Evaluation of Growth Performance, Nutrient Utilization, Hematology, and Condition Factor in African Catfish (*Clarias gariepinus*) Fingerlings Fed Black Soldier Fly Maggot Diets

BY

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DEDICATION

I most thankfully dedicate this work to the Almighty God who made this work possible and to him be all the glory.

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CERTIFICATION

I certify that Mr. Patrick Saboleh, ID No. 23403 carried out this research work titled "Evaluation of Growth Performance, Nutrient Utilization, Hematology, and Condition Factor in African Catfish (*Clarias gariepinus*) Fingerlings Fed Black Soldier Fly Maggot Diets″ which shall tender a partial academic fulfilment, has been thoroughly examined and meet the requirement governing the award of master's degree in Aquaculture and Fisheries Management.

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DEFINITION OF KEY TERMINOLOGIES

Aquaculture: The farming of aquatic organisms such as fish, crustaceans, mollusks, and aquatic plants under controlled conditions.

Clarias gariepinus: Commonly known as African catfish, a fast-growing freshwater fish widely cultured in Africa for its economic and nutritional value.

Fish Meal (FM): A high-protein feed ingredient derived from fish, traditionally used in aquaculture diets but often expensive and unsustainable.

Black Soldier Fly (BSF) [*Hermetia illucens*]: An insect species whose larvae are rich in protein and fat, making them suitable for use as a sustainable feed ingredient.

Black Soldier Fly Larvae Meal (BSFLM): A protein-rich feed ingredient obtained from dried and processed BSF larvae, used as a substitute for fish meal in aquafeeds.

Insectarium: A controlled facility designed for breeding and mass production of insects such as BSF for commercial or research purposes.

Food Security: The availability and accessibility of sufficient, safe, and nutritious food for all people always.

INCiTiS-Food Project: INtegrated and Circular Technologies for Sustainable city region FOOD systems in Africa.

LIST OF ABBREVIATIONS AND ACRONYMS

AA	Amino Acid(s)
AFM	Aquaculture and Fisheries Management
BSFLM	Black Soldier fly Larvae Meal
BSF	Black soldier fly, *Hermetia Illicucens*.
BSFL	Black Soldier Fly Larvae
EAA	Essential Amino Acid(s)
FAO	Food & Agriculture Organization of the United Nation
EU	European Union
FM	Fish Meal
FO	Fish Oil
G	Grinding
INCiTiS	Integrated and circular technologies for sustainable city region food system in Africa
IPIFF	International Platform of Insects for Food and Feed
MM	Maggot Meal(s)
NRM	Natural Resources Management
NU	Njala University

ABSTRACT

The high cost and limited availability of conventional fish feed constrain small-scale aquaculture in developing countries such as Sierra Leone. This eight-week study assessed the effects of substituting fishmeal with Black Soldier Fly (BSF, *Hermetia illucens*) meal on growth, feed utilization, water quality, and nutrient retention in *Clarias gariepinus* fingerlings. A total of 165 fingerlings of African catfish (mean weight 7.91g) were distributed into five treatments with fifteen replicates, each containing 11 fingerlings. Five diets were formulated with 0%, 10%, 15%, 20%, and 25% BSF meal inclusion. Water quality remained within optimal limits (pH 7.21–7.44; dissolved oxygen 9.60–9.71 mg/L; ammonia 0.28–0.30 mg/L; nitrite 0.03–0.15 mg/L; temperature 27.32–27.60°C), with no significant differences among treatments. Growth performance improved with BSF inclusion, with the 25% BSF diet yielding the highest weight gain (7.91 g), specific growth rate (0.60%/day), feed intake (490 g), and condition factor (K = 0.97), compared with the control (4.28 g; 0.42%/day; 376.6 g; K = 0.85). Feed conversion ratio (0.6–0.8) and protein efficiency ratio (~0.9) indicated efficient feed utilization, particularly in the higher BSF treatments. Proximate analysis showed that the 25% BSF diet had the highest protein (69.35 ± 3.00%), fat (15.09 ± 1.60%), and nitrogen-free extract (11.01 ± 0.79%), while the 20% BSF diet had the lowest moisture (4.58 ± 0.50%). Mineral retention increased with BSF inclusion: phosphorus, potassium and calcium were highest at 25% BSF, magnesium highest at 0% (control), while sodium remained stable (0.071–0.083%). Hematological results showed that white blood cell (WBC) counts in the control (105.8×10^9/L) were higher than in all treatments. Moderate WBC counts in TR-2, TR-3, and TR-4 indicated stable immune function, whereas very low WBC in TR-1 suggested immunosuppression. Fluctuations observed in TR-5 implied variable immune responses. Baseline lymphocyte counts (98.6, 93.2%) were higher than treatment means but remained dominant

(>60%) in most treatments. Drops in TR-1 and TR-5 indicated mild immunological stress, possibly due to handling. The findings of this study demonstrate that BSF meal is a sustainable, locally available protein alternative that can improve growth, feed efficiency, and nutrient retention in *C. gariepinus*, supporting aquaculture development in Sierra Leone. It is however suggested that future studies should explore higher inclusion levels of BSF meal to establish the optimal substitution rate, while also evaluating its economic viability in comparison with traditional protein sources such as fishmeal and soybean meal.

CHAPTER ONE

1.1 Background

Food security remains one of the most critical global challenges of the 21st century, particularly as the world's population continues to expand rapidly. Ensuring that people have reliable access to sufficient, safe, and nutritious food is essential for maintaining active and healthy lives (Clapp et al., 2022; McCarthy et al., 2018). In recent decades, the scope of food security discussions has broadened beyond the Green Revolution focus on yield increases to include sustainability, biodiversity protection, and socio-economic equity. These concerns are especially pressing in developing countries, where weak economies, fragile infrastructure, and environmental vulnerabilities compound the challenge of meeting nutritional needs. As a result, sustainable food production strategies must integrate environmental protection, efficient biodiversity use, and improved livelihoods across both developed and developing regions (Godfray et al., 2010; Surendra et al., 2016).

A central issue within food security is the availability of protein-rich foods. Proteins are fundamental macronutrients required for growth, health, and the development of both humans and livestock. Demand for animal proteins has been steadily rising due to urbanization, population growth, and improved incomes (Kearney, 2010; Merino et al., 2012). Among animal proteins, fish plays a particularly significant role, serving as a primary dietary source for billions worldwide. Since the 1960s, per capita fish consumption has nearly doubled, increasing from 9.9 kg annually to 18.4 kg by 2009 (FAO, 2012). Initially, capture fisheries were able to sustain this demand, but by the late 1970s, many fish stocks became overexploited or fully depleted (Arnason et al., 2008).

This decline in wild catch placed increasing pressure on aquaculture to fill the growing demand gap (Naylor et al., 2021).

In West Africa, and particularly Sierra Leone, aquaculture has gained recognition as a means of addressing food and nutrition insecurity. Fish constitutes a major source of protein in Sierra Leonean diets yet capture fisheries alone cannot satisfy national demand. Aquaculture, therefore, has emerged as a promising alternative for bridging the gap between supply and consumption (FAO, 2020). However, despite its potential, aquaculture development in Sierra Leone faces several challenges, such as limited access to affordable fish feed, poor seed quality, inadequate technical expertise, and high production costs (Aloo et al., 2017; Awuor et al., 2019; Nyonje et al., 2018). Feed production remains the most critical bottleneck since it accounts for about 60–70% of total aquaculture operating costs (van Huis, 2013). Heavy reliance on fishmeal, an expensive and increasingly scarce feed component, further undermines the profitability and sustainability of aquaculture systems (Tran et al., 2022).

The reliance on fishmeal is a global concern, not just a local one. Fishmeal remains widely used in aquafeeds because of its high protein levels, digestibility, and favorable amino acid profile (Daniel et al., 2018). Yet, growing competition for fishmeal in livestock and aquaculture sectors has driven prices upward while supplies remain unstable (Onsongo et al., 2018). In Sierra Leone, where aquaculture enterprises are mostly small- or medium-scale, these high feed costs present a significant barrier to growth (Olapade & Saboleh, 2022). To sustain aquaculture and reduce dependency on fishmeal, researchers have increasingly focused on identifying alternative protein sources that are cost-effective, locally available, and nutritionally sufficient.

One of the most promising alternatives is insect-based protein, particularly from the black soldier fly (*Hermetia illucens*). Insects offer nutritional qualities comparable to animal proteins, with high protein and lipid contents, and can be produced at scale using organic waste streams (Sheppard, 2002; Ogunji et al., 2006; Teguia et al., 2002). The larvae of the black soldier fly (BSFL) are of special interest because of their ability to efficiently convert agricultural by-products, food scraps, and animal manure into biomass rich in protein (~40% dry matter) and lipids (~30% dry matter) (Diener et al., 2009; Oonincx et al., 2015). This process not only produces sustainable feed ingredients but also addresses waste management and environmental concerns.

Several studies have demonstrated the effectiveness of BSFL meal as a fishmeal substitute. Research shows that BSFL can replace up to 50% of fishmeal in diets for species such as Atlantic salmon, Nile tilapia, and rainbow trout without negatively affecting growth or feed conversion (Belghit et al., 2019; Fisher et al., 2020; Tippayadara et al., 2021). In addition to its nutritional value, BSFL aligns with circular economy principles, as it valorizes waste streams while contributing to sustainable food systems (Hopkins et al., 2021; Lalander et al., 2019).

Despite these advantages, several obstacles hinder the widespread adoption of insect proteins in aquaculture. The high cost of production compared to conventional ingredients like soybean meal and fishmeal remains a major challenge, particularly in regions lacking infrastructure for large-scale insect farming (Koeleman, 2014). Furthermore, there are gaps in knowledge regarding species-specific inclusion levels, long-term health effects on fish, and consumer acceptance of fish reared on insect-based diets (Naylor et al., 2021).

However, the growing global demand for protein and the rising costs of fishmeal make it necessary to explore sustainable feed alternatives. In Sierra Leone, where aquaculture is still in its developmental stage, reliance on imported and expensive fishmeal limits its expansion. Black soldier fly larvae present a viable solution due to their high nutritional value, environmental benefits, and ability to reduce feed costs. However, further local research is required to evaluate their effectiveness under Sierra Leonean conditions, particularly in commonly farmed species such as *Clarias gariepinus*. This study therefore investigates the incorporation of BSFL meal into the diet of *C. gariepinus* juveniles, focusing on growth performance, feed efficiency, and overall condition factor.

1.2 Problem Statement

The global population is expanding at an unprecedented rate, exerting immense pressure on food systems to supply adequate and nutritious diets. By 2050, the demand for animal-based protein sources such as fish, meat, and milk is expected to rise between 58% and 70% compared to 2020 levels (Jennings et al., 2016). Of these, fish consumption is projected to increase more sharply than meat products due to its affordability, high nutritional value, and growing consumer preference (Barrett, 2021; Kwasek, 2013). Fish is considered a vital food commodity, providing easily digestible protein, essential fatty acids, vitamins, and minerals crucial for human growth and overall health (Béné et al., 2015). Yet, the global capacity to meet this demand is constrained as wild fish stocks have reached their maximum sustainable yield or are in decline. This has placed aquaculture at the forefront of efforts to close the widening gap between supply and demand.

Aquaculture has emerged as the fastest-growing food production sector globally and, by 2022, it overtook capture fisheries as the leading source of fish for direct human consumption (FAO, 2024). This growth illustrates its potential to strengthen food security. However, the sector faces a critical challenge sustainable feed supply. Feed accounts for approximately 60% of aquaculture production costs, and fishmeal remains a major protein source because of its high protein content, balanced amino acid profile, digestibility, and palatability (Daniel et al., 2018). Fishmeal production depends largely on wild-caught small pelagic fish, with global annual production estimated at 20 million tonnes (Tacon & Metian, 2015). This reliance not only exacerbates pressure on marine ecosystems but also competes with human consumption of fish, particularly in regions where such species form dietary staples.

The economic and environmental implications of this dependence are significant. Fishmeal supply is highly unstable, with erratic price fluctuations that threaten farmer profitability and sector growth (Roques et al., 2020). In sub-Saharan Africa, the challenge is further magnified by high taxation on imported inputs, lack of local feed production infrastructure, limited technical expertise, and restricted access to affordable quality feed (Opiyo et al., 2018; Koroma et al., 2019). Sierra Leone provides a clear example: fish is the most important source of animal protein, accounting for over 60% of dietary protein intake, yet aquaculture development is minimal, and the nation remains heavily reliant on capture fisheries (Koroma et al., 2019). Without viable, sustainable alternatives to fishmeal, the expansion of aquaculture in such regions will remain stifled, limiting progress toward achieving food security.

Consequently, global attention has turned toward identifying alternative protein sources for aquafeeds that are cost-effective, sustainable, and nutritionally competitive. Among the options, insects—particularly black soldier fly larvae (*Hermetia illucens*)—have shown great promise. BSFL is rich in protein, essential amino acids, and lipids, and it can be reared on organic waste, thereby supporting circular economy principles, and reducing environmental burdens (Sánchez-Muros et al., 2016). Additionally, insect farming offers socioeconomic benefits by creating employment, reducing reliance on imports, and enabling localized feed production (Makkar et al., 2014).

Despite these advantages, large-scale adoption of insect-based meals is hindered by several constraints. Production costs remain relatively high compared to soybean meal and fishmeal (Koeleman, 2014). Furthermore, challenges such as inadequate infrastructure, limited research capacity, financing constraints, and absence of comprehensive regulations hinder commercialization, particularly in developing nations (van Huis, 2013). Safety and quality assurance also remain concerns, with risks linked to waste substrates, product hygiene, and occupational hazards in composting facilities (Liu et al., 2022).

The central problem, therefore, lies in the aquaculture sector's unsustainable dependence on fishmeal and the limited availability of scalable, cost-effective alternatives. While insect proteins, particularly black soldier fly larvae, present a promising substitute, their integration into aquafeeds requires further scientific validation, economic assessment, and policy support to ensure sustainability. For countries like Sierra Leone, where aquaculture could significantly contribute to food security, it is essential to explore BSFL and other insect proteins as substitutes for fishmeal. Failure to address these challenges will constrain aquaculture's potential to supply affordable fish, thereby limiting progress in combating malnutrition and meeting the growing protein needs of the global population.

1.3. Justification

Food insecurity, malnutrition, and hidden hunger remain pressing global issues, particularly in developing countries such as Sierra Leone, where the population heavily depends on fish as a primary source of protein (McNeill, Pauly, & Zeller, 2017). The imbalance between food demand and supply in the region highlights the limitations of current agricultural systems and the need for innovative strategies in food production. Studies indicate that projected improvements in crop yields alone will not meet global protein demand by 2050 (Bajželj et al., 2014). Consequently, expanding animal production, especially aquaculture, is essential to bridge the protein gap while contributing to food security and household nutrition.

