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Use of black soldier fly larvae and freshwater shrimp to partly substitute commercial diet for Nile tilapia cultured in smallholder fish farms – A case study in Busia County, Kenya

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Fish-farming in Kenya is challenged by the availability and high cost of feed ingredients, especially protein sources. Using black soldier fly larvae (*Hermetia illucens*) (BSFL) directly or indirectly as a feed ingredient to feed fish is interesting as they efficiently convert organic wastes into high-quality proteins. In addition, the freshwater shrimp (*Caridina nilotica*) (CN), an important by-catch of the silver cyprinid (*Rastrineobola argentea*) fisheries in Lake Victoria, could be another alternative protein source. Therefore, this study determined whether dried BSFL or dried CN could partly substitute the commercial diet when growing Nile tilapia (*Oreochromis niloticus*) in a smallholder farm aggregated in an aquapark. The nutritional values and cost-effectiveness of the alternative feeding strategies were compared to commercial diet (CD) only. During an 84-day experimental period, Nile tilapia were fed one of the three feeding strategies, including the use of only the commercial diet, to be compared with diets replacing 20% of the commercial diet with BSFL or CN. The fish were fed to apparent satiation twice a day. At the end of the trial, biomass, the number of fish, growth, survival rate, total fish production, economic feed conversion rate and productivity per pond, were determined. As such, Body Weight (BW) was similar across feeding strategies ($P > 0.05$), measured 63.2 ± 3.9, 68.0 ± 7.4 and 68.0 ± 7.4 g for fish-fed diets with CD, BSFL and CN, respectively. Hence, nutritionally and from a production point of view, the three feeding strategies used in this study performed equally well. Notably, the use of BSFL led to a significantly higher economic return ($P < 0.05$) compared to the use of CN and commercial diet alone. The trials in this study demonstrate that BSFL and CN can be used to partly substitute commercial diet. In addition, the trial show that the use of BSFL to partly substitute the commercial diet can boost sustainable fish production in a smallholder farm set-up aggregated in an aquapark.

KEYWORDS

black soldier fly larvae (BSFL), Caridina shrimp, alternative protein, feeding strategies, smallholder farmers, cost-effectiveness, food security, Kenya

1 Introduction

Fish-farming in sub-Saharan Africa is challenged by the availability of sustainable protein providing feed ingredients (Vernooij et al., 2019). Kenya imports nearly 70% of its animal feed ingredients. Major protein source ingredients like soybean and fish meal are often of low quality, very expensive for smallholder fish farmers (Opiyo et al., 2018; Soma, 2023; Soma et al., 2023), or imported from distant less sustainable sources (Chianu et al., 2008; Abro et al., 2020). In Kenya, many initiatives have recently been started to culture black soldier fly (*Hermetia illucens*) larvae (BSFL), both at small and large scales (Chia, 2019). In most cases, the BSFL are cultured on locally available organic agricultural and food by-products which otherwise are disposed in landfills. As such, the BSFL culture is judged a sustainable way of producing protein for feeding fish and livestock, especially for chicken and pigs (Pishgar-Komleh et al., 2022). Sustainability is further enhanced because BSFL efficiently converts organic wastes into high quality proteins (Shit, 2021), and produces a biproduct of high-quality organic fertilizer, referred to as *frass*.

Using BSFL meal in formulated diets for fish has shown that it is a promising ingredient (Hua, 2021; Tippayadara et al., 2021). However, the production of BSFL meal needs processing able to convert BSFL into a full-fat meal, a defatted meal, or an oil product for direct application in a commercial diet. This often leads to prices going up, often making the ingredients too expensive for many smallholder farmers. Moreover, expensive taxes and ingredients such as soya imported with large climate footprints, make feed a critically important input and cost factor in food production systems where animals are fed. The challenge is thus to ensure high-quality locally produced feed to make it accessible, climate neutral and at affordable prices to the smallholder farmers. An alternative investigated in this study consists of smallholder BSFL producers and fish farms that are operating in the same locality (aquapark) to produce the BSFL on-site to apply the larvae as to partly substitute a commercial or a farm-made diet. If this approach is adopted, it is expected to promote decentralized production with BSFL grown on smallholder fish farms, strengthening the value chain of BSFL and possibly improving the social economic position of the smallholder farms.

