ± 0.68^{b}
H1	8.35 ± 0.02^{a}	273.2 ± 0.7^{a}	2.48 ± 0.04^{a}	0.69 ± 0.02^{a}	34.06 ± 0.54^{a}
NO	8.36 ± 0.03^{a}	252.3 ± 0.3^{b}	2.07 ± 0.03^{b}	0.57 ± 0.01^{bc}	34.49 ± 0.42^{a}

Note: Numbers with different superscript letters in the same column are significantly different ($p < 0.05$).
Abbreviations: TN, total nitrogen; TP, total phosphate.
CTR (control): Vegetables irrigated with tap water, no fertilization at all.
Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied.
L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized.
Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied.
M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized.
Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied.
H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized.
NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices.

higher market values than small sized tilapia. Similarly, Salehe et al. (2017) reported that tilapia at more than 500 g were preferred by consumers around Lake Victoria, on the Tanzanian side.

The effect of using fish tank water and different fertilization regimes for vegetable cultivation was evident across treatments. A relatively higher yield from M1, Ho and H1 over NO (non-IAA treatment) indicates the advantage of IAA systems because despite low fertilizer inputs and use of fish tank waste water, the yields from these treatments were above those from NO, which was fully fertilized. This indicates that water from fish tanks had sufficient nutrients to replace both the manure and the synthetic fertilizers commonly applied by farmers. The nutrient input from the fish tank water was also reflected in the increased nutrient concentration in soil samples irrigated with this water. These results are similar to those by Mulokozi, Berg, et al. (2020), who reported a significantly higher yield for the first amaranth harvest, which was irrigated with fish pond water in an IAA system, than the amaranth yield in a non-IAA system irrigated with tap water. Considering the high fish mortality recorded in HSD and the fact that both Mo and Ho gave the same yield as NO, while Lo were lower, this indicates that an IAA system can benefit from slightly higher stocking density than five fish m^{-3}, but if it becomes too high, the fish could easily die due to a decreased water quality.

Aquaculture could be regarded as a water efficient food production system, as long as the water in the pond is not depleted but is rather recycled for continued fish production or other purposes (Ahmed et al., 2014). In the present study, vegetable irrigated with fish tank water had both significantly higher WUE (kg m^{-3}) and WP (USD m^{-3}) than control vegetables that were irrigated with tap water because of the additional production of fish. Similarly, Van der Heijden (2012) in Egypt reported an improved water use efficiency when fish ponds were integrated with the production of fruits (mango, banana and orange), vegetables, flowers and alfalfa. Additionally, in an experiment involving fish and vegetables, Abdul-Rahman et al. (2011) found a 20% increase in WUE and WP from radish, when irrigated with effluents from tilapia tanks instead of being irrigated with well water. Although the use of tank water from HSD led to significantly higher vegetable WUE, due to high nutrient concentrations, this also resulted in a poorer water quality for the fish and consequently a comparably low survival at only 28%,

TABLE 9 pH, organic matter and nutrient concentrations in soils from amaranth plots under different irrigation and fertilization regimes (mean ± SE)

Treatment	pH	NO_3 (mg/kg)	TN (g/kg)	TP (g/kg)	Organic matter (g/kg)
Before experiment	8.16 ± 0.11^a	150.5 ± 1.0^h	0.71 ± 0.01^g	0.12 ± 0.01^f	13.4 ± 0.2^b
CTR	7.78 ± 0.04^a	130.5 ± 0.8^g	0.56 ± 0.01^f	0.23 ± 0.01^g	11.5 ± 0.3^b
Lo	7.8 ± 0.02^a	157.4 ± 0.5^f	1.13 ± 0.01^e	0.32 ± 0.01^e	13.3 ± 0.3^b
L1	7.87 ± 0.02^a	187.8 ± 1.0^e	1.63 ± 0.01^d	0.49 ± 0.02^c	33.9 ± 0.1^a
Mo	8.23 ± 0.27^a	204.6 ± 0.6^d	1.45 ± 0.04^c	0.46 ± 0.01^d	14.5 ± 0.8^b
M1	7.83 ± 0.01^a	220.6 ± 0.5^c	1.88 ± 0.03^b	0.59 ± 0.01^b	35.0 ± 0.2^a
Ho	8.13 ± 0.08^a	227.8 ± 0.5^b	1.96 ± 0.01^b	0.57 ± 0.01^b	14.2 ± 0.5^b
H1	7.94 ± 0.02^a	248.6 ± 0.6^a	2.32 ± 0.02^a	0.67 ± 0.0^a	33.4 ± 0.7^a
NO	8.1 ± 0.18^a	229.6 ± 0.3^b	1.9 ± 0.02^b	0.53 ± 0.01^b	34.9 ± 1.0^a

