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REVIEW

Utilization of Black Soldier Fly (*Hermetia illucens* Linnaeus) Larvae as a Protein Source for Fish Feed: A Review

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Abstract

Aquaculture plays a major role in curbing malnutrition and food insecurity. Nonetheless, aquaculture sustainability is threatened by expensive fish feeds due to the overreliance on fish meal (FM) as the main source of protein. Fish meal is not only expensive but also scarce due to declining capture fisheries and competition from other animal feed producers. This has prompted research on potential FM replacers, amongst them the black soldier fly (BSF) larvae (*Hermetia illucens*). The BSF larvae can effectively convert organic wastes into a potential valuable feed source, and its high nutritional content (crude protein of up to 64% dry matter) is vital for fish feed formulation. Nevertheless, there are no documented studies on the complete replacement of FM in the diets of fish using BSF larvae. Therefore, the current study reviewed 107 research publications related to BSF larvae *vis-a-vis* fish feeds production to build capacity for existing theories, identify gaps, and suggest new and further research directions, based on the previous studies available in the area of larvae production and utilization in aquaculture nutrition. The study results are expected to help farmers make an informed decision on how to reduce the cost of fish production, increase yields, thus promoting food security, livelihoods, and ecological balance.

Introduction

The growing global human population coupled with the rising living standards are factors attributed to the high demand for animal-derived protein sources (Béné et al., 2016). Fish is one of the main sources of quality protein for the human population (Little et al., 2016). However, the aquaculture industry is faced with the challenge of fish feeds, which represents up to 60-70% of operational costs in fish production (Holeh et al., 2020). Fish meal and fish oil have over the years been the main source of protein and essential fats in aquatic feed production (Betancor et al., 2016). This is due to the high nutritional value of fish meal, balanced essential amino acids profile, high essential fatty acids, and phospholipids near to requirement levels of most cultivated aquatic organisms (NRC, 2011; Tacon et al, 2011). However, climate change, high global demand, and competition for fish meal and fish oil by both humans and other animal feed manufacturers have increased the pressure on global supplies coupled with rising market prices of the products (Van Huis et al., 2013; Tschirner and Simon, 2015; FAO, 2020). The use of non-conventional ingredients from both plant and animal-based sources have shown limited success in replacing fish meal due to unbalanced nutrition, presence of anti-nutritional factors and processing challenges (Amza and Tamiru, 2017; Hua et al., 2019; Mertenat et al., 2019, Musyoka et al., 2020).

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Insects have been a subject of discussion as potential replacements of fish meal in aquaculture because they contain relatively high protein levels with high availabilities for animals (Veldkamp et al., 2012; Van Huis et al*.,* 2013; Bosch et al., 2014). Various species of Coleoptera and Diptera, including BSF (*H. illucens*) (Newton et al., 2005a), common houseflies (*Musca domestica)* (Awomyi, 2007) and beetles (*Tenebrio molitor)* (Li et al., 2013) that have been reared on low-grade bio-wastes have effectively converted organic wastes into high-quality proteins. The BSF larvae appear to be superior among other insects as a potential source of protein in the fish feed formulations (Muin et al., 2017). This is due to its polyphagous, voracious nature and effectiveness in converting organic waste into high-quality nutrients (Kim et al., 2011; Veldkamp et al., 2012). Moreover, BSF, being neither a non-vector nor a pest, is easy to culture in simple structures. In addition, it is known to reduce the presence of harmful bacteria from the food substrates (Erickson et al., 2004; Liu et al., 2008) and has a prebiotic effect on the fish (Gariglio et al., 2019). Successful dietary inclusion of BSF larvae in fish diets has shown improved fish yields and reduced production cost, thus promoting profitability and resource utilization.

Review Method and Scope

The scoping review methodology (Arksey and O'Malley, 2005) and systematic reviews approach were adopted in the present study to generate a comprehensive literature review on the potential of the BSF larvae as an alternative protein source in fish feed production. The literature review is focused on the nutritional value of BSF larvae, biotic and abiotic conditions that affect its performance and suitability as fish feed. To meet the set objectives, a wide range of keywords were searched in online database tools and scientific domains of Science Direct, Research Gate, Google Scholar and Web of Science to establish the value of *H. illucens* in terms of the utilization of fish feeds. The collected literature database was organized in copies, excerpts and notes according to topics. The current paper is a result of 107 research publications that met the inclusion criteria for the review paper.