In line of this reasoning, the aquapark includes a relatively high number of smallholder farms and can be used for aggregating the production of BSFL, as well as fish at reduced costs. Aquaparks refer to an aggregation of production systems where several smallholder fish farmers are grouped and assisted to produce fish in large quantities, thereby promoting the profitability of aquaculture (Odende et al., 2022). This promotes learning and exchange. A pilot cluster-based smallholder aquapark is currently operating in Busia, a County in Western Kenya, and managed by a community of smallholder fish farmers. The aquapark is coupled with a deliberate establishment of aquaculture-enabling infrastructure with enhanced efficiency, profitability, and productivity (Odende et al., 2022). The Bukani aquapark in the Samia Sub- County is an aggregation of 100 fishponds owned and collectively managed by smallholder farmers involved in mixed agriculture activities on land. Currently, the aquapark focuses on the production of fish and vegetables, with the potential to expand its production of feed inputs, which are used in fish feed at the aquapark. The aquapark consists of 100 smallholder farmers who also cultivate seasonal crops like arrow roots and maize in the area. Notably, real scaling of the ideas is most likely to happen on privately owned farms where local private ownership is high, which is needed for private investments and for taking risks. As such, the aquapark can contribute positively with learning, exchange and motivation.

An alternative option to BSFL could be the use of dried freshwater shrimp (*Caridina nilotica*) (CN) (Maundu et al., 2022). *Caridina nilotica* is a freshwater shrimp species thriving in Lake Victoria (Lehman et al., 1996). It is an important by-catch of Lake Victoria sardines (*Rastrineobola argentea*) commonly referred to as "Omena" or "Dagaa" and is found in large quantities as a result of fishing activities (Budeba and Cowx, 2007). Using local ingredients such as by-catch as a protein source contributes to a circular local economy and resource efficiency. Several studies using Caridina meal in formulated diets for fish have shown it is a viable ingredient (Mugo-Bundi et al., 2015; Kubiriza et al., 2018). If dried freshwater shrimp can be fed directly by partly substituting a commercial diet, it could improve the social economic position of the smallholder farms.

Against this background, the main aim of this study is to determine whether chopped dried BSFL and chopped dried CN partly can substitute a commercial diet and are suitable and cost-effective feeding strategies for rearing Nile tilapia in ponds at the smallholder farm level.

2 Material and methods

2.1 Experimental setup

The experiment was carried out at the community-owned fish farm "Bukani Aqua Park" located in the very west of Kenya, north of Lake Victoria in Busia County, Kenya. Nine ponds were chosen randomly after consideration of the stability of the water supply and the size of the ponds. The ponds were owned by different farmers in the aquapark. The experiments consisted of three feeding strategies; (1) CD (100% commercial diet), (2) BSFL (80% CD + 20% chopped dried BSFL) and (3) CN (80% CD + 20% chopped dried *Caridina nilotica*). The commercial diet was obtained from Unga Farmcare Ltd, Nairobi, *Caradina nilotica* was obtained from Lenalia fish feeds Ltd, Limuru while the BSFL was obtained from Biobuu Ltd, Kilifi. All the feeds were purchased at retail market prices. The CD consisted of the brand Skretting Optiline, including two different sizes of 2 mm and 3 mm. Crude protein and crude fat ranged from 38% to 42% and 2.6% to 3.9% for Optiline 2 mm and 3 mm, respectively. While the BSFL consisted of 51.1% crude protein and 11.8% crude fat, the CN consisted of 60.1% crude protein and 2.49% crude fat (Table 2). The three diets were tested in triplicates of nine experimental units, in nine separate ponds. Nile tilapia monosex fingerlings (Lake Victoria strain) of 10–12 g produced through hormonal sex reversal were purchased from Hydro Tilapia hatchery in Samia, Busia County. The fingerlings were stocked at three fish per m^2 in nine earthen ponds, of which three of the ponds had a size of 250 m^2 and six ponds had a size of 200 m^2. The feeding strategy was random but equally divided over the different pond sizes. The fish were fed by hand to apparent satiation two times daily (10.00 AM and 4.00 PM) to achieve maximum feed intake. The external factors were similar because the ponds were in the same location and thereby experiencing the same conditions. The treatments were randomly allocated to the ponds to reduce any biases.

