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Potential use of black soldier fly, *Hermetia illucens* larvae in chicken feed as a protein replacer: a review

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ABSTRACT. The increasing human population and improved living standards in developing countries have led to a higher demand for animal proteins, which has resulted in increased costs of animal feed ingredients such as fish meal, fish oil, soybean meal, and cereals. The global economic slowdown, has further compounded this challenge, making it crucial for the animal production industry to find innovative methods to secure future social, environmental and economic needs. Black soldier fly (BSF) larvae have emerged as a promising nutrient alternative due to their high protein and fat contents and a rich source of vitamins and minerals comparable to soybean and fish meal. Black soldier fly larvae (BSFL) has the potential to reduce the cost of chicken feed formulations by partially replacing soybean and/or fish meals. This is one of the primary reasons why insects like BSF are seen as viable alternative protein sources for animal feeds. This review attempts to assess the challenges faced by the poultry industry and strategies to overcome feeding issues through the use of BSFL.

Introduction

In comparison to other animal industries, the global chicken industry has made remarkable progress, with generally two major productions – broilers and layers. Malaysia and many other countries have exceeded local demand and are now exporting poultry and poultry products abroad (FLFAM, 2011). However, poultry feed and feeding have always been major issues in poultry production, with feed costs accounting for 60–70% of the total cost of production (Van Huis et al., 2013). As a reuslt, alternative feed ingredients need to be proposed to reduce the usage of currently expensive feed ingredients. Insects, such as black soldier fly larvae, have emerged as promising alternative protein sources for chickens. They are cold-blooded, can be raised on organic waste streams and have a favourable feed conversion efficiency (Premalatha et al., 2011), making them a sustainable and cost-effective option for poultry feed. Insects are high in energy, proteins, essential amino acids, fatty acids, and minerals such as copper, iron, and zinc (Van Huis et al., 2013). The majority of insects have crude protein levels greater than 30% on a dry matter basis (Premalatha et al., 2011), and amino acid compositions that meet the needs of growing pigs and broiler chickens (Makkar et al., 2014). Moreover, insects are especially rich in lysine, threonine and methionine, which are important limiting essential amino acids in low-protein grain and legume-based pig and poultry diets (Verkerk et al., 2007). Insect species such as *Tenebrio molitor* and *Hermetia illucens* have been identified as excellent sources of metabolisable energy and digestible amino acids for broiler chickens (De Marco et al., 2015). Several studies have concluded that insects can partially substitute traditional protein and fat sources in feed formulations without compromising animal performance or product quality (De Marco et al., 2015).

Insects like the black soldier fly (*H. illucens*), common housefly (*Musca domestica*) and yellow meal worm (*T. molitor*) show great potential for large-scale production as they have the ability to upgrade low-value organic waste streams into high-value proteins with an estimated global production of 1.3 billion tonnes per year (Veldkamp et al., 2012). This article describes the challenges facing the poultry industry and considers the potential use of insects, particularly black soldier fly larvae, as a component of poultry feed.

Concerns in poultry industry

The global poultry industry has experienced remarkable growth over the last few decades, with over 23 billion birds worldwide, i.e. approximately three birds per person (FAOSTAT, 2016). Poultry farming practices have evolved, and chickens are now reared and raised in a variety of production systems, and their main products are meat, eggs and manure for crop fertilisation. Poultry meat and eggs are among the most widely consumed animal-source foods worldwide, and they play a crucial role in addressing food security and nutritional needs in different cultures and traditions. In comparison to other livestock, poultry emerges as the most efficient sub-sector in terms of natural resource utilisation and protein production to meet a growing worldwide demand (Alexandratos and Bruinsma, 2012). Poultry is a rapidly growing agricultural sub-sector that plays a vital role in both large-scale commodity production and providing essential nutrition for smallholders and poor rural and urban populations. While private investments fuel its expansion, public concern about the industry's impact on the environment and human health, its contribution to climate change and the local and global economy persists (Alexandratos and Bruinsma, 2012).

Poultry industry, especially broilers, is one of the main branches in many countries, including Malaysia. Broiler meat is the main type that Malaysian consume of all livestock products sold in Peninsular Malaysia. Furthermore, Malaysian broiler industry has been self-sufficient in broiler production since 1984 (Department of Veterinary Services, 2012), however, it continues to face challenges, particularly in terms of the high dependence on imported raw materials for animal feed, which is currently characterised by unstable prices (Abdurofi et al., 2017). The cost of chicken feed accounts for more than 65% of the total cost of production (Abdurofi et al., 2017) due to the broiler industry consumption of nearly four million tonnes of imported soybean and maize annually. These ingredients are imported mainly from Argentina and Brazil. Other than Malaysia, China, the Netherland, Mexico, Egypt and Vietnam also imported their animal feed ingredients. The prices of soybean and maize are not solely based on global demand, which further impacts the chicken industry and the price of its products.