Basic Culture Method of *Hermetia illucens*

Biology and reproduction

Understanding the biology, growth, survival and reproduction is vital for the utilization of BSF larvae as an ingredient for fish feed formulation. The BSF (*H. illucens*) belongs to the order *Diptera* and in the *Stratiomyidae* family (Awasthi et al., 2020). The *H. illucens* occurs in the tropical and sub-tropical regions of the world, and possess holometabolous metamorphosis (Dortmans et al., 2017). Their life cycle starts from an egg, which also marks the end of the previous life stage *i.e.,* the female dies after laying eggs (Dortmans et al., 2017). A female fly lays 400 to 800 eggs in tiny, dry and well-sheltered cavities and close to a food source, preferably decomposing organic matter. This is to protect the eggs from predators and prevent dehydration of the egg packages from direct sunlight alongside increasing the chances of the survival of the larvae upon hatching (Dortmans et al., 2017). After hatching, the cream-like larvae take up large amounts of decomposing organic matter and increase from few millimeters to approximately 2.5 cm in length and 0.5 cm in width (Dortmans et al., 2017). The voracious feeding allows for the storage of enough fats and proteins to aid in the process of pupation, fly emergence, mating and oviposition.

Larval development takes a period of 14 to 16 days under optimal conditions (Shumo et al., 2019) as shown in Table 1. The optimum temperature required by BSF ranges between 26°C and 27°C (Dortmans et al., 2017). Temperatures above 30°C trigger the larvae to move away from the substrate in search of cooler areas while temperatures below 24°C reduce the metabolic activity of the insect leading to reduced growth (Holmes et al., 2016; Dortmans et al., 2017). The optimum relative humidity for growth of the BSF larvae ranges between 60-70%, while the recommended substrate moisture ranges between 52-70% (Holmes et al., 2012). Nevertheless, the BSF larvae have the ability to prolong their life cycle during unfavorable conditions (Shumo et al., 2019).

The pupae stage is symbolized by the replacement of the larval mouth-parts with a hook-shaped structure and the change in colour from cream to dark brown-charcoal grey. The pupa uses its hook-shaped structure to move out and away from the substrate into a shaded and protected environment safe from predators (Zurbrügg et al., 2018). The pupation stage takes between two to three weeks and is marked by the transformation of the pupa into a fly. The emergent fly does not feed and is only dependent on water for development along the life cycle (Zurbrügg et al., 2018). During this phase, the adult searches for a partner, copulates and the female lays eggs. The flies have been found to prefer copulating in shaded areas during the morning light and females lay their eggs in well-shaded

Table 1. Abiotic factors for rearing black soldier fly (BSF). *Adapted from (*Barragan *et al*., 2017*).*

	Minimum	Optimal	Maximum	References
Temperature (°C)	12	26-27	36	Holmes *et al*., 2016
Relative Humidity (%)	25	60-70	99	Gobbi *et al*., 2013
Substrate Moisture (%)	40	52-70	70	Holmes, 2010
Light Intensity/m^2/s	60	135-200	-	Zhang *et al*., 2010

dark crevices near substrates (Au, 2021). Light intensity affects both the mating and egg fertilization of BSF (Zurbrügg et al., 2018). However, it has been suggested that light spectral composition plays a more important role in fertilization than light intensity. Light-emitting diodes producing wavelengths in the UV, blue and green ranges have proved to increase the proportion of fertilized eggs (Oonincx et al., 2016).

Culture substrates for BSF larvae

Like most organisms, the growth, production and maturation of *H. illucens* is highly dependent on the quantity and nutritional quality of the culture substrates as well as the environmental conditions. Adult BSF does not take up any food (Tomberlin, et al. 2002) but instead survives on the food reserves built up during the larval stage and water (Diener et al., 2011; Nguyen et al., 2015). It is only the larvae stage in the life cycle of the BSF that feeds. Therefore, successful larval growth and performance are highly influenced by the dietary composition of the substrates. Substrates rich in protein and carbohydrates result in good larval growth and translate to larvae with high crude protein and fats (Dortmans et al., 2017). Whereas, culture substrates that have high oily amounts produce larvae with high lipid levels, which subsequently translates to lower protein contents, because of the inverse relation of proteins and lipids in animal tissues (Mohanta et al., 2016; Musyoka et al., 2019).

