

Article

Producing Affordable Tilapia in Sub-Saharan Africa by Replacing Feed with Farm-Produced Black Soldier Fly Larvae

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Abstract

Fish remains unaffordable for communities in many parts of Sub-Saharan Africa where malnutrition is common. High aquaculture production costs due to feed and labour prevent the production of affordable fish. Substitution of commercial with farm-made feed can lower production costs. In this study, on a small-scale Ugandan tilapia farm, commercial feed was substituted with black soldier fly larvae (BSFL), grown using fruit and vegetable waste. Data on the cost of establishing larvae production facilities, operating costs and fish production were used to test the economic feasibility of substituting feed with BSFL to produce affordable tilapia. We found that feed could successfully be substituted with up to 66% BSFL with no effect on fish production. Economic analysis revealed that 55% substitution was needed to produce tilapia at US\$2.00/kg with a Feed Conversion Ratio of 2.4. Profitability improves if fish sales are supplemented with sales of frass (used substrate) and any leftover BSFL. Substitution of feed with BSFL grown on local low-cost waste materials provides a sustainable and circular approach to tackling food security in some of the world's poorest communities.

Keywords: aquaculture; food security; circular economy; insects; sustainable production; economic feasibility

1. Introduction

The black soldier fly (*Hermetia illucens*) is a tropical to subtropical species of the order *Diptera* found widely around the globe. It has gathered interest since the early part of the millennium as a possible solution to provide protein-rich feed ingredients for animals, including a wide range of livestock and companion species. It has been of particular interest in the aquaculture industry [1,2], which has historically drawn much of its feed supply from marine sources, such as anchoveta and other fishmeals [3,4]. Fishmeals (FMs) are highly prized for their nutrient profiles and high digestibility [4,5], especially in diets of high-value aquaculture species, such as salmon and shrimp [6,7] that are still largely dependent on some inclusion of marine ingredients for optimum welfare and performance in commercial settings [8]. However, marine ingredients are in short supply, owing to the main fisheries contributing to marine ingredients already being fully exploited since the 1990s [4,9]. Although there has been significant extra contribution from fishery and aquaculture by-products, the capacity for growth at the required rate to maintain historic inclusion levels is limited due to many factors [10].



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Farmed production of lower-value, freshwater fish species, which vastly outweighs the volume of marine species and is of high importance for providing food security in Lower-to-Middle-Income Countries (LMICs) [11], is often overlooked in discussions about the need for alternative feed ingredients. Chinese and Indian carps form the top seven species of cultured finfish in the world, followed by tilapia spp. [12]. Tilapia and carp are not dependent on marine ingredients to the extent that carnivorous species are, and therefore feeds typically have much lower inclusions of marine ingredients than salmon or shrimp feeds. However, access to quality and competitively priced feed is a major constraint to producing fish at prices that are affordable to the poorest people in LMICs. In Sub-Saharan Africa, especially, there is a heavy reliance on imported feed and feed ingredients [13]. A key challenge is to develop models that can cut the cost of production. The common semi-intensive production model relies on fertilisation to increase the natural productivity of pond systems, along with supplementary feeding, usually a mix of agricultural by-products, grains and some commercial feed. In many cases, farmers may produce their own feed materials on the surrounding land, often making use of by-product and waste resources, but often there is a trade-off between the cost of commercial feed and the cost of labour to produce feed ingredients and other integrated activities [14]. To reduce costs, the farmer must reduce the amount spent on feed and feed materials, or on labour to produce their own farm-made feed materials.

Black soldier fly larvae (BSFL) are voracious feeders of organic material, including decomposing animal and vegetable matter. They can, therefore, be used to convert wasted and spoilt resources into usable protein for feeds [1,15]. In this respect, there has been a lot of attention on replacing FM with BSFL meals in a variety of aquaculture species [16,17], particularly salmon diets in Europe [18]. Many studies have shown good results when partially replacing FM with BSFL meals in compound diets for a number of species, including Atlantic salmon [19], rainbow trout [20], Nile tilapia [21] and others [2]. However, the model for producing BSFL meals for formulated aquaculture diets is challenged by several factors. The original concept of using BSFL as a feed was that they could be grown on waste, but typical organic waste, e.g., from agriculture or municipal sources, is inherently inconsistent in quality and quantity, which is reflected in BSFL fed on such wastes, i.e., their nutritional profile changes according to what they are fed [2,22–24]. However, intensive aquaculture systems such as for salmon use precisely formulated diets that require highly processed and consistent ingredients in quality and quantity [5,25]. This means that consistent feedstocks must be used to produce consistent BSFL, and potentially costly processing such as defatting of BSFL meals is often required to meet feed producer expectations [26]. EU regulations, which currently cover Norwegian and Scottish salmon production, consider BSFL to be farmed animals and therefore do not allow the use of what is typically considered organic waste, such as manure, catering waste, animal mortalities, etc. [27,28], as a feedstock for the larvae. Therefore, only “feed grade” substrates and by-products (e.g., middlings, DDGS, etc.) can be used, potentially diverting them from direct livestock feed applications [29]. The use of carefully selected and managed feedstocks, together with high energy requirements to produce BSFL in temperate locations (where salmon are grown) and further processing of larvae into meals of consistent quality and quantity, means the production of suitable BSFL meals has often been considerably more expensive than many of the competing ingredients on the market [26,30]. The current price of defatted BSF meal in the global marketplace is approximately US\$5000 [26,31] compared to US\$1600 for fishmeal [32]. BSFL meal is often touted as a “sustainable” replacement for fishmeal, yet it is often much more expensive with much higher environmental impacts than most fishmeals in life cycle assessments [4,33].