2.2 Water quality monitoring

To ensure the right conditions for the treatments, water monitoring was critically important. Temperature, pH, and dissolved oxygen (DO) were measured twice a week in the morning and evening, and total ammonium nitrogen (TAN), nitrite (NO_2) and nitrate (NO_3) were measured twice a week in the morning (Boyd and Tucker, 1998).

2.3 Fish sampling

The mean weight of the fish per pond was determined every 21 days, by weighing a representative sample of 10% of the total fish stocked per pond. At day 84, the end of the trial, the feed given in dry matter, total biomass per pond, number of fish per pond, average fish weight, growth in gram and growth in metabolic body weight, survival rate, total fish production, the economic feed conversion rate and productivity were determined, after which the optimal dietary treatment was estimated based on the performance parameters of the fish. The total biomass and number of fish per pond at the start and the end of the trials were used to calculate the average individual fish weight, survival rate and total fish production. Using the average body weight at the start (BWt0) and at the end of the trail (BWt84), the growth in gram fish^{-1} was calculated per pond, which was considered the experimental unit. Growth expressed in gram per kg of metabolic weight per day (g kg$^{-0.8}$d^{-1}), was calculated using the formula: $(BW_{(end)}\text{-}BW_{(start)})/(((BW^*_{(end)}BW_{(start)}))\wedge 0.5/1000)\wedge 0.8)/t)$ with $BW_{(start)}$ and $BW_{(end)}$, the bodyweight at the start and the end of the trial, 0.8 the component correcting for the body - surface area of the animal and t representing the duration of the growth period (Lupatsch et al., 1998; Ende et al., 2016; Palstra et al., 2018). The apparent feed intake per pond fed on dry matter (dm) is the sum of the feed given. The economic feed conversion ratio based on dry matter (eFCRdm) is the amount of feed used of fish as output. The eFCRdm was calculated by dividing the apparent feed intake, or feed given as dry matter, by the biomass increase or total fish production on wet weight basis (eFCRdm = apparent feed intake based on dry matter/biomass increase). The productivity was calculated by dividing the biomass increase or fish production by the surface area of the pond. The dry matter content was determined by gravimetry, for which porcelain crucibles were cleaned using acetone and double distilled water, oven-dried at 135°C for 2 h, cooled to room temperature in a desiccator (for 30 min) and weight (W_0). Moreover, two grams of the ground sample was separately placed in the oven-dried porcelain crucibles and the weight of the sample + crucible recorded (Ws). The samples were then dried at 135°C for 2 h before cooling to room temperature in a desiccator and their weight recorded (W_{S2}) (AOAC, 1990). The samples were analyzed in triplicates.

TABLE 1 Partial enterprise budget input costs.

Item	Units	Unit cost ($)
Nile tilapia fingerlings	Piece	0.04
Commercial diet	kg	1.36
Black soldier fly larvae	kg	1.02
Caridina nilotica	kg	1.27
Labor (feeding and pond management)	$/pond/month	0.47
Cost of transporting fish	$/kg	0.02
Cost of packaging fish	$/kg	0.009
Tax on the sale of fish (Municipal tax)	$/harvest	0.40

2.4 Partial enterprise budget analysis

A partial enterprise budget was used to evaluate the economic implications of substituting the commercial diet with either chopped-dried BSFL or chopped-dried CN while feeding Nile tilapia. Variable costs included the cost of labor, feeds, and fingerlings. The cost of the commercial diet, BSFL, and CN were judged based on prevailing market retail prices in Nairobi (September 2022). Labor costs were based on the prevailing market prices within the experimental site. The US dollar exchange rate against Kenya shillings was pegged at KES118 being the Central Bank of Kenya exchange rate at the time of the experiment. The study assumed that all other costs of production were constant for all dietary treatments and thus not considered. Fish harvested per treatment was sold at US$ 5.08 kg^{-1}, which was the local market price of Nile tilapia.