Aquaculture has emerged as one of the fastest-growing food production sectors worldwide, providing a significant source of affordable, high-quality protein (Tobor, 1996). Farmed fish benefit households both nutritionally and economically, as they can be consumed directly and sold to generate income, thereby enhancing purchasing power (Ahmed & Lorica, 2002; Dey et al., 2006; Jahan, Ahmed, & Belton, 2009). In Sierra Leone, fish contributes over 60% of dietary protein intake, yet the aquaculture sector remains underdeveloped, with limited production capacity and reliance on capture fisheries. For aquaculture to remain sustainable, profitable, and environmentally responsible, it is critical to identify alternative protein sources that meet nutritional requirements, including essential amino acids, fatty acids, and phospholipids, while reducing dependence on costly and unsustainable fishmeal.

Feed costs are the largest component of aquaculture production, accounting for 60–80% of total expenses in Africa (Orire & Sadiku, 2014; Adekunle, Oladunjoye, & Ojebiyi, 2012). Despite decades of research, fishmeal remains the primary protein source in aquafeeds, limiting the growth potential of the sector due to its high cost, limited supply, and environmental implications (Olsen & Hasan, 2012; Daniel, 2018). The reliance on fishmeal also exerts pressure on wild fish stocks, which are already fully exploited or declining, and contributes to volatile market prices that affect farmer profitability. Therefore, the identification of sustainable, affordable, and nutritionally adequate alternatives to fishmeal is a critical challenge for aquaculture development in Sierra Leone and other developing countries.

Insects, particularly the black soldier fly (*Hermetia illucens*), have recently gained attention as an alternative protein source for aquafeeds due to their high protein content, favorable amino acid profile, and essential fatty acids (Matteo, Gasco, & Fuso, 2020). Black soldier fly larvae meal (BSFLM) has been successfully incorporated into the diets of various fish species, including rainbow trout (*Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*), tilapia species (*Oreochromis aureus*), and yellow catfish (*Pelteobagrus fulvidraco*), without compromising growth performance or feed efficiency (Kroeckel et al., 2012; Xiao et al., 2018). Additionally, BSFLM has been used in ornamental fish culture, where it can replace 25–50% of fishmeal in diets for species such as guppies (*Poecilia reticulata*) (Sanjaya, Widjaja, & Prakoso, 2020).

Beyond their nutritional value, black soldier fly larvae offer environmental benefits. They convert organic waste into valuable products, producing larval biomass suitable for animal feed and frass, a nutrient-rich by-product that can be used as organic fertilizer (Čičková et al., 2015; Lu, Yang, & Luo, 2022; Lopes, Lalander, Vidotti, & Vinnerås, 2022). This dual use contributes to circular economy principles, reduces environmental pollution, and provides an additional revenue stream for farmers. Furthermore, BSFL has a superior amino acid profile compared to conventional plant-based proteins, such as soybean meal, making it a nutritionally attractive replacement for fishmeal (Tran, Heuzé, & Makkar, 2015).

The adoption of BSFLM in aquaculture also presents socio-economic opportunities. In Africa, several start-up companies have emerged to produce BSF larvae on a small scale, supplying local aquafeed manufacturers and creating employment opportunities (Rumbos, Karapanagiotidis, & Athanassiou, 2021). Despite these advancements, large-scale production remains limited due to technical, financial, and regulatory challenges, as well as the need for cost-effective mass-rearing systems (Rehman et al., 2021). Addressing these barriers is essential to fully realize the potential of BSFL as a sustainable feed alternative that can support aquaculture expansion and contribute to food security in Sierra Leone.

Given the nutritional, economic, and environmental advantages of BSFLM, this study is justified as it seeks to evaluate the feasibility of using BSFL as an alternative protein source for African catfish (*Clarias gariepinus*) fingerlings in Sierra Leone. If successfully implemented, BSFLM can reduce dependency on fishmeal, lower production costs, increase aquaculture productivity, and promote sustainable and environmentally friendly practices. Ultimately, integrating BSFL into nutrition, and income generation.

1.3. Aim and objectives

1.3.1 Aim

The aim of this study is to investigate the effect of using black soldier fly maggot meal as alternative protein ingredient to produce fish feed for *Clarias gariepinus* (Burchell 1822) juvenile in Sierra Leone.

1.3.2. Objectives

i. Evaluate the growth response and nutrient utilization of *C. gariepinus fingerlings* fed diet containing BSF maggot meal.

ii. Evaluate the water quality parameters of the culture water and condition factor of the experimental fish.

iii. Evaluate the hematological parameters of the experimental fish before and after the experiment.

iv. Evaluate the weight-length relationship and condition factor of the experimental fish as a means of ascertaining the water and nutritional quality of the experimental diets.

1.5. Research Questions

i. What is the growth response and nutrient utilization of *C. gariepinus fingerlings* fed diet containing BSF maggot meal?

ii. What are the water quality parameters of the culture water and condition factor of the experimental fish?

iii. How does the weight and length of fish as a means of ascertaining the nutritional quality of the experimental diets.

iv. What is the optimal inclusion level of BSF meal in the developed experimental diets?

1.6. Significance of the Study

This study is considerably significant as it aim to promote the sustainable aquaculture growth and hence a sector that holds the potential to contribute greatly to food security job creation in Sierra Leone. The findings would also help to showcase that research has the potential to minimize the issue of dependency on the use of fish meal in feed formulation.

1.7. Scope of the Study

The study was carried out to examine the effect on utilization of black soldier fly larvae meal as a substitute for fishmeal in the diets of African catfish (*Clarias gariepinus*) fingerlings. It further evaluates growth response, feed utilization, water quality parameters, and fish condition factors under controlled experimental conditions. The findings are expected to provide baseline data for scaling up BSFL use in aquaculture in Sierra Leone.

1.8 Limitations

Limitation takes account of unavailability of sufficient quantities of substrates for trapping wild black soldier fly eggs from the wild. Lack of modern laboratory equipment to analyze some major parameters such as proximate composition of the experimental fish and hematological analyses.

1.9 Research hypothesis

H_{01}: Inclusion of Black Soldier Fly (BSF) maggot meal in diets has no significant effect on the growth performance and nutrient utilization of *Clarias gariepinus* fingerlings.

H_{02}: Water quality parameters and condition factor of *C. gariepinus* are not significantly affected by diets containing BSF maggot meal.

H_{03}: Hematological parameters of *C. gariepinus* show no significant differences before and after feeding with BSF-based diets.

H_{04}: The weight–length relationship and condition factor of *C. gariepinus* are not significantly influenced by BSF-based diets or culture water conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Nutritional Needs of Fish

A healthy diet must include sufficient protein containing all essential amino acids, lipid with essential fatty acids (EPA/DHA), vitamins and minerals (HLPE, 2014). Quality feed after being made must contain 20-70% protein, 15% carbohydrates, 10% fat, and 5% vitamins, water, and minerals (Murtidjo, 2001). Generally, nutrition forms 70% of the total cost of animal production thus making feed efficiency an important parameter for a successful business (Craig et al*.,* 2017). Since fish feeds generally represent the largest single cost items of most fish farm operations, it follows that the selection of meal ingredients for use within diets will play a major role in dictating its ultimate nutritional and economic success (Ovie and Eze, 2013). Glencross et al. (2020) cited by Hoerterer et al (2021) posited that the challenge of feeding farmed fish with diets that are nutritious but at the same time economically and environmentally sustainable is a major issue to ponder. Fish feed is said to be of good quality if after being processed and made, has the appropriate shape and texture for buoyancy and good density for durability (Mujiman**,** 2000), and contains nutritional values needed by fish.

In aquaculture, good nutrition enhances the economic production of a healthy, high-quality product with high survival rate, growth, development of gonads and successful breeding protocols. Growth performance and nutrient utilization of fish is determined by gross composition of the feed ingredients, processing, and storage of the feed products. The development of new species-specific feed formulations supports the aquaculture industry as it expands to satisfy an increasing demand for affordable, safe, high-quality fish and seafood products. To achieve and establish high growth rates in fishes, it is not only necessary to have protein rich feed mixtures, but the perfect ratio of all the dietary amino acids is obligatory (Li et al., 2009).

In order to formulate and compound aquafeeds that will meet the nutrient requirements of the catfish at affordable cost, several conventional and non-conventional animal by-products and plant residues have been tested to substitute or replace fishmeal. The growing intensification in the commercial culture of *Clarias gariepinus* and its various hybrids has resulted in the need to use formulated pelleted diets. The development of a balanced diet for the *Clarias* catfish will become increasingly important and much research is currently being conducted on the specific nutrient requirements of *C. gariepinus* (Van Weerd, 1995; Ng, 2002). The development of new species-specific feed formulations supports the aquaculture industry as it expands to satisfy an increasing demand for affordable, safe, high-quality fish and seafood products. To achieve and establish high growth rates in fishes, it is not only necessary to have protein rich feed mixtures, but the perfect ratio of all the dietary amino acids is obligatory (Li et al., 2009).

Since the protein found in BSF larvae is straightforward to digest, it is highly appropriate to use as a substitute for fish feed. The coefficient of digestibility of crude protein, dry matter, and energy in the BSF larvae diet was studied to be remarkably higher than those in the fish flour (Muin & Taufek, 2022). A combination of BSF larvae flour and fish meal has been demonstrated to significantly affect the increase of weight in laying quail rations (Mawaddah et al., 2018; Pandra, 2021). BSF larvae are helpful as a fish feed mixture in addition to being used as animal feed (pellets). A study found that using BSF larvae as pellets can fulfill the nutritional requirements of catfish fish and can maintain the ammonia levels; thus, water quality can be preserved (Irfan & Manan, 2013).

2.2 Protein in Fish Diets

Protein is the most expensive macronutrient in fish feed and when dietary requirements are exceeded, it is used for energy rather than for growth (Stone, 2003). It is important therefore to target the protein requirements to efficiently utilize protein for growth whilst limiting nitrogen discharge. The dietary protein requirements of most fish species range from 24 – 62% on a DM basis and depend on the fish size, water temperature, dietary composition, protein digestibility, and fish feeding preferences as well as the amino acid profile (Wilson, 2003; Oliva-Teles *et al.*, 2020). Inappropriate ratios of dietary protein and energy can lead to poorer fish performance, increased lipid and glycogen accumulation in somatic tissues and the liver, heightened nitrogenous waste output, and greater production costs. Excessive dietary protein, when not matched with adequate energy, can hinder growth due to the metabolic demands associated with nitrogen excretion (Ahmad et al., 2012). Deficiency in protein can result in stunted growth and poor tissue development and while an excess of protein can lead to increased nitrogenous waste excretion, which may result in significant economic losses. The levels of dietary protein and energy doesn't only affect growth and body composition but also influence the activity of digestive enzymes and plasma metabolites in various fish species (Yamamoto et al., 2006).

In aquaculture, protein requirements vary across species, typically ranging from 18–20% for marine shrimp, 28–32% for catfish, 32–38% for tilapia, and 25–30% for Indian major carps under optimal pond conditions. In aquaculture, particularly when producing feed for catfish fingerlings, the quality of protein sources is vital to meet their nutritional requirements. Catfish require a sufficient food supply that is well proportioned and nutritionally balanced to support growth, energy, reproduction, movement, and other activities (Umaru et al., 2016). The formulation of fish feed for catfish fingerlings is particularly important, as this input accounts for 40-50% of production costs (Steven and Louis, 2009). Since African catfish have a high protein demand in their feed, it is imperative to determine the optimal protein levels in their diet while incorporating low-cost, locally available feed ingredients.

Insects serve as a valuable alternative protein source, with levels comparable to fish meal. For instance, insect meals derived from *Boopedon flaviventris* (76.0%), *Melanoplus mexicanus* (77.1%), and *Sphenarium histrio* (74.8%) contain notably high protein concentrations. Among the various options, the black soldier fly (*Hermetia illucens*) is one of the most extensively researched for use in animal nutrition. Its protein content ranges from 29.7% to 63.1% on a dry matter basis, depending on factors such as developmental stage, rearing substrate, and the method used for protein measurement.

2.3 Importance of Amino Acids

Basically, amino acids play a critical role in the organism as they perform important metabolic functions, regulating processes such as digestion, nutrient transport, and the production of enzymes and hormones. Amino acids are also very essential in maintaining immune system of animals in general. In fish farming, amino acids (AAs) are essential nutrients that play a critical role in fish nutrition and are therefore considered when selecting feed ingredients. They are fundamental for supporting the growth and development of fish udder culture thereby enhancing reproductive performance and strengthening disease resistance in aquatic species (Andersen et al., 2016; Musyoka et al., 2019). Ten amino acids including arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine are classified as essential in fish nutrition. Among these, methionine, lysine, and arginine are the most extensively studied in relation to fish growth requirements. It chiefly is one of the ten essential amino acids that can be used as a reference amino acid, there are several reasons to choose lysine as a reference amino acid. First, a major function of lysine in the animal body is the deposition of protein tissues since its requirements are not affected by the metabolic roles. Second, depending on the fish species and the type of feedstock, lysine usually has a major role in limiting amino acids because it is known that the need for lysine is much greater than for other amino acids (Miles & Chapman 2007).

Fish meal is being successfully substituted with other plant protein sources in fish feed, and there is some concern that current assessments of essential amino acid requirements are an unsatisfactory target, and some AAs may turn into a limiting factor and thus need to be supplemented in species feed important fishes (LIU, 2017). Some amino acids are added to fish diets if they are not available in the natural sources of the diet in the required quantity for the body, and the body does not originally form other acids. Among these additions are methionine and lysine (the amino acid glycine may be added to detoxify the benzoic acid in poultry) (Nang Thu et al., 2009). Also, some insect's particularly the black soldier fly larval meal is a suitable ingredient in fish diets, because of its high contents of amino acids and calcium, and its good palatability. Regarding essential and limiting amino acids (AAs), species within the order *Diptera* exhibit the closest similarity to fish meal.

2.4 Fats and Oils in Fish Nutrition

Fats and oils are concentrated energy sources that play a vital role in fish growth, reproduction, and immune function. They supply essential fatty acids (EFAs), particularly omega-3 and omega-6, which cannot be synthesized by fish and must be obtained from the diet. Lipids also improve feed palatability and support the absorption of fat-soluble vitamins (A, D, E, and K). In aquaculture, they typically make up about 7–15% of fish diets**,** serving as an economical energy source that spares dietary protein for growth (Hasan, 2001). For catfish, Wilson (2000) recommended dietary lipid levels of 5–6%, since excessive fat may lead to fatty liver or unwanted fat deposition in tissues.