Production of BSFL meal in Africa does not have the same regulatory constraints and can be considerably cheaper than in Europe, but replacement of FM with cheaper BSFL meals in tilapia diets does not necessarily equate to substantially cheaper feed, as FM inclusions in tilapia feeds are typically low. This makes the European model of replacing FM with BSFL meal in compound feed for aquaculture in LMICs unlikely to substantially reduce costs. Some economic analyses have shown small economic gains from substituting FM for BSFL meal in tilapia diets, such as Kariuki et al. (2024) [16]. However, Kariuki et al (2024) [16] reported tilapia prices over US\$5.00/kg, which is well above that which is deemed affordable by poor communities in East Africa [34].

The semi-intensive model of fish production is of more interest in developing countries, whereby farmers could reduce their costs by replacing feed directly with farm-produced BSFL, rather than purchasing compound feed containing BSFL meal. Kals, et al. (2024) [35] showed good profitability substituting chopped, dried BSFL directly for feed, but reported the price of BSFL at over US\$1.00/kg, which is not dissimilar to compound feed, along with fish prices over US\$5.00. In Kariuki et al. (2024) [16] and Kals et al. (2024) [35], the improved profitability was due to improved fish yield compared to the control, which has not been borne out by most nutrition studies [2]. In traditional semi-intensive aquaculture, supplementary feed is either based on cheap agricultural by-products or produced by the farmer themselves, and critically, the savings on commercial feed must be balanced against the price of labour to produce feed materials. This is especially so if the price of tilapia is to be affordable to poorer consumers. In this study, we aimed to demonstrate the production of small tilapia (approximately 150 g–200 g) at US\$2.00/kg at farm gate, according to similar prices reported by Kaminski et al. (2024) [34], by reducing feed costs without requiring excessive extra labour demand.

African and other tropical LMICs often have a problem with high rates of food spoilage and subsequent waste management [36]. Waste could be converted quickly to usable protein in the form of BSFL and used directly as live feed on-farm as a contribution to other supplementary feeding along with fertilisation. Although BSFL quality could be highly variable, this would be unlikely to be a major issue, as much of the nutrition in semi-intensive systems comes from the natural productivity of the fertilised pond [37]. Potentially, by substituting out commercial feed for live, untreated BSFL, the overall feeding cost could be reduced without substantially increasing labour associated with feed production. However, overfeeding with BSFL could result in negative welfare and performance issues, particularly protein digestibility due to elevated chitin content of unprocessed BSFL, although this may be variable between species [17] and more likely an issue with prepupae [38], which have higher chitin content than larvae [39,40]. While many nutritional studies are positive, as above, and some do provide some economic feasibility data, none explore the resilience of the model, considering variable costs and returns.

On-farm production of insect larvae for feeding fish is not a new concept, with studies stretching back decades. The challenges concern the logistics of transport of large volumes of low-value “waste”, the sale of various co-products, and the resilience of the system to various economic and logistical changes [41]. In this study, we sought to investigate different levels of replacement of commercial feed with farm-produced BSFL larvae in a semi-intensive earthen-pond tilapia production system in Uganda and understand its economic implications in different scenarios. We provide an integrated growth assessment, complemented with primary economic data that we have modelled using comprehensive sensitivity analysis to ascertain system viability beyond previous studies. The goal was to ascertain whether production costs could be reduced without adversely affecting the performance of production, i.e., the welfare, growth and other production parameters of the fish. Ultimately, the aim was to see if fish could be sustainably and profitably produced

and offered at an affordable price, accessible to poor communities in Sub-Saharan Africa, in this case, Uganda. We did not seek to ascertain the nutritional performance of live BSFL in fish diets, but to investigate how BSFL feeding strategies could provide a sustainable and resilient production model for affordable fish nutrition. Therefore, only basic growth performance data were collected along with production cost data to establish the economic performance of the production strategy using various scenario analyses. The aim was to be self-sufficient in BSFL production that would feed farmed fish and, in some cases, surplus BSFL could be further utilised or sold for extra profit as detailed below. In all cases, there are comparatively large volumes of frass (BSFL excreta mixed with uneaten substrate), which could be sold or used on-farm as a fertiliser and soil amendment [15].

2. Methods

2.1. BSFL Production

A new BSFL production facility was established close to Rukungiri, Uganda, using 1 m² concrete bays in a wooden shed for larval rearing and a polytunnel system to breed the adult flies (Figure 1). A colony was set up using locally purchased eggs. Breeding occurred naturally within the polytunnel, and flies laid their eggs in cardboard strips situated near a waste source. Fertilised eggs were collected daily from the cardboard for incubation. The larvae were allowed to hatch into moist maize flour, which was then introduced to concrete bays in the main larval growing area. The growing substrate was waste and spoilt fruit and vegetables from a local market, which was collected daily, mashed using a hammer mill, and then mixed. The mixed fruit and vegetable waste was stored in plastic drums until it was needed. The substrate was put into the bays at approximately 30 cm depth. The newly hatched larvae were introduced to a new bay every three days. The larvae were managed on an informal basis, as would be expected in a subsistence or semi-commercial operation. The substrate and larvae were turned at least twice per day to ensure aeration and good mixing. If the substrate was considered to be too wet, rice husks were added to improve the structure of the substrate to allow more aeration and to absorb moisture. The temperature inside the growing facility was ambient, from 20 °C at night to 37 °C in the warmest part of the day. Larvae were harvested after 14 to 20 days before reaching the pre-pupae stage and used within the growth trial.



Figure 1. BSFL production facilities, Rukungiri, Uganda, showing concrete bays for ongrowing (left), and the breeding polytunnel next to the ongrowing shed (right).