Further, to gauge the profitability of the alternatives, the break-even price was calculated by adding the total fixed cost, consisting of municipal tax for sale of fish, to the variable cost per unit of the fish sold. Using the prices for the dietary strategies at the time of writing which were ∼$1.28, $0.96, and $1.20 for Optiline, chopped dried BSLF and dried freshwater shrimp, respectively, and using the eFCRdm per feeding strategy, the cost of the dietary strategies were estimated to be $2.86 ± $0.38, $2.35± $0.38 and $2.91 ± $0.76 per kg of fish produced and statistically similar. The following information (Table 1) was used for a cost-benefit analysis of each dietary treatment.

2.5 Statistical analysis

The normality (Shapiro-Wilk) of data was assumed, and homogeneity of variances (Levene) was tested. The statistical analyses were carried out using one-way ANOVA to test dietary effects followed by Fisher LSD *post-hoc* test for any difference between individual treatments. Values with $P < 0.05$ were considered significant. The

TABLE 2 The macro-nutritional composition and content of important minerals of two commercial diets from Skretting® (Optiline 2 mm and 3 mm), as well as dried black soldier fly larvae (BSFL) and *Caridina nilotica* (CN), were used as experimental feeds in smallholder farms.

Parameter	Unit	Optiline (2 mm)	Optiline (3 mm)	BSFL	CN
Gross Energy	MJ/kg	10.00	9.78	14.40	14.30
Crude Protein	%	41.70	37.80	51.10	60.10
Ash	%	7.10	7.57	15.60	20.50
Crude Fat	%	2.58	3.85	11.80	2.49
Fiber	%	2.72	3.24	7.10	2.41
Dry matter	%	92.20	92.10	93.80	90.50
Calcium	%	1.10	0.97	4.28	5.98
Potassium	%	1.24	1.46	1.22	1.06
Magnesium	%	0.24	0.33	0.35	0.21
Phosphorus	%	1.07	1.08	0.91	1.57
Sulfur	%	0.52	0.42	0.38	0.89
Boron	pp^m	17.30	19.10	4.40	3.63
Molybdenum	pp^m	1.52	273.00	1.19	0.12
Iron	pp^m	518	533.00	1970.00	2040.00
Copper	pp^m	17.70	16.00	11.90	88.80
Zinc	pp^m	155.00	138.00	166.00	74.40
Manganese	pp^m	66.90	80.00	2280.00	214.00
Sodium	pp^m	719.00	692.00	1620.00	4520.00
Cobalt	pp^m	0.18	0.13	0.88	0.20

statistical analyses were done using the SPSS statistical program version 27 (IBM, New York, United States of America).

3 Results

3.1 Composition commercial diet, dried BSFL and *Caridina nilotica*

The macro-nutritional composition and content of important minerals of two commercial diets (Skretting Optiline 2 mm and 3 mm feed), as well as one diet including dried BSFL and one diet including dried *Caridina nilotica* shrimp (CN), are shown in Table 2.

3.2 Water quality parameters

The trial started on the 14 October 2022 and ended on the 5 January 2023. The water quality parameters; temperature, pH, dissolved oxygen (DO) total ammonium nitrogen (TAN), nitrite (NO_2) and nitrate (NO_3) are shown in Table 3, which all stayed within the acceptable range (Boyd and Tucker, 1998), and with no difference between treatments ($P > 0.05$).

TABLE 3 The water quality parameters between treatments.

Parameter	Unit	Dietary treatment†			p*
		CD	BSFL	CN	
Temperature	°C	27.6 ± 0.2	27.6 ± 0.1	27.6 ± 0.1	0.82
DO	mg l^{-1}	8.1 ± 0.1	8.1 ± 0.1	8.1 ± 0.0	0.53
pH	-	7.8 ± 0.0	7.8 ± 0.0	7.8 ± 0.1	0.17
TAN	mg l^{-1}	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	1.00
NO_2	mg l^{-1}	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.00
NO_3	mg l^{-1}	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.00

†Dietary treatments CD (100% commercial diet, Skretting Optiline 2 and 3, crude protein 38%-42%, crude fat 2.6%-3.9%), BSFL (80% CD + 20% chopped dried BSFL) and CN (80% CD + 20% chopped dried Caridina niloticus). P, p-value. With DO, dissolved oxygen; pH, potential of hydrogen; TAN, total ammonia nitrogen; NO_2, nitrite and NO_3, nitrate.

