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A REVIEW OF BLACK SOLDIER FLY (*HERMETIA ILLUCENS*) AS A POTENTIAL ALTERNATIVE PROTEIN SOURCE IN BROILER DIETS

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Abstract

Since *per capita* global meat utilization is predicted to increase to 40% from 2019 to 2050, global use of cultivable land in livestock, poultry, and feed production is 30%. Use of alternative protein sources as animal feed can be a solution to minimize cropland usage in conventional feed production. Commonly used protein sources in animal diets like soybean meal and fish meal are facing challenges of high demand, but the current production might not fulfill their dire need. To overcome this issue, the discovery of alternative protein sources is the need of the hour, insect meals like black soldier fly (BSF) are one of these alternative protein sources. These flies are non-infectious, bite-less, can convert the variant types of organic waste (food wastes, animal and human excreta) proficiently into rich profile biomass with reduced harmful bacteria count and do not serve as a vector in disease transmission. Based on the substrate used, the BSF larvae protein, fat and ash contents vary from 37 to 63%, 7 to 39% and 9 to 28% on dry matter basis, respectively. Previous studies have reported using BSF and its by-products as alternative protein sources in broiler diets with partial or complete replacement of conventional protein sources. In this review, a brief introduction to insect meal, BSF origin, life cycle, nutritional profile, influences on growth performance, carcass characteristics, fatty acid profile of meat, biochemical properties of blood, gut morphology and microbiota of the caecum along with its influence on laying performance of layers has been discussed in detail. Studies have concluded the partial replacement of conventional protein sources with BSF is possible, whereas complete replacement may cause poor performance due to reduced digestibility up to 62% attributable to chitin content (9.6%). Further studies to corroborate the effect of dietary BSF on growth performance, carcass characteristics, fatty acid profile of meat, and gut morphology and caecum microbiota are required to standardize the inclusion levels in feeds for higher performance of poultry.

Key words*:* black soldier fly, broiler, growth performance, carcass characteristic, gut morphology

Livestock production requires intensive use of grains in animal diets. According to an estimate, approximately 35% of global crop production ends in animal feed to produce food for human consumption like dairy, poultry, and meat products (Foley et al., 2011). Protein, a major food component, is usually supplied through animal-origin foods. Human population has seen an incessant increase over the past decades, and it is expected to reach 12.3 billion by the end of this century (Roser et al., 2019). Such a huge population requires a humungous quantity of good-quality food. Chicken meat and eggs can satiate the protein requirements of humans, being a cheap food source and having a shorter production cycle. It implies that the demand for poultry feed will continue to increase in future. Asia Pacific's animal feed market is expected to be 140 US$ billion in 2024 (Anonymous, 2020). Due to increasing demand for poultry-derived products, feed ingredients might become insufficient to support such a huge poultry production and operations (Thirumalaisamy et al., 2016). During the last decade, the insufficiency of conventionally used feed resources led to greater feed prices that posed a dire need to develop alternate protein sources for poultry. Insect meals offer many alternative protein sources due to their high protein content and rich essential amino acid profiles (Van Huis et al., 2013). Insects can be collected naturally or grown commercially inexpensively with a shortened production cycle (Oonincx and De Boer, 2012). Consumption of insects in human food originated in tropical countries since old times (DeFoliart, 2012). Apart from being a protein source, fat obtained from insects during meal extraction can be used in poultry diets to spare the use of soybean or other vegetable oils (Ahmed et al., 2020 a).

Insects including common houseflies, yellow mealworm, black soldier fly (BSF), and blowfly are potential alternative protein source for use in poultry diets (Čičková et al., 2015). Insects are rich in minerals like zinc and iron (Finke, 2013) and vitamins like folic acid, riboflavin, thiamine, cyanocobalamin, and traces of retinol (Rumpold and Schlüter, 2013). Insects also possess a certain type of peptides that show antioxidant activity beneficial for animal health (Schiavone et al., 2017 a). Unlike other plant and animal-based protein hydrolysate products, water soluble products from insects have shown better antioxidant and free radical scavenging properties (Di Mattia et al., 2019). This review highlights the use of BSF in poultry diets on various traits due to the potential of insect meals as an alternative protein source in poultry diets, in addition to compiling the scattered but a great deal of available literature.