2.2. Growth Trial

A growth trial was conducted in hapas (3 m by 2 m) placed in a standard fertilised freshwater earthen pond used for commercial tilapia production close to the BSFL production facility in Uganda. The water was 1.5 m deep as standard, and hapas were placed 1.5 m apart. Each hapa was stocked with 100 fish of average weight 40.2 g. All the fish had been acclimated to the farm for two months and introduced to the trial pond two days prior to stocking into hapas. There were four treatments in triplicate, and hapas were allocated randomly as follows. Treatment 1: no feed (NF), Treatment 2: commercial feed only (CF), Treatment 3: 33% replacement of commercial feed with live BSFL (33BSF), and Treatment 4: 66% replacement of commercial feed with live BSFL (66BSF). All substitutions of commercial feed with BSFL were made on a live weight BSFL basis. Feed provision was calculated at 3.5% bodyweight per day, calculated from periodic weight measurements, split equally between a morning and evening feed. Feed provision was calculated on a weekly basis for each hapa accordingly, based initially on biomass measurements, with all treatment groups weighed every three weeks, and an assumed 10% increase in feed each week between sampling. The trial ended on day 105 post-stocking, at which all fish individual weights and lengths were collected. We took a least intervention approach to minimise stress, so sample weighing and other disturbances were kept to a minimum. Therefore, individual fish variation amongst treatments was only measured at the final weighing, and variation between average weights was presented for all interim weight measurements. The Specific Growth Rates (SGRs) and Fulton's K Condition Index [42] for all treatments were calculated based on final measurements. Average final weights, lengths and Fulton's K for each replicate were analysed using a one-way ANOVA test, followed by a post hoc Tukey's pairwise comparison.

2.3. Economic Data

Economic analysis was performed concerning the theoretical setup and operations of BSFL facilities and management on an existing tilapia farm, producing 6000 kg of fish per year based on primary data collected from the BSF facility setup in Rukungiri. The maximum capacity of the BSFL unit was estimated to be 10,080 kg of live BSFL per year, judged to be enough to produce 6000 kg of fish with 70% replacement of commercial feed at a Feed Conversion Ratio (FCR) of 2.4, which is towards the upper end of that expected in a commercial setting [43]. Capital costs for BSFL production included the price of building a polytunnel breeding unit and on-growing in concrete bays, such as those in Figure 1. Operating costs included the maintenance of capital items, along with the cost of feed and the amount of labour and its associated hourly rate. In our model, it was assumed that a loan would be required for the CAPEX of building the BSFL facilities, but the tilapia farm was already established with no extra building or other outstanding costs. Primary data were collected on the amount of market waste substrate used and the costs involved in its collection, including fuel and labour requirements. Other labour requirements included the daily management of BSF egg collection and incubation, mashing substrate using a hammer mill and storing it for later use, larvae management, including turning the substrate and collecting the larvae for use as supplementary feeds, and finally the feeding activities on the fish farm site. These labour costs were balanced against the cost of commercial feed, including its collection. All costs were calculated with a 15% additional miscellaneous costs and a 10% contingency on top of actual monies paid, to account for uncertainty in the quantity and quality of waste collected and production efficiencies. Therefore, the economic costings are likely very conservative in their assessment.

Economic evaluation was made based on feasibility assessments using Net Present Value (NPV) over 10 years with a 10% discount rate. This was tested over several sensitivity

scenarios: (1) changing the substitution rate of BSFL for commercial feed within the fish diet incrementally from 0% to 70% at FCRs of 1.8 and 2.4, (2) changing the price of frass for 33% and 66% substitution rates and corresponding sales, (3) changing the cost of waste used as a substrate for BSFL production with 33% and 66% substitution rates, and (4) changing the price of BSFL and corresponding sales at increasing levels of substitution at an FCR of 2.4. For initial costings of the theoretical enterprise, where excess larvae were produced, they were assumed to be sold at \$0.25 per kg, and frass was assumed to be sold at US\$0.10 per kg. This was for demonstration purposes only, and in reality, sales of BSFL and frass may be difficult to establish in the short term. In the subsequent scenarios, the effects of waste costs and frass and BSFL prices were tested using sensitivity analysis, shown in Table 1. All other data on costs and returns were based on the economic data obtained from setting up the BSF facility and operating costs on the associated tilapia farm in Rukungiri where the growth trial took place.

Table 1. Black soldier fly larvae production scenarios to test sensitivity of cost–benefit analysis.

	Scenario 1 Substitution Rate	Scenario 2 Frass Price	Scenario 3 Waste Price	Scenario 4 BSFL Price
Substitution rate with BSFL, %	0–70	33 and 66	33 and 66	0–70
Price of Frass per kg	\$0.00	\$0.00–\$0.20	\$0.00	\$0.00
Cost of market waste per kg	\$0.00	\$0.00	\$0.00–\$0.10	\$0.00
Price of BSFL larvae per kg	\$0.00	\$0.00	\$0.00	\$0.00–\$0.60

3. Results

3.1. Fish Nutrition

The results of the growth trial (Figure 2) showed that commercial feed could be successfully substituted with BSFL at 33% and 66% with no negative effects on growth ($p < 0.001$). Clearly, from the no feed (NF) treatment, there was insufficient nutrition obtained from the pond, as the fish suffered a loss in weight for over 40 days before starting to recover. However, all other treatments grew well, with an average SGR of 0.80 between the three fed treatments over the 105 days of the trial, and there was no significant difference between the final weights ($p < 0.0001$, $R^2 = 96.98$), lengths of fish ($p < 0.0001$, $R^2 = 96.32$) or the Fulton’s K condition index ($p = 0.001$, $R^2 = 86.33$) of the three fed groups (Figure 3). The NF treatment had lower final weight, length and Fulton’s K than all other treatments, as expected. However, final individual measurements revealed there was a large variation between growth rates in all treatments (Figures 2 and 3), which could be due to a number of factors and possibly influence farm scheduling that may ultimately affect the economic performance.