The BSF is naturally found in and around faecal waste piles of livestock, poultry, swine and humans (Dortmans et al., 2017). Further, they are found colonizing domestic and industrial residues such as vegetable and fruit wastes, decaying coffee pulp and municipal organic effluents (Barragan et al., 2017). The presence of bacterial and fungal communities in these wastes acts as decomposition aids to further breakdown organic matter making it easier for the larvae to access the nutrients (Dortmans et al., 2017). In BSF culture units, the larvae can be fed with a wide range of organic residues, which are rich in nitrogen and calcium (Dortmans et al., 2017). The larvae prefer food substrates with moisture content between 52-70% but it exhibits phenotypic plasticity allowing them to adapt to any environmental variability (Tomberlin et al., 2002; Wang and Shelomi, 2017; Shumo et al., 2019).

It is important to note that, the popularization in the use of insects as food sources in the modern-day culture are closely tied with the issues of food safety. For example, in Europe there are more stringent rules and policies that prioritize risk avoidance such as those regarding insects as food sources. The EU framework terms BSF larvae as at risk of carrying biological and/or chemical food safety hazard as a function of feeding substrate (Wang and Shelomi, 2017). Nonetheless, as of May 2017, this regulation had identified seven insect species, *Hermetia illucens* included, that fulfill the safety conditions for insect production for farmed and pet animal feed. The regulation has however placed restrictions on the substrates fed to BSF larvae not to contain products of animal origin and not to be obtained from flesh and manure (human food waste) - EU Commission Regulation of 2017 (Tan et al., 2018).

On the other hand, the Food and Drug Administration (FDA) of USA only approves the utilization of dried larvae of *Hermetia illucens* cultured exclusively in feed grade substrates containing not less than 34% crude protein and 32% fat. Consequently, this regulation equally limits the rearing of BSF larvae destined for fish/chicken or human feed with kitchen wastes, animal manure or municipal wastes.

Biochemical Composition of BSF Larvae in Relation to Fish Feed Production

Crude protein and fat content

The BSF has a relatively higher crude protein (CP) and crude fat (CF) composition compared to other insects that have been utilized in the formulation of animal feeds among them: mealworm beetle (*Tenebrio molitor)* (Barroso et al., 2014), cricket (*Gryllus campestris*) (Rothman et al., 2014), drone fly (*Eristalis tenax)* (Kuntadi et al., 2018) and beetles; (Huang et al., 2019) (Table 2). Previous studies have reported BSF larvae to have relatively high protein and fat contents of up to 64% and 30%, respectively. (St-Hilaire et al., 2007a; Zheng et al., 2012). The quality and quantity of substrate plays a big role in determining the body composition of the larvae (Gobbi et al., 2013; Nguyen et al., 2015). Newton et al. (2005b) and St-Hilaire et al. (2007b), reported higher protein contents in larvae fed on swine manure (43.6%) than those fed cattle manure (42.1%). Also, a study by Nguyen et al. (2015) found that larvae fed fish and liver contained more proteins and fats than those fed chicken feed. Similarly, several studies have reported higher fat content in larvae reared on cattle manure (34.8%) in comparison to chicken (27.9%) and swine manure (26.4%) as shown in Table 3.

Further, the crude protein content of BSF larvae is influenced by the processing method. Higher CP

Table 2. Crude protein and crude fat contents in raw BSF (*H. illucens*) compared to mealworm beetle (*Tenebrio molitor)*, cricket (*Gryllus campestris*) and Drone fly (*Eristalis tenax)*, (g/100 g dry matter)