3.3 Growth performance of fingerlings fed using different diets

The development of the average individual weight during the trial is shown in Figure 1. Average body weight (BW) at the start was similar across treatments ($P > 0.05$; Table 4). At the end of the trial, BW was 63.2 ± 3.9, 68.0 ± 7.4 and 68.0 ± 7.4 g for fish-fed diets CD, BSFL and CN, respectively, and

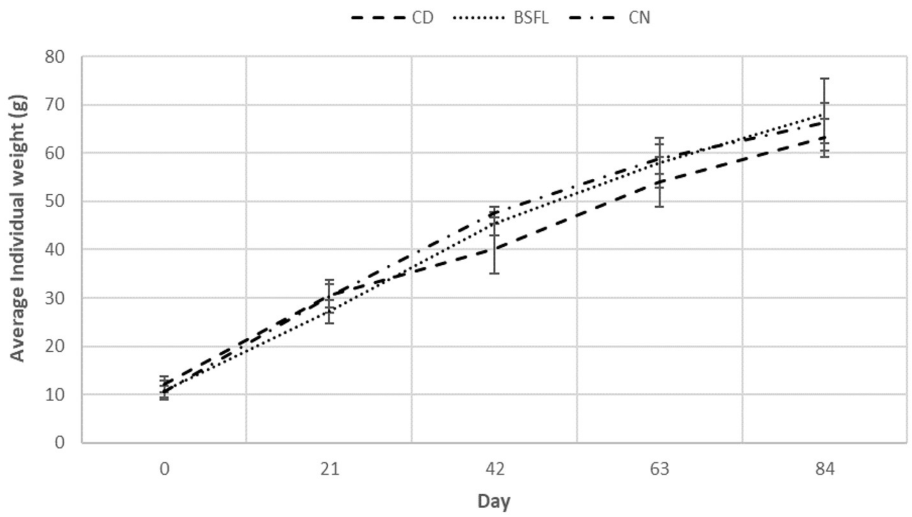

FIGURE 1
Development of the average individual weight of the fish fed either the commercial diet (CD) or the commercial diet partly substituted with black soldier fly larvae (BSFL) or *Caridina nilotica* (CN) in smallholder farm.

TABLE 4 Performance parameters determined of Nile tilapia fed either the commercial diet (CD) or the commercial diet partly substituted with black soldier fly larvae (BSFL) or *Caridina nilotica* (CN) in smallholder farm.

Parameters	Dietary treatment†				
	Unit	CD	BSFL	CN	p†
BW_{start}	G	12.1 ± 1.7	10.9 ± 1.9	10.6 ± 1.2	0.55
BW_{end}	G	63.2 ± 3.9	68.0 ± 7.4	66.3 ± 4.2	0.58
WG fish	G	51.1 ± 5.6	57.1 ± 5.7	55.7 ± 4.8	0.41
GMBW	$g\ kg^{-0.8}.d^{-1}$	10.8 ± 1.6	12.2 ± 0.5	12.1 ± 1.2	0.35
Feed given as fed	kg	51.3 ± 2.1^{a}	51.3 ± 5.2^{a}	60.7 ± 2.8^{b}	**0.03***
Feed given as dry matter	kg dm	47.1 ± 1.9^{a}	47.2 ± 4.8^{a}	55.5 ± 2.6^{b}	**0.03***
Survival rate	%	89.4 ± 0.9	86.9 ± 6.2	85.4 ± 3.5	0.52
Fish production	$kg\ pond^{-1}$	21.2 ± 3.0	25.1 ± 7.0	25.5 ± 8.3	0.69
$eFCRdm_{end}$	–	2.2 ± 0.3	1.9 ± 0.3	2.3 ± 0.6	0.56
Productivity	$g\ m^{2}$	98 ± 11	115 ± 16	116 ± 22	0.43