Note: Numbers with different superscript letters in the same column are significantly different ($p < 0.05$).
Abbreviations: TN, total nitrogen; TP, total phosphate.
CTR (control): Vegetables irrigated with tap water, no fertilization at all.
Lo: Vegetables irrigated with water from fish cultured at low stocking density (LSD), no fertilizer applied.
L1: Vegetables irrigated with water from fish cultured at LSD, partially fertilized.
Mo: Vegetables irrigated with water from fish cultured at medium stocking density (MSD), no fertilizer applied.
M1: Vegetables irrigated with water from fish cultured at MSD, partially fertilized.
Ho: Vegetables irrigated with water from fish cultured at high stocking density (HSD), no fertilizer applied.
H1: Vegetables irrigated with water from fish cultured at HSD, partially fertilized.
NO: Vegetables irrigated with tape water with full fertilization, non-IAA vegetables, that is, farmer's practices.

which consequently affected overall yield and economic returns. This finding indicates the need to optimize fish stocking densities and other management strategies, such as feeding and water exchange, in order to balance the benefits and tradeoffs for both the fish and crops in IAA systems (Van der Heijden, 2012). In this study, a medium stocking density of eight fish m^{-3} exhibited better WUE and WP for both fish and vegetables.

The high profitability recorded from the Mo vegetables was linked to the increased revenue due to the high yield (tons ha^{-1}), which partly was because of the use of tank water rich in valuable nutrients for vegetable growth, that also minimized the cost for both water and fertilizers. The higher net income from fish raised in combination with vegetables than that for fish and vegetable grown separately was due to the fact that integrated agriculture and aquaculture systems build on an increased recycling of nutrients and matter, and provide room for diversification of the outputs from existing subsystems leading to an overall higher farm yield and income (Prein, 2002). Similar results were reported by other researchers in Tanzania and other parts of Africa. For example, Mulokozi, Berg, et al. (2020) in Dar es Salaam reported that the net income from the integration of fish and amaranth was 3.2, 2.3, 2.6, and 1.8 higher than from non-IAA amaranths, IAA-amaranths, non-IAA fish, and IAA fish subsystems, respectively. In an experiment involving fish-vegetable integrated system in Kilombero, Limbu et al. (2017) reported a higher annual net cash flow from integrated tilapia-catfish-spinach farming than when fish and vegetables were farmed separately. These results also corroborate well with those by Dey et al. (2010) in Malawi, who reported a 11% higher production from IAA farmers than non-IAA farmers.

Apart from increasing the overall farm productivity, profitability and water use efficiency, based on recycling of resources through synergism between the subsystems, IAA technology can contribute to more diverse and nutritional food production, and also a diversification of livelihoods for households in Tanzania. For a farmer practicing an integrated tilapia-Chinese cabbage-amaranth farming system, tilapia can be a good source of animal protein rich in high quality essential amino acids and micronutrients (Kawarazuka & Béné, 2011). Chinese cabbage and amaranth are also rich in important nutrients such as minerals, vitamins (especially A and C) and other substances considered to have health-promoting effects for humans (Olasantan, 2001; Fahey, 2016). Thus, this kind of integrated systems can provide the household with diversified nutritional crops, which could help in the fight against "hidden hunger", a term that refers to people who do not get enough minerals, vitamins and proteins (WHO-FAO 2014). Proper implementation of the findings from this study could thus contribute to sustainable development goal number two (SDG2), which is committed to ending all forms of hunger including food and nutrition insecurity, and SDG6 which is geared to ensuring availability and sustainable management of water and sanitation for all.

5 | CONCLUSION

As water demand for food production is expected to increase globally, water utilization efficiency will have to be improved. Multiple water use, first for fish farming and next for crop irrigation in IAA farming system, is a good way to increase the water use efficiency. In IAA, compared to stand-alone farming systems, the overall productivity and profitability per unit water used is improved. Additionally, the use of fish pond water rich in nutrients for crop irrigation contributes to savings on fertilizer and other costs. It is noted from the present study that using tank water from fish cultured at high stocking densities to irrigate the vegetables resulted into significantly higher vegetable yield due to high nutrient content. However, too high fish stocking density led to low survival rates due to poor water quality, which consequently affected the fish yield, revenue and net returns negatively, which in turn could create financial risks for the farmers. On the other hand, integration of vegetables with fish cultured at medium stocking density improved the yield, financial returns and water utilization for both the fish and vegetables. As the study aimed at finding the optimal combination between fish at different stocking densities and vegetable combinations, we recommend sex-reversed tilapia stocking at a medium density (eight fish m^{-3}) in integration with the production of vegetable for optimized farm productivity, profitability and water use.

AUTHOR CONTRIBUTIONS

Deogratias Mulokozi: Conceptualization; Data curation; Formal analysis; Validation; Writing — original draft. Hakan Berg: Conceptualization; Investigation; Supervision; Writing — original draft. Rashid Tamatamah: Funding acquisition; Supervision; Visualization; Writing — review & editing. Torbjorn Lundh: Conceptualization; Methodology; Visualization; Writing — review & editing. Paul Onyango: Conceptualization; Methodology; Supervision; Writing — review & editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

The study was carried out in accordance with the law on the protection of animals against cruelty (Act No. 12/1974. of the United Republic of Tanzania) upon its approval by the Institute of Marine Sciences, University of Dar es salaam.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon a reasonable request.

PEER REVIEW

The peer review history for this article is available at: https://publons.com/publon/10.1002/aff2.76.

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