Insect	Crude protein	Crude fat	References
Mealworm beetle (*Tenebrio molitor*)	38.3	26.7	Kuntadi *et al*., 2018
Cricket (*Gryllus campestris*)	32.6	29.2	Kuntadi *et al*., 2018
Drone fly *(Eristalis tenax)*	40.9	5.8	Barroso *et al*., 2014
BSF (*H. illucens*)	42.0	36.2	Huang *et al*., 2019

contents have been recorded in highly defatted larvae as compared to partially defatted and full-fat larvae (Schiavone et al., 2017; Cardinaletti et al., 2019) as shown in Table 4. Defatting is usually done by freezing and cutting the larvae into small pieces (to allow the intracellular fat to leach out), pressing the flesh using tincture pressure at 60°C for 60 minutes, then finally drying the material for 20 hours in an oven at low temperature of about 60°C before grinding to a meal (Kroeckel et al., 2012). Besides, defatting of the larvae leads to lower amounts of fat content in the larvae making it easier for the formulation, grinding and pelletization of fish feeds (Briggs et al., 1999).

Amino acid content

Essential amino acids (AA) are vital nutrients that are considered when selecting a fish feed ingredient. These AA promote growth and reproduction rates alongside improving the disease resistance to aquatic organisms (Andersen et al., 2016; Musyoka et al., 2019). The AA content in BSF larvae is mainly influenced by the processing of the larvae. Defatting, which involves the mechanical or chemical removal of fat from the larvae has been found to help increase the amino acid content of dried BSF larvae meal (Andersen et al., 2016; Renna et al., 2017). Most studies have shown that the amino acid contents of the BSF larvae do not differ much (Table 5). Several studies have reported a relatively low methionine content of the BSF larvae meal when compared to fish meal. However, the BSF larvae meal have a good overall protein quality superior to fish meal and have higher contents of alanine, methionine, histidine, and tryptophan, but a lower content of arginine than soybean meal (Barragan et al., 2017).

Fatty acids in BSF larvae

The BSF larvae meal is rich in monounsaturated fats and has lower polyunsaturated fatty acid percentages than most insects such as the housefly maggots, mealworms, and adult crickets (Ghosh et al., 2017). Several studies have shown BSF larvae to contain between 58-72% saturated fatty acids and 19-40% mono and polyunsaturated fatty acids (Makkar et al., 2014; Surendra et al., 2016). Equally, the BSF larvae have been shown to contain high levels of lauric, palmitic and oleic acids (Surendra et al., 2016). The quality and quantity of fatty acid content in the BSF larvae are highly influenced by the type of substrate used. If the larvae are fed on lipid-rich animal diet, they accumulate more lipids in their bodies (which are more palatable to the fish) when compared to vegetable oils (Wang and Shelomi, 2017). Additionally, BSF larvae fed on fish offal have been reported to have relatively lower values of monosaturated fatty acids as compared to those fed on swine manure (Wang and Shelomi, 2017) an indication that the type of substate has an influence on the fatty acid of the larvae. When BSF were fed with fish by-products, an increased levels of n-3 polyunsaturated fatty acids in their tissues were noted (Renna et al., 2017). St-Hilaire et al (2007a) reported an increase in the desirable fatty acids such as a-linolenic acid (ALA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) when the larvae is fed on waste materials from fish processing plants. In addition, BSF larvae oil has been found to possess a good balance of saturated and unsaturated fatty acid (Makkar et al., 2014) (Table 6). Black soldier fly larvae provide the necessary fatty acids to meet the different nutritional requirements of different fish species (Table 7).

Table 3. Content of crude protein (CP) and crude fat (CF) of BSF larvae reared on different substrates. Adapted from (Barragan *et al*., 2017).

Substrate	% CP*	%CF	References
Cattle manure	42.1	34.8	Li *et al*., 2011b
Chicken manure	40.1	27.9	Arango *et al*., 2005
Swine manure	43.6; 43.2	26.4	St-Hilaire *et al*., 2007b; Li *et al*., 2011a
Palm kernel meal	42.1; 45.8	27.5	Rachmawati *et al*., 2010
Restaurant waste	-	39.2	Zheng *et al*., 2012
Chicken feed	47.9	14.6	Bosch *et al*., 2014; Oonincx *et al*., 2015b
By-products**	41.7	-	Oonincx *et al*., 2015a
Liver	62.7	25.1	Nguyen *et al*., 2015
Fruits and vegetables	38.5; 30.84	26.63; 33.10	Nguyen *et al*., 2015, Cardinaletti *et al*., 2019
Fish	57.9	34.6	Nguyen *et al*., 2015

* All values are expressed on a dry matter basis. ** Beet molasses, potato steam peelings, spent grains and beer yeast, bread remains.