Black soldier fly (*Hermetia illucens*)

The BSF originated in America and was distributed in temperate and tropical regions from Argentina to central America (Sheppard et al., 1994). It is transported to other regions of the world including Europe, Asia, Australia, and Africa, by means of human activity. The widespread of BSF in different regions is attributable to the tolerance of BSF against a wide range of environmental conditions (Martínez-Sánchez et al., 2011; Gujarathi and Pejaver, 2013). The BSF belongs to a polyphagous class and the gut excretions show protease, amylase, and lipase activities (Kim et al., 2011). These qualities make it a suitable candidate for recycling faeces (Oonincx et al., 2015 a), animal leftovers (Myers et al., 2014), and other forms of organic leftovers (Gujarathi and Pejaver, 2013). Owing to these characteristics, it converts animal waste into quality products (having high protein and fat) that can be used in animal feed as an alternative protein source in poultry diets (Veldkamp et al., 2012). Unlike house flies, BSF production does not require special attention due to the absence of pest behaviour (Liu et al., 2008). The BSF larvae contain antimicrobial peptides like defensins, cecropins, atacins, and diptericins (Müller et al., 2017). Therefore, larval extracts have degraded bacterial biofilms produced by *Escherichia coli*, *Micrococcus luteus*, *Pseudomonas fluorescens*, and *Bacillus subtilis* (Papuc et al., 2020). In the last decades, antibiotic resistance has been a topic of interest due to microbial resistance against antibiotics. To overcome this issue antimicrobial peptides (AMPs) are the preferred choice. These are small cationic peptides. The AMPs are also called naturally occurring antibiotics of insects and show activity against viral, parasitic, fungal, and bacterial infections (Wang et al., 2016). Park et al. (2014) reported that insects AMPs mainly attack the membrane of bacteria without causing resistance against bacteria. Different types of AMPs reduced broilers' bacterial load (Choi et al., 2013). The BSF can make animal protein sources using liquid manure from common household and agriculture (Caruso et al., 2014). The BSF reduces odour of waste material by inhibiting bacterial growth (Van Huis et al., 2013) along with the production of biofertilizer as an organic chemical (Newton et al., 2005). Consequently, a term has been coined 'sustainable type of circular economy' for BSF, defining the production of beneficial products efficiently without the generation of waste product, even though it develops a positive relationship between economics and the environment.

Ground or whole BSF larvae can be used in poultry diets. However, the digestibility of nutritional components of BSF larvae varies depending on the physicochemical characteristics of the diet, processing, and difference in physiology of digestion (Khan et al., 2003). Various studies have reported the nutrient digestibility of BSF and BSF-derived by-products. Digestibility of partially and highly defatted BSF larvae meal ranges from 59% to 63% for dry matter (DM), 62% for crude protein (CP), and 93% to 98% for ether extract (EE) (Schiavone et al., 2017 b).

Defatted BSF is one of the most important insect meals because of its high protein content (Dabbou et al., 2018), making it one of the ideal alternative protein sources of soybean meal (Shit, 2021). Dietary inclusion levels between 5 and 19% in broiler chickens improved the growth performance, carcass quality, health status, and meat quality (Dabbou et al., 2018; Schiavone et al., 2019). The above results help recommend defatted BSF meal in poultry diet formulation. While processing of BSF for the production of a meal, another side product is produced having a high percentage of fat. This fatty by-product can be used in poultry feed to replace soybean or corn oil. Enhancement of growth performance occurs due to gut health improvement because of medium-chain fatty acid present in BSF-derived fat (Zeitz et al., 2015). These medium-chain fatty acids also improve energy utilization without extra deposition of lipids in the body (Li et al., 2016). Schiavone et al. (2017 a) reported that partial (50%) and complete (100%) replacement of soybean oil with BSF fat in broiler diets results in suitable carcass quality, growth, and production performance of broiler chickens. The nutritional composition of BSF and BSF-derived by-products has been shown in Table 1.

Life cycle of black soldier fly

The life cycle of BSF consists of five stages (Alvarez, 2012) (1) egg; which hatches approximately in four days, (2) larva; this stage consists of five instars over a period ranging between 13 and 18 days, (3) prepupa; the sixth and final instar that consists of approximately seven days, (4) pupa; varies from 10 to 30 days depending upon favorable conditions to become an adult one, and (5) adult; normally survives from five to eight days. Instars are a division of larval stage comprising of exoskeleton molting each time. Diverse species of flies have different numbers of instars. Larva feeds up to its maximum capacity during molting from each instar and stores fat in the body that is utilized during the adult stage. The adults do not feed, they just mate and hatch eggs while consuming the fat reservoirs of the body. The adult flies die after the depletion of body fat (Myers et al., 2014).

Table 1. Summary of literature data on the nutritional profile of black soldier fly, larvae, prepupae and pupae

Nutrient (%)	BSF[1]	BSFL[2]	BSFPP[3]	BSFP[4]
Dry matter	ND[5]	27.74	35.67	39.95
Crude protein	36.20–65.50	35.30–56.10	31.81–44.80	31.27–52.10
Ether extract	7.00–38.60	11.90–47.85	21.20–47.65	19.17–39.85
Ash	2.70–19.70	5.35–12.60	7.30–10.40	9.24–13.90
Lysine	2.10–4.14	2.20–5.40	2.31–2.51	5.40
Methionine	0.54–1.33	0.58–1.40	0.74–1.31	1.70
Threonine	1.52–2.37	1.42–3.60	1.55–2.26	3.60
Arginine	1.73–3.27	1.94–3.70	2.20–3.46	4.20
Valine	2.20–5.13	2.25–5.50	2.38–3.17	5.70
Isoleucine	1.72–3.18	1.91–2.49	1.71–2.55	4.20
	(Barroso et al., 2014; De Marco et al., 2015; Spranghers et al., 2017; Mwaniki et al., 2018; Marono et al., 2017; Cullere et al., 2016)	(Fischer et al., 2022; Patterson et al., 2021; Bosch et al., 2014; Kawasaki et al., 2019)	(Elangovan et al., 2021; Smets et al., 2020; Fischer et al., 2022; Kawasaki et al., 2019)	(Bosch et al., 2014; Smets et al., 2020)

[1]black soldier fly; [2]black soldier fly larvae; [3]black soldier fly prepupae; [4]black soldier fly pupae; [5]not determined.

Larvae can feed on various materials like the kitchen and restaurant leftovers, animal and human fecal matter, rotten fruits and vegetables, and rotten meat (Nguyen, 2010). The total life cycle duration depends on different factors like diet availability and the surrounding environment's parameters. Diener et al. (2009) stated that the total larval life span is approximately 40 days, governed by different factors. Nymphs just after hatching search feed nearby and start feeding, due to this reason, females lay eggs near food sources. The maggots consume feed continuously if the situations are feasible for them like 60–90% moisture content (Diener et al., 2009), and 27–30°C of optimal temperature (Sheppard et al., 2002). The maggots produce heat while consuming organic material, making them survive if the temperature falls from the optimal range. Before consumption of waste material, maggots produce a specific type of enzymatic secretion like amylase or maltase (Gold et al., 2018) that make leftovers consumable for them. Fatchurochim et al. (1989) stated that moisture level is crucial for maggots as it directly affects the life cycle.

The BSF maggots produce specific chemical substances called allomones like repellents that emit signals to other flies indicating them to avoid feeding, laying, and propagation simultaneously (Bradley and Sheppard, 1984). Nutritional profile of BSF is greatly dependent on the composition of waste material (Tomberlin et al., 2002) that can be modified by changing the substrate (Tschirner and Simon, 2015). Omega-3 fatty acid profile of BSF can be altered in a short time by feeding substrate medium enriched with n-3 fatty acid (Barroso et al., 2017). After feeding up to a limit, maggots start the migration to a drier and darker place for the pupation process far away from a food source. Time to find small spaces to hide for pupation is the main factor affecting BSF's life cycle duration. The color of maggot starts changing as it finds suitable circumstances like 60% humidity level and temperature between 27°C and 30°C (Holmes, 2010). One interesting fact about maggots is that whenever they find a suitable place for pupation, they secrete special kinds of chemicals like carbon dioxide, methane, or physiological activity like body heat which is mostly used in insects (Despommier, 2007). The BSF larvae are also suspected of leaving such chemical trail to signal other maggots to reach a suitable place. These chemicals help other maggots find a suitable place for pupation, resulting in a shorter time to achieve pupation. The pupation medium should be porous with proper ventilation and away from predators or it may adversely affect the pupation process. Depth of pupation medium is an important factor that determines the fate of hatched flies. Too deep medium will hinder the hatched flies to come out whereas, superficial medium makes maggots uncomfortable that start wandering due to unsuitable pupation medium thus leading to the consumption of stored body fat and the death of adult flies before mating and hatching. According to Holmes (2010), 15–20 cm is absolute pupation medium depth that takes five to seven days for proper pupation of maggots.

The adults mate typically two days after pupation with other pupated ones (consisting of six instar stages). Different factors that influence the mating behavior of flies are the appropriate intensity of light and temperature. Natural sunlight is ideal for mating flies; however, artificial light can be provided to facilitate the mating behavior of the flies. Generally, mating occurs in the air and eggs are laid after two days of appropriate mating. Nowadays, light-emitting diodes, specially designed according to the requirement of BSF (effective for mating) visual spectrum, are available in the market namely BSF LED (black soldier fly light-emitting diode) (Liu et al., 2020). The light of wavelengths ranging between 450 and 700

nm affects the mating behavior of BSF (Zhang et al., 2010). The site selection for hatching is very important as just after hatching. Larvae require feeding for normal propagation of the life cycle. Sheppard et al. (2002) stated that female flies could detect decaying organic material with the help of specific volatile chemicals produced by the waste material. A study reported that naphthalene, toluene, p-isopropyl toluene, and ethylbenzene are the aromatic volatile chemicals on municipal solid waste that attract the female flies (Komilis et al., 2004).

After selecting an appropriate place for hatching, females lay eggs near decaying material and produce specific chemical markers. These markers help other female flies find a pertinent place to lay eggs. To obtain optimum hatchability (approximately 80%) ideal humidity is 60% and the temperature is 27°C (Holmes, 2010). For artificial propagation of BSF, the best medium to favor maximum oviposition and attraction of flies is cow manure (Nyakeri et al., 2017).

Influence of substrate on nutritional profile of BSF

The substrate used during the life cycle of BSF and BSF-derived products is directly influenced by the BSF's nutritional composition. These substrates include different manure types (cattle, chickens, and pigs), waste from the restaurant, agriculture and related industries, and food industry, seaweed, sugar beet pulp, cadavers, and liver (Diener et al., 2009; Oonincx et al., 2015 b; Tschirner and Simon, 2015; Liland et al., 2017; Nguyen et al., 2013; Banks et al., 2014). The substrate not only governs the nutritional composition of BSF larvae, but also influences the transition period of different life stages of BSF (Spranghers et al., 2017; Tschirner and Simon, 2015; Nguyen et al., 2013). Fiber and protein-rich substrate slowed down the development of BSF larvae compared with those grown on a balanced diet comprised of cereal residues whereas, growth of larvae ceased in response to a fiber-rich diet (Tschirner and Simon, 2015). Crude protein of BSF larvae was 418.8, 307.5, 344.3, and 529.6 g/kg using a mixture of vegetables and fruits, fruits only, winery, and brewery by-products, as substrates, respectively (Meneguz et al., 2018). Similarly, BSF prepupae propagated on biogas digest, vegetable waste, chicken feed, and restaurant waste had 422, 399, 412 and 431 g/kg crude protein, respectively (Spranghers et al., 2017). Likewise, 342, 347, 222, and 340 g/kg crude protein was reported in BSF prepupae fed wheat, alfalfa, and barley along with a cornmeal diet, respectively (Danieli et al., 2019). Studies have reported that substrate affects the crude protein content of BSF and BSF-derived products and influences the composition of fatty acids (Danieli et al., 2019; Moula et al., 2018 b; Oonincx et al., 2015 c, 2020). The fats of BSF larvae fed cow manure contained 21% lauric acid, 16% palmitic acid, 32% oleic acid and 0.2% omega-3 fatty acids whereas, the concentration of these fatty acids was respectively 43, 11, 12, and 3% for larvae fed substrate containing 50/50 fish offal and cow manure (Makkar et al., 2014). It implies that the n-3 fatty acid levels of BSF larvae improved from 0.2% to 3% as the substrate was changed from cow manure to 50/50 fish offal and cow manure. Nutritional composition of BSF and BSF-derived by-products as a function of substrate has been depicted in Table 2.

Table 2. Summary of literature data on influence of substrate on nutritional profile of black soldier fly

Substrate composition	Nutritional composition (% of DM)								Reference
	protein	lipid	methionine	lysine	threonine	valine	alanine	arginine	
1	2	3	4	5	6	7	8	9	10
Spent coffee	ND	ND	0.7	2.6	1.6	3.0	2.9	1.9	Romano et al. (2021)
Sweet potato	ND	ND	0.7	2.6	1.7	2.9	2.6	1.8	
Spent coffee	48	ND	0.7	2.5	1.5	3.0	3.2	1.5	Fischer et al. (2021)
Donut dough	54	ND	0.8	2.6	1.7	3.2	2.9	2.2	
Wheat bran: quail manure (60:40)	49.41	28.0	4.5	6.0	4.2	5.7	7.5	4.8	Marco et al. (2021)
Pig manure	42.8	36.5	0.8	2.5	1.9	1.9	2.3	2.1	Wang et al. (2020)
Food waste	43.7	37.2	0.8	2.4	1.9	2.0	2.4	2.0	
Cow manure	41.2	35.7	0.7	2.3	1.8	1.9	2.3	2.0	
Kitchen-potato peel, rice, carrot, bread	33.0	ND	0.8	0.5	ND	0.1	ND	0.5	Shumo et al. (2019)
Brewery by-product spent grains	41.3	ND	0.7	0.5	ND	0.9	ND	0.3	
Household organic waste	ND	ND	0.7	2.5	1.5	2.4	2.3	2.2	Kawasaki et al. (2019)
Zucchini, apple potato, beans, carrot, pepper, kiwi, orange, plum	39.4	35.6	1.8	2.0	2.5	2.5	3.9	4.8	Cappellozza et al. (2019)
Food waste	39.2	ND	1.8	8.3	3.9	5.8	5.9	4.9	Lalander et al. (2019)
Fruit and vegetable mix apple, potato	41.3	ND	1.5	5.1	3.5	6.0	5.5	4.5	

Table 2 – contd.

1	2	3	4	5	6	7	8	9	10
Restaurant-potato, rice, pasta, vegetables	43.1	ND	0.7	2.3	1.6	2.8	2.8	2.0	Spranghers et al. (2017)
Chicken feed	41.2	ND	0.8	2.3	1.6	2.4	2.5	2.0	
Digestate	42.2	ND	0.9	2.6	1.7	2.5	2.4	2.0	
Vegetable waste	39.9	ND	0.8	2.3	1.5	2.5	2.4	2.0	
Wheat	40.0	33.8	1.7	6.2	3.9	5.8	6.2	4.6	Liland et al. (2017)
Wheat brown algae *A. nodosum*	33.7	22.2	1.4	5.6	4.0	5.7	6.8	4.6	
Brown algae *A. nodosum*	41.3	8.1	1.4	5.6	3.9	5.5	6.4	6.5	
Food waste	43.7	31.8	0.9	2.2	1.5	2.4	2.7	2.2	Surendra et al. (2016)
Wheat middling	37.2	ND	1.6	5.9	3.9	5.7	7.8	4.8	Tschirner and Simon (2015)
DDGS	44.6	ND	ND	ND	ND	ND	ND	ND	
Sugar beet	52.3	ND	ND	ND	ND	ND	ND	ND	

DDGS = distillers dried grains with solubles; ND = not determined.

Table 3. Summary of literature data on the effect of black soldier flies on growth performance of broilers

Inclusion level (%)	Optimal	Age (d)	FI (g)	BWG (g)	FCR	Reference
0, 7.5, 15	0	0–35	–0.55	+4.75	+5.09	Kim et al. (2021)
0, 17, 25, 34	17	1–42	–10.12	–10.47	+2.63	Murawska et al. (2021)
0, 5	5	0–21	+5.16	+2.14	–2.41	Elangovan et al. (2021)
0, 5	5	4–38	–2.98	+1.54	–0.72	Bellezza et al. (2021)
0, 25, 50, 75, 100	75*	28	+18.91	+21.91	+3.50	Wahid et al. (2021)
0, 2, 4, 6, 8	8	14–56	–18.35	+2.92	+20.72	Attivi et al. (2020)
0, 5, 10, 15	10	1–10	+9.22	+9.35	+0.85	Dabbou et al. (2018)
0, 5, 10, 15	5	1–35	–1.02	–0.90	NF	Dabbou et al. (2018)
0, 2, 4, 6, 8, 10	8	1–42	–1.35	+7.55	+8.28	Kareem et al. (2018)
0, 2	2	1–13	ND	NF	+7.94	Moula et al. (2018 a)
0, 5, 10, 15	5	7–28	–1	+0.16	NF	Onsongo et al. (2018)
0, 5, 10, 15	5	28–49	+3.14	+3.48	+5	Onsongo et al. (2018)
0, 5, 10, 15	15	7–49	–4.02	–1.01	+5.55	Onsongo et al. (2018)
0, 14.5, 14.5(+)	14.5(+)	1–21	+6.37	+7.11	+1.6	Velten et al. (2018)
0, 11.9, 11.9(+)	11.9(+)	22–34	–4.82	+6.30	+10.41	Velten et al. (2018)
0, 11.9, 11.9(+)	11.9(+)	1–34	–0.22	+6.19	+6.67	Neumann et al. (2018)
0, 12.25, 12.25(+)	12.25(+)	1–35	–0.64	+6.40	+5.83	Neumann et al. (2018)
0, 21, 21(+)	21(+)	1–34	–5.43	+9.17	+13.8	Neumann et al. (2018)
0, 4	0	21–49	–2.80	-2.30	+0.70	Mohammed et al. (2017)
0, 5, 7.5, 10	5	0–26	+42.06	+45.51	+5.34	Dahiru et al. (2016)
0, 5, 10, 15	15	1–35	–0.40	+2.08	+6.25	

ND = not given; FI = feed intake; BWG = body weight gain; FCR = feed conversion ratio; NF = no effect; (+) = supplementation of essential amino acids; +/- = improved/adverse effect at optimal inclusion level, *based on percentage replacement with fish meal.

Dietary black soldier fly in broiler chickens

Effects on growth performance

Growth performance is a vital variable to gauge the efficacy of diets presented to the broiler chickens. Diet composition, intake, optimal digestion, and appropriate absorption reflect in the growth performance (Swennen et al., 2007). A detailed summary of previous studies describing the effect of dietary BSF and BSF-derived products on the growth performance of broiler chickens is shown in Table 3. Effects of BSF and associated by-products on the growth performance of broiler chickens remain unsettled. Studies have reported a positive effect of BSF and its derivatives on the growth performance of broiler chickens. Murawska et al. (2021) reported an

improvement in FCR of broiler chickens fed 17% BSF larvae meal (BSFLM) in a 42-d experiment. Improvement in FCR occurred in broiler chickens fed diets with partial replacement of fish meal (75%) with BSFLM (Wahid et al., 2021). Replacement of dietary 2, 4, 6, and 8% fish meal with BSF maggot meal (BSFMM) in broiler chickens from 14 to 56 days improved the feed conversion ratio (FCR), increased the body weight gain (BWG), and reduced the feed intake (FI) compared to the control diet (Attivi et al., 2020). Use of dietary 2, 4, 6, 8, and 10% BSFLM in broiler chickens improved the FCR, increased the BWG, and suppressed the FI in 8% of BSFLM group (Kareem et al., 2018). Broiler chickens consuming 2% defrosted BSF larvae (BSFL) for 13 days reduced the FCR without affecting the BWG (Moula et al., 2018 a). Feeding 15% BSF prepupae meal (BSFPM) from seven to 49 days enhanced the FCR of broiler chickens while reducing the FI (Onsongo et al., 2018). Feeding 14.5 or 11.9% BSFDM along with exogenous amino acid improves the growth performance of broiler chickens (Velten et al., 2018).

A series of three experiments concluded that different dietary levels of partially defatted BSFLM with the supplementation of exogenous amino acids improve the growth performance of broiler chickens (Neumann et al., 2018). Dahiru et al. (2016) described that broiler chickens consuming diets with 5% BSFLM had greater FI and BWG and lower FCR compared to control group. Improvement in growth performance of broiler chickens fed BSF derivatives appears to have occurred due to the reduction in FI and elevation of BWG in most studies. The reduction in FI might be due to better digestion and increased bioavailability of nutrient from BSF derivatives thereby meeting the nutrient requirements of broiler chickens at reduced feed consumption. Another possible explanation might be the positive interactions between the feed ingredients and BSF derivatives that might have resulted in reduced FI. Besides these, enhancement of growth performance in studies reporting the use of exogenous amino acids along with BSF derivatives in diets for broiler chickens seems due to the availability of extra amount of limiting amino acids for protein synthesis and deposition in muscles thus yielding heavier body weight that reflected in the growth performance (Havenstein et al., 2003; Ahmed et al., 2020 b). In contrast, addition of 15% dietary BSF defatted meal (BSFDM) suppressed the growth performance of broiler chickens whereas, 10% BSFDM was deemed optimum compared to the chickens fed diets without BSFDM (Dabbou et al., 2018). Inconsistent effects of dietary BSF and BSF-derived products might be associated with the differences in the nutritional composition of these products that depends on the substrate used for the growing BSF having a direct effect on the nutritional composition of BSF and its derivatives. In addition, the suppression of growth performance might be attributed to the chitin levels that go beyond the tolerance levels when BSF is added in diets at higher inclusion rates.

Carcass yield and characteristics

Carcass yield and characteristics largely depend on the growth performance of broiler chickens. Table 4 presents a detailed summary of carcass yield and characteristics of broiler chickens fed diets with BSF and BSF-derived products. Previous studies have shown inconsistent effects of BSF-derived products on carcass yield and characteristics. Carcass yield and characteristics remained unaffected despite a numerical increase in breast, thigh, and whole carcass yield of broiler chickens fed 5, 10, and 15% dietary BSFLM (Schiavone et al., 2019). Likewise, the inclusion of 5, 10, or 15% BSFPM did not affect carcass and thigh yields but rather reduced the breast yield in broiler chickens (Pieterse et al., 2019). Kareem et al. (2018) reported no effect of increasing dietary BSFLM (0, 2, 4, 6, 8, and 10%) on breast yield of broiler chickens. Consistent with these findings, Uushona (2015) reported no effect of dietary 0, 5, 10, or 15% BSFPM on carcass, breast, and thigh yields of broiler chicken. Although no statistically appreciated significant effects were evident on carcass and parts yields in the above-mentioned studies, numerical increase in yields was noted. It is known that protein synthesis in broiler chickens is governed by the supply of essential amino acids that increase the muscles' protein accretion (Estévez et al., 2020). The studies reporting no effect on carcass and parts yields had balanced dietary amino acids, and isonitrogenous and isocaloric diets despite the inclusion of BSF-derived products in diets for broiler chickens. This might be the possible explanation of no effect of BSF derivatives on carcass yield and characteristics of broiler chickens. In contrast, use of 5 and 10% BSFPM in broiler diets