An emerging alternative source of dietary lipids is insect fat. Insects can accumulate valuable fatty acids based on their diets, making them a sustainable option for aquafeeds. Unlike most insect oils, which are liquid at room temperature, black soldier fly (BSF) fat remains solid. Insect oils are generally rich in unsaturated fatty acids, sometimes accounting for up to 60% of total fatty acids (Sosa & Fogliano, 2017). Beyond lipids, insect meals contain 42–63% crude protein, comparable to soybean meal and slightly lower than fishmeal (Manzano-Agugliaro et al., 2012). Studies have shown that partially replacing fishmeal with insect meal (10–50%) can enhance fish muscle fat content without negatively affecting fatty acid profiles, aroma, or consumer-perceived taste (St-Hilaire et al., 2007; Makkar et al., 2014). Thus, balanced lipid inclusion, whether from conventional oils or insect-derived sources, is critical to optimizing fish growth, feed efficiency, and product quality.

2.5 Carbohydrates as Energy Source

Carbohydrates are in a group of compounds that include sugars, starches, celluloses, and other closely related substances among the most abundant organic compounds found in nature. They are the primary energy form stored in seeds, roots, and tubers, making up 60% to 70% of the dry weight of most grains. Carbohydrate is an economical source of energy for fish. They are the least expensive sources of energy for fish diets. It helps to reduce the feed cost. Utilization of carbohydrates as an energy source varies with different species. Fats and proteins supply most of the energy in fish diets (Parker, 2011). Dietary carbohydrates are not essential for fish as they can convert lipids and proteins into glucose by gluconeogenesis. Nevertheless, carbohydrates are commonly included in fish feed as an energy source due to their low price and worldwide availability. Moreover, carbohydrates can improve pellet binding, floating, and stability. In nature, carbohydrate intake by most fish species is limited to chitin found in, amongst others, algae, crustaceans, and insects (Kaushik *et al.*, 2022).

Carbohydrates improve growth and provide precursors for some amino acids and nucleic acids.

There is actually no dietary requirement for carbohydrate for catfish because they, as other animals, are capable of synthesizing carbohydrates from lipids and proteins. A typical catfish feed contains 35–40% or more digestible carbohydrates, plus an additional 3–7% crude fiber. The fact that catfish can utilize carbohydrate relatively well is fortunate, not only because it is an inexpensive energy source, but also because starch is necessary to make a floating feed. Also, fats and oils, which are the most concentrated and most highly digestible energy sources for catfish, must be used sparingly because high levels can be detrimental to fish growth and product quality. Therefore, the predominant energy source in commercial catfish feeds is from carbohydrates contained in grains (primarily corn) and grain milling by-products. The presence of carbohydrates in insects has received little attention in the literature. In general, insects have modest amounts of carbohydrates (Finke, 2002).

2.6 Minerals in Fish Diets

Minerals are inorganic elements that are necessary for the fish to function. Maintenance of cells, immune system, and bones, all require minerals. Minerals are required in trace amounts for normal growth, reproduction, health, and general metabolism. Deficiency symptoms usually occur in intensive system where natural food is not sufficient. They are classified either as macro elements, which are needed by the body in large quantities, or micro elements, needed by the body in small quantities (FAO 2017; Thompson et al. 2005); though the requirements of trace elements by fish is not clear yet. Basically, the trace elements are required for skeletal growth, cellular respiration, oxygen transport, immune function, and regulation of acid–base equilibrium, they are also important components of hormones, enzymes, and enzyme activators. Key minerals needed by fish are calcium and phosphorus. Small traces of sodium, magnesium, iron, iodine, chloride, copper, potassium, sulfur, and zinc are also needed.

Fish have unique physiologic mechanisms to absorb and retain minerals from their diets and from the surrounding water (Lall SP 2002). BSF larvae contain higher mineral concentrations compared to other insects used in managed feeding programmers (Di**ere**nfeld and King, 2009). Manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), phosphorus (P) and calcium (Ca) are found in high concentrations, which are very essential for fish growth. (Makkar *et al.*, 2014). Sodium (Na) occurs in a lower concentration compared to the levels in other insects (Arango Gutierrez, 2005; Dierenfeld and King, 2009). Previous studies have reported higher values of various minerals in black soldier fly larvae as compared to other insects like crickets (*Acheta domesticus*) and mealworm (*Tenebrio molitor*) that are utilized in fish feed formulation (Finke, 2013). Similarly, the mineral content in the BSF larvae is mainly influenced by the type of substrates (Fasakin et al., 2003).

2.7 Role of Vitamins in Fish Growth

Vitamins, though required in small quantities, are essential for growth, immunity, reproduction, and metabolism. Water-soluble vitamins, such as vitamin C and the B-complex group, function mainly as coenzymes in energy metabolism. Fat-soluble vitamins (A, D, E, and K) play critical roles in vision, bone formation, antioxidant defense, and overall health. Deficiencies can result in poor survival, weakened immunity, and developmental abnormalities (Halver & Hardy, 2002; NRC, 2011).

Vitamins are structurally diverse organic compounds that support normal growth and reproduction. In catfish, deficiency symptoms can be induced experimentally under controlled laboratory conditions when purified diets lack specific vitamins. However, such deficiencies are rarely seen in natural fish populations or cultured catfish, since vitamins are available from natural food sources, and some can be synthesized in the intestine. Commercial fish feeds also include inherent vitamins from plant and animal ingredients.

Insects have been identified as an additional vitamin source, with several species containing B vitamins such as biotin, pyridoxine, riboflavin, pantothenic acid, folate, niacin, and B12 (cobalamin) (Nowak et al., 2014; Rumpold & Schlüter, 2013; Schabel, 2010). Notably, both fish and humans are among the few higher animals that require an external dietary source of vitamin C (Halver, 1985).

2.8 Hematological studies in Aquaculture Management

Hematological studies, long established in human and livestock health assessments, are increasingly recognized as essential tools in aquaculture. According to Akinrotimi et al. (2007), fish hematology can be applied to evaluate feed quality, monitor fish health, detect toxic effects, and diagnose diseases. Despite this potential, baseline hematological data for many fish species remain limited, and where available, values often vary due to methodological differences and lack of standardization (Fazio et al., 2019). Hematological and biochemical analyses provide reliable insights into the physiological and pathological condition of fish, complementing morphological or biometric parameters that may not fully capture internal changes (Adakole, 2012; Tavares-Dias & Moraes, 2007). Blood parameters are therefore considered sensitive indicators of overall fish health (Docan et al., 2011a).

These parameters are particularly valuable in assessing stress responses, where elevated cortisol and blood glucose levels are typically observed alongside reductions in red blood cell counts, hemoglobin, and hematocrit values, with a corresponding rise in white blood cell counts (Atmadi et al., 2016; Barton et al., 2002). Such alterations serve as practical markers of stress in cultured fish. Environmental fluctuations, including changes in water quality, stocking density, or handling, act as major stressors influencing metabolism, immunity, growth, reproduction, and survival (Roche et al., 2003; Barton et al., 2002). Aquaculture practices themselves can significantly affect hematological indices, with hemoglobin levels and red blood cell counts varying under high stocking densities (Docan et al., 2011a; Docan et al., 2011b). Overall, hematological parameters represent powerful diagnostic and management tools, allowing aquaculture practitioners to monitor fish health, evaluate culture conditions, and promote sustainable aquaculture practices.

2.9 Cost Benefit Analysis in Fish Farming

In fish nutrition, cost–benefit analysis plays a critical role in determining the profitability of different dietary formulations by comparing the relative economic advantages of key nutritional variables. Such evaluations provide insights into how feed choices impact overall production costs and returns, guiding farmers, and researchers in optimizing aquaculture practices. One of the most promising innovations in this regard is the incorporation of Black Soldier Fly (BSF) larvae meal. The rearing of BSF larvae offers substantial economic advantages, as it transforms low-value organic waste into high-value protein and mineral sources at comparatively low production costs (Spranghers et al., 2017; Diener et al., 2010).

The primary financial benefits are derived from two main aspects: first, the potential reduction in reliance on expensive fishmeal, and second, the environmental and economic gains associated with converting organic waste into nutritionally rich insect biomass (Barry, 2004; Amatya, 2008; Alvarez, 2012). This dual advantage not only improves farm profitability but also supports environmental sustainability by reducing waste disposal challenges. The efficiency of BSF in waste valorization, coupled with its high protein yield, makes it a cost-effective and sustainable alternative protein source for aquaculture. In this study, cost estimation of formulated feeds was carried out based on ingredient inclusion levels in the overall diet mix, enabling an assessment of the economic feasibility of BSF meal as a partial or complete substitute for fishmeal.

2.10 Insect Proteins as Alternatives to Fishmeal

In the past decade, aquaculture has attracted significant private investment, often surpassing interest in other agricultural sectors. Considerable research has therefore focused on enhancing the profitability of African catfish farming and other cultured species to justify these investments (Nath, 1995). Since the early 2000s, aquaculture development has accelerated, largely due to its potential to alleviate malnutrition, strengthen food security, and reduce unemployment (Cai et al., 2017). Leading aquaculture producers in Africa include Egypt, Nigeria, Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi, and South Africa (Satia, 2011; Satia, 2017), while Sierra Leone has also promoted aquaculture to address current and future food production challenges. The growth of aquaculture in these countries has been driven by improved capacity building, supportive governance, access to credit, research initiatives, and active private-sector engagement

(Satia, 2017). Private investments have encouraged better management practices, innovative production systems, advanced feed formulations, and the establishment of dynamic producer associations (Satia, 2011). Despite this progress, many African aquaculture producers still face challenges in achieving sustainable expansion (Soliman & Yacout, 2016).

A major limitation to aquaculture growth is the instability of fishmeal (FM) supply. Global FM production is constrained by declining sustainable fish catches, environmental variability, fuel costs, and reduced quotas. For example, fishmeal supply in 2023 was 23% lower compared to 2022 (IFFO, 2024). This scarcity, combined with rising prices, has increased interest in alternative feed ingredients (Oliva-Teles et al., 2015; Hardy, 2010). Insects have recently emerged as a promising substitute for fishmeal in aquaculture feeds (Stamer, 2015). Insect farming provides a sustainable option for protein production and could help meet global food security demands. Among various insect species, the Black Soldier Fly (BSF; *Hermetia illucens*) has attracted particular attention as an innovative and eco-friendly feed ingredient. The BSF industry is rapidly expanding, with an estimated 200–300 billion individuals reared annually (Rowe, 2020). Compared to fishmeal, BSF larvae are more cost-effective, and their inclusion in diets has been shown to enhance fish growth, including ornamental species such as bettas (*Betta splendens*) (Irfan & Manan, 2013) and food fish like tilapia (*Oreochromis niloticus*) (Muin & Taufek, 2022). Importantly, the nutritional profile of BSF-based feeds is comparable to conventional fishmeal diets, making them a viable replacement strategy for sustainable aquaculture.

The Food and Agriculture Organization (FAO) has recognized insect farming as a viable approach to meeting rising demand for sustainable animal protein (van Huis et al., 2013). In addition to BSF, other insects under consideration include yellow mealworms (*Tenebrio molitor*), lesser mealworms (*Alphitobius diaperinus*), silkworms (*Bombyx mori*), locusts (*Locusta migratoria*, *Schistocerca gregaria*), crickets (*Acheta domesticus*, *Gryllodes sigillatus*, *Gryllus assimilis*), and houseflies (*Musca domestica*). Large-scale production efforts are already underway for BSF and mealworms, both recognized for their efficiency in recycling waste into valuable feed ingredients (van Huis, 2020). As aquaculture continues to expand, the demand for alternative feed sources will rise further. Reducing dependence on fishmeal has become a priority, particularly in West Africa, where many small-scale farmers are experimenting with farm-made feed pellets that substitute fishmeal with insect protein, especially BSF (Gabriel et al., 2007).

2.11 The Black Soldier Fly (*Hermetia illucens*)

The black soldier fly (*Hermetia illucens*) (BSF), a tropical fly originally from the American continent (Fachin et al. 2021), lays its eggs in the vicinity of decomposing organic material to provide feed for the larvae when they hatch (Lemke et al. 2022). It belongs to the order Diptera and is native to South America, though it is now widely distributed in tropical and temperate regions due to its high adaptability (Giunti et al., 2018). Unlike pest flies, BSF adults are harmless as they neither feed on human food nor transmit diseases. The BSF life cycle is strongly influence matting. Studies indicate that bright, natural sunlight or artificial light simulating natural spectra is essential for courtship and copulation (Tomberlin & Sheppard, 2002). The black soldier fly has a life cycle consisting of five main stages: egg, larva, prepupal, pupal and fly (Purkayastha & Sarkar 2022). Mating typically occurs in flight, with males defending territories through lekking behavior and aerial displays (Giunti et al., 2018).

Once mating has occurred, females deposit eggs within 2–4 days in protected cavities near organic matter, continuing the cycle. Each female lays 400–800 eggs in dry, sheltered cracks or cavities near decomposing material, but never directly on moist substrates, ensuring protection against predators and desiccation (Diclaro & Kaufman, 2009). Eggs hatch in about 4–5 days, after which the female dies (ESR International, 2008). Upon hatching, larvae feed intensively on organic matter and bury themselves in the substrate. Moisture content strongly influences their growth and survival: although BSF larvae can tolerate a wide range (10–97.5%), optimal development occurs between 60–80% (Fatchurochim et al., 1989; Lalander et al., 2020). Their importance lies in their larvae, which efficiently convert organic waste into nutrient-rich biomass. After the larval stage, individuals enter the prepupal phase, cease feeding, and migrate to drier areas to pupate (Diener et al., 2011). Pupation lasts 14–20 days, during which metamorphosis occurs, culminating in the emergence of adult flies. Adults survive for 7–9 days, living on stored larval fat reserves and requiring only water (Banks, 2014).

2.12 Managing BSF Colonies and Pupation

In order to produce new larvae, called seed larvae, for the treatment, a BSFL composting facility needs to manage all the stages of the life cycle. This is called BSF-colony management which can be divided into three fractions including Puparium management, where pupae emerge into flies; BSF-net management, where flies mate and lay eggs; Nursery management, where eggs hatch and newly hatched larvae, called neonates, grow to seed larvae. To make the process feasible, it is crucial to determine efficient treatment techniques, identify optimal environmental conditions for the larvae, limit the risk of process failure posed by parasites, pathogens and pests (Barrett et al. 2022) and improve BSF-colony management (Singh & Kumari 2019). The purpose of BSF-nets is to ensure mating, egg laying, and fast and effortless harvest of eggs (Joly & Nikiema 2019). Therefore, the BSF-net management need to enable and maximize mating and egg laying, which has been found to be impacted by various factors. In the wild, BSF live for seven to nine days, and egg laying takes place within four days after emerging from the pupa (Purkayastha & Sarkar 2022).