Table 4. Nutritional value of a partially defatted and a highly defatted BSF (BSF) larvae (*H. illucens* L.) meal.

Nutrition	BSF full fat* meal	BSF partially defatted** meal	BSF highly defatted** meal
Dry matter, g/kg diet	791	942	985
Organic matter, g/kg DM	-	901	907
Crude protein, g/kg DM	308	553	655
Ether extract, g/kg DM	331	180	46
Gross energy, MJ/kg DM	-	24.4	21.2
Chitin, g/kg DM	-	50	69

Note: * Cardinaletti *et al*., 2019, ** Schiavone *et al*., 2017

Table 5. Amino acid profile of the BSF larvae (g/kg dry matter). *Adapted from* Spranghers *et al.,* (2017).

	Chicken feed	Digestate	Vegetable waste	Restaurant waste
Essential amino acids				
Isoleucine	17.2	18.4	17.3	19.1
Leucine	28.6	29.5	28	30.6
Lysine	23.4	25.7	22.6	23
Arginine	20.3	20.3	20	19.9
Methionine	7.6	8.7	7.6	7.1
Histidine	13.6	13.5	12.4	3.8
Phenylalanine	17	18.7	16.3	16.4
Threonine	16.4	16.8	15.4	16.2
Non-essential amino acids				
Alanine	25.2	24.3	24.2	27.8
Cystine	2.5	2.4	2.1	2.2
Glutamic acid	41.9	39.8	41.3	45.8
Glycine	22.6	22.6	22.2	25.2
Proline	22.5	22.1	21.4	25.1
Serine	16.6	15.5	15	15.9
Aspartate	37.8	33.6	35.9	36.9
Tryptophan	6.7	6.2	5.8	5.4
Valine	24.1	24.9	24.8	28.2

Mineral content in BSF larvae

BSF larvae have superior mineral content when compared to most insects that have been used in the formulation of fish feeds (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) (Table 8). Similarly, the mineral content in the BSF larvae is mainly influenced by the type of substrates used as shown in Table 9 (Fasakin et al., 2003). For instance, a study by Newton et al. (1977) reported higher levels of phosphorus in BSF larvae reared on poultry manure than those reared on swine manure. The BSF accumulate high concentrations of manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), phosphorus (P) and calcium (Ca) but sodium or sulfur concentrations have been found in small quantities compared to the larvae in other insects (Wang and Shelomi, 2017). The high Ca concentration and ash contents (9 and 28% dry matter, respectively) in the larvae are attributed to the secretion of calcium carbonate ($CaCO_3$) by the epidermis (Finke, 2013; Makkar et al., 2014). On the other hand, the low Ca content (0.03%) in the newly emerged adults has been attributed to the fact that the pupal cuticle that is concentrated with Ca is shed off to give rise to the adult fly (Finke, 2013).

Chitin in BSF

Chitin is a naturally occurring biopolymer that is made up of a mixture of mainly unbranched polymer of N-acetyl-D-glucosamine and a small amount of D-glucosamine (Soetemans et al., 2020). Chitosan is a common derivative of chitin produced by deacetylation reaction (Khayrova et al., 2019). In association with different assortments of cuticle and peritrophic matrix proteins, the yielded complex bio-composites have a wide range of physicochemical and mechanical properties that are important in healthcare, (waste) water treatment, agrochemicals, food and beverages and cosmetic application (Zhu et al., 2016). However, the crystalline nature of chitin is a major limitation in its utilization (Soetemans et al., 2020). Wang et al. (2020) recorded a gradual increase of the chitin crystalline index with development from larvae to adults i.e. 33.09% and 87.92%, respectively. The same authors found a significant difference in the chitin contents of larvae, prepupae, puparium and adults of 3.6%, 3.1%, 14.1% and 2.9%, respectively. In another study done by Soetemans et al. (2020), the chitin content in (larvae, prepupae, pupae, flies, shedding and cocoons) ranged between 8% to 24% of the total biomass with the cocoons and shedding recording the highest values. Likewise, Wang et al. (2020) indicated that the physicochemical structure of chitin was not significantly different in all the developmental stages of BSF (larvae, prepupa, puparium and adult). Chitin has been reported to be a non-digestible fibre that reduces the efficiency of nutrient absorption from the intestinal tract consequentially reducing the absorption and digestibility of lipids and proteins in animals (Razdan and Pettersson, 1994; Han et al., 2009).