†Dietary treatments CD (100% commercial diet, Skretting Optiline 2 and 3, crude protein 38-42%, crude fat 2.6-3.9%), BSFL (80% CD + 20% chopped dried BSFL) and CN (80% CD + 20% chopped dried Caridina niloticus). P, p-value; BW, bodyweight, WG, weight gain, GMBW, growth in metabolic body weight; eFCRdm, economic feed conversion rate based on dry matter. [ab]Values with the same superscript within rows are not significantly different based on the Fisher LSD *post-hoc* test ($P < 0.05$). *P values in bold are significant.

similar across feeding strategies ($P > 0.05$; Table 4). Consequently, the average weight gain in gram, and growth in metabolic body weight (GMBW), were similar ($P > 0.05$; Table 4). The weight of feed fed was 51.3 ± 2.1, 51.3 ± 5.2 and 60.7 ± 2.8 kg as given or 47.1 ± 1.9, 47.2 ± 4.8 and 55.5 ± 2.6 kg of dry matter for diet CD, BSFL and CN, respectively, with the highest feed intake for CN ($P < 0.05$; Table 4). However, the survival rate in % of the total population at stocking, fish production in kg $pond^{-1}$, the economic feed conversion rate based on dry matter and productivity of fish per m^2 were not affected by the different feeding strategies/diets ($P > 0.05$; Table 4).

3.4 Partial enterprise budget analysis

The mean yield, i.e., fish production in kg $pond^{-1}$, was higher for the fish fed on a 20% substitute of commercial feed with black soldier fly larvae (BSFL) and *Caridina nilotica* (CN), but with no significant differences across the treatments (Table 5). The fish fed on a 100% commercial diet (CD) reported significantly lower net return, which is estimated as the gross revenue subtracting the variable- and fixed costs. The net return on fish fed on BSFL was significantly higher than the other treatments ($P < 0.05$). Moreover, the variable cost and total cost were lower for the fish fed on the CD and the BSFL but were not significantly different

TABLE 5 A partial enterprise budget for Nile tilapia fed either the commercial diet (CD) or the commercial diet partly substituted by black soldier fly larvae (BSFL) or *Caridina nilotica* (CN) in smallholder farm.

Parameters (per treatment)	Dietary treatment[†]			
	Units	CD	BSFL	CN
Mean yield	kg	21.20	25.10	25.50
Gross revenue	$	107.70[a]	127.51[b]	129.54[b]
Variable costs	$	97.85[a]	94.34[a]	108.70[b]
Fixed costs	$	0.40	0.40	0.40
Total costs	$	98.25[a]	94.74[a]	109.10[b]
Net return above total costs	$	9.45[a]	32.77[b]	20.44[c]
Unit selling price	$	5.08	5.08	5.08
Break-even price (total costs)	$	4.63[a]	3.77[b]	4.28[a]
Break-even price (variable costs)	$	4.62[a]	3.76[b]	4.26[a]
Break-even Yield (total cost)	kg	19.34[a]	18.65[a]	21.48[b]

[†]Dietary treatments CD (100% commercial diet, Skretting Optiline 2 and 3, crude protein 38%-42%, crude fat 2.6%-3.9%), BSFL (80% CD + 20% chopped dried BSFL) and CN (80% CD + 20% chopped dried Caridina niloticus). [abc]Values with the same superscript within rows are not significantly different based on the Fisher LSD *post-hoc* test ($P < 0.05$).

($P > 0.05$). Fish fed on CN had significantly higher total costs and variable costs. The break-even price (total cost) per pond was significantly different, with the lowest value (US $ 3.77) being recorded for fish fed on BSFL ($P < 0.05$). The break-even yield was significantly higher for fish fed on CN ($P < 0.05$) compared to the other treatments. The economic feed conversion did not differ significantly between the diets, though it was numerically the highest for CN and lowest for BSFL (Table 4).

4 Discussion

The results in this study confirm that alternative locally produced protein sources can partly substitute commercial diets. Given that feed is on average around 70% of the cost price of fish production, a reduction in the cost price for feed is important (Nairuti et al., 2021), especially from a smallholder business perspective. If the share of 20% of the feed can be replaced by, for instance, BSFL produced within the communities at a competitive price' or CN as by-catch sold to low cost in local markets, this can have a positive effect on business models, opportunities to invest and grow, as well as for food security for the most vulnerable and low-income populations in Kenya (Soma et al., 2023). Note that at present, smallholder farmers are not yet producing BSFL independently from taking part in larger commercialized businesses, but this can become relevant in near future (Soma, 2023). This study has shown that if 20% of the CD is substituted by locally produced BSFL, or available by-catch of CN, for cultivating Nile Tilapia, an increase of two-three times in net return (profit) can be obtained by adopting community practices of feeding, compared to feeding the commercial diet only.