2.13 Systems for Producing BSF Larvae

The resource insect black soldier fly (BSF), *Hermetia illucens*, can efficiently convert livestock manure (poultry or dairy), along with other organic waste, and produce larval biomass rich in protein and fat, which can be used directly or after drying as animal feed (Liu et al., 2017; Shorstkii et al., 2020). BSF larvae (BSFL) have an extraordinary ability to feed on almost any bio-waste stream, including food waste, vegetable waste, human faeces, animal manure (pig, poultry, cattle), fish and fish offal, to mention a few (Hopkins et al., 2021; Lalander et al., 2019). The black soldier fly larvae production protocols is a very critical phenomenon and can be influenced by its egg trapping techniques. Egg-trapping efficiency is paramount to the effectiveness of BSF larvae production system (Sripontan *et al.*, 2017). The major determinant of egg-trapping is the baiting material used in luring gravid females. For over the past decades, the production of black soldier fly larvae has nowadays become a significant part of the animal diets produced by the feed industry. Production of BSF larvae can be achieved using a wide variety of organic waste streams. Several studies have tested the suitability of many organic waste streams on the growth, development, and proximate composition of BSF, with promising results (Banks *et al.*, 2014; Čičkova *et al.*, 2015; Miranda *et al.*, 2019). In most BSF production systems, adults are reared in cages to obtain eggs that are placed on the most suitable and available substrates (Caruso *et al.*, 2014; Diener *et al.*, 2009).

Given that BSF larvae consume a wide range of organic resources, recycling nutrients not only adds to overall sustainability of its production, but the use of locally produced material to feed

BSF larvae might contribute to the economic efficiency of the operations, reducing the costs of the feed. Therefore, small systems have been developed for individual farmers or hobby gardeners, consisting of exposing substrates to naturally occurring BSF females for laying eggs (Kenis *et al.*, 2018; Nyakeri *et al.*, 2017). In a simple system such as natural oviposition that relies on wild fly populations, it is crucial to select substrates that are suitable for stimulating oviposition and meet the nutritional requirement for the development of the larvae.

The 'preference-performance principle' postulates that gravid female insects prefer to oviposit in substrates that maximize offspring fitness (Jaenike, 1978). Such behaviour is common among phytophagous species (Gripenberg *et al.*, 2010), and it has also been observed in detritivorous flies (Baleba *et al.*, 2019). In holometabolous insects such as BSF, where the juveniles are incapable of relocating after hatching and with no parental care, females should favour oviposition substrates that are most suitable for larval development. Based on this principle, the study focused on whether substrates preferred by wild BSF females for oviposition were the most suitable for optimum larval development.

2.14 BSF in Waste Recycling

The rise in living standards and the human population has resulted in an ever-increasing need for food; as a result, food waste is rising at an alarming rate and poses several socio-economic issues (Kim et al., 2021). Global concerns are rising toward the amount of waste generated by human activities nowadays, Organic wastes which include animal manures, crop residues, and food processing wastes, municipal biosolids and wastes from some industries (Westerman and Bicudo, 2005). The globe generates more than 2.1 billion tonnes of municipal solid waste every year; 45% of municipal solid waste is made up of food waste; however, only approximately 16% of that waste gets recycled, and more than 46% is wasted (Bras et al., 2020; Deus et al., 2019; Verisk Maplecroft, 2019). As a result, food waste is gradually growing, contributing too many socio-economic problems. According to the FAO, food waste is defined as wasted food, often during the retail and consumption phases (Liu et al., 2016, 2020). With 30 to 40% of the food produced globally currently wasted or lost (FAO, 2011) and the intensification of the livestock industry expecting to generate twice more manures by 2050 (FAO, 2006), sustainable solutions are most wanted. Managing organic wastes is more challenging due to their large natural and rapid biodegradability (Nanda and Berruti, 2021; Yin et al., 2014). In the context of organic waste valorization, a promising new strategy is a use of organic waste to produce insects usable for feed and food, recognized as a rich source of protein and fat, which can also be utilized for the production of biodiesel (Rehman et al., 2018; Shorstkii et al., 2020; Singh and Kumari, 2019). *Hermetia illucens*, otherwise called the Black Soldier Fly (BSF), produces larvae that contribute significantly to reducing living waste. Utilizing BSF larvae in the management of organic waste is an innovative and sustainable strategy for reducing landfill loads (Lopes et al., 2022; Pahmeyer et al., 2022; Salam et al., 2022). The application of black soldier fly larvae (BSFL) for organic waste treatment is getting significant momentum among insect researchers nowadays (Kim et al., 2021).

Essentially, waste treatment by the BSF consists of feeding organic waste to BSF larvae to produce energy-rich larvae and organic fertilizer. Several features of BSF make the insect mostly eye-catching for valorizing municipal wastes. The use of waste streams or mass flows of no or low economic value not yet harnessed in other value chains (low competition) is the most favourable option to consider to farm insects cost-efficiently and sustainably (PROteINSECT, 2016a) and thanks to their ability to feed on and benefit from nutrient-poor substrates, insects are usually cultured on organic wastes or by-products from the food and agro-industry (van Huis *et al.*, 2013).

2.15 BSF Composting and Soil Improvement

Black soldier fly (*Hermetia illucens*) larva composting is a waste management technique suitable for a variety of organic wastes, such as food waste, abattoir waste, and animal and human manure (Lalander et al. 2018a; Liu et al. 2022). BSF larvae have a life phase in which they primarily function as decomposers who can convert substantial amounts of living waste into protein-rich biomass (Fahmi, 2018). The larvae compost is the most straightforward approach to producing organic fertilizer. BSF larvae contain numerous symbiotic bacteria, including *Bacillus sp.,* which are helpful as pathogen control agents and growth-promoting *rhizobacteria* (Kusumawati et al., 2018; Lopes et al., 2022). This activity causes the compost produced by the larvae's decomposition to be cleaner and devoid of dangerous microbes that can impair the health of humans, cattle, and plants. The larvae compost is advantageous to agriculture since it is quickly processed (Fauzi et al., 2022; Lopes et al,). The process of composting only takes 4 weeks, much faster than composting leaf litter, which takes 14 weeks. The larvae compost still needs to be fermented before they can be used as organic fertilizer. Without the ripening process, microbial activity in the larvae compost is still very high, which possibly reduces the oxygen and nitrogen content in the soil and inhibits plant growth (Dortmans et al., 2017). The larvae compost can be utilized in monoculture, multicultural, or integrated farming activities such as mina-rice (rice and fish), duck-rice, or cow-corn. There are numerous alternatives to integrated farming patterns, such as crop-livestock-fish combinations. Integrated agriculture has grown in popularity since combining plants, livestock, and fish can improve soil quality, increase diverse food yields, and encourage the efficiency of land use. BSF larvae produce compost during their life phase, the final residue of the BSF larval metabolic processes (excretion and secretion) (Fahmi, 2018). The nutrient content of BSF larvae compost (locally called '*kasgot'*) has good nutrients for plant growth. Using BSF larvae compost as an organic fertilizer is a part of maintaining eco-friendly sustainable agriculture (Lopes et al., 2022; Pahmeyer et al., 2022; Salam et al., 2022). According to the literature, the macro and micronutrients contained in larvae compost can promote *Cabbage* growth and add biomass.

2.16 Using BSF Larvae in Fish Feeds

Since the end of the twentieth century, there have been significant changes in the composition of aquafeeds but also advances in manufacturing. Today, animal feed production strongly relies on protein and fat derived from forage fishery. In 2002, fishmeal and fish oil were primarily used worldwide for intensive food production, i.e., 24% for pigs, 22% for poultry and 46% for aquaculture (Alder et al., 2008). Many studies in several aquaculture species have proven that BSFLM has the potential to replace FM partially or completely in aquafeeds. These transformations have originated from the need to improve the economic profitability of aquaculture as well as to mitigate its environmental impacts. Today, the major supply of proteins and lipids in fish feed comes from plants, but also commonly from other sources, including insect meals, poultry by-products and blood meal (Tacon and Metian 2008). However, the driving forces behind these changes is the need to decrease the amount of fishmeal (FM) and fish oil (FO) in the feeds. Alltech's yearly survey (Alltech 2017) reveals that total animal feed production broke through 1 billion metric tons, with a 3.7% increase in production from 2015 despite a 7% decrease in the number of feed mills. China and the USA dominated production in 2016, accounting for 35% of the world's total feed production. Many studies have shown that FM can be successfully replaced by soybean meal in aquafeeds, but soybean meal has anti-nutritional factors such as trypsin inhibitors, soybean agglutinin and saponin, which limit its use and high replacement percentages in farming carnivorous fish. High FM replacement by plant meals in fish diets can also reduce nutrient bioavailability in fish, which results in nutrient alterations in the final quality of the product (Gatlin et al. 2007). Most of the alternative plant-derived nutrient sources for fish feeds contain a wide variety of anti-nutritional factors that interfere with fish protein metabolism by impairing digestion and utilization, therefore leading to increased N release in the environment which can affect fish health and welfare. Research into the utilization of alternative plant and animal protein sources and low trophic fish feed ingredients is ongoing.

Next to nutrient quality, Proper diet formulation is one of the most important factors in commercial aquaculture as feed production costs and associated impact on subsequent fish growth are major expenses (Haghbayan & Shamsaie Mehrgan, 2015). However, the continued growth of the aquaculture industry has been limited by a shortage in global production of, and competition for, FM by livestock and poultry. The Food and Agricultural Organization has highlighted the potential of insects as food and feed sources (van Huis et al., 2013). Research has investigated the potential as an alternative feed source in aquaculture activities, considering it cheaper than fishmeal. (Dickinson et al., 2019). The species permitted to be used are black soldier fly (*Hermetia illucens*), common housefly (Musca domestica), yellow mealworm (*Tenebrio molitor*), lesser mealworm (*Alphitobius diaperinus*), house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus*) and field cricket (*Gryllus assimilis*).

2.17 Effects of BSF Residues on Soil Microorganisms

Recently, Barragán-Fonseca et al. (2022) urged the clarification of the impact of insect residues on plant growth promoting rhizobacteria, crop growth and of potential underlying mechanisms. Several authors studying the application of insect, particularly the black soldier fly residues in agricultural contexts suggest an indirect effect on the crop through an impact on the soil microbiome (Setti et al., 2019; Gebremikael et al., 2022; Tanga et al., 2022). In addition to the sustainable potential of the larva, the extensively accruing residues from insect rearing, i.e., excreta, undigested substrates and shed exoskeletons, bear the chance of returning versatile services to the agri-food chain *via* their provision of nutrients, bioactive molecules, and potentially beneficial microbes when amended to the soil–plant system (Poveda, 2021; Barragán-Fonseca et al., 2022).

The BSFL residues are likely to contain further bioactive compounds of importance for the soil micro-biome, since BSFL genes encoding for several antimicrobial peptides and their diet-dependent expression were identified (Elhag et al., 2017; Vogel et al., 2018). The fertilizer effect of BSFL residues (in some studies also referred to as "frass") on plants has been subjected to several studies. Its functional capacity to influence soil fertility and thus crop performance (Van Der Heijden et al., 2016; Saleem et al., 2019) has gained increasing attention in sustainable food production. The soil microbiome is essential to the viability of global ecosystems, since it is a major driver of soil structure formation, organic matter breakdown, nutrient provisioning, plant growth promotion, and stress and disease control (Barrios, 2007).

Chitin and its derivate stemming from molting BSFL are associated with plant performance promotion through inhibition of pathogenic and support of beneficial soil microbes as well as through a direct stimulation of plant growth (Sharp, 2013). In former studies, BSFL can substantially influence microbial community composition in its residues presumably *via* fecal transmission, leaving behind a characteristically imprinted residue. Chirere et al. (2021) pointed out that the generally higher nutrient contents of BSFL residues compared to other organic soil amendments make the residues an ergonomically practical alternative. It should be noted that, depending on the substrates fed to BSFL, physicochemical properties of the residues may strongly differ (Klammsteiner et al., 2020a), which results in distinct effects on soil fertility (Gebremikael et al., 2022).

2.18 Market Dynamics of Black Soldier Fly Products

The market for Black Soldier Fly (BSF) products is still emerging and marked by considerable uncertainty. Product prices vary depending on local demand, market conditions, and processing levels (Diener & Gold, 2022). BSF products are typically priced in line with conventional commodities they aim to replace. For instance, dried larvae and protein meal, containing 45–60% protein, are comparable to fishmeal and other animal-based meals, generally ranging from USD 1,500 to 2,000 per ton (Fantechi, Califano, Caracciolo, & Contini, 2023). BSF fat prices fluctuate based on purity and fatty acid composition, serving as potential substitutes for cooking oils or animal fats, with costs between USD 900 and 2,500 per ton. Frass, an insect-derived fertilizer, is often compared to compost or other organic soil amendments (Diener & Gold, 2022).

While animal feed demand remains relatively stable throughout the year, the use of BSF frass as a soil conditioner is more seasonal, requiring adequate storage management. BSF companies often emphasize additional benefits—such as sustainability, improved animal welfare, and enhanced functionality—to differentiate their products from conventional alternatives. Nevertheless, price sensitivity among livestock and aquaculture farmers, for whom feed represents the largest operational cost, remains a major challenge (Siddiqui & Gärttling, 2022). Pet food markets, particularly in Europe, are more receptive to BSF-based products, as consumer's value sustainability and functional benefits, enabling companies to charge a premium (Fantechi et al., 2023).

Regulatory challenges further influence market growth. In regions like Europe and North America, strict regulations on feedstock and insect-derived products can limit market access, and inconsistent frameworks across countries complicate expansion (Siddiqui & Gärttling, 2022). Despite the sustainability advantages of BSF technology, profitability is crucial. High operational and energy costs, particularly in non-tropical regions, make it difficult for many companies to compete with established protein sources such as fishmeal and soymeal (Diener & Gold, 2022).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This study was conducted in Moyamba District, Southern Province, Sierra Leone, at Njala University, an area with diverse aquatic resources suitable for aquaculture research. The experiment investigated the use of Black Soldier Fly (BSF, *Hermetia illucens*) larvae as a protein source in formulated diets for *Clarias gariepinus* fingerlings. BSF eggs were collected using wooden slats ("eggies") and organic waste baits, and larvae were reared for inclusion in feed. Other feed ingredients, including fishmeal, soybean meal, vitamins, minerals, amino acids, and carbohydrate sources, were procured locally and blended into diets with varying BSF meal inclusion levels (0%, 10%, 15%, 20%, and 25%). This research is important for aquaculture in Sierra Leone, as it explores a sustainable, locally sourced protein alternative that could reduce dependence on imported fishmeal, lower production costs, and support the growth of the domestic aquaculture industry.