Several studies have reported reduced feed intake and growth in different fish species mainly attributed to the low chitinase activity of the fish species. Chitin is said to decrease the lipid digestibility and inhibit nutrient absorption from the intestinal tract (Kroeckel et al*.,* 2012). For instance, Gopalakannan and Arul (2006) and Olsen et al. (2006) reported a decrease in feed intake and growth in common carp (*Cyprinus carpio*), tilapia (*Oreochromis niloticus × O. aureus*), and Atlantic salmon (*Salmo salar*) at a dietary inclusion level of 1%. Further, a dietary inclusion level of 10% chitin led to reduced

Table 6. Fatty acid profile of the black soldier fly larvae (Data adapted and modified from (Larouche, 2019).

Fatty acid (% lipid)	Larvae [a, b]
Lauric (C12:0)	29-61
Myristic (C14:0)	7-10
Palmitic (C16 :0)	8-17
Palmitoleic (C16: 1n-7)	3-7
Stearic (C18 :0)	1-3
Oleic (C18 :1n-9)	8-18
Linoleic (C18 :2n-6)	4-17
Alpha-Linolenic (C18 :3n-3)	0-2
Unsaturated fatty acid	18–37
Saturated fatty acid	58-80

[a] - Oonincx et al., 2015, [b] - Liu et al., 2017

Table 7. Fatty acid requirements of some fish species (Taşbozan & Gökçe., 2017)

Species	Requirements of fatty acids (in dry feeds %)
Carnivores	
Rainbow trout (*Oncorhynchus mykiss*)	Linolenic 1%
	Linolenic 0.8%
	EPA + DHA 0.4-0.5%
Sea bass (*Dicentrarchus labrax*)	EPA+DHA 1%
Sea Bream (*Sparus aurata*)	EPA+DHA 1%, EPA: DAHA= 1
	EPA+DHA 1.9%, EPA: DAHA= 0.5
Omnivores	
Common carp (*Cyprinus carpio*)	Linoleic 1%; Linolenic 0.5-1%
Japanese eel (*Anguilla japonicus*)	Linoleic 0.5%; Linolenic 0.5%
Herbivores	
Grass carp (*Ctenopharyngodon Idella*)	Linoleic 1%; Linolenic 0.5%
Tilapia (*Tilapia Zilli*)	Linoleic 1%; Linolenic 1%
Tilapia (*Oreochromis niloticus*)	Linoleic 0.5%

Table 8. Mineral contents of some insects reported by different authors.

Nutrient	Crickets (Dierenfeld & King, 2009)	Black soldier fly larvae (Dierenfeld and King, 2009)	Mealworm (Klasing *et al*., 2000)	Silkworm pupae (non deffated) (Jintasataporn, 2012)
Ca, g/kg	1.6	31.4	2.7	3.8
P, g/kg	9.1	12.8	7.8	6
K, g/kg	12.1	19.6	8.9	-
Mg, g/kg	1.1	7.9	2.3	3.7
Na, g/kg	4.6	2.7	0.9	-
Cu, mg/kg	18.9	17	16	15
Fe, mg/kg	77.7	368	57	326
Mn, mg/kg	32.7	364	9.0	28

Table 9. Means of mineral composition of BSF larvae reared on three different rearing substrates. Data adapted and modified from (Shumo *et al*., 2019)

Mineral/Substrate used	Cattle manure	Kitchen waste	Spent grain	Requirements by fish*
Phosphorus	3.9	4.1	4.6	7 g
Potassium	4.9	5.7	4.4	1-3 g
Calcium	3.2	2.0	1.7	5 g
Magnesium	4.0	3.3	3.5	500 mg
Iron	0.6	2.2	0.3	50-100 mg
Copper	0.4	0.2	0.5b	1-4 g
Manganese	1.4	0.9	1.1	20-50 mg
Zinc	0.3	0.3	0.3	30-100 mg