The average body weight and growth in metabolic weight were similar for all three feeding strategies, indicating that the substitution of 20% of the commercial diets with BSFL or CN did not affect the growth of the fish. These results are in line with those of Mugo-Bundi et al. (2015) who found that CN substitution had no significant difference in fish growth. However, Wachira et al. (2021) found differences in the growth performance of fish that had diets with varying levels of substitution (from 0% to 100%) of fish meal with BSFL; though the cost-benefit ratio of all diets was similar, showing that all levels of substitution were economically viable. Feed intake was significantly higher for CN compared to the other two feeding strategies, which could probably indicate that CN was slightly more palatable than the other diets. The survival rate of fish was similar for all three feeding strategies. Hender et al. (2021) found a rather positive influence on the immune response of fish fed on diets that partly substituted fish meal with BSFL. Further, partial replacement of fishmeal and fish oil with BSFL diets improved bactericidal activity, immune-related cytokine expression, and mucin cells in both gut and skin which are an indication of improved immunity of barramundi (*ibid.*). These findings are particularly interesting for smallholder farmers because drying of BSFL is relatively easy and can be done even with little experience in compounding feed and administering the substitution of the commercial diet.

The net return above total costs (profit) was positive for all treatments, showing that it was profitable to farmers to use either of the three feeding strategies. However, profit was significantly higher for the BSFL and the CN diets which had a 247% and a 116% higher net return, respectively, compared to the commercial diet. These could translate to enormous benefits to the farmers, especially with the recently increasing feed costs. The feed intake and feed costs were significantly higher for the CN diet than the other diets, and consequently, the economic feed conversion ratio of the CN diet was also the highest causing a higher break-even yield. This study confirms that the use of BSFL and CN as alternative sources of protein increases the profitability of fish farming, which concurs with the results of other studies that worked with fish (Mugo-Bundi et al., 2015; Ngugi et al., 2016; Onsongo et al., 2018; Chia, 2019; Shit, 2021; Wachira et al., 2021; Çetingül and Shah, 2022; Limbu et al., 2022). Interestingly, it has further been demonstrated that utilization of CN can effectively substitute up to 75% of fish meal without compromising growth performance, survival, nutrient utilization and economic benefits, however, when substitution was as high as 100%, the performances declined (Mugo-Bundi et al., 2015).

In another study, Limbu et al. (2022) found that a replacement of fishmeal with BSFL at 75% in tilapia fingerlings diet led to a 30% decrease in feed cost and a 4% increase in economic returns. Similarly, Mugo-Bundi et al. (2015) estimated a 42% higher net returns after deducting full costs in a diet that replaced 25% of fish meal with *Caridina nilotica* meal in Nile tilapia, without compromising its performance and economic benefits. *Caridina nilotica* is readily available as a by-catch of the *Omena* fishery and can be obtained around Lake Victoria.

At the current market prices of $1.36, $1.02 and $1.27 per kg for CD, BSFL and CN diets, respectively, and considering their protein level and dry matter content in Table 1, it can be derived that 1 kg of protein would cost $3.91, $2.13 and $2.33 on average for CD, BSFL and CN, respectively, making locally produced BSFL the cheapest source of protein in this trial. Also Nyakeri et al. (2017) estimated BSFL to be a much cheaper alternative source of protein than conventional sources like fish meal. This study uses the current market price of $1.02 at the time of the study, which judged is affordable to farmers. However, to further reduce the costs of using BSFL, and to enhance its competitiveness and sustainability as feed ingredient of the future, a vertically integrated fish-livestock-crop arrangement is needed for production of farm-produced feed as inputs, especially for the BSFL. Hence, the farmers can produce crops and livestock and use the waste from the farm to produce BSFL to feed the fish farms, as well as the livestock. Consequently, the added benefits of the production of BSFL can stay at the aquapark. The production of BSFL also has a positive environmental impact locally, because the household organic wastes and by-products generated from mixed farming on land by (pond) farmers in the vicinity of the farms can be aggregated and used to feed the BSFL. Diener et al. (2011) reported that BSFL has the capacity for waste treatment and generation of valuable products for scale farmers and entrepreneurs.