3.2 Study Area

Sierra Leone is a small West African country located between the 7th and 10th parallels north of the equator. It is bordered by Guinea to the north and northeast, Liberia to the south and southeast, and the Atlantic Ocean to the west (Levert, 2006). The country covers a total area of 71,740 km², of which 71,620 km² island and 120 km² is water (CIA, 2024). Geographically, Sierra Leone consists of four main regions: the coastal swamp, the Sierra Leone Peninsula, the interior plains, and the interior plateau and mountain region. The coastal swamp stretches approximately 320 km along the Atlantic coast, while the Peninsula, home to Freetown, features densely wooded mountains running parallel to the sea for about 40 km.

The climate is tropical, with alternating rainy and dry seasons, generally hot and humid. Coastal areas have mean monthly temperatures in the mid-20s to upper-20s °C, while inland areas are slightly cooler. In the northeast, temperatures range from 10–15 °C in January to over 30 °C in March. The rainy season occurs from May to October, dominated by humid Atlantic air masses. Annual rainfall varies from more than 5,000 mm in the Peninsula Mountains to about 2,000 mm in the northeast (CIA, 2024).

Agriculture is the backbone of the economy, employing over 60% of the population. Rice is the staple crop, cultivated on swamplands and uplands, alongside cassava, millet, groundnuts, sweet potatoes, and oil palm. Major cash crops include palm kernels, cocoa, coffee, piassava, and ginger, primarily produced by smallholder farmers. Sierra Leone's rivers, lakes, and coastal waters provide diverse fish resources, including bonga, snapper, butterfish, and sole, as well as shrimp, lobster, and oysters. Aquaculture has been gradually expanding as an important food production sector (FAO, 2002).

The population is ethnically diverse, comprising about 18 groups with shared cultural features such as chieftaincy systems, patrilineal descent, and farming traditions. The Mende (mainly in the south and east) and Temne (central and northwest) are the largest groups. Creoles, descendants of freed slaves, are concentrated around Freetown. Other groups include Sherbro, Loko, Limba, and smaller Lebanese and Indian communities engaged in trade. English is the official language, while Arabic is spoken among Lebanese traders and some Muslim communities. Islam is the dominant religion, followed by Christianity, with smaller populations practicing traditional religions, Hinduism, and Judaism (Levert, 2006).

This study was conducted in Moyamba District, located in the Southern Province. The district borders the Atlantic Ocean to the west, Port Loko and Tonkolili districts to the north, Bo District to the east, and Bonthe District to the south. Moyamba District, the largest in the province, comprises fourteen chiefdoms: Lower Banta, Upper Banta, Timdale, Bagruwa, Kagboro, Dasse, Kowa, Kaiyamba, Kongbora, Kori, Kamajei, Fakunya, Ribbi, and Bumpe. The district capital is Moyamba, with other notable towns including Taiama, Rotifunk, and Shenge. The population is predominantly Mende (≈60%), with Sherbro, Temne, and Loko communities also present.

Hydrologically, Moyamba District features both external and internal water systems. It is adjacent to the Atlantic Ocean and estuaries, and internally drained by the river Jong (locally River Taia), which flows across Kori Chiefdom into the Atlantic, supporting diverse aquatic flora and fauna. Njala Town, located along the River Jong in Kori Chiefdom, hosts Njala University, the second-largest university in Sierra Leone. Njala University attracts students from across the country and neighboring West African nations, serving as an important academic and research hub where this study was conducted (NRC, 2011; APHA, 2017).

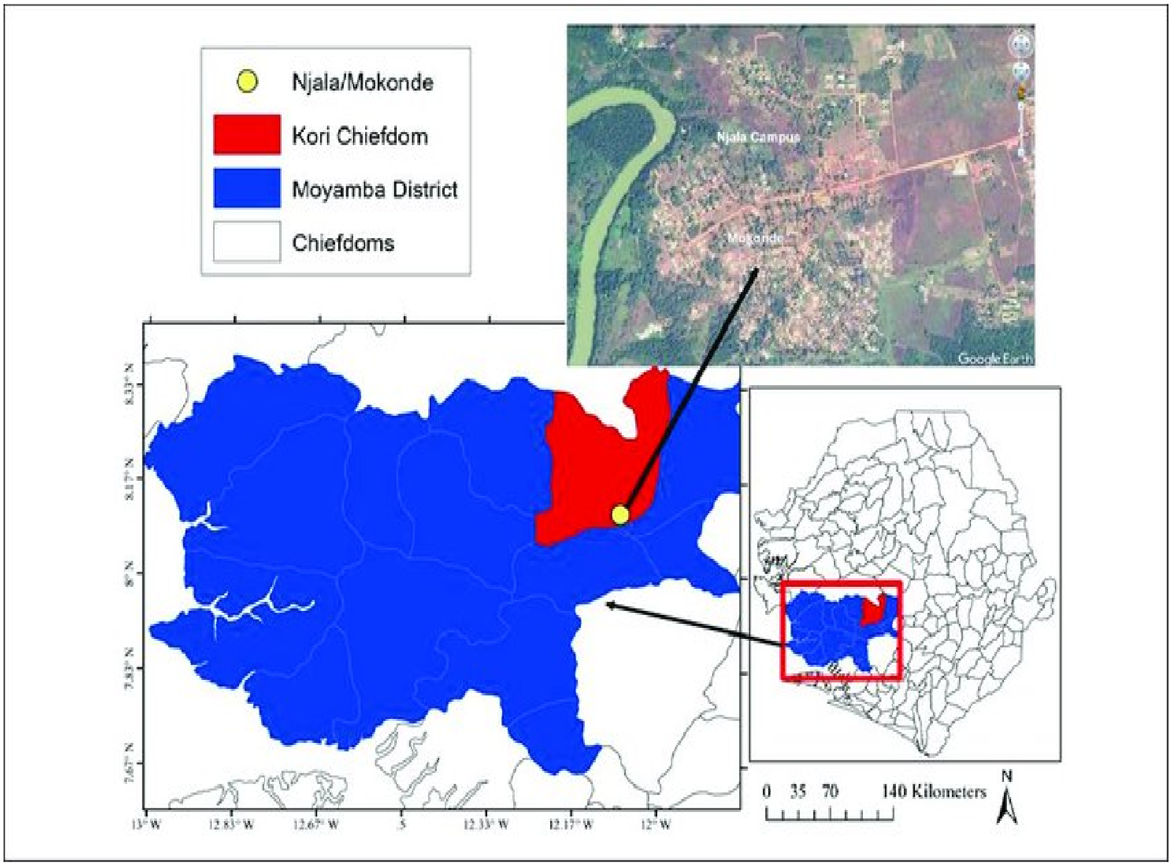

Figure 1. Map of Sierra Leone showing Njala University

3.3 Project Location

This research was conducted at the INCiTiS Food Living Laboratory (NUSL LL) within the Department of Aquaculture and Fisheries Management, School of Natural Resources, Njala University, located in Southern Sierra Leone, West Africa.

3.4. Materials Used

Table 1. Materials Used for BSF Rearing and Fish Feeding

No.	Material	Purpose/Description
1	Weighing Scale	Measures feed ingredients and fish body weights.
2	Attractant Substrates	Organic wastes used to lure and trap wild BSF eggs.
3	Eggies (Egg Traps)	Wooden slats providing oviposition sites for female BSF
4	Bulk Tank	Rears BSF larvae until pre-pupal stage.
5	BSF Maggot Meal	Protein-rich replacement for fish meal.
6	Rearing Troughs	Units for raising catfish fingerlings.
7	Protective Hand Gloves	Prevents contamination and maintains hygiene.
8	Mixing Containers	Homogenizes feed ingredients during formula

Bottom of Form

3.5. Source of BSF Eggs for Larval Protein Production

BSF eggs used for larval protein production were collected using the wild egg-trapping method. The procedure involved three main components: eggies (wooden slats for oviposition), attractant substrates, and rectangular plastic containers. Female black soldier flies typically lay eggs near decaying organic matter, which serves as a food source for their larvae. A mixture of fruit wastes (pineapple, mango, banana, avocado peels), vegetable wastes (spoiled onions, garden eggs), and fish scraps was used as attractants. Eggies, made of two small wooden pieces bound with a rubber band, were placed on top of each container to provide cavities for oviposition. Traps were positioned at different locations within the Njala University forestry area and inspected daily to monitor egg deposition and prevent interference from environmental or biological factors.

Figure 2. Setting trap for wild BSF eggs

Figure 3. BSF laying eggs on substrate

3.6 Sourcing of Experimental Feed Ingredients

In aquaculture, obtaining high-quality feed ingredients from reliable sources is critical, as feed quality directly affects fish growth and profitability. In this study, BSF larvae protein was sourced using the wild egg-trapping method described previously. Other ingredients including fishmeal, soybean meal, methionine, lysine, cornmeal, carbohydrate sources, limestone, vitamin premix, ascorbic acid, and FPC booster were procured from various local markets in Sierra Leone based on cost, availability, and suitability for feed formulation.

Table 2. Experimental feed ingredients and their primary nutrient contributions

Variables	Control	Diet 1	Diet 2	Diet 3	Diet 4

	(0% BSF)	(10% BSF)	(15% BSF)	(20% BSF)	(25% BSF)
Fishmeal	40	35	30	25	20
BSF	0	10	15	20	25
SBM	11.5	6.5	6.5	6.5	6.5
WM	22.5	22.5	22.5	22.5	22.5
Maize	7.5	7.5	7.5	7.5	7.5
Vitmin Premix	1.0	1.0	1.0	1.0	1.0
Starch	10	10	10	10	10
Fish oil/FPC	2.1	2.1	2.1	2.1	2.1
Ascorbic Acid	2	2	2	2	2
Lysine	2.2	2.2	2.2	2.2	2.2
Methionine	1.2	1.2	1.2	1.2	1.2
Total	100	100	100	100	100

3.7 Weighing and Blending of Ingredients

All feed ingredients were accurately weighed using an electronic balance. The ingredients were then transferred to a clean rubber bowl and thoroughly mixed to achieve a homogeneous blend, with small amounts of clean water added to facilitate mixing. The mixtures were prepared according to the required proportions for each diet, packed in airtight plastic bags, and stored under hygienic conditions until used in diet formulation.

3.8 Source and Acclimation of *Clarias gariepinus* Fingerlings

A total of 165 *Clarias gariepinus* fingerlings of uniform size and mean weight were obtained from Timrex Integrated Fish Farm Limited, Yoni Chiefdom, Tonkolili District, Northern Sierra Leone. The fingerlings were transported to the INCiTiS Living Laboratory, Department of Aquaculture and Fisheries Management, Njala University. Upon arrival, they were stocked in nursery tanks within a recirculating aquaculture system (RAS) for a two-week acclimation period. During this time, fish were fed two millimeters (2mm) commercial feed twice daily. To prepare for experimental diets, fingerlings were starved for 24 hours prior to stocking to empty gut contents, following FAO (2002) recommendations.

3.9 Experimental Diets with BSF Maggot Meal as Fishmeal Substitute

Five experimental diets were formulated in which fishmeal protein was progressively replaced with black soldier fly maggot meal (BSFMM) at inclusion levels of 0% (control), 10%, 15%, 20%, and 25% (Table 3). The diets were carefully balanced to meet the nutrient requirements of *Clarias gariepinus* fingerlings, following guidelines provided by the National Research Council (NRC, 2011). Previous studies have highlighted the suitability of BSF larvae as a sustainable alternative protein source in aquaculture, showing that it can reduce dependence on conventional fishmeal without compromising growth or feed utilization (Makkar et al., 2014; Henry et al., 2015).

The feed ingredients were thoroughly mixed and processed into 2 mm pellets, a size selected to facilitate easy ingestion by fingerlings while minimizing feed wastage. After extrusion, the pellets were spread evenly on plastic sheets and sun-dried for seven days to lower moisture content. This step enhanced feed durability, improved storage stability, and preserved nutrient integrity until the beginning of the feeding trial (FAO, 2020).

Table 3. Inclusion levels of Black Soldier Fly (BSF) meal in experimental diets

No.	Level of BSF Meal	Treatment	Description
Table 1	0%	T1 (Control)	Diet without BSF meal
Table 2	10%	T2	Diet with 10% BSF meal
Table 3	15%	T3	Diet with 15% BSF meal
Table 4	20%	T4	Diet with 20% BSF meal
Table 5	25%	T5	Diet with 25 BSF meal replacement

3.10 Experimental Setup

The experiment was arranged as a completely randomized design (CRD) with five dietary treatments, each replicated three times, resulting in a total of 15 experimental units. Transparent plastic tanks (50 × 45 × 35 cm) were placed on wooden platforms and filled with 30 L of clean water. Each tank was stocked with 11 fingerlings of uniform size. Prior to stocking, fish were weighed and counted to record baseline data. Tanks were covered with nets to prevent fish from escaping.

3.11 Feeding of Experimental Fish

Fish were hand-fed twice daily at 10:00 am and 4:00 pm at a ration equivalent to 0.5% of their body weight. The daily ration was divided equally between the two feeding times. Feed quantities were adjusted biweekly based on weight changes recorded during sampling. The feeding trial lasted for eight (8) weeks.

Figure 4. Experimental setup

3.12 Monitoring of Fish Growth and Water Quality

The initial and subsequent body weight of each fish was recorded using an electronic kitchen electronic scale model EK-3250 before stocking. Fish were then weighed every two weeks throughout the 8-weeks experimental period. Total length and standard length were measured using a ruler calibrated in centimeters. Water quality was maintained by renewing tank water every three days and removing uneaten feed after each feeding to reduce organic load. Key water parameters including temperature, pH, dissolved oxygen, ammonia, and nitrite were monitored regularly. Temperature was measured with a smart sensor thermometer, while pH, dissolved oxygen, ammonia, and nitrite were determined using a Fish Farmers Water Quality Test Kit. Fish were also observed daily for changes in behavior, physical condition, or mortality, following standard procedures (APHA, 2017).

Figure 5: Water quality analysis in the LL

3.13 Fish Growth and Nutrient Utilization Determination

The experimental fish growth performance and nutrient utilization was based on the following biological parameters.