Note: * – NRC (2011)

growth and feed intake in rainbow trout (*Oncorhynchus mykiss*) (Lindsay et al., 1984). This has prompted studies to look into possibilities of isolating chitin from other nutritional constituents especially protein to improve the growth performances of the animals fed on diets containing BSF larvae. Separation of lipids from chitin is relatively easy as opposed to the separation of protein from chitin since the lipid is easily recovered by organic solvents. Separation of protein from chitin was carried out through alkali extraction whereby 96% of the protein was recovered (Caligiani et al., 2018). The extraction and production of chitosan involve the procedures: defatting, demineralization, de-deproteinization and deacetylation. The yielded chitosan is undertaken through an additional purification step by a reprecipitation from a solution in acetic acid (deacetylation reaction) that involves the removal of the acetyl groups from the chitin molecule (Khayrova et al., 2019).

Utilization of BSF Larvae in Fish Feed Formulation

Insect meals have been utilized in the formulation of fish feed diets for a very long time (Barragan et al., 2017). With BSF larvae having a higher reproductive capacity, short life cycle, ability to convert organic matter into high-quality protein and to thrive in a wide array of environments, the larvae have attracted enormous attention to be included in the formulation of fish diets (Barragan et al., 2017). Besides, the high protein content, digestibility and amino acid profiles of the BSF larvae have been the selling point for this meal in fish diets as shown in Table 10. The BSF meal has successfully replaced other conventional protein sources in the diets of Channel catfish (*Ictalurus punctatus*) (Bondari and Sheppard, 1981, 1987; Zhang et al., 2014a,b), blue tilapia (*Oreochromis aureus*) (Bondari and Sheppard, 1981, 1987), Nile tilapia (*Oreochromis niloticus*) (Muin et al., 2017), *O. niloticus* crossed with Sabaki tilapia (*Oreochromis spilurus*) (Furrer, 2011), rainbow trout (*Oncorhynchus mykiss*) (St-Hilaire et al., 2007b; Sealey et al., 2011), Atlantic salmon (*Salmo salar*) (Lock et al., 2015), turbot (*Psetta maxima*) (Kroeckel et al., 2012), yellow catfish (*Tachysurus fulvidraco*) (Zhang et al., 2014a) and African catfish (*Clarius gariepinus*) (Adewolu et al., 2010; Idowu and Afolayan, 2013).

The inclusion of BSF larvae meals in the diets of *O. niloticus* did not lead to any negative effects on the body weight gain (BWG) and specific growth rates (SGR) of the fish (Devic et al., 2018; Toriz- Roldan et al., 2019). Similarly, a partial or total dietary replacement of FM with BSF larvae meal did not lead to differences in the BWG and SGR of juvenile Japanese bass (*Lateolabrax japonicus)* and rainbow trout (*Oncorhynchus mykiss*),

Table 10. Summary of growth performance of different species of fish fed on BSF larvae meal diets. Bolded values represent the recommended replacement levels.