The insights created by these trials are thus 3-fold; firstly, chopped dried BSFL or chopped dried CN is a suitable and cost-effective feeding strategy to replace at least up to 20% of the commercial diet compared to feeding a commercial diet only when growing Nile tilapia in ponds at the smallholder farm level. Secondly, the partial substitution of the commercial diet with BSFL and CN provide an opportunity to increase food security and business development opportunities for the low-income groups of the Kenyan population using locally produced BSFL and/ or CN. Abro et al. (2020) estimated that if only 5% of conventional protein sources are replaced by BSFL in commercial chicken feeds in Kenya, this will have large societal impacts, including an increase of 25,000 more jobs, reduction of production prices of 2.7% for eggs and 1.7% for poultry, which could result in lower prices. Moreover, it was estimated that if BSFL replaces fishmeal by 5%—15%, it could respectively increase the availability of *Omena* fish, i.e., Silver cyprinid (*Rastrineobola argentea*) for human consumption by 1,650–4,950 tons annually, which could feed about 432,000 additional individuals, and as such contribute to increased food security and business opportunities, especially for low-income families. Thirdly, the waste issue is tackled by the production of BSFL transformed into a high-quality by-product organic fertilizer called frass, as well as the protein source to feed, according to the principles of a local circular economy, where waste is demanded as an input in the production cycle. This is addressed by a study of Abro et al. (2020), who estimated that a replacement of 5% of conventional protein sources by BSFL in commercial chicken feed in Kenya would need more than half of the organic waste produced in Nairobi, with the potential to offer a great solution to waste management challenges a the city level.

5 Conclusion

With the main aim to determine whether chopped dried BSFL and chopped dried CN partly can substitute a commercial diet and be cost-effective as feeding strategies for rearing Nile tilapia in ponds at the smallholder farm level, this study concludes that nutritionally and from a production point of view, this has been proven. A total of three dietary strategies; (1) feeding a commercial diet only, (2) feeding the commercial diet partly substituted with chopped dried black soldier fly larvae (BSFL), or (3) feeding the commercial diet partly substituted by freshwater shrimp (*Caridina niloticus*) (CN), perform equally well on the growth, survival rate and economic feed conversion rate of tilapia fingerlings.

It has also been estimated that the substitution of BSFL gave substantially higher economic returns compared to the commercial diet alone, or to the diet substituting commercial feed with CN, and is therefore highly recommended for use by smallholder farmers to reduce the cost of feed for tilapia farming. The study hence confirms that smallholder farmers can buy CN affordably in the local market, or can produce the BSFL affordably within the communities.

The BSFL and the CN can thus be used to substitute at least 20% of the commercial diet, which can be supportive to the development of vertically integrated production systems of fish, livestock, and crops in a so-called integrated aquapark structure. Drying BSFL or CN can possibly be done on the farm, and be combined with production of own made high quality fertilizer from BSFL production, i.e., frass, while also treating large amounts of organic waste needed to feed the BSFL. The share of substitution of protein rich locally available feed sources has been set to 20% in the trials of this study; however, future research must confirm whether a larger share can be substituted with no differences in growth. The aquaparks can be seen as hubs contributing with learning, exchange and motivation, for which real scaling of the ideas are most likely to happen in privately owned farms where local private ownership needed for private investments and for taking risks are higher.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JK: Conceptualization, Writing—original draft, Writing—review & editing, Data curation, Methodology, Supervision, Validation. MO: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing—original draft, Writing—review & editing. ER: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing—review & editing. KS: Conceptualization, Funding acquisition, Writing—original draft, Writing—review & editing. AN: Conceptualization, Validation, Writing—original draft, Writing—review & editing. AV: Funding acquisition, Project administration, Resources, Supervision, Validation, Writing—review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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