Weight Gain (Tacon & De Silva, 1997) Is the increase in body mass over the culture period.

Weight Gain = *Final Weight– Initial Weight*

Mean weight gain (%) (Hepher, 1988) is the proportional weight increases relative to initial size.

$$\text{Mean weight gain } (\%) = \frac{\text{Final body weight} - \text{Initial body weight (g)}}{\text{Initial body weight (g)}} \text{ X } 100$$

Specific growth rate (Ricker, 1979) is the Relative growth per day on a logarithmic scale.

$$\text{Specific growth rate} = \frac{\text{Logw2} - \text{Logw1}}{\text{T}} \text{ X } 100$$

Where:

W_2 = Final Body Weight, W_1 = Initial Body Weight of fish, T = Duration of study in days

Daily Growth Rate (Tacon, 1990) is the average daily weight increment.

Daily Growth Rate= $\frac{\text{fish weight gain}}{\text{number of culture days}}$

Total feed intake (FI) (Jobling, 1994) is the total feed consumed during the trial.

FI = Feed offered – Feed not eaten

Feed Conversion Ratio (FCR) (Brett & Groves, 1979) is the efficiency of feed used for biomass gain.

Feed Conversion Ratio (FCR) = $\frac{\text{feed consume (g)}}{\text{Mean weight (g)}}$

Survival rate (Brown, 1957) is the percentage of fish alive at the end of the study.

Survival rate (SR) = $\frac{N1-N0}{N1}$ X 100

Where:

No = number of fish stocked,

N_1 = number of fish at the end of experiment

Protein Intake (PI) (Lovell, 1989) is the total protein consumed through feed.

Protein Intake (PI) = Feed intake X percentage protein in feed

Protein Efficiency Ratio (PER) (Meyer & Fracalossi, 2004) is the growth achieved per unit protein consumed.

Protein Efficiency RatioProtein Efficiency Ratio = $\frac{\text{feed weight gain(g)}}{\text{protein intake(g)}}$

Condition Factor (K) Le Cren (1951)

The indicator of fish well-being and robustness

$$\text{Condition Factor (K)} = 100\frac{W}{L^3}$$

Where:

W = Final mean body weight (g); L = Mean standard length (cm)

The relationship between the length and weight of fish is commonly described by the allometric equation (Le Cren, (1951):

$W = aL^b$

Where:

W = the body weight (g),

L = the total or standard length (cm),

a = the intercept (condition factor), and b = the slope or growth exponent

`a` value of `b` = 3 indicates isometric growth, where fish maintain their body proportions as they grow, while $b \neq 3$ reflects allometric growth, where proportions change with size.

To facilitate linear regression analysis, the equation is usually transformed logarithmically (Ricker, 1975; Froese, 2006; Le Cren, 1951) as follows:

$$LogW=loga+blogL$$

3.14 Hematological Analysis

Blood samples were collected from *Clarias gariepinus* fingerlings to evaluate their physiological and health responses to the experimental diets. Each fish was individually captured using a hand net, and blood was drawn from the caudal vein, located near the vertebral column, using a 5 ml disposable syringe fitted with a hypodermic needle. The collected blood was immediately transferred into sterile ethylene diamine tetra-acetic acid (EDTA) bottles, with each bottle labeled according to the respective dietary treatment. EDTA was selected as the anticoagulant because it effectively prevents clotting and preserves blood cell integrity, ensuring reliable hematological measurements (Blaxhall & Daisley, 1973; Akinrotimi et al., 2007; Gabriel et al., 2011). Mythic automated hematology analyzer instrument was used for fish blood analysis; and it is an advanced instrument designed to perform rapid and accurate blood analyses.

Table 4: Hematological Parameters, Abbreviations, Units, and Descriptions

Parameter	Abbreviation	Unit	Description
White Blood Cell Count	WBC	$\times10^9$/L	Total white blood cells; indicator of immunity.
Lymphocytes	LYM	$\times10^9$/L	Immune cells for adaptive defense.
Monocytes	MON	$\times10^9$/L	Phagocytic and inflammatory immune cells.
Lymphocyte Percentage	LYM%	%	Proportion of lymphocytes in WBC.
Monocyte Percentage	MON%	%	Proportion of monocytes in WBC.
Hemoglobin	HGB	g/dL	Oxygen-carrying pigment in blood.
Hematocrit	HCT	%	Percentage of red blood cell volume.
Mean Corpuscular Volume	MCV	fL	Average red blood cell size.
Mean Corpuscular Hemoglobin	MCH	pg	Hemoglobin per red blood cell.
Mean Corpuscular Hemoglobin Concentration	MCHC	g/dL	Hemoglobin concentration in red blood cells.

3.15 Data Analysis

The collected data were systematically organized using Microsoft Excel (version 17.0) and subjected to statistical analysis with SPSS (version 26.0). One-Way Analysis of Variance (ANOVA) was employed to evaluate differences in mean growth parameters, including weight and length, among the experimental treatments. Where significant differences were observed, Duncan's Multiple Range Test (DMRT) was applied for post-hoc comparisons. Hematological indices, including white blood cell count, hemoglobin concentration, and hematocrit, were also analyzed to assess physiological responses. All statistical tests were conducted at a 95% confidence level ($p < 0.05$) to ensure the accuracy and reliability of the findings.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the effects of varying levels of Black Soldier Fly (BSF) meal on the growth performance and mineral composition of *Clarias gariepinus* fingerlings. Results are structured according to the study objectives, including growth performance, feed utilization, water quality, and nutrient composition. Statistical analyses were conducted to identify significant differences among treatments, and findings are discussed in relation to existing literature to contextualize the outcomes and address the study hypotheses.

4.2 OBJECTIVE ONE

4.2.1 Evaluate the growth response and nutrient utilization of *C. gariepinus fingerlings* fed diet containing BSF maggot meal.

Null Hypothesis

- It was hypothesized that dietary inclusion of BSF meal would have no significant effect on growth performance, feed utilization, and condition factor of *Clarias gariepinus* (H_0).
- Alternatively, it was expected that increasing levels of BSF meal would significantly enhance these parameters, with higher inclusion levels (TR.4 and TR.5) producing the most favorable outcomes (H_1).

The results of this study indicated that the growth performance, feed utilization, and condition factor (K) of fish under the different dietary treatments (TR.1–TR.5) are summarized in Table 4 below. The results showed clear differences among treatments in weight gain, mean weight gain percentage, specific growth rate (SGR), daily growth rate (DGR), feed conversion ratio (FCR), protein efficiency ratio (PER), and condition factor. The results further proved that fish in TR.5 recorded the highest growth values, while TR.1 which is the control showed the lowest. Generally, growth improved from TR.1 to TR.5, with TR.4 and TR.5 showing the most favorable outcomes. Weight gain and SGR increased steadily across treatments, reaching maximum values in TR.5 (7.91 g; 0.60%/day). In contrast, TR.1 had the lowest performance (4.28 g; 0.42%/day). These results suggest that the diets in TR.4 and TR.5 provided a better balance of nutrients and energy, supporting more effective growth. Previous studies have also shown that optimized protein-to-energy (P: E) ratios enhance growth performance. According to Taj et al. (2019) who reported improved feed utilization and growth in juvenile fish with balanced P:E ratios and while Mengistu et al. (2020), highlighted the influence of diet quality, feed intake, and environmental factors on tilapia growth. The results also showed that, feed intake ranged from 376.6 g in TR.1 to 490 g in TR.5. The result indicated that, fish in TR.4 and TR.5 consumed more feed and showed higher growth, indicating efficient nutrient conversion. FCR values ranged from 0.6 to 0.8, with TR.1 and TR.2 showing lower values and TR.4 and TR.5 slightly higher. Although FCR values below 1.0 are rare in commercial aquaculture, where typical values range between 1.0 and 2.4 (Tacon & Metian, 2008) these results indicate efficient feed utilization. The trend rightfully confirms that the diets in TR.4 and TR.5 allowed fish to convert feed into body mass more effectively. Protein intake increased from 11.6 g in TR.1 to 14 g in TR.5. The highest PER was observed in TR.4 and TR.5 (0.9), showing that protein was used more efficiently for growth, while TR.3 had the lowest

PER (0.3), indicating poor protein utilization. Similar observations have been reported in African catfish, where balanced amino acids improved protein retention (Amoah, 2021). El-Sayed and Teshima (1992) also noted that PER improves with increasing dietary protein up to an optimal level, after which further protein is used for energy rather than growth. These findings suggest that diets in TR.4 and TR.5 likely provided near-optimal protein utilization for the fish. Condition factor (K) values were relatively consistent across treatments (0.85–0.97), indicating that fish maintained good body condition. The highest K (0.97) was recorded in TR.5, reflecting its superior growth, while TR.2 had the lowest (0.85). Since Fulton's K is widely used as an indicator of fish health and robustness (Datta et al., 2013), these values suggest that all fish remained healthy. Small variations in K are expected and may result from differences in growth pattern, energy allocation, or body composition (Deekrachang & Paphavasit, 2016). Generally, diets in TR.4 and TR.5 produced the best results in terms of growth, feed efficiency, and protein utilization. These outcomes are likely due to higher feed intake, balanced nutrient composition, and more efficient protein use. The results reinforce previous findings that optimizing protein levels, energy balance, and feed formulation is essential for maximizing growth and feed efficiency in aquaculture species (NRC, 2011; Mengistu et al., 2020). Although the low FCR values in this study are unusual, the relative differences among treatments clearly demonstrate that diets promoting higher intake and better protein utilization improve fish performance.

Table 5. Growth Performance and Feed Utilization of Fish under Different Diets

Treatment	Weight Gain (g)	Mean weight gain (%)	Specific growth rate %	Daily Growth Rate g/day	Total feed intake	Feed Conversion Ratio	Protein Intake (g)	Protein Efficiency Ratio	Condition Factor (K)
TR.1	4.28	57.45	0.42	0.09	376.6	0.6	11.6	0.7	0.87
TR.2	5.87	77.14	0.52	0.12	410.7	0.6	12.0	0.5	0.85
TR.3	6.12	81.38	0.53	0.13	379.2	0.7	11.0	0.3	0.96
TR.4	6.73	92.81	0.58	0.14	430.3	0.8	13.0	0.9	0.92
TR.5	7.91	95.30	0.60	0.16	490.0	0.8	14.0	0.9	0.97

4.2.2 Proximate and mineral composition of *Clarias gariepinus* fingerlings, showing changes from the initial fish sample under different diets.

Null Hypothesis

- There is no significant change in the proximate and mineral composition of *Clarias gariepinus* fingerlings fed with diets TR1 to TR5 when compared to the initial fish sample (H_0).
- There is a significant change in the proximate and/or mineral composition of *Clarias gariepinus* fingerlings due to the different experimental diets (TR1–TR5), suggesting that the diet influences nutrient uptake and body composition (H_1)

The results show that the proximate and mineral composition of *Clarias gariepinus* fingerlings varied significantly across the experimental diets compared to the initial fish sample, indicating that dietary formulation strongly influenced nutrient retention and overall physiological composition. The initial fish had moderate moisture (11.61%), high protein (64%), moderate fat (10.41%), ash (11.14%), and low nitrogen-free extract (2.90%), with phosphorus (0.37%), calcium (0.401%), magnesium (0.181%), potassium (0.150%), and sodium (0.067%) as the baseline mineral levels. The results indicate that the experimental diets produced notable changes in fish composition. TR1 and TR2 showed significantly higher moisture (17.64–17.82%), suggesting increased water retention, but lower crude protein (55.76% and 60.64%) and fat (9.00% and 7.01%) compared to the initial fish, indicating reduced nutrient deposition. In contrast, TR5 exhibited significantly higher crude protein (69.35%), fat (15.09%), ash (14.18%), and nitrogen-free extract (11.01%) than the initial sample, demonstrating that this diet promoted enhanced nutrient assimilation, energy storage, and growth potential. TR4 also recorded elevated fat

(13.22%) and ash (15.44%) levels but had the lowest moisture (4.58%) and reduced magnesium (0.07%), suggesting selective nutrient accumulation and concentration of dry matter.

The results further show that mineral composition was strongly influenced by diet. Phosphorus levels remained relatively stable in TR5 (0.3767%) but were lower in TR3 (0.29%), indicating diet-dependent phosphorus retention. Calcium was highest in TR5 (0.426%) and lowest in TR4 (0.277%), demonstrating that TR5 improved mineral deposition, whereas TR4 was less effective. Magnesium decreased across all treatments compared to the initial fish, which may indicate insufficient magnesium availability in the experimental diets. Potassium levels were fairly stable, with TR2 (0.149%) closely matching the baseline, whereas sodium increased in all experimental fish, with TR5 (0.083%) and TR4 (0.080%) showing the highest accumulation, indicating enhanced sodium uptake under these diets. Taken together, these results suggest that dietary treatments significantly affected the proximate and mineral composition of *Clarias gariepinus*, with TR5 showing the most favorable outcomes in protein, fat, ash, nitrogen-free extract, calcium, and sodium deposition. This trend indicates that high-quality, nutrient-rich diets can enhance growth performance, energy storage, and mineral retention, while diets in TR1 and TR2, which increased moisture but reduced protein and fat, were less efficient in promoting growth. The observed decrease in magnesium across all treatments may reflect a need for dietary supplementation to maintain optimal mineral balance. Overall, the findings demonstrate that diet formulation plays a critical role in determining the nutritional composition, growth potential, and physiological health of cultured fish, consistent with previous studies (Blaxhall & Daisley, 1973; Akinrotimi et al., 2007; Gabriel et al., 2011).