Fish species tested	Attribute/element tested	Replacement levels (%)	Author (s)
Jian carp (*Cyprinus carpio*)	A study by Li *et al*. 2017 suggested that it is possible to substitute up to 100% FM by BSF larvae meal in diets for Jian carp without negative effect on growth performance and feed utilization efficiencies	0, 25, 50, 75, **100**	Li *et al*. (2017)
Mearger (*Argyrosomus regius*) juvinilles	10% of *Hermetia illucens*, can be included in Meagre diets without major adverse effects on growth, feed utilization, whole-body composition and fatty acid profile, further increase in the substitution rates lead to a negative effect on the growth performance parameters	**10**, 20, 30	Guerreiro *et al*. 2020)
Nile tilapia (*Oreochromis niloticus*)	Replacement of soya protein concentrate by partly defatted BSF larvae meal up to a level of 50% had no negative effect on growth performance and improved the dietary protein quality of tilapia feeds under study	25, **50**, 100	Dietz and Liebert (2018)
Siberian sturgeon *(Acipenser baerii*)	Overall, this study showed that it is possible to replace up to 25% of FM with BSF larvae meal in the diet of Siberian sturgeons (equal to 18.5% HIM inclusion level) without affecting the growth performance	**25**, 50, 100	Caimi *et al*. (2020)
Rainbow trout (*Oncorhynchus mykiss*)	The maximum inclusion of BSF larvae meal recommended in rainbow trout diets is 13% further increase in the substitution lead to a decrease in the growth parameters	0, 6.6, **13.2**, 26.4	Dumas *et al*. (2018)
Nile tilapia (*Oreochromis niloticus*)	The study suggests that substitution of FM with BSF larvae upto 100% is possible without any negative effects on the growth performance, feed utilization efficiency, body composition	0, 25, 50, 75, **100**	Muin *et al*. (2017)
European sea bass (*Dicentrarchus labrax*)	With the 3 substitution levels of FM with BSF larvae meal at (25, 35, 50 %), BSF larvae meal can effectively replace FM upto 50% without any negative effects on the growth performance	25, 35, **50**	Abdel-Tawwab *et al*. (2020)
Rice field eel (*Monopterus albus*)	Lower substitution rates (5.26, 10.52%) of FM by BSF larvae meal in the diets of Rice field eel, exhibited low values of the growth performance parameters as compared to a higher substitution rates of FM by BSF larvae meal made at 15.78%	5.26, 10.52, **15.78**	Hu *et al*. (2020)
African catfish (*Clarius gariepinus*)	Substitution of FM by BSF larvae up to 75% lead to no negative effects on the growth performance and nutrient utilization	0, 25, 50, **75**	Fawole *et al*. (2020)
Juvenille turbot (*Psetta maxima*)	The maximum inclusion of BSF larvae meal recommended in Juvenile turbot diets is 33% further increase in the substitution lead to a decrease in the growth performance parameters and nutrient utilization	0, 17, **33**, 49, 64, 76	Kroeckel *et al*. (2012)

respectively (Wang and Shelomi, 2017; Belghit et al., 2019). A study by Fawole et al. (2020) on *C. gariepinus* found out that 50% replacement of FM with BSF larvae produced significantly higher values of final weight (19.84g, 14.79g), BWG (15.83g, 10.82g), protein efficiency ratio (1.62, 1.29), SGR (2.66%, 2.19%) and feed intake (23.26, 20.09) as compared to control diet that contained 0 % BSF larvae meal. Similarly, Muin et al. (2017) reported highest weight gain and SGR values of 8.74 and 2.43%, respectively when BSF larvae meal was used to replace FM in the diets of *O. niloticus* with substitution at 0, 25, 50, 75 and 100%. Additionally, BSF meal has shown to be a promising fish meal replacement in the diets of the pacific white shrimp (*Litopenaeus vannamei*) at a 25% inclusions level (Cummins et al., 2017). Importantly, the utilization of BSF larvae in fish feeds have shown the potential of lowering the production costs when compared to conventional feed sources such as FM and soyabean meal (Diener and Trockner, 2009). In Kenya the cost of BSF larvae ranges from 0.8 to 1.2 U$D/kg while fish meal is from 1.2 to 1.5 U$D/kg and soybean meal is from 0.9 to 1.6 U$D/kg. These low costs of BSF larvae are associated with the low cost of feeding them (they feed on low value organic wastes) and the simplicity of the culture systems used (Diener and Trockner, 2009; van Huis, 2013).

Conclusion

The BSF larvae have a high potential of providing quality protein in fish diets thanks to their superior nutritional values, fostering good growth and reproduction rates. With proper culture systems and processing methods (principally to defatting and removing the chitin contents) the BSF is sustainable and can be better utilized to improve fish growth performance, reduced aquaculture production costs and improve resource utilization, thus promoting food security, livelihoods and ecological balance.

Ethical Statement

This is a review and all data used were not from lab experiments but rather from reviewing articles.

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Author Contribution

RNN: Conceived the study, designed the methods, performed data curation, drafted and edited the original manuscript. **SNM**: Conceived the study, designed the methods, commented and edited the manuscript. **MJY**: Performed data curation, commented and edited the manuscript. **MAO**: Conceived the study, designed the methods, supervised the work, commented and edited the manuscript.

Conflict of Interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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