3.2. Economic Appraisal

Table 2 shows the capital, operating and fixed costs and parameters for the BSFL production facility and fish production model for 33% and 66% BSFL substitution at an assumed FCR of 2.4. During BSFL production, there was considerable variation in the quality of the substrate, particularly the water content and the mix varied daily according to what was available from the local market. However, fruit and vegetable waste was collected daily, mashed and mixed in storage barrels until needed, so some of the variation was evened out, but it could not be eliminated altogether. Therefore, the waste and frass-to-larvae ratios used in the economic modelling are approximate averages based on several weeks of real production. The price of fish was already established from the farm operations, but the price of larvae and frass were assumptions.

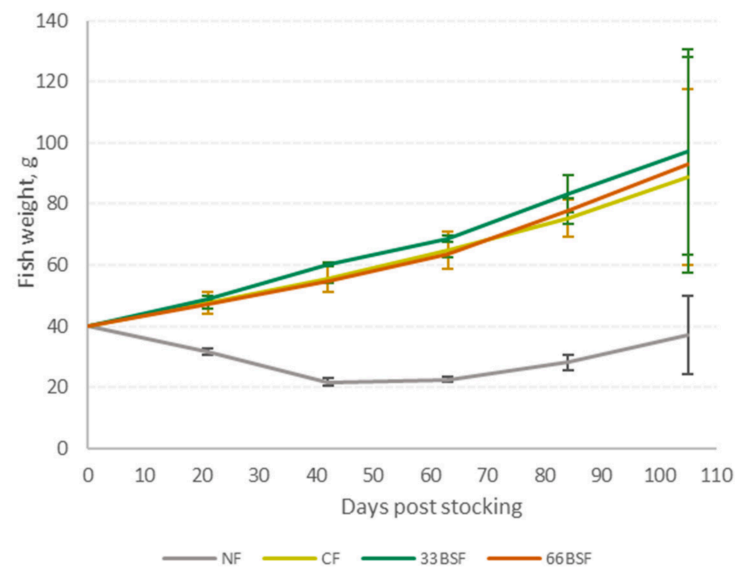


Figure 2. Growth of tilapia produced using four different feeding regimes over 105 days showing averages and SD between treatments to day 84 and individual averages and SDs at day 105; NF—no feed, CF—commercial feed, 33BSF—33% replacement of commercial feed with live BSF larvae, 66BSF—66% replacement of commercial feed with live BSF larvae. All fed treatments were fed at 3.5% of body weight per day, split between morning and afternoon feeding.

Table 2. System parameters and costs for complementary BSFL and tilapia production in Uganda with two levels of substitution at an FCR of 2.4. Includes sales of spare BSFL and frass.

System Parameters	
Amount of waste to produce 1 kg larvae	15 kg
Amount of frass produced per kg larvae	4 kg
Price of fish per kg	\$2.00
Price of feed per kg	\$1.00
BSFL production capacity, kg	7800
Fish production, kg	6000
Capital Costs, \$US	
Aggregates	60.90
Bricks	60.90
Concrete	112.40
Hut Shelter	415.20
Hammer mill	913.00
Plastic sheeting	102.90
Shading	85.20
Timber	160.00
Storage	20.90
Measuring	15.00
Utensils	62.25
Other	15.65
TOTAL CAPEX	2753.70
Fixed operating costs, US\$	
Labour (stockworker) *	521.74
Labour (BSF manager)	1304.35
Fuel	216.00
Maintenance of BSF infrastructure and facilities	258.39
Interest on loan	535.26
TOTAL FIXED OPERATING COSTS	2835.73

Table 2. Cont.

System Parameters			
Variable operating costs, US\$	CF	33BSF	66BSF
Feed	14,400	9648.00	4896.00
Miscellaneous costs, 15%	2238.26	1753.51	1040.71
Contingency, 10%	1716.00	1370.20	823.72
TOTAL VARIABLE OPERATING COSTS	18,354.26	12,771.71	6760.43
TOTAL OPERATING COSTS	18,570.26	15,607.44	9596.16
Fixed Income, US\$			
Fish sales		12,000.00	
Variable Income, US\$	CF	33BSF	66BSF
Spare BSF sales (\$0.25/kg)	0.00	1332.00	144.00
Frass sales (\$0.10/kg)	0.00	4032.00	4032.00
TOTAL SALES	12,000.00	17,364.00	16,176.00
PROFIT	−6570.26	1756.55	6579.83

* For fixed operating costs, the CF scenario includes stockworker and other fish production costs but not the costs associated with BSFL management.

The only variable costs were related to feed, miscellaneous costs, plus the contingency related to production between substitution rates. Fixed operating costs included labour, fuel, maintenance, and interest on the loan required to build the BSF facilities. Income came from fixed fish and frass sales; although the quantity of larvae production was fixed, sales varied according to the amount of spare BSFL and could be sold between the different feed substitution rates and FCRs. There was also some small income from bank interest as the facility became profitable, and this also varied between the two substitution rates.

Figure 4 shows the NPV for the various different scenarios (Table 1) over ten years at a 10% discount rate. Scenario 1 shows the effect of changing the BSFL substitution rates at FCRs of 1.8 and 2.4, from no substitution (CF) up to 70% substitution, with no additional income from frass or spare BSFL. With no substitution, fish production is not profitable for either FCR rate and remains loss-making for both FCRs up to approximately 40% substitution for an FCR of 1.8 and approximately 55% for an FCR of 2.4. At low substitution rates (<20%), the savings on feed do not outweigh the cost of setting up the BSFL facility.

With a 33% substitution rate, the enterprise remains unprofitable at FCRs of 1.8 or 2.4 from selling fish at US\$2.00 and no further income from either frass or BSFL. At 66% substitution with BSFL, the enterprise is profitable with a payback period of 2 yrs at FCRs of 1.8 and 2.4.

Scenario 2 (Figure 4b) shows the same model as for Figure 4a but with a fixed FCR of 2.4 for 33% and 66% BSFL substitution rates and a variable price of frass (Scenario 2). Although frass is less valuable than BSFL, the volumes are much greater (Table 2) and therefore have the potential to add a lot of income to the farm if it can be sold. Selling frass at above \$0.12 per kg results in both 33% and 66% substitution rates being profitable, whereas organic fertiliser such as manure has low availability [44] and is increasingly being substituted for costly inorganic fertiliser in Uganda [45].

Scenario 3 (Figure 4c) investigated the effect of increased waste costs using a fixed FCR of 2.4 for 33% and 66% BSFL substitution rates, as in Scenario 2. Raising the price of waste leads to a sharp reduction in profits, so that the 33% substitution rate becomes even more unprofitable, remembering that the facility's BSFL production is constant. At 66% BSFL substitution, the system remains profitable with a waste price up to approximately US\$0.08/kg. It seems that the system is more sensitive to waste prices than larvae

prices overall, as changing the price of larvae has much less effect than the price of waste (Figure 4c), and substitution rates of between 40% and 50% are required for the enterprise to be profitable for prices of larvae between \$0.00 and \$0.60/kg (Figure 4d). If all larvae were sold, they would need to fetch above \$0.40 per kg to match the cost of investment in the facilities and production costs. However, maximising the profitability through sales of frass and larvae is essential to enable tilapia to be sold at the target price of \$2.00/kg and remain profitable. Selling frass at \$0.10/kg enables a tilapia break-even price of \$2.00/kg with 35% BSFL substitution, but would require approximately 53% substitution if only selling the spare BSFL at \$0.25/kg (Figure 5).

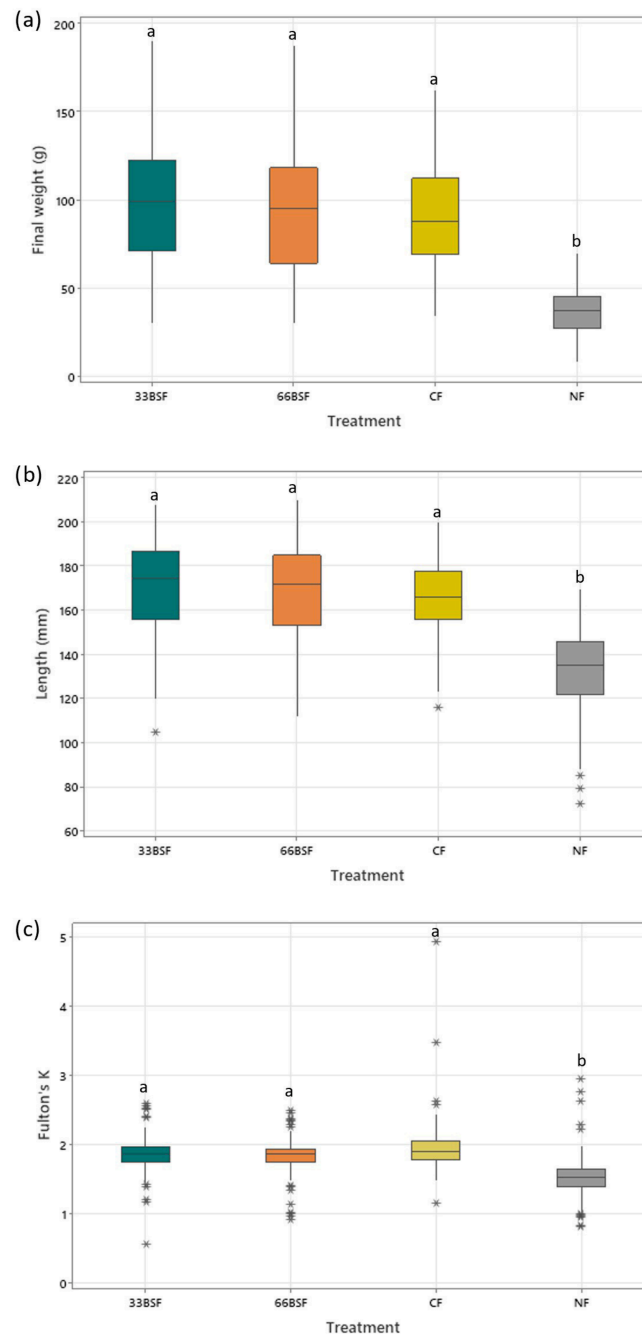


Figure 3. (a) Final weight, (b) length, and (c) Fulton's K condition factor of tilapia produced using four different feeding regimes over 105 days; NF—no feed, CF—commercial feed, 33BSF—33% replacement of commercial feed with live BSF larvae, 66BSF—66% replacement of commercial feed with live BSF larvae. Different letters above plots denote significant differences.

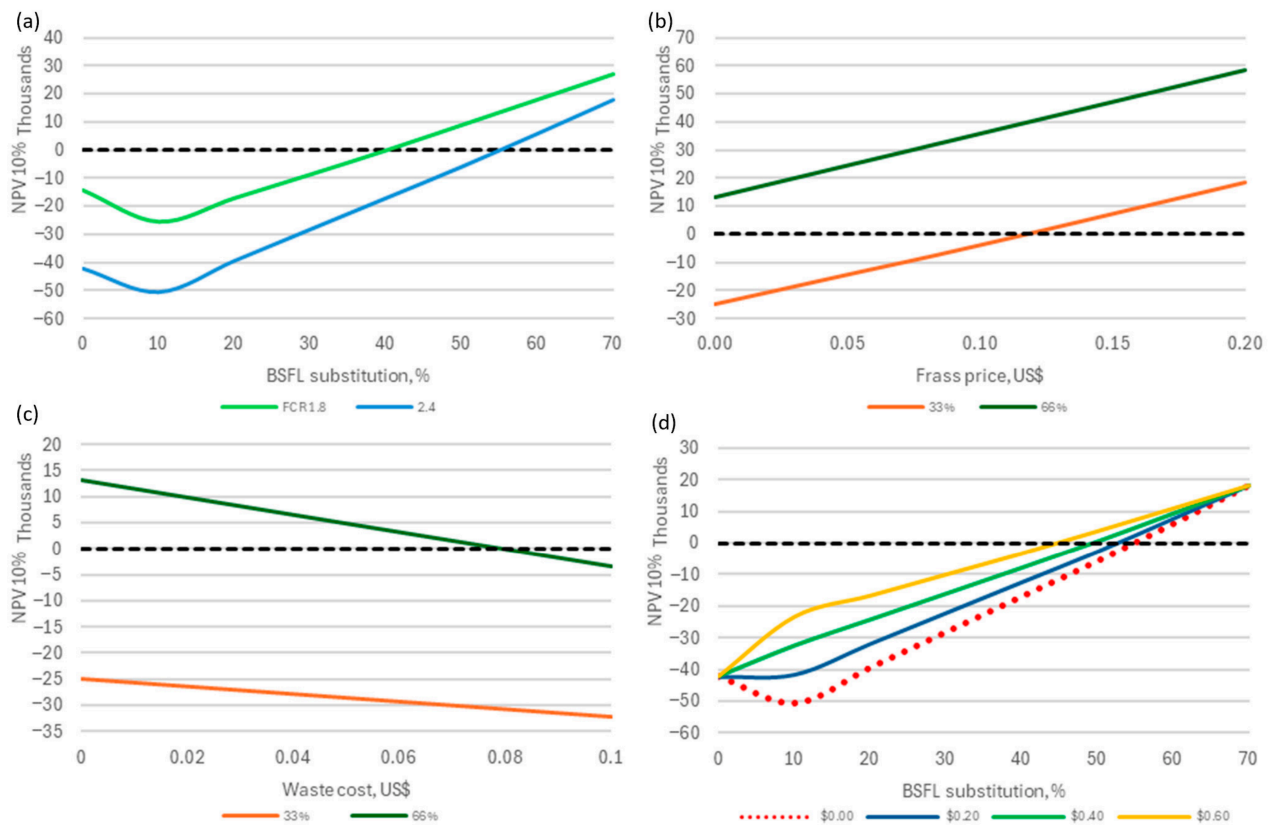


Figure 4. Modelled net present value (10% discounted) for a Ugandan tilapia farm with supplementary BSFL feed; (a) incrementally substituting live BSFL for compound feed (WW basis) at two different FCRs; (b) effect of frass price on the profitability of 33% and 66% substitution rates at FCR 2.4; (c) effect of waste (substrate) price on the profitability of 33% and 66% substitution rates at FCR 2.4; (d) effect of BSFL price (\$0.00 to \$0.60/kg) on profitability showing incremental BSFL substitution at FCR 2.4.

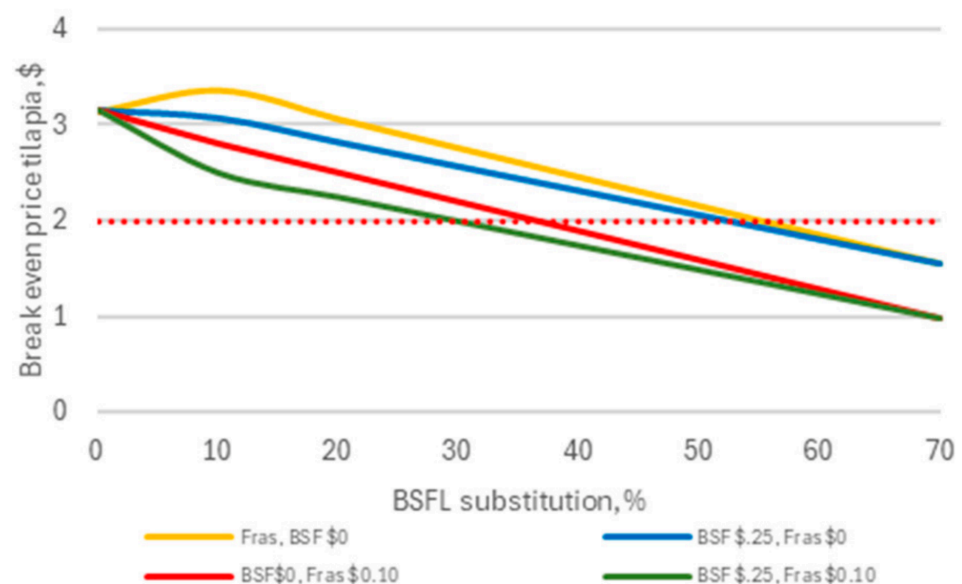


Figure 5. Break-even prices of tilapia from a theoretical combined BSFL and tilapia production enterprise in Uganda, showing increasing BSFL substitution with and without BSFL and frass sales (FCR = 2.4).

Commercial feed cost is by far the most significant, and substituting feed for low-cost alternatives, such as BSFL, reduces the vulnerability to shocks in the price of feed and poor FCR. Figure 6 shows the range of profitability within each coloured area, with higher and lower FCRs at the lower and higher end of the range, respectively. As would be expected, the higher the level of substitution, the narrower the range becomes between the FCRs as the price of feed increases.

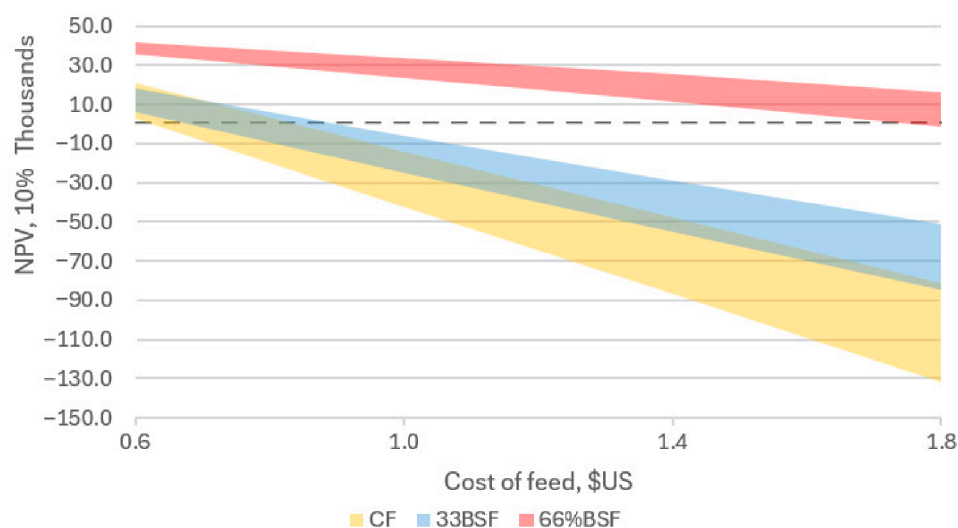


Figure 6. Effect of feed cost on the profitability of combined BSFL and tilapia production in Uganda, showing NPV discounted at 10% for 0%, 33% and 66% substitution rates of BSFL for feed with FCR ranging between 1.8 (upper) and 2.4 (lower).

4. Discussion

The feed substitution trial showed that large amounts of live BSFL can replace commercial feed in diets with no negative effects on growth. However, considerable variation in growth was apparent within all treatments, especially the fed fish. Variability can be due to a number of reasons, such as competition and hierarchies within the fish populations, which lead to dominant individuals acquiring more feed. However, it is more likely that inherent genetic variability within the seed, along with mixed sex stock, led to the variation in all treatments. There have been mixed results in feeding BSFL as a replacement for feed [2]. Several studies have been conducted on using BSFL in tilapia feeds, including Devic, et al. (2018) [46], Muin H., et al. (2017) [47] and Tippayadaraet al. (2021) [21], with most studies showing diets with modest inclusions of BSFL performing as well as control diets. Most literature has focused on replacing feed ingredients, especially marine ingredients, within commercial pelleted diet formulations, rather than replacing the commercial feed itself. Of the few studies that looked at replacing feed, Kals et al. (2024) [35] showed that up to 20% of a formulated tilapia feed could be replaced by dried and chopped BSFL without any negative effects on growth. In contrast, a study on rainbow trout by Ozturk et al. (2022) [38] showed that replacement of commercial feed with BSF prepupae resulted in a significant reduction in growth and poor welfare outcomes, leading to high mortality. However, BSF prepupae are considerably higher in chitin than BSFL, which was given as the main reason for the poor results. Also, much depends on the quality of the formulated feed, with some studies showing that maintaining moderate levels of marine ingredients with relatively large inclusions of BSFL did not adversely affect growth in tilapia trials [17,48,49], although increasing levels of chitin adversely affect digestibility [17]. However, the digestive anatomies of tilapia and trout are also considerably different, with trout being highly carnivorous compared to the omnivorous tilapia, which obtains much of its nutrition from

natural feeds in semi-intensive systems [37]. However versatile semi-intensive systems may be, the nutritional profile of the supplementary feed, i.e., BSFL in this case, is still of importance for the health of the cultured animal and the conditions within the pond. Poor nutrition leads to wasted feed, poor conversion and growth, and deteriorating water quality. The quality of substrate fed to BSFL affects their nutritional profile that in turn affects fish performance and their nutritional profile [50,51], but the level of chitin within the larvae is of particular interest, which could be affected by the production conditions of the larvae [52,53]. In this study, commercial feed was substituted on a weight-for-weight basis, and this obviously led to some differences in the overall nutritional content of the supplementary feed provided. Larvae contain more moisture, and the levels of protein and lipid can vary considerably according to the substrate supplied. Considering that the larvae were supplied with fruit and vegetable waste from a consistent source, which was mixed, macerated and stored prior to use, it could be assumed to be of fairly consistent composition. Eke, et al. (2025) [54] showed that BSFL larvae could achieve protein levels of over 45% (DM) when fed with fruit and vegetable waste, with dry matter contents of between 20% and 44%. Direct substitution of feed with unprocessed larvae may result in an overall lowering of protein available in the supplementary feed provided, but this does not seem to influence growth performance. Similar results have been discussed by El Sayeed (2008) [55] that lower protein than considered optimal often produced comparable results in semi-intensive systems where over 50% of nutritional needs can be sourced directly from fertilised ponds [37]. The nutritional parameters of larvae are an important consideration, but perhaps less so as a supplementary feed than the logistics of larvae production, such as their growth rates and harvesting time, which could affect the timing of BSFL availability, and therefore the amount of commercial feed required and the profitability of the whole operation. Perez-Pacheco et al. (2022) [50] showed that production time of BSFL was longest using fruit waste compared to more protein-rich substrates. While this may not be an issue in well-managed production facilities, it is a consideration where substrate streams could be highly variable.

The economic analysis shows that the model of producing BSFL larvae to replace feed can be viable for small-holder farmers. The viable levels of substitution are a key factor in determining the profitability of the model. Whereas many studies have shown maximum BSFL meal inclusion rates in feed of approximately 15% to 20%, here we have demonstrated a substitution of 66% of feed with live BSFL with no detrimental effect on growth, allowing profitable production of low-priced tilapia. The main considerations are the price of feed, labour effort and possible cost of waste (substrate). There is considerable uncertainty around some of these parameters, which was addressed in the sensitivity analysis shown in Figure 4. The economic returns from frass are perhaps one of the most important areas of uncertainty, as the volumes are high and returns could be significant, given good market conditions (Figures 4 and 5). Furthermore, with no returns at all from the frass, substitution needs to be maintained above 50% for the enterprise to be profitable if tilapia sales are to be maintained at affordable rates. The analysis of the theoretical facility shows that the price of labour required is low compared to that of feed, and the daily contribution to BSFL management is not considerable compared to the cost of feed and the possible savings. The level of expertise is also not a barrier, with the main consideration being knowledge of maintaining good egg production. The baseline model assumes that waste is “free” apart from the cost to collect, store and prepare it for use and, in practice, the farm paid less than \$0.02/kg on average. However, the calculations show that if there were significant competition for the waste resource, then the profitability of the farm declines rapidly. This has often been the case in Europe, where only feed-grade substrates are permissible and therefore in direct competition with other end users in most cases. For example, Wehry

et al. (2022) [29] showed that almost all feed-grade agricultural by-products in Scotland were already utilised, with the exception of some whisky by-products, whereas Smetana et al. (2019) [33] showed that over 30 kg of feed-grade substrate was required to produce 1 kg of BSFL meal. In Africa, where rates of spoilage are high, waste management is underdeveloped, and there are fewer restrictions on the types of by-products or waste that are permissible, this level of competition is not likely to occur. High rates of spoilage, due to the Sub-Saharan climate, render many by-products such as market waste unusable for other livestock but ideal for BSFL [15,56], but if “waste” were to find other more lucrative markets, the economic model would be challenged as it has been in Europe.

The model presented in this study is different from that of some similar publications, which did not rely on farm-produced BSFL, but bought them from external sources. The price of feed is more critical than other inputs. At the time of this study, feed was approximately 80,000 UGX for a 20 kg bag, equating to just over US\$1.00 per kg, although this is now rising. A few studies have shown improved profits when including BSFL in different forms, e.g., [57,58], but few details were given on feed or larvae prices. Kals et al. (2024) [35] substituted chopped, bought larvae costing US\$1.02 for feed, which was costed at US\$1.36. Kariuki et al. (2024) [16] showed better economic performance when substituting fishmeal for BSFL meal, but due mostly to better survival compared to the control diet, whereas other studies show no difference in survival. Both Kals et al. (2024) [35] and Kariuki et al. (2024) [16] declare tilapia prices to be US\$5 per kg or more, on average, which is well over the Ugandan price of approximately 14,000 UGX, or US\$3.80. However, price depends on the size of the fish, with larger fish selling for higher prices, with some competition from frozen imports [34]. Fish prices for large fish are unaffordable for poor communities, and within this study, we hoped to significantly reduce the price of fish that could be offered (US\$2/kg), so as to make them more accessible to poorer consumers and improve their nutritional outcomes. However, although more affordable with higher sales volume, smaller fish typically return less profit [34]. Therefore, margins must be improved, and production models made more resilient. However, growing smaller fish has certain benefits, such as potentially lower FCRs, higher stocking densities and shorter cycles, all of which can reduce risk to the farmer [34]. By using partial harvests, farmers can produce a range of fish sizes, which target different markets and further reduce risk [59]. The growth trial did not reach the target weight of 150 g–200 g in the 15-week time frame; however, the economic model was informed by the growth trial to produce a set volume of fish at US\$2.00 per kg and the necessary inputs to achieve that goal. The growth trial demonstrated a high variation in final fish sizes, and therefore the partial harvest approach could be the most appropriate, which would produce fish at a range of prices. Diversification reduces exposure to volatile externalities, including costs of inputs and is often used as a strategy to overcome risk and market uncertainty, particularly by small-scale farmers in LMICs who can adjust quickly to market conditions [14]. Sometimes this may be by adopting integrated production practices or diverse polycultures such as in China [60], or in other cases by integrating with food service or even recreational fishing [61] in Europe and elsewhere. Adopting BSFL production allows for diversification in several ways: by producing surplus larvae and frass for direct sale or by using them onsite to feed other animals such as poultry and fertilise crops on site. In some cases, the frass may be used to fertilise fish ponds or even included in fish diets themselves [62,63].

Figure 6 shows how susceptible the profitability is to rising prices of feed and therefore the importance of good feed management. Reducing FCR has a large effect, with less substitution of feed necessary to maintain profitability. Poor feed conversion results in a loss unless commercial feed is substituted with BSFL by at least 50%, assuming no change in feed performance as shown within the growth trial. The models presented here are from

a small-holder perspective. Scaling up diversified production systems has shown to be challenging, as balancing the various needs of the farm inputs and outputs becomes more complex. Therefore, it cannot be assumed that approaches that work at a small scale will inevitably apply at larger scales. Although it is difficult to put a limit on the scalability of such a system, typically, diversified models such as Integrated Agriculture Aquaculture are practiced by small-scale farmers who are able to draw on family labour with few external inputs. As farmers increase scale and require additional, perhaps expensive labour inputs, there becomes an increased trade-off between labour and other inputs [64]. Greater intensification often follows, with more commercial feed and greater water quality management, including aeration, which leads to a move away from the more labour-intensive diversified models.

5. Conclusions

Although our analysis should not be considered a complete feasibility study, our economic modelling and sensitivity analysis showed that producing low-cost fish with farm-produced supplementary feeding models is possible but relies on good feed management and diversification strategies such as those offered by BSFL production. El-Sayed [65] claimed that the majority of small-scale tilapia production in Sub-Saharan Africa is on farm-made feeds because of the cost and perceived low quality of commercial diets, and although this is no longer the case, the cost of feed remains a major barrier to aquaculture growth. Access to good quality feed ingredients is therefore of paramount importance. On-farm production of BSFL as a supplementary feed is a promising approach to the challenges faced by small-scale tilapia producers in Sub-Saharan Africa.

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