Table 6. Proximate and Mineral Composition of Experimental Fish (Mean ± SD)

Treatment	*%Moisture*	*%Crude Protein*	*%Crude Fat*	*%Ash*	*%NFE*	*%P*	*%Ca*	*%Mg*	*%K*	*%Na*
Initial Fish Sample	11.61	64.00	10.41	11.14	2.90	0.37	0.401	0.181	0.150	0.067
TR1	17.64 ± 10.87[b]	55.76 ± 3.97[a]	9.00 ± 2.90[b]	13.80 ± 3.47[b]	3.89 ± 1.12[a]	0.31 ± 0.01[b]	0.343 ± 0.063[b]	0.114 ± 0.008[b]	0.116 ± 0.008[a]	0.072 ± 0.010[a]
TR2	17.82 ± 6.96[b]	60.64 ± 8.20[b]	7.01 ± 2.61[a]	12.28 ± 4.41[a]	2.34 ± 1.96[a]	0.36 ± 0.03[c]	0.337 ± 0.063[b]	0.107 ± 0.023[a]	0.149 ± 0.013[c]	0.076 ± 0.013[a]
TR3	9.80 ± 2.20[a]	60.90 ± 6.58[b]	11.23 ± 2.83[b]	12.63 ± 1.33[a]	5.54 ± 5.31[b]	0.29 ± 0.01[a]	0.357 ± 0.068[c]	0.1083 ± 0.023[a]	0.1197 ± 0.0101[b]	0.0713 ± 0.010[a]
TR4	4.58 ± 0.50[a]	59.35 ± 9.62[b]	13.22 ± 2.34[c]	15.44 ± 2.71[c]	7.49 ± 5.64[b]	0.32 ± 0.03[b]	0.277 ± 0.014[a]	0.07 ± 0.010[a]	0.129 ± 0.013[b]	0.080 ± 0.012[b]
TR5	11.29 ± 3.14[a]	69.35 ± 3.00[c]	15.09 ± 1.60[c]	14.18 ± 3.53[c]	11.01 ± 0.79[c]	0.3767 ± 0.006[c]	0.426 ± 0.099[c]	0.105 ± 0.024[a]	0.119 ± 0.010[b]	0.083 ± 0.007[b]

4.3 OBJECTIVE TWO

4.3.1 Evaluate the water quality parameters of the culture water and condition factor of the experimental fish.

Null Hypothesis

- The inclusion of Black Soldier Fly (BSF) meal at varying levels in the diets of *Clarias gariepinus* fingerlings has no significant effect on the water quality parameters of the culture environment or the condition factor (K) of the fish (H_0).
- The inclusion of Black Soldier Fly (BSF) meal at different dietary levels significantly influences water quality parameters and improves the condition factor (K) of *Clarias gariepinus* fingerlings, particularly at higher inclusion levels (e.g., TR.4 and TR.5) (H_1).

The growth performance of *Clarias gariepinus* (Burchell 1822) fingerlings was evaluated under five dietary treatments containing different levels of Black Soldier Fly (BSF) meal (0%, 10%, 15%, 20%, and 25%). Water quality parameters as a key component were monitored throughout the experiment to ensure that the observed growth differences were due to diet rather than environmental stressors. Table 4 shows result on water quality parameters measured across the five treatments of the experiment. The result showed slight variations but were generally within the suitable range for aquaculture production. The results indicated that the environment in which the experimental *Clarias gariepinus* fingerlings were cultured was well maintained throughout the culture period. The result shows that the mean pH in treatment 1ranges from 7.21 to 7.44 in Treatment 3, with an oval mean of 7.30 which were optimal for *Clarias gariepinus* fingerlings efficient growth and feed utilization. The result further shows that the minimum and maximum values ranged from 6.20 to 8.60 and while all treatments remained within the neutral to slightly alkaline range (6.2–8.6). Similar findings have been reported by Cummins et al. (2017) who highlighted BSF meal as a sustainable protein source that does not negatively impact water quality. The results show no significant difference (P>0.05) in the mean values of pH in the treatment groups during the trial period. The result also displays that the dissolved oxygen levels were consistently high ranging from 9.60 mg/L (T2) to 9.71 mg/L (T1), with a total mean of 9.66 mg/L. the results further shows that the minimum dissolved oxygen (DO) was 8.00 mg/L, while the maximum reached 10.00 mg/L. Similarly, the obtained results were consistent with the findings of Boyd (2015), who demonstrated that adequate oxygen availability is critical for metabolic processes and feed conversion efficiency in catfish fingerlings production. The result also shows that the levels of ammonia across all the treatments were low, with means values ranging from 0.28mg/L to 0.30mg/L with a total mean value of 0.29mg/L while the minimum was 0.20mg/L, and the maximum was 0.4mg/L. These values of low ammonia concentrations obtained suggest that the tanks were efficiently well maintained throughout the culture period. This result aligns with the work of El-Sayed (2006), who emphasized the importance of controlling ammonia and nitrite for sustainable aquaculture. In addition, the results also indicated that the nitrite concentrations were generally very low across all the treatment, with means ranging from 0.03 mg/L to 0.15 mg/L. Treatment 1 showed a slightly higher mean (0.15 mg/L) compared to the other treatments, which ranged between 0.03 and 0.04 mg/L. Maximum nitrite levels did not exceed 0.40 mg/L. These results indicate minimal risk of nitrite toxicity, which can impair oxygen transport in fish. Additionally, the also demonstrated that the water temperature remained stable across all treatments with mean values ranging from 27.32°C (T2) to 27.60°C (T5), and an overall mean of 27.46°C. It also further shows that the minimum and maximum temperatures ranged from

23.8°C to 30.1°C. These values obtained are suitable for the growth performance and metabolism of C. gariepinus fingerlings. These results were all significantly the same p (>0.05) in all the experimental containers for *C. gariepinus* fingerlings throughout the cultured period providing optimal thermal conditions for fingerling metabolism and growth (FAO, 2019).

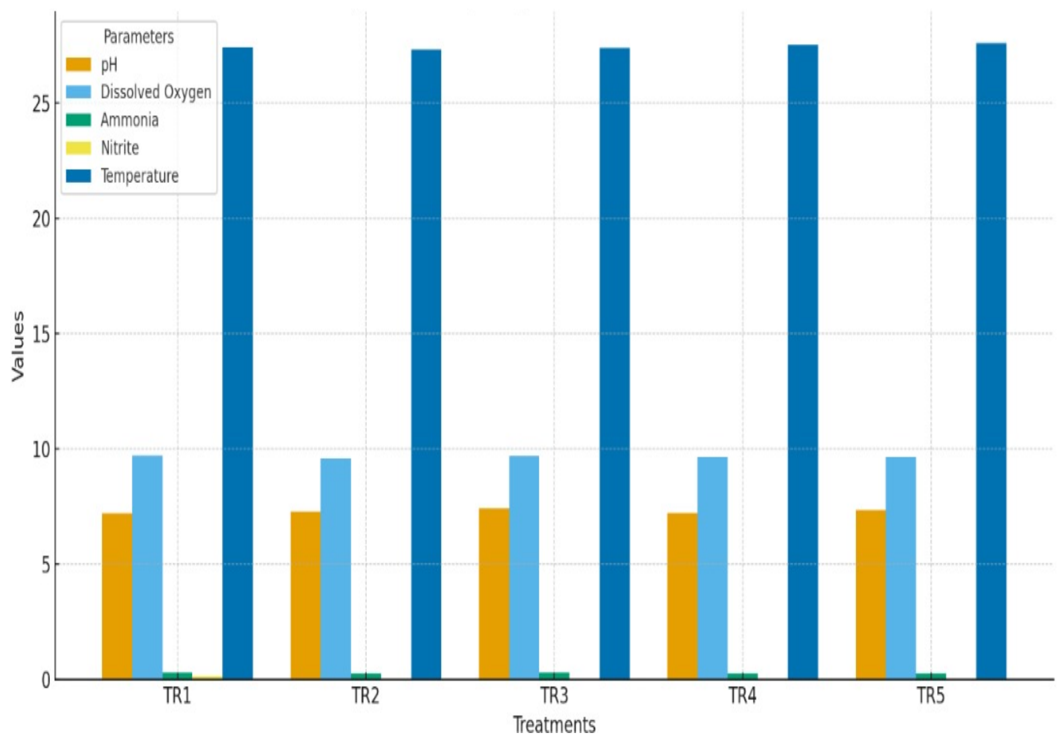

Figure 6: Summary of water quality parameters across treatments

4.4 OBJECTIVE THREE

4.4.1 Evaluate the hematological parameters of the experimental fish before and after the experiment.

Null Hypothesis

- The inclusion of varying levels of Black Soldier Fly (BSF) meal in the diets of *Clarias gariepinus* fingerlings has no significant effect on their hematological parameters before and after the feeding trial (H_0).
- The inclusion of varying levels of Black Soldier Fly (BSF) meal in the diets of *Clarias gariepinus* fingerlings has a significant effect on one or more hematological parameters before and after the feeding trial (H_1).

The results indicated that the initial fish had a WBC of **105.8 $\times 10^9$/L**, reflecting normal immune status. Experimental diets showed variable WBC values, ranging from **28.07 ± 34.85 in TR-1** to **81.60 ± 37.47 in TR-4,** demonstrating that diet significantly influenced leukocyte levels. TR-1 and TR-5 recorded lower WBC and lymphocyte counts compared to the baseline, suggesting possible immunosuppression or stress caused by inadequate dietary composition. In contrast, TR-2 and TR-3 maintained higher WBC and lymphocyte levels (**57.08 ± 39.93 and 67.79 ± 45.19),** demonstrating that these diets supported immune function. Monocyte counts were slightly elevated in TR-1 and TR-5, which may indicate a compensatory response to dietary stress. These findings are consistent with previous research showing that feed protein and quality influence leukocyte populations in *Clarias gariepinus* (Adeyemo et al., 2017; Faggio et al., 2020).

Red blood cell counts showed that the initial fish had 1.97 $\times 10^6$/µL, while TR-3, TR-4, and TR-5 demonstrated higher RBC values **(**2.31 ± 1.59, 2.41 ± 1.92**),** indicating enhanced erythropoiesis likely supported by adequate dietary protein. TR-1, however, had a lower RBC **(**1.27 ± 1.01**),** suggesting potential anemia or reduced oxygen transport. Hemoglobin (HGB) and hematocrit (HCT) results further demonstrated that TR-2 and TR-4 maintained values closer to baseline, showing effective erythropoietic activity, whereas TR-1 exhibited low HGB **(**11.43 ± 12.66 g/dL**)** and HCT **(**6.67 ± 6.90%**),** indicating poor physiological condition due to nutritional stress.

Red blood cell indices (MCV, MCH, and MCHC) were variable among treatments, particularly in TR-5, demonstrating heterogeneity in erythrocyte size and hemoglobin content. MCV was slightly lower in TR-1 and TR-3, indicating smaller erythrocytes, possibly due to limited nutrient intake.

Overall, the results demonstrated clear trends: TR-1 showed lower WBC, RBC, HGB, and HCT, reflecting poor physiological performance; TR-2 and TR-3 maintained moderate immune parameters; and TR-4 and TR-5 showed improved RBC and HGB, suggesting better oxygen transport. Comparison with initial fish indicated that diet composition strongly affected both immune and erythropoietic parameters. Among the diets tested, TR-4 produced the most favorable hematological profile, maintaining parameters close to physiological baseline ranges.

In conclusion, the study showed that experimental diets significantly influenced hematological parameters in *Clarias gariepinus*. Diets providing adequate protein and nutrients supported immune competence and erythropoiesis, whereas deficient diets impaired physiological health. These findings emphasize the importance of balanced diet formulation in aquaculture to optimize fish health and growth performance.

Table 7. Hematological Parameters of Experimental Fish (*Clarias gariepinus)* (Mean ± SD)

Parameter	*Initial Fish*	*TR-1*	*TR-2*	*TR-3*	*TR-4*	*TR-5*
WBC ($\times 10^9$/L)	105.8	28.07 ± 34.85	66.31 ± 50.23	76.97 ± 50.99	81.60 ± 37.47	45.97 ± 53.68

LYM	98.6	25.63 ± 31.63	57.08 ± 39.93	67.79 ± 45.19	69.93 ± 28.95	35.53 ± 50.61
MON	6.6	1.18 ± 1.52	6.58 ± 4.93	7.76 ± 5.28	9.23 ± 10.05	7.68 ± 7.42
RBC	1.97	1.27 ± 1.01	1.79 ± 1.03	1.73 ± 0.90	2.31 ± 1.59	2.41 ± 1.92
LYM %	93.2	63.23 ± 32.62	90.87 ± 1.99	73.87 ± 30.03	89.73 ± 13.78	61.23 ± 32.87
MON %	6.2	13.11 ± 12.97	5.63 ± 3.92	14.23 ± 13.13	8.83 ± 9.98	16.53 ± 13.95
HGB (g/dL)	6.9	11.43 ± 12.66	8.43 ± 4.96	7.90 ± 6.03	9.10 ± 6.02	7.13 ± 5.51
HCT (%)	25.8	6.67 ± 6.90	30.43 ± 1.85	13.73 ± 10.80	27.37 ± 20.01	17.10 ± 18.80
MCV (fL)	131.0	116.47 ± 3.90	125.47 ± 5.54	120.57 ± 6.18	114.93 ± 9.11	123.87 ± 2.19
MCH (pg)	35.0	56.77 ± 59.73	47.97 ± 13.74	52.67 ± 44.10	40.03 ± 5.03	82.77 ± 46.62

MCHC (g/dL)	26.7	47.53 ± 46.27	36.33 ± 5.30	57.20 ± 27.20	35.30 ± 5.04	62.30 ± 38.65

4.5 OBJECTIVE FOUR

4.5.1 To evaluate the weight and length of fish as a means of ascertaining the nutritional quality of the experimental diets.

4.5.1.1 Weight and Length

Null Hypothesis

- There is no significant difference in the weight and length of *Clarias gariepinus* fingerlings fed diets with varying levels of Black Soldier Fly (BSF) meal (H_0).
- There is a significant difference in the weight and/or length of *Clarias gariepinus* fingerlings fed diets with varying levels of Black Soldier Fly (BSF) meal (H_1).

The results indicated that the growth of fish under the five dietary treatments (T1–T5) over eight weeks showed clear differences in both weight and length (Table 1). As shown in Table, fish in T5 gained the most weight (16.24 ± 1.0 g), which was significantly higher than the weights recorded in T1 (12.24 ± 1.0 g), T2 (13.48 ± 1.0 g), T3 (13.91 ± 1.0 g), and T4 (14.09 ± 1.0 g). This shows that the T5 diet provided better nutrients or was more easily digested, leading to faster growth. Hassan et al. (2020) also reported that balanced diets and proper feeding rates improve fish growth, while Li et al. (2024) found that good feed formulation and stocking density enhance the growth of juvenile gibel carp. A similar trend was seen in fish length. At the end of the trial, fish in T5 reached the longest total length (13.57 ± 0.5 cm) and standard length (12.19 ± 0.3 cm), while fish in T1 were the shortest. The statistical differences, shown by superscript letters in the table, confirm that T5 fish were significantly longer than those in other treatments. This agrees with Simasiku et al. (2024), who observed better growth in fish given high-quality commercial diets compared to low-quality feeds. Standard length increased steadily in all treatments from week 0 to week 8, showing continuous growth. At the beginning, there were no significant differences among treatments, which means all fish started at about the same size. By week 4, differences appeared: fish in T5 had a larger standard length (11.11 ± 0.06 cm) compared to fish in the other groups. By week 8, the difference became even clearer, with T5 recording the highest value (12.19 ± 0.06 cm) and T1 the lowest (11.21 ± 0.06 cm). This shows that fish fed a nutrient-rich diet (T5) continued to grow better throughout the trial. The differences among treatments are likely due to the composition and quality of the diets. T5 seems to have supplied the right balance of protein and energy, supporting both weight and length growth. On the other hand, T1 may have been low in protein or other essential nutrients, limiting fish growth. Similar results have been reported in other studies, which highlight that diet formulation and feeding practices are key factors in improving growth, feed efficiency, and overall fish health (Li et al., 2024; Hassan et al., 2020; Simasiku et al., 2024). In conclusion, diet had a strong influence on the growth of fish in this study. T5 consistently gave the best results for weight, total length, and standard length, showing that it provided the most suitable nutrients for fish development. This highlights the importance of proper feed formulation and balanced nutrition in aquaculture to achieve faster growth, healthier fish, and more sustainable production.