The poultry industry has become a significant source of affordable protein for many countries, including Malaysia. For example, the ex-farm value of poultry in Malaysia in 2019 exceeded 6 billion USD, representing almost 76% of the total livestock ex-farm value (DOSM, 2019). Therefore, annual per capita poultry consumption in Malaysia had increased approximately 40% between 2006 and 2019, from 35 kg to 49 kg, and is projected to surpass 50 kg in 2025. Globally, poultry consumption is on par with fish and seafood consumption, at around 55 kg per person per year (Friend, 2015). However, poultry feed and feeding have always been major issues in poultry production worldwide, accounting for 60–70% of the total cost of production. Therefore, alternative approaches such as insect rearing have been explored to reduce the cost of animal feed production.

Insect industry

Insect are often labelled as pests and considered to be filthy and disease-carrying. On the other side of the coin, insects can also serve as a food and feed source, providing an alternative protein option. The Food and Agriculture Organization of the United Nations (FAO, 2018) reported that the number of undernourished people has been on the rise since 2014, and it was estimated to have reached 821 million in 2017. The situation of undernourishment and severe food insecurity is increasing in some countries, particularly in Africa and South America. However, the undernourishment rate has remained stable in most regions of Asia (FAO, 2018); FAO (2018) has also reported that in 2017, 124 million people faced the "crisis" of acute food insecurity level, and some had to take immediate emergency action to preserve their livelihoods.

Insects play an important role in the farming and livestock industry, particularly in the food chain. Some insect species are edible and can be used as feed sources for animals (Song et al., 2018). In fact, FAO has suggested promoting insects as a viable option for feeding both humans and animals (Van Huis et al., 2013). This is because edible insects have significant nutritional benefits, such as rich content of protein, vitamins and amino acids, they reduce the environmental footprint stemming from food production such as the reduction of greenhouse gas emission, and provide more sustainable economic opportunities, thereby reducing worldwide poverty (Van Huis et al., 2013). Furthermore, World Health Organization (WHO) stated that insects have excellent amino acid profile, with protein content varying between 35% and 61% (FAO, 2008). These prove that edible insects provide satisfactory protein and energy levels, and are rich in several micronutrients and amino acids required for humans and animals (Rumpold and Schlüter, 2013).

The recent development of insect industry has created jobs and businesses that fuel economic growth. Song et al. (2018) found that the insect industry holds great promise as an agricultural resource and has been steadily expanding in Korea following rearing for mass production. In recent years, numerous western countries have begun to introduce a variety of edible insects to cater to the growing interest in insects as a food source (Reverberi, 2017). Besides their use as food and feed, insects also offer several ecosystem services, such as being used as traditional medicines, natural food colouring and silk production (Suzana and Bashah, 2018). Therefore, incorporating insects into our food and feed systems could be a viable solution to address protein shortages.

Insects as poultry feed ingredient

Global food demand is projected to reach 9 billion people by 2050, leading to an estimated 100% increase in food demand by that time (Makkar et al., 2014). Concurrently, agriculture production for animal feed and human food is expected to grow by 60% (Tomberlin et al., 2015). However, maize, rice, wheat, and soybean supplies are forecast to face shortages of approximately 67%, 42%, 38% and 55%, respectively (Ray et al., 2013), posing a significant risk of local, national and global disease outbreaks, with the number of undernourished individuals reaching approximately 805 million (Tomberlin et al., 2015). To address this issue, it is imperative to explore alternative food and feed sources that are rich in proteins, essential amino acids, fatty acids and micro-nutrients such as calcium, iron and zinc.

Edible insects are gaining global recognition as a novel and sustainable alternative protein source for both animal feed and human food (Van Huis et al., 2013). Due to being a potential food source, efficient food conversion rate, short breeding cycle and high protein contents, they have become a popular group of organisms worldwide (Oonincx et al., 2015). Insects offer a promising solution of resource scarcity in the food and feed industry because they are a major animal protein source with significant potential for development (Boland et al., 2013). Furthermore, nutritional insect analyses have revealed their potential to alleviate human malnutrition (Payne et al., 2016). Insects can effectively replace traditional protein sources such as soybean and fish meal in livestock, poultry and aquaculture feeds due to their high crude protein (CP) and crude fat (CF) contents and economic value (Stamer, 2015).

Several insect species such as black soldier fly (BSF), house fly (HF), yellow mealworm (TM), lesser mealworm, house cricket, banded cricket and field cricket have been approved for specific purposes in animal feeds (Food and Agriculture Organization, 2012). Among these species, BSF, HF and yellow mealworm have been recommended as the most promising ingredients for animal feeds (Van Huis, 2020), given their high protein and fat content. However, proximate analysis has revealed common nutritional differences between these species (Table 1).

Table 1. Proximate compositions (minimum and maximum) of yellow mealworm, black soldier fly and house fly larvae in comparison to soybean and fish meal

Insect	Proximate compositions			Reference
	Dry matter, %	Crude protein, %	Crude fat, %	
Yellow mealworm	36.3	49.8	31.1	Kim et al., 2016
Black soldier fly	38.7	45.1	36.1	Finke, 2013
House fly	8.3	60.9	14.1	Pretorius, 2011
Soybean meal	90.0	40.0	3.0	Cromwell, 2012
Fish meal		61.9	8.9	Ween et al., 2017

Black soldier fly

The black soldier fly (*Hermetia illucens* L.) is a synanthropic, polysaprophagous fly native to the Neotropics, but has spread over decades throughout the warmer zoogeographic regions of the world. BSF morphometrics are based on key taxonomic characteristics of the adult, including head morphology (eye and antenna), thorax (prothorax, mesotho-

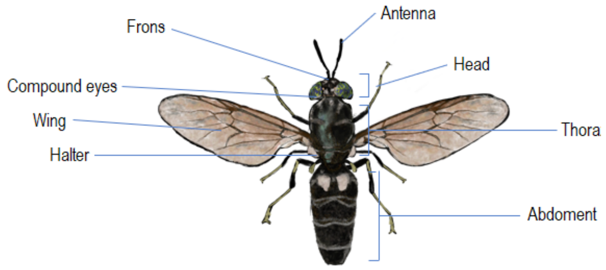

Figure 1. Morphological features of adult black soldier fly

rax, and metathorax), leg wings, halter, abdomen and genitalia (Yang et al., 2014). Morphological characteristics of adult BSF are shown in Figure 1.

A study by Cai et al. (2022) investigated the morphological characteristics of adult BSF and found that female BSF adults had slightly larger bodies and wings compared to male adults. The width of the head of both male and female adults was similar to that of the thorax. The antennae segments of BSF are club-shaped and consist of the scape (proximal antennomere, black colour), pedicel (second antennomere, yellow colour), and flagellum (a flat terminal segment, black colour. The length of the antennae serves as a sensory perception for motion, orientation, odour, sound, humidity, and variety of chemical cues (Oliviera et al., 2016). The BSF thorax consists of three segments: prothorax, mesothorax, and metathorax. The mesothorax is well-developed and relatively large, covered with dense short setae, including the mesotum, transverse suture and scutellum, and is black in colour. The metathorax has two blue halters that help maintain balance during flight. The thorax bears the pair of wings with internal flight muscles and is an important base for adult flying mechanism (Oliviera et al., 2016).

Adult BSF individual possess six legs each composed of coxa, trochanter, femur, tibia, and tarsus. The abdomen is long and slender, covered with dense short hairs that protect the insect's internal anatomy from the environment. Additionally, BSF has two hairless translucent windows located at the first and second visible segments of its abdomen. These windows are initially blue and green in colour at the early stages of adulthood, which subsequently change to white and finally become colourless and empty towards the end of BSF life cycle. These segments function as an energy storage in the form of fat, which is entirely consumed by adult BSF for living, mating, breeding and bioluminescent signalling purposes (Oliviera et al., 2016).

H. illucens has gained popularity as a sustainable solution for organic waste management, composting and animal feed supplementation over the past few decades (Sheppard et al., 1994). Although the exact original distribution of black soldier fly is unknown, records suggest that its larvae (BSFL) were found in the south-eastern United States in the late 19th century, particularly in Alabama in 1887.

Currently, black soldier fly is distributed worldwide, with a notable presence in equatorial tropics (Brammer et al., 2007). The larvae feed on a variety of organic wastes, including rotting fruits, vegetables waste, animal manure and municipal organic waste (Li et al., 2011). Furthermore, this insect exhibits remarkable resilience, being able to survive under challenging environmental conditions, such as droughts, food shortages and low oxygen levels (Diener et al., 2011). A healthy adult BSF are typically 15 and 20 mm long and prefer to live, breed and lay eggs in environments that are conducive for their larvae to thrive (Sheppard et al., 2002). Adult BSF are not perceived as a threat or a pest since they are not attracted to human households or food (Furman et al., 1959) as they do not consume any food but rather live on stored fats from their larval stage. BSF larvae are omnivorous, and mainly feed on kitchen waste, decaying organic matter and manure. Female BSF produce 350 to 700 eggs within their short life span of five to eight days (Fok, 2014). It is the larvae that have become the focus of researchers around the world due to their ability to digest various types of wastes and produce a nutritious feedstuff for livestock, with a biomass containing 40% protein and 30% fat whilst feeding on waste and manure (Newton et al., 2005). The short live cycle of BSF allows for large-scale and sustainable production, providing a reliable food source due to their frequent reproduction (Park et al., 2015).

The life cycle of BSF (Figure 2) lasts between 40 and 44 days (Fok, 2014) and comprises four stages: egg, larva, pupa and adult (Li et al., 2011). Once the fly becomes an adult, it takes a few days for females to find a mate, and lay eggs shortly after mating in a suitable environment, i.e. proximity of decaying organic matter such as kitchen waste or manure. Fertilised eggs take between 102 and 105 h to hatch at 24 °C (Li et al., 2011), and within four days, they develop into larvae (Sheppard, 1992), which begin to consume organic waste and convert it into high protein and fat contents during the larval and pupal phases. Erickson et al. (2004) reported that the bioconversion of waste by larvae could help reduce waste volume, minimise the presence of pathogens, and decrease levels of nitrogen and phosphorus (Newton et al., 2005). Subsequently, the

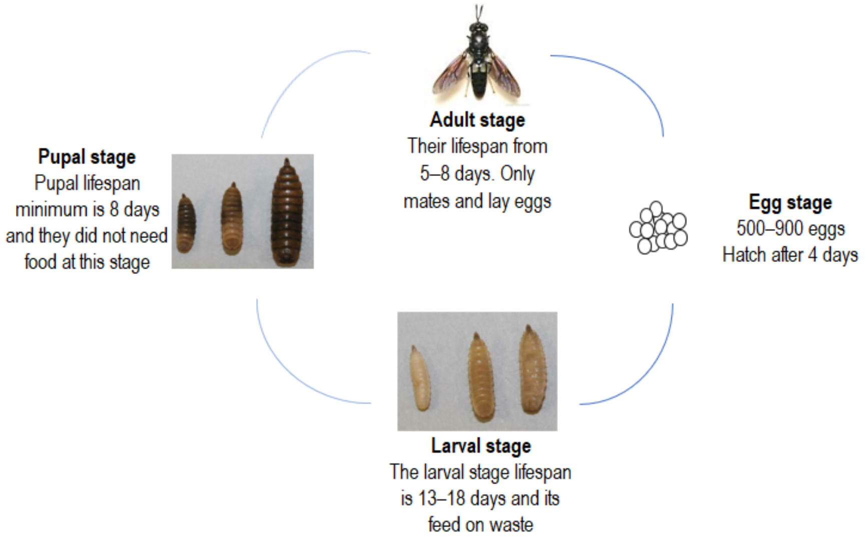

Figure 2. Black soldier fly life cycle

mouthparts of the larvae change to a hook-movement mechanism, which is known as the wondering phase in the prepupae stage. They no longer feed on waste but seek to escape and position themselves as pupae. This prepupae behaviour is used in mass-rearing as a self-collection method (Diener et al., 2011). The larvae reach full maturity in two weeks under suitable environmental conditions (Larouche et al., 2019), although this may take even several months in the unfavourable environment (Sheppard et al., 2002). Overall, the use of larvae for waste disposal is a viable option (Sheppard, 1992).

Black soldier fly larvae are rich source of lipids, proteins, polysaccharides and calcium, making them a good nutrient source for animal feed (Popa and Green, 2012). Dried, full-fat larvae typically contain between 35% (Haasbroek, 2016) and 44% crude protein (Surendra et al., 2016), while prepupae contain approximately 40% protein and between 30% and 39% fat (Haasbroek, 2016). Defatting process reduces the crude fat content in larvae and prepupae to obtain a higher crude protein content, which can reach up to 64% using solvent-extraction defatting technique (Surendra et al., 2016), while other methods, such as defatting press, may result in approximately 50% crude protein in larvae (Cockcroft, 2018). The crude fibre content in BSF prepupae is approximately 10% in both full-fat and solvent extracted forms (Kroeckel et al., 2012; Surendra et al., 2016). The crude fibre content in prepupae is expected to be higher than in larvae due to the more developed chitin exoskeleton of prepupae (Kroeckel et al., 2012). According to Surendra et al. (2016) and Cockcroft (2018), the defatting process slightly decreases the gross energy from 24.1 MJ/kg for full-fat to 19.3 MJ/kg following solvent extraction. Processed prepupae contain the highest crude protein and crude fat contents, ranging between 38% and 60% protein and 34% fat, followed by prepupae full fat with 30% to 40% protein and 30% fat (Cockcroft, 2018).

In general, the high protein content of BSF is comparable to that of fish meal, making it a valuable protein source for animal feed formulations. However, neither fish meal nor soybean meal can provide all the amino acids required by broiler chickens. Therefore, it is advisable to combine BSFL meal with other protein to achieve the ideal amino acid profile for livestock (Kim et al*.*, 2016). Although BSFL's amino acid profile is similar to the optimal requirements for broiler chickens, some essential amino acids are still lacking and need to be compensated for (Newton et al*.*, 2005). Nonetheless, BSFL have higher levels of amino acids compared to both soybean and fish meals, particularly lysine, threonine, isoleucine and valine (Cockcroft, 2018).

Newton et al. (2005) found that BSFL had significantly higher levels of calcium, manganese and iron than soybean meal, but lower of potassium. Kroeckel et al. (2012) reported that BSFL contained 6.5% calcium and 0.7% phosphorus, which was higher than the 5% calcium but lower than the 1.5% phosphorus reported earlier by Newton et al. (1977). It is important to note that the chemical compositions of BSF can be influenced by many factors, such as defatting and age of BSF larvae, drying method, substrate used, laboratory methods, and the type of analysis chosen for different nutrients, especially amino acid and fat determinations (Newton et al. 2005; Jansen, 2018). Nevertheless, the high protein and fat contents of BSFL are key reasons why they are suggested as a useful alternative for animal

Table 2. Proximate dry mass analyses of black soldier fly larvae following different treatments in comparison with those of Driemeyer (2016) and Haasbroek (2016), and with fish meal and soybean meal

Treatment	Crude protein, %	Crude fat, %
FF larvae meal	36.11	42.90
Driemeyer, 2016	35.90	NA
Haasbroek, 2016	38.05	33.87
DR larvae meal	48.18	31.54
EX larvae meal	43.10	30.24
Pressed larvae meal (Surendra et al., 2016)	53.1	19.7
Fish meal (NRC, 1994)	61.39	10.11
Soybean oilcake meal	49.44	0.45

FF – full fat larvae meal, DR – dry rendered larvae meal, EX – extruded larvae meal

feed source. Table 2 shows the approximate compositions of BSFL compared to fish and soybean meals (Jansen, 2018).

The crude protein content of BSFL ranges from 36.1% to 48.2%, depending on the processing method, with the lowest value in full fat meal and the highest in dry rendered meal. These values are similar to the protein content of soybean oilcake meal (Hopley, 2015), although Driemeyer (2016) reported a lower range of crude protein (30–40%) in BSFL. Pressed larvae meal (Surendra et al., 2016) contained the highest protein level, which was similar to the fish meal protein content (NRC, 1994). Surendra et al. (2016), using prepupae as a treatment, showed that the early stage of larvae contained more protein but less fat. The fat content of BSFL after different processing treatments varies between 30.2% and 42.9%, which is higher than the fat content of fish meal and soybean oilcake meal (Hopley, 2015). The full fat meal had the highest fat composition, whereas the dry rendered approach the lowest.

Processing seems to affect the mineral composition of the larval diet. Fasakin et al. (2003) found that hydrolysis and defatting processes increased the content of specific minerals, likely due to the fact that oil extraction reduced the available feed products, resulting in a higher concentration of specific minerals. Thus, the extruded approach resulted in the highest ash value, whereas the dry rendered method resulted in the lowest. However, these ash levels were slightly lower than those reported by Newton et al. (2005) and Haasbroek (2016). In conclusion, dry rendered meal has a high crude protein content, which is higher than that of soybean oilcake meal. Therefore, the three different methods of processing black soldier fly larvae could be used for the preparation of alternative protein sources for animal feed.

Amino acid composition of black soldier fly larvae

Amino acids serve as building blocks for peptides and proteins (Wu et al., 2013). However, the animal body cannot synthesize certain amino acids, known as essential amino acids (EAA), i.e. cysteine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, tyrosine and valine, making it necessary for animals to obtain them through dietary supplementation to maintain physiological functions (Baker, 2009). In addition, there are non-essential amino acids (NEAA), such as glutamine, glutamate, proline, glycine, and arginine (Wu et al., 2013), which animal body can generate by transforming other amino acids to meet requirements for maintenance, growth and health. Animal and cell culture studies have demonstrated that NEAA, including glutamine, glutamate and arginine play important roles in multiple signalling pathways regulating gene expression, intracellular protein turnover, nutrient metabolism and oxidative response (Yao et al., 2008). Additionally, they contribute to nutrient metabolism for tissue growth and white adipose tissue reduction (San Gabriel and Uneyama, 2013). While typical plant proteins, such as soybean meal, are deficient or insufficient in most amino acids, insect proteins are highly desirable due to their versatile and compatible amino acid compositions (Józefiak and Engberg, 2017).

Differences in amino acid requirements exist among animal species due to different physiological stages (McDonald et al., 2002). Methionine is the first limiting amino acid in poultry, followed by lysine, which however, unlike methionine, is not affected by metabolic functions and conversions (Lemme et al., 2004). Lysine is the ideal amino acid for poultry and all essential amino acids are expressed as a ratio to lysine (Han and Baker, 1994). Furthermore, essential amino acids related to lysine are unaffected regardless of genetic, dietary, and environmental factors (Schutte and de Jong, 2004). Table 3 shows the ratios of individual amino acids to lysine in BSFL, soybean meal and fish meal compared to the ideal composition for broiler feed, revealing that each meal lacks certain amino acids and requires supplementation with the necessary amino acids. Therefore, BSFL may need to be combined with other protein sources or synthetic amino acids to balance the diet formulation and meets amino acid requirements.

Jansen (2018) conducted an experiment to determine the amino acid composition in BSFL, using full fat larvae (FF), dry rendered larvae (DR) and extruded larvae (EX). Table 4 shows the

Table 3. Calculated amino acid to lysine ratios in comparison to the ideal amino acid composition for broilers (Cockcroft, 2018)

Amino acid	Black soldier fly larvae	Soybean meal	Fish meal	Ideal amino acids for broilers
Lysine	100	100	100	100
Methionine + cysteine	NA	47.54	48.00	38.00*
Threonine	62.66	63.93	54.67	74.00
Isoleucine	67.22	75.41	57.33	73.00
Valine	84.23	78.69	65.33	82.00

* only methionine; NA – not analysed

differences in amino acid compositions between individual BSFL processing techniques.

Schutte and De Jong (1999) identified the ideal amino acid ratio relative to lysine in broiler chicken as approximately 75% methionine + cystine, 65% threonine, 18% tryptophan, 110% arginine, 80% valine and 70% isoleucine. Based on the amino acid compositions displayed in Table 4, BSFL appears to meet the ideal amino acid requirement for broilers.

Table 4. Comparison of amino acid compositions from three different black soldier fly larva processing techniques, expressed as a ratio (%) to lysine compared to the ideal amino acid composition for poultry

Amino acid	Jansen, 2018			Leeson and Summers, 2005	Bregendahl et al., 2008
	Full fat larvae	Dry rendered	Extruded larvae		
Lysine	100	100	100	100	100
Methionine	44	50	31	51	47
Arginine	135	139	101	103	NA
Threonine	90	102	80	80	77
Valine	129	133	103	89	93

The methionine to lysine ratio is particularly important for poultry performance, and Bregendahl et al. (2008) recommended the full fat larvae methionine-lysine ratio, while Leeson and Summers (2005) recommended the dry rendered larvae methionine-lysine ratio. Therefore, both full fat and dry rendered larvae are suitable feed ingredients with respect to their amino acid profiles. Furthermore, the arginine to lysine ratio also plays a significant role in poultry metabolism, and disturbed balance between these aa can lead to their competition in renal tubules, leading to a reduction in arginine retention (Jones et al., 1966). Austic and Nesheim (1970) demonstrated that an increase in dietary lysine could lead to increased oxidation of arginine, while Jones et al. (1966) found even small amounts of excess lysine could reduce hepatic glycine transaminidase activity in chicks. Generally, insect meals contain approx. 3% lysine. If a meal contains more than 3% lysine, it could lead to arginine degradation by renal arginase, reduced glycine transamidinase activity and loss of appetite and arginine in the urine (Austic and Scott, 1975). Table 5 shows that the arginine to lysine ratio in all BSFL meals ranged between 1.01 and 1.39, indicating their potential use as a feed for poultry.

Black soldier fly larva mineral composition

Minerals are essential inorganic components of animal feed, which can be categorized into two groups, macro- and micronutrients. They play critical roles in various body processes, such as bone formation, growth, enzymatic, and osmotic balance regulation (NRC, 1994). Calcium, magnesium, iron, and manganese are among the most important minerals for animals. Animals require calcium concentrations ranging from 1 to 24 g/kg, magnesium between 2.8 and 4.5 g/kg, iron between 39.7 and 171.65 mg/kg, and manganese between 6.79 and 159.28 mg/kg, and BSFL are rich sources of all these minerals. Table 5 provides a comparison of mineral compositions in different insect species.

Table 5. Mineral compositions (g/kg) of selected insect species

Insect species	Mineral							References
	Ca	Mg	P	Cu	Fe	Mn	Zn	
Black soldier fly	2.4	4.5	9.2	10.4	171.7	159.3	144.9	Finke, 2013
Yellow mealworms	1.2	2.8	14.2	17.8	39.7	6.8	131.0	Barker et al., 1998
Housefly	0.93	NA	1.43	34.0	465.0	370.0	275.0	De Marco et al., 2015

NA – not analysed

While yellow mealworm (*T. molitor*) has a high phosphorus concentration, and housefly has high concentrations of iron, manganese and zinc, black soldier fly remains one of the best insects for nutritional uses containing important minerals such as calcium, phosphorus and magnesium that play critical roles in bone development and maintenance. In fact, BSFL contain a higher calcium concentration than milk, i.e. approximately 2400 mg/kg compared to milk's calcium content of 900–1300 mg/kg (Kim et al., 2016). Other minerals such as zinc, copper, iron and manganese are also important. Zinc is responsible for enzyme activities in catalysis activation, cell division and eliciting positive immune responses (King et al., 2000). Copper is a valuable component of many oxidizing enzymes involved in oxidation-reduction reactions (Kim et al., 2016).

Iron is responsible for efficient oxygen transportation within the blood and myoglobin, and is also a co-factor for multiple enzymes (Kim et al., 2016), while manganese is responsible for proper activity of certain enzymes such as hydrolases, transferases, kinases and decarboxylases. Furthermore, manganese also plays a role in enzymatic activity in fatty acid metabolism, protein synthesis and balancing neurological functions in the body (Watts, 1990). These findings demonstrate that BSFL contain the necessary minerals to meet animals' requirements in this aspect.

Black soldier fly larvae as a feed ingredient

BSF, BSFL and prepupae are potential animal feed components that have been extensively studied in fish but not as widely in monogastric and other animals (Sealey et al., 2011). Recently, BSF has been tested as a potential protein-rich feed ingredient for other animals such as pigs and poultry (Awoniyi et al., 2003). Insects are a natural part of the diet for wild birds and have been consumed in various forms, including adults, pupae and larvae (Zuidhof et al., 2003). In fact, the formulation of poultry feed using BSFL is not an entirely original concept. Quail (*Coturnix japonica*) was the first poultry species to be fed a BSFL diet, with studies showing that a diet containing 50% BSFL resulted in high feed intake and improved feed conversion ratio (FCR) (Widjastuti et al., 2014). Earlier studies by Pearson et al. (1983) and Agunbaide et al. (2007) investigated maggot meal as replacement for fish meal in layer hens' diet, as fish meal containing trimethylamine (TMA) oxide can result in a fishy taint in eggs. Maggot meal supplementation did not affect egg quality, and replacing soybean meal with maggot meal had no adverse metabolic or health consequences in layer hens (Maurer et al., 2016).

Uushona (2015) included 15% BSF prepupae in chicken feed and did not observe a negative impact on broiler chicken growth or meat quality, and there was no adverse effect on the sensory characteristics of cooked chicken breast. Additionally, increasing the level of BSF prepupae in the feed resulted in an increased calcium content in the tibia bone, indicating high bioavailability of calcium from BSF prepupae. Notably, Uushona (2015) demonstrated that defatted BSF prepupae showed higher nutrient digestibility than full-fat BSF prepupae. Unfortunately, the latter author did not evaluate the nutrient compositions of the prepupae used in the study, limiting the potential for in-depth comparisons. Another study by Aneibo and Owen (2010) reported that the nutrient composition of BSF larvae varied with age, with protein content decreasing and fat content increasing as the larvae matured.

Mat et al. (2021) conducted a study to evaluate the use of defatted black soldier fly larvae meal as a protein source in chicken diet. The study involved feeding four different diets containing different levels of defatted BSFL to groups of 360-day-old chicks for six weeks. The diets included 0%, 4%, 8%, and 12% BSFL (Table 6).

Table 6. Proximate analysis (g/100 g dry weight) of four experimental diets containing black soldier fly larvae (BSFL) (Mat et al., 2021)

Nutrient composition, %	Control (0% BSFL)			T1 (4% BSFL)			T2 (8% BSFL)			T3 (12% BSFL)		
	S	G	F	S	G	F	S	G	F	S	G	F
Crude protein	22.2	19.7	18.1	21.6	19.7	19.7	22.3	20.5	19.5	23.3	21.0	20.0
Crude fat	2.0	13.6	12.9	2.2	14.2	14.2	5.9	14.8	13.1	6.0	13.1	15.4
ME	2773	3503	3450	2755	3393	3393	2928	3421	3426	2827	3397	3524

S – starter, G – grower, F – finisher, ME – metabolizable energy

The crude protein content of the starter, grower and finisher rations used in the study met the recommended minimum specification for broilers (Yan et al., 2010). However, the crude protein content in the starter and grower diets (23% and 21.5%, respectively) were lower than the formulations reported by Dabbou et al. (2018), but were better than those recorded by Al-Qazzaz et al. (2016), where the crude protein content ranged from 16% to 19%. The differences in crude protein contents between the present and other studies were due to the use of a large proportion of high-protein ingredients such as maize, soybean meal, maize gluten and fish meals (Al-Qazzaz et al., 2016). Yan et al. (2010) noted that the crude protein content in the starter diet should be high for faster growth performance, but would result in less efficient crude protein conversion into body weight gain (BWG). The ether extract (EE) content in the starter diet of all treatments were lower compared to the previous study by

Dabbou et al. (2018), ranging from 7.1% to 7.3%. However, the EE content was higher in the grower and finisher diets of all treatments, ranging from 8.01% to 9.89% (Dabbou et al., 2018) and 7.1% to 10.3% (Schiavone et al., 2016). The insect-rearing medium and defatting process have been identified among the factors that affect the ether extract content (Schiavone et al., 2016). ME in the starter ration of all treatments ranged from 2600 kcal/kg to 2800 kcal/kg, which was similar to the study of Al-Qazzaz et al. (2016), but lower than that reported by Dabbou et al. (2018) at 2999.3 kcal/kg. Metabolisable energy (ME) in the grower and finisher diets was higher in this study (3400–3500 kcal/kg) compared to the results reported by Dabbou et al. (2018) at 3099–3199 kcal/kg – where the diets were primarily maize and wheat-based. Mat et al. (2021) revealed that the average individual feed intake of broiler starter and finisher ranged between 39.8 g and 44.8 g and between 60.5 g and 71.4 g, respectively, which was consistent with previous research. However, the broiler live weight was lower compared to the study by Dabbou et al. (2018). Table 7 presents the performance of chickens supplemented with different BSFL levels.

Similarly, Choi et al. (2012) found that the live weight of broilers in the finisher phase was higher than in the study by Mat et al. (2021). In fact, the live weight of chickens in the current study was below the average weight for Cobb broilers. This result was due to the rainy season during the feeding trial. Moraes et al. (2002) argued that temperatures of 20 °C or lower stressed the birds and reduced their body weight, especially during brooding. Nevertheless, the average daily gain (ADG) in this study was similar to a previous study at both starter and finisher stages (Dengah et al., 2016). Furthermore, the lower performance of broiler chickens in the current study was also due to the presence of chitin in BSFL, which reduced feed digestibility and resulted in increased feed intake and decreased live weight and daily gain (Schiavone et al., 2016). Overall, broilers that were fed a 4% defatted BSFL diet showed the highest performance compared to other treatment diets. Therefore, it can be concluded that BSFL is a promising alternative protein source for animal feed that can partially replace fish meal and soybean meal.

Table 7. Performance of broiler chickens supplemented with different levels of black soldier fly larvae (BSFL) for six weeks

Parameters	Growth stage	Diet			
		Control (0% BSFL)	T1 (4% BSFL)	T2 (8% BSFL)	T3 (12% BSFL)
Average daily intake, g/bird	Starter	13.3	12.7	21.0	9.0
	Grower	34.0	37.7	35.6	28.3
	Finisher	51.5	54.5	31.9	27.8
Body weight, g/bird	Day-old	45.8	45.9	46.4	42.4
	Starter	127.0	122.9	186.4	126.4
	Grower	467.0	353.8	311.3	264.5
	Finisher	891.5	1043.8	713.0	686.8
Average daily weight gain, g/bird	Starter	5.8	5.5	10.0	6.0
	Grower	24.3	16.4	8.9	10.0
	Finisher	30.3	49.5	17.7	30.0

Murawska et al. (2021) conducted a study on the growth performance of broiler chickens fed with different levels of full-fat *H. illucens* larvae meal as partial replacement for soybean meal. In contrast to the study of Mat et al. (2021), larvae meal was included in the diets at four different levels: 0%, 50%, 75% and 100%, and the chickens were reared until 42 days of age (Table 8).

The authors noted an improvement in growth performance in broilers that received 25% and 50% *H. illucens* (HI), while the average daily gain (ADG) was lower than that of birds fed standard diets. Loponte et al. (2017) and Marono et al. (2017) suggested that feed colour could affect the daily feed intake (DFI) of broilers, as HI meal appeared darker than soybean meal, and chickens were less willing to consume it. On the other hand, Sánchez-Muros et al. (2014) believed that the high chitin content in the HI diet could be a reason for the low ADG and DFI, and thus it was not suitable for monogastric animals. Furthermore, chitin negatively affects protein digestibility, e.g. Józefiak and Egberg (2017) demonstrated that diets containing insect proteins compromised the intestinal absorption in broiler chickens, due to the presence of peptides with biological activities that adversely affected the gastrointestinal

Table 8. Live body weight (LBW), average daily gain (ADG) and daily feed intake (DFI) in broiler chickens fed diets with different levels of full-fat *Hermetia illucens* meal (Mat et al., 2021)

Parameter	Age, days	Diets			
		HI0	HI50	HI75	HI100
LBW	1	41.12	41.51	42.31	42.32
	14	446.57	404.41	389.11	337.53
	35	2524.10	2201.03	1906.06	1713.04
	42	3046.00	2727.00	2504.50	2378.00
ADG	1–14	28.96	25.92	24.77	21.09
	14–35	98.73	98.73	72.42	65.36
	35–42	75.71	75.71	84.29	95.71
DFI	1–14	35.57	31.64	32.07	31.57
	14–35	144.76	124.29	110.19	101.57
	35–42	177.86	159.86	159.14	142.43

HI0 – *H. illucens* inclusion 0%, HI50 – *H. illucens* inclusion 50%, HI75 – *H. illucens* inclusion 75%, HI100 – *H. illucens* 100%

microbiota. Similarly, Dabbou et al. (2018) observed that the inclusion of 15% defatted HI larvae meal in chicken diet negatively affected the FCR, whereas Ognik et al. (2020) found that diets containing 15% HI meal had a beneficial influence on FCR in young turkeys. However, the high dose of HI larvae supplementation at 50% and 75% did not compromise the FCR between day 1 and 42, except at 100% replacement rate. This was because chickens that were supplemented with 50% and 75% HI meal consumed less feed, but the FCR values were comparable to the control group. However, the final body weight of broilers was lower with the inclusion of higher dietary levels of HI larvae, which could considerably compromise production. In summary, Murawska et al. (2021) showed that replacing soybean meal with a high level (between 50% and 100%) of full-fat HI meal in broiler diets throughout the rearing period was unfavourable because it compromised growth performance. From the two studies that used different BSFL levels in broiler diets described here, we could conclude that BSFL exerted a positive effect when offered at low levels, between 5% and 20%. Higher levels might result in no change or a negative impact on growth performance.

Conclusions

Insects, and in particular black soldier fly larvae, are a promising alternative ingredient for traditional raw feed due to their high content of crude protein and crude fat, as well as a good amino acid profile and minerals for animal growth and production. The study demonstrated that including 4% to 12% BSFL in feed was the optimal percentage for improving broiler performance. While high levels of BSFL (50% to 100%) did not have a significant effect on broiler performance compared to lower levels (4% to 12%), they also did not negatively impact broiler health. Therefore, including approx. 5% to 15% BSFL in feed can help sustain poultry weight and health, while also potentially reducing feed costs.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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