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Formulating cost-effective black soldier fly larvae (*Hermetia illucens*) based Nile tilapia (*Oreochromis niloticus*) diet for sustainable food security

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ABSTRACT

Globally, food insecurity is a fundamental problem. The aquaculture sector plays a vital role in supplying food with great potential to enhance food security. A significant challenge for the industry is the scarcity of protein sources in fish feeds and high prices that escalate production costs beyond economic viability. A growing paradigm shift for sustainability in the aquaculture sector is the usage of alternative insect-based diets like the black soldier fly (*Hermetia illucens*) larvae meal (BSFLM). The cost of fish production is always a pertinent issue in the aquaculture sector. Therefore, farmers would benefit from minimised and feed costs using technologies such as linear programming, which considers input costs and nutrient levels on different feed ingredients to ensure the production of least cost nutrient-dense diets. This study focused on applying the linear programming technique in Nile tilapia (*Oreochromis niloticus*) feed formulation using BSFLM as an alternative source of protein. In determining the least cost diet, five feeds were formulated with BSFLM at the following levels (0, 25, 50, 75, and 100%) using ready to use excel solver function for linear programming. The study shows that replacing fishmeal with BSFLM at 100% is cost-effective and may reduce the cost of feeding by as much as 26.8%. This study focuses on minimising feed cost in the aquaculture.The study recommends that a further study be conducted to test the diets on fish growth performance.However the level of pprotein content in the diets formulated is also a good since they meet the requirements for juvenile Nile tilapia.Reduced feed costs will enable aquaculture farmers to increase their income and enhance food security

Keywords: Fish feeds, feed formulation, linear programming, production cost

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1 Introduction

Food security is multi-sectoral, normally interlinked with healthcare, governance, trade, economics, agri-food systems, global food trade politics, the environment, and the demographic dividend. For instance, the COVID-19 pandemic, a healthcare concern, illustrates the comprehensive global interlinkage between health and food security. Food insecurity is a crisis in many developing countries, especially in Africa and Asia (Baquedano et al., 2021; FAO, 2021b). In 2020, 768 million people were undernourished, with 54.4% living in Asia. A total of 282 million people encountered food insecurity in Africa, with more than 125 million people, almost 44% living in Eastern Africa (FAO, 2021a). Of the 47.5 million Kenyans, about 13 million people were estimated to be undernourished between 2018 and 2020 (FAOSTAT, 2021). Food insecurity was severe in 2020 in the urban areas due to the COVID-19 pandemic restrictions and containment that interrupted the urban population's food supply and economic livelihood (FAO, 2020).

Fish is a significant protein source and provides essential macro and micro-nutrients that can reduce malnutrition in third world countries like Kenya. Globally, Asia is the highest producer and consumer of fish, with a per capita consumption of 24.1 kg per annum compared to Europe and Africa' per capita consumption of 21.6 and 9.9 kg per annum, respectively (FAO, 2020). In Kenya, the per capita consumption is very low at 5 kg per annum (Obiero et al., 2019), only a quarter of the world average of 20.5 kg per capita (FAO, 2018). Capture fisheries have contributed significantly to food security over the years. In the recent past, aquaculture production has consistently contributed to food security, with a steady increase of 7.5% annually since 1970 (FAO, 2020). In 2020, fish farming contributed about 16% of Kenya's total freshwater fish output, with an increase of 14% from 18,542 tonnes produced in 2019 to 19,945 tonnes in 2020 (KNBS, 2021). It is estimated that aquaculture production in Kenya needs to increase to 150,000 metric tons by 2030 to satisfy the increasing demand (Munguti et al., 2021) or reach 550,000 tonnes to bring fish consumption per capita to the African average (Obiero et al., 2019).

According to KMFRI (2017), the Nile tilapia (*Oreochromis niloticus*), a warm-water cichlid primarily cultured in a freshwater environment, is the main species in aquaculture, accounting for about 80% of the production. Several desirable properties make tilapia suitable for cultivation in most geographic areas, making it the second most farmed fish globally after the carp (Islam et al., 2015; FAO, 2020). It is desirable to practice monosex fish farming, improving food security and incomes (Islam et al., 2015) to achieve fast growth and obtain more profits from aquaculture.

Despite aquaculture's potential to improve food security and income among resource-constrained households, the high costs of ingredients used in fish feed formulation present a significant production challenge. The high cost of feed ingredients is attributed to inconsistent global supply and demand variables (Fontes et al., 2019). Furthermore, feed prices are influenced by fluctuations in oil prices and transport costs. For small scale fish farmers in developing countries, feed costs and other expenses are often too high to be offset by low-profit margins. The feed cost represents about 50 to 80% or more of the total cost of production (Bogard et al., 2017), and the aquaculture sector uses about two to five times more fishmeal than human consumption (Huntington and Hasan, 2009; Stevens et al., 2018) leading to competition for fishmeal as a direct food and the feed industry sector.

Sourcing fishmeal from the wild has led to overfishing natural fish stock (Hollingsworth, 2017). Fishmeal has historically been the primary protein source for fish feeds. Due to its high protein content, balanced amino acid profile, digestibility, palatability and presence of essential fatty acids (Hardy and Tacon, 2002; Jackson, 2006). However, limited supply of fishmeal and rising prices due to high demand for poultry and livestock feeds, will cause reliance on fishmeal as a single protein source in aquafeeds (Oliva-Teles et al., 2015; Bendiksen et al., 2011; Kim et al., 2019). Therefore, substituting locally available and less expensive feed ingredients for fishmeal has proven vital for the future development of the aquaculture industry (Olsen and Hasan, 2012). Numerous alternatives to fishmeal have been investigated as potential alternatives. The results show that the degree of partial or complete substitution success varies significantly based on the species of fish cultured (Burr et al., 2012; Soltan et al., 2008; Yousif et al., 2019; Perera and Bhujel, 2021; Yossa et al., 2021).

In advancing aquaculture, full utilization of insects seem to offer an alternative protein ingredient for fish feeds (Van Huis et al., 2013). Insects are natural diets for freshwater and marine fish species, including Nile tilapia. Insects are rich in protein, essential amino acids, lipids, minerals, and vitamins. They can be reared in large numbers with minimal quantities of water or feeds, with promising results from the black soldier fly (*Hermetia illucens*), the common house fly (*Musca domestica*), and the yellow mealworm (*Tenebrio molitor*) (Sogari et al., 2019).

The black soldier fly is widespread and considered a non-pest species with no capacity to carry pathogens, unlike *Musca domestica* (Joosten et al., 2020; Shishkov et al., 2019). Under optimal conditions (30 °C), a growth cycle of BSFL takes 15 days to gain an average larva weight of 0.25 g although feed safety has not been thoroughly evaluated (Adjavon et al., 2021; Čičková et al., 2015), the larvae grow fast and have an excellent feed conversion rate of about 1.58-8.90

(Broeckx et al., 2021). They consume around 25-500 mg of fresh matter daily and feed on various substrates, from manures to food wastes and left-overs (Diener et al., 2011). Thus reduce the dry matter content dramatically by 65-75% in an open field (Diener, 2010) but generating an additional valuable product, the prepupae. The larvae nutritional value is dependent on the feed substrates they consume. Crude protein levels range from 28 to 48%, and lipid levels from 12 to 42% (Barragan-Fonseca et al., 2017; Liland et al., 2017). They have an amino acid profile similar to fishmeal and can be an excellent source of lipids subject to the feed the larvae are bred on (English et al., 2021; Liland et al., 2017; xi Wang et al., 2017). Apart from being a feed source, the larvae also offer a promising opportunity to develop the collection and treatment of organic waste as a source of income for small entrepreneurs.

Moreover, there is no need for specialized infrastructure to produce BSFL. Initial production costs include constructing dark and comfortable cages for pupae and breeding flies and feeding crates for the larvae. The initial setup costs vary based on the materials and types of substrate that a farmer chooses to use. Once the basic production infrastructure is in place, labour and waste substrate delivery to the farm are significant costs only.

2 Materials and Methods

Data for this study was obtained for the feed ingredients' prices and their nutritional composition was obtained from the standard feed tables (NRC, 2011). In addition, consideration was put for the nutritional requirement for the Nile tilapia at juvenile stage. Before formulating the diets, a database with all the current feed ingredients used in fish feed formulation with their nutritional values was developed. The nutritional composition of the feeds included in the database was compiled from standard feed tables (NRC, 2011) and proximate analyses conducted for fish meal and BSFLM. The nutritional limiting levels for juvenile Nile tilapia used as constraints were obtained from the standard feed tables (NRC, 2011). Tables 1 and 2 illustrate the feed ingredients levels and the restrictions put on the nutritional requirements in formulating feed for the juvenile Nile tilapia. The four formulated feeds substituted with BSFLM were then compared with the control to determine the most cost-effective diet. Eleven ingredients were identified for the feed formulation based on availability and local market prices in Bondo, Siaya county (Table 1). The diets were formulated by substituting fish meal and BSFLM in various percentages (FM 0, BSFLM2 25, BSFLM3 50, BSFLM4 75, and BSFLM5 100%). The least-cost feed was determined using linear programming, based on the price of per kg feed ingredients, the *Oreochromis niloticus* diet's nutrient requirement, and the compounded feed's total weight. Data was analysed using the excel solver linear programming tool. The model considered the cost of ingredients, the nutritional requirements, constraints for each feed and the objectives function as illustrated below.

2.1 The linear programming model

The mathematical model is shown below, where the objective of the model was to minimize the total cost of feed ingredients used to formulate feed.

$$\text{Min } Z = \sum_{i=1}^{r} = 1C_i x_i \quad (1)$$

Subject to:

$\sum_{i=1}^{r} = 1x_i = M$ (Demand requirement)

$\sum_{i=1}^{r} = 1a_{ki}b_k \geq b_k$ (Minimum requirement)

$\sum_{i=1}^{r} = 1a_{ki}x_i \leq b_k$ (Maximum requirement)

$\sum_{i=1}^{r} = 1a_{ki}b_k = b_k$ (Restricted requirement)

where Z is the sum of total cost of feed used in formulating the diets, x_i are the decision variables.

Let k = Ingredients nutrient components, and $k = 1, 2, \ldots, r$; i = Ingredients components, and $i = 1, 2, \ldots, j$; x_i = Ingredients quantities i in the feed mixture; C_i = Ingredient i unit cost; M = Weight (kg) of formulated feed; Z = Total feed ingredients cost; a_{ki} = Quantity of nutrient n in feed ingredient i; b_k = Nutrient requirement n for the fish species; and i_1 to i_{11} denotes black soldier fly larvae meal, maize, soya meal, wheat pollard, wheat bran, sunflower cake, sunflower oil, fish meal, salt, dicalcium phosphate, and vitamin premix, respectively.

2.2 Model formulation

The problem was to determining the quantities of the 11 feed ingredients so that the nutritional requirements of the Nile tilapia are met. Based on this information, a linear programming was formed as follows: (i) total weight of the feed to be formulated = 100 kg; (ii) crude Protein $\geq$ 30 kg; (iii) ash $\geq$ 5 kg; (iv) carbohydrate $\geq$ 36 kg; (v) fibre $\geq$ 9 kg; (vi) lipid $\geq$ 15 kg; and (vii) energy $\geq$ 18 MJ ME/kg.

Minimize Z $= 85x_1 + 50x_2 + 65x_3 + 25x_4 + 25x_5 + 30x_6 + 110x_7 + 200x_8 + 30x_9 + 80x_10 + 250x_11$
Subject to:

Constraint 1:
$0.377x_1 + 0.076x_2 + 0.36x_3 + 0.157x_4 + 0.153x_5 + 0.324x_6 + 0.626x_7 + 0.0135x_8 \geq 30$; (Protein Requirement)

Constraint 2:
$0.326x1 + 0.036x2 + 0.1841x3 + 0.042x4 + 0.033x5 + 0.022x6 + 0.99x7 + 0.095x8 + 0.039x9 \geq 9$; (Lipid Requirement)

Constraint 3:
$0.237x1 + 0.061x2 + 0.208x3 + 0.168x4 + 0.164x5 + 0.194x5 + 0.164x6 + 0.186x6 + 0.158x7 \geq 14$; (Gross energy Requirement)

Constraint 4: $0.008x1 + 0.638x2 + 0.053x4 + 0.312x5 + 0.194x6 + 0.061x7 \geq 36$; (Carbohydrate Requirement)

Constraint 5:
$0.252x1 + 0.107x1 + 0.012x3 + 0.051x4 + 0.039x6 + 0.048x7 + 0.071x8 + 0.0005x9 \geq 5$; (Ash Requirement)

Constraint 6: $0.087x1 + 0.023x2 + 0.056x3 + 0.007x4 + 0.092x6 + 0.279x7 + 0.003x8 \geq 9$; (Fibre Requirement)

Constraint 7: $x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9 + x10 + x11 = 100$; (Demand Requirement)

The objective is to minimize cost of Z, illustrated above, subject to the constraints shown below. Computation by Solver module of MS-excel results.

3 Results and Discussion

Results of the linear programming using an excel solver for the five formulated diets were shown in Table 3 and Table 4 below. The cost of feeds decreased with the increased substitution levels of fishmeal. As the levels of BSFLM increased in the diets, the feed cost per kilogram also reduced further. The control diet (FM) cost KES 71.23 per kg with a crude protein content of 33.23%. By adding 25% of BSFLM2, the price of the fish feed decreased by KES 4.78 per kg while the protein content decreased slightly by 0.91%. By increasing the BSFLM to 50% (BSFLM3) and 75% (BSFLM4), the crude protein content decreased further by 1.82% and 2.72%, respectively, relative to the control.

The most cost-effective diet (KES 52.14 per kg) was formulated using BSFLM at 100% (BSFLM5) (Table 3). The BSFLM5 diet illustrated economic savings of KES 19.09 per kg, representing a 26.8% reduction in fish feed production cost. These findings align with Udo et al. (2011), who found a significant decrease in the cost of catfish fingerling feed using linear programming. In addition, Olorunfemi (2006), managed to reduce feed cost by about 20.82% in formulating a broiler finisher diet using linear programming where nonconventional duckweed used as a protein source. Complete replacement of fishmeal protein with BSFLM contributed significantly towards cutting costs in feed formulation. The finding illustrates the low cost of BSFLM in fish feed production. Since BSFLM can be reared on wastes (Nguyen et al., 2015; Shumo et al., 2019; Hopkins et al., 2021), its cost of production is relatively low; hence helps in lowering feed costs. Its supply can also be guaranteed for feeds when proper management practices are put in place, thus it is sustainable as a protein source for aquaculture. Although in this research, there was a decrease in protein content with an increase in BSFLM meal, the final content remained within the protein content allowable for juvenile Nile tilapia optimal growth-30-35% (FAO, 2021a). The results for the least cost diet substituted completely by BSFLM met all the nutritional requirements for juvenile Nile tilapia. Therefore, farmers are more advantaged when they use the linear programming method in feed formulation as they can easily depict the most cost-effective diet. In addition, using insect-based feeds such as BSFLM significantly reduces the cost of feeds in aquaculture production.

4 Conclusion

Diet substituted completely with black soldier fly larvae (BSFLM5) had a crude protein content of 29.6%, priced at KES 52.1 per kg,while the control (FM) had a crude protein content of 33.23%, costing KES 71.23 per kg. Complete substitution with BSFLM illustrates the economic savings of KES 19.09 per kg, a reduced cost of about 26.8% in a feed that completely replaces fishmeal. However, in-depth research is required to understand the effect of BSFLM on Nile tilapia growth and its cost implication. Farmers can use excel spreadsheets incorporating linear programming to formulate cost-effective diets with the fisheries extension workers' guidance. The optimal feed (BSFM5) illustrated how available ingredients could be used to develop cost-effective diets. Therefore, linear programming using excel solver ad inns will go a long way in formulating the least cost feeds suitable for the aquaculture sector and ensuring the sector's sustainability. The study recommends that formulating diests using linear programming in fish feed formulation and replacing black soldier fly larvae meal with fishmeal will helping in reducing feed costs.Further experiment with the feeds can be carried out to determine the growth performance on fish.

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Table 1. Ingredients composition and market price of feed ingredients

Ingredients	Cost (Ksh/kg)	Protein (%)	Energy (MJ ME/kg)	Carbohydrate (%)	Ash (%)	Fibre (%)	Lipid (%)
BSFLM	85	37.7	23.7	0.8	10.7	8.7	32.6
Maize	50	7.6	16.1	63.8	1.2	2.3	3.6
Soya meal	65	36	20.8	5.3	5.1	5.6	18.4
Wheat pollard	25	15.7	16.8	31.2	3.9	7	4.2
Wheat bran	25	15.3	16.4	19.4	4.8	9.2	3.3
Sunflower cake	30	32.4	19.4	6.1	7.1	27.9	2.2
Fish meal	110	0	16.4	0	0.05	0	99
Sunflower oil	200	62.6	18.6	0	17.8	0	9.5
Salt	30	0	0	0	0	0	0
DCP	80	0	0	0	89.5	0	0
Vitamin premix	250	13.5	15.8	0	5.3	3	3.9
Min		30	14.3	25	5		5
Max		35		40		5	15

BSFLM: Black soldier fly larvae meal, DCP: Dicalcium Phosphate, Min: Minimum inclusion level, Max: Maximum Inclusion level

Table 2. Linear programming matrix in excel solver

Ingredients†	Cost (Ksh/kg)	Protein (%)	Energy (MJ ME/kg)	Carbohydrate (%)	Ash (%)	Fibre (%)	Lipid (%)
BSFLM	85	41.68	23.7	0.8	4.6	8.6	41
Maize	50	7.6	16.1	63.8	1.4	2.5	4.1
Soya meal	65	44.1	19.5	31.9	5.8	4.9	1.9
Wheat pollard	25	15.7	16.8	31.2	3.9	7	4.2
Wheat bran	25	15.3	16.4	19.4	4.8	9.2	3.3
Sunflower cake	30	32.4	19.4	6.1	7.1	27.9	2.2
Fish meal	200	63.5	18.6	0	15.2	0	14.5
Sunflower oil	110	0	16.4	0	0.1	0	99
Salt	30	0	0	0	99.3	0	0
DCP	80	0	0	0	89.5	0	0
Vitamin premix	250	13.5	3.9	0	5.3	3	3.9
Min		30	14	25	5	5	5
Max		35	23	40			15

† 1 kg ingredients; BSFLM: Black soldier fly larvae meal, DCP: Dicalcium Phosphate, Min: Minimum inclusion level, Max: Maximum Inclusion level

Table 3. Inclusion levels of feed ingredients in formulated diets

Ration	FM	$BSFLM_2$	$BSFLM_3$	$BSFLM_4$	$BSFLM_5$
BSFLM	0	4.15	8.3	12.45	16.6
Maize	10	10	10	10	10
Soya meal	33.5	33.5	33.5	33.5	33.5
Wheat bran	14	14	14	14	14
Wheat pollard	20	20	20	20	20
Sunflower cake	5	5	5	5	5
Sunflower oil	0.1	0.1	0.1	0.1	0.1
Fish meal	16.6	12.45	8.3	4.15	0
DCP	0.1	0.1	0.1	0.1	0.1
Salt	0.2	0.2	0.2	0.2	0.2
Vitamin premix	0.5	0.5	0.5	0.5	0.5

BSFLM: Black soldier fly larvae meal, DCP: Dicalcium Phosphate

Table 4. Nutritional composition and cost of the formulated fish pellet diets

Treatment	FM	$BSFLM_2$	$BSFLM_3$	$BSFLM_4$	$BSFLM_5$
Cost of formulated diet (Ksh/kg)	71.23	66.45	61.68	56.91	52.14
Nutrtional composition					
CP (%)	33.23	32.32	31.41	30.51	29.6
EE (%)	4.98	6.08	7.91	8.29	9.39
CF (%)	5.98	6.35	6.71	7.07	7.42
ME/kg/DM	17.95	18.16	18.37	18.59	18.9
Ash (%)	6.72	6.29	5.85	5.41	4.97

DM: Dry matter, CP: Crude protein, EE: ether extracts, CF: crude fibre, ME: Metabolizable energy per kg, DM: dry matter

in the Sustainable Use of Insects as Food and Feed (INSEFOODS).

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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