Table 8. Final Biometric Measurements and Weekly Changes in Standard Length (SL, cm)

Treatment	*Final Weight (g)*	*Final Total Length (cm)*	*Final Standard Length (cm)*	*SL Week 0 (cm)*	*SL Week 2 (cm)*	*SL Week 4 (cm)*	*SL Week 6 (cm)*	*SL Week 8 (cm)*
T1	12.24 ± 1.0	12.36 ± 0.5	11.21 ± 0.3	9.34 ± 0.03^{a}	12.13 ± 0.05^{a}	10.12 ± 0.04^{a}	11.48 ± 0.05^{a}	11.21 ± 0.06^{a}
T2	13.48 ± 1.0	12.33 ± 0.5	10.88 ± 0.3	9.43 ± 0.04^{a}	9.76 ± 0.06^{a}	10.25 ± 0.05^{a}	11.22 ± 0.04^{a}	10.88 ± 0.5^{ab}
T3	13.91 ± 1.0	12.83 ± 0.5	11.45 ± 0.3	9.55 ± 0.03^{a}	9.99 ± 0.05^{a}	10.48 ± 0.05^{a}	11.39 ± 0.05^{a}	11.45 ± 0.06^{abc}
T4	14.09 ± 1.0	12.98 ± 0.5	11.73 ± 0.3	9.19 ± 0.04^{a}	9.87 ± 0.05^{a}	10.48 ± 0.05^{a}	11.37 ± 0.05^{a}	11.73 ± 0.06^{bc}
T5	16.24 ± 1.0	13.57 ± 0.5	12.19 ± 0.3	9.46 ± 0.03^{a}	10.03 ± 0.05^{a}	11.11 ± 0.06^{b}	11.71 ± 0.05^{a}	12.19 ± 0.06^{c}

4.5.1.2 Standard and Total Lengths

Hypothesis

- There is no significant difference in the growth (standard length and total length) of *Clarias gariepinus* fingerlings among the five dietary treatments over the 8-week feeding trial (H_0).

- There is a significant difference in the growth (standard length and total length) of *Clarias gariepinus* fingerlings among the five dietary treatments over the 8-week feeding trial, with higher BSF meal inclusion (e.g., T5) resulting in significantly greater growth (H_1).

The growth of *Clarias gariepinus* fingerlings over the 8-week feeding trial varied among the five dietary treatments. At the start (Week 0), fingerlings were similar in size, with standard lengths (SL) ranging from 9.19 ±0.04 cm (T4) to 9.55 ±0.03 cm (T3) and total lengths (TL) from 10.53 ±0.03 cm (T4) to 10.85 ±0.03 cm (T3). This uniformity ensures that later differences were due to diet composition. By Week 8, fish fed Treatment 5 (T5) showed the highest growth, reaching 12.19 ±0.06 cm (SL) and 13.57 ±0.06 cm (TL), significantly higher than T1 and T2 ($p < .05$). T4 (SL: 11.73 ±0.06 cm; TL: 12.98 ±0.06 cm) and T3 (SL: 11.45 ±0.06 cm; TL: 12.83 ±0.06 cm) had intermediate growth. T1 and T2 showed the lowest growth (SL: 11.21 ±0.06 cm and 10.88 ±0.05 cm; TL: 12.36 ±0.06 cm and 12.33 ±0.05 cm), with T2 significantly lower than T5. Percentage increases in SL (15.4–28.9%) were higher than TL (14.6–25.7%), suggesting that internal body growth responded more strongly to diet quality. Higher BSF meal inclusion, as in T5, likely improved protein quality, amino acid availability, and digestibility, resulting in better growth. Lower growth in T1 and T2 reflects insufficient nutrients or lower feed efficiency. These results align with previous studies showing that diet quality, especially protein content and digestibility, strongly influences fish growth (Adewolu, Olaniyi, & Olatunji, 2011; El-Sayed, 2021; NRC, 2011). Using BSF meal as an alternative protein source can improve growth and support sustainable aquaculture by reducing reliance on conventional fishmeal (Kumar, Singh, & Patel, 2020; FAO, 2020). T5, with the highest BSF meal inclusion, consistently promoted the best growth in both SL and TL, showing that higher BSF inclusion provides optimal nutrition for fingerling development.

Table 9. Weekly Changes in Standard Length (SL, cm)

Treatment	*TL Week 0*	*TL Week 2*	*TL Week 4*	*TL Week 6*	*TL Week 8*
T1	9.34 ±0.03 ^{a}	12.13 ±0.05 ^{a}	10.12 ±0.04 ^{a}	11.48 ±0.05 ^{a}	11.21 ±0.06 ^{a}
T2	9.43 ±0.04 ^{a}	9.76 ±0.06 ^{a}	10.25 ±0.05 ^{a}	11.22 ±0.04 ^{a}	10.88 ±0.05 ^{ab}
T3	9.55 ±0.03 ^{a}	9.99 ±0.05 ^{a}	10.48 ±0.05 ^{a}	11.39 ±0.05 ^{a}	11.45 ±0.06 ^{abc}
T4	9.19 ±0.04 ^{a}	9.87 ±0.05 ^{a}	10.48 ±0.05 ^{a}	11.37 ±0.05 ^{a}	11.73 ±0.06 ^{bc}
T5	9.46 ±0.03 ^{a}	10.03 ±0.05 a	11.11 ±0.06 ^{b}	11.71 ±0.05 ^{a}	12.19 ±0.06 ^{c}

Table 10. Weekly Changes in Total Length (SL, cm)

Treatment	*TL Week 0*	*TL Week 2*	*TL Week 4*	*TL Week 6*	*TL Week 8*
T1	10.55 ±0.03 ^{a}	11.15 ±0.04 a	11.64 ±0.05 a	11.48 ±0.04 a	12.36 ±0.06 ^{a}
T2	10.77 ±0.04 a	13.86 ±0.05 a	11.80 ±0.05 a	11.22 ±0.04 a	12.33 ±0.05 a
T3	10.85 ±0.03 a	11.45 ±0.05 a	12.03 ±0.05 a	11.39 ±0.04 a	12.83 ±0.06 ab
T4	10.53 ±0.04 a	11.33 ±0.05 a	11.99 ±0.05 a	11.37 ±0.04 a	12.98 ±0.06 ab
T5	10.80 ±0.03 a	11.48 ±0.05 a	11.96 ±0.06 a	11.71 ±0.05 a	13.57 ±0.06 ab

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study was conducted to evaluate the effects of diets with varying levels of Black Soldier Fly (BSF) meal on the growth performance, nutrient utilization, water quality, hematological parameters, proximate and mineral composition, and morphometric development (weight and length) of *Clarias gariepinus* fingerlings. The results showed that dietary treatments had a significant impact on fish performance across all measured parameters. Specifically, fish fed with TR4 and TR5 diets exhibited statistically significant ($p < 0.05$) improvements in weight gain, specific growth rate (SGR), protein efficiency ratio (PER), and feed conversion ratio (FCR) compared to the control group (TR1). TR5 recorded the best performance overall, indicating that higher inclusion of BSF meal led to better nutrient absorption and utilization. Condition factor (K) values were also higher in these groups, reflecting better body condition.

Water quality remained within the optimal range across all treatments, with parameters such as pH (6.2–8.6), dissolved oxygen (8.00–10.00 mg/L), ammonia (0.20–0.40 mg/L), nitrite (0.03–0.40 mg/L), and temperature (23.8–30.1°C) showing no significant variation ($p > 0.05$) between groups. This confirmed that the culture environment was stable and not a contributing factor to the differences in fish growth or health. The condition factor across treatments remained favorable, further supporting the conclusion that the observed performance differences were due to dietary composition rather than environmental conditions.

In assessing hematological responses, significant differences were observed between treatments. Fish fed TR4 and TR5 diets showed significantly higher ($p < 0.05$) red blood cell (RBC) counts, hemoglobin (HGB) concentrations, and improved white blood cell (WBC) profiles compared to those in TR1. These results indicate enhanced oxygen transport capacity and immune function in fish receiving the higher BSF meal diets, whereas the control group showed lower hematological values, likely due to nutritional deficiencies. These findings highlight the role of diet in maintaining physiological and immune health and support the use of hematological parameters as reliable indicators of fish wellbeing.

The proximate and mineral composition of the fish also varied significantly across treatments. Fish in TR5 showed significantly higher ($p < 0.05$) levels of crude protein, fat, ash, and nitrogen-free extract (NFE) compared to TR1 and TR2, reflecting superior nutrient retention and metabolic efficiency. Similarly, calcium and sodium levels were elevated in TR5, while magnesium decreased across all treatments. In terms of morphometric growth, TR5-fed fish achieved the highest final weight and length measurements, with values significantly different **(**$p < 0.05$) from those recorded in TR1. These results confirm that diets containing higher levels of BSF meal significantly improve growth, nutrient composition, and overall health of *Clarias gariepinus*, thereby meeting all study objectives and supporting the inclusion of BSF meal as a functional and sustainable protein source in aquaculture.

5.2 Recommendations

The following recommendations, based on the outcomes of this study, should be considered and implemented to support the aquaculture sector in the production of Black Soldier Fly Meal

(BSFMM). Therefore, in order to strengthen aquaculture and reduce dependence on fish meal in Sierra Leone, it is recommended that:

- It is recommended that private and public sectors support the establishment of modern insectariums and sustain BSF larvae production beyond the INCiTiS-Food Project to encourage long-term aqua-feed investment.
- It is recommended that Njala University integrate insect larvae production into aquaculture teaching, research, and extension programs, while offering students advanced training opportunities in insect farming.
- It is recommended that fish farmers receive training to produce high-quality BSF meal ingredients locally, thereby reducing fish meal shortages.
- It is recommended that national awareness and dissemination of information on insect-based feeds be promoted to enhance adoption across the aquaculture sector.

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APPENDIX

Treatment	*WBC*	*LYM*	*MON*	*LYM%*	*MON%*	*HGB*	*HCT*	*MCV*	*MCH*	*MCHC*	*RBC*
TR-1.1	68.3	67.6	0.6	99	0.9	5.2	14.9	112.9	39.4	34.9	1.32
TR-1.2	7.07	2.78	1.85	39.3	26.2	3.1	3.1	119.9	119.9	100	0.26
TR-1.3	8.83	4.54	1.08	51.4	12.2	26	2	116.6	9	7.7	2.23
TR-2.1	11.8	11.7	0	99.1	0.3	1.5	4.4	118.9	40.5	34.1	0.37
TR-2.2	35.45	32.72	0.42	92.2	1.1	13.3	30.6	130.6	56.8	43.5	2.34
TR-2.3	109.1	98.8	9.4	90.6	8.6	9.7	29.9	121.1	39.3	32.4	2.67
TR-3.1	19.5	6.47	5.89	33.1	30.2	5.6	5.8	120.3	110.4	91.4	0.48
TR3.2	108.9	97.8	9.9	89.8	9.1	9.2	29.7	123.2	38.2	31	2.41
TR-3.3	104.9	97.9	6.5	93.3	6.2	8.9	26.8	116.5	38.7	33.2	2.3
TR-.4.1	106.4	76.7	22.9	72.1	21.5	15.6	48.7	126.2	40.4	32	3.86
TR-4.2	99.9	94.9	4.7	95	4.7	8	24.4	108.4	35.6	32.8	2.25
TR-4.3	38.5	38.2	0.1	99.3	0.3	3.7	9	108.4	44.6	41.1	0.83
TR-5.1	110.7	99.7	18.3	99.8	16.5	13.3	39.8	124.3	40.9	35.7	3.3
TR-5.2	15.28	6.08	4.67	39.7	30.5	5.4	8.4	123.7	79.4	64.3	3.68
TR-5.3	1.91	0.84	0.05	44.2	2.6	2.7	3.1	123.6	128	87.1	0.25
Treatment	**WBC**	**LYM**	**MON**	**LYM%**	**MON%**	**HGB**	**HCT**	**MCV**	**MCH**	**MCHC**	**RBC**
TR-1.1	68.3	67.6	0.6	99	0.9	5.2	14.9	112.9	39.4	34.9	1.32
TR-1.2	7.07	2.78	1.85	39.3	26.2	3.1	3.1	119.9	119.9	100	0.26

TR-1.3	8.83	4.54	1.08	51.4	12.2	26	2	116.6	9	7.7	2.23
TR-2.1	11.8	11.7	0	99.1	0.3	1.5	4.4	118.9	40.5	34.1	0.37
TR-2.2	35.45	32.72	0.42	92.2	1.1	13.3	30.6	130.6	56.8	43.5	2.34
TR-2.3	109.1	98.8	9.4	90.6	8.6	9.7	29.9	121.1	39.3	32.4	2.67
TR-3.1	19.5	6.47	5.89	33.1	30.2	5.6	5.8	120.3	110.4	91.4	0.48
TR3.2	108.9	97.8	9.9	89.8	9.1	9.2	29.7	123.2	38.2	31	2.41
TR-3.3	104.9	97.9	6.5	93.3	6.2	8.9	26.8	116.5	38.7	33.2	2.3
TR-.4.1	106.4	76.7	22.9	72.1	21.5	15.6	48.7	126.2	40.4	32	3.86
TR-4.2	99.9	94.9	4.7	95	4.7	8	24.4	108.4	35.6	32.8	2.25
TR-4.3	38.5	38.2	0.1	99.3	0.3	3.7	9	108.4	44.6	41.1	0.83
TR-5.1	110.7	99.7	18.3	99.8	16.5	13.3	39.8	124.3	40.9	35.7	3.3
TR-5.2	15.28	6.08	4.67	39.7	30.5	5.4	8.4	123.7	79.4	64.3	3.68
TR-5.3	1.91	0.84	0.05	44.2	2.6	2.7	3.1	123.6	128	87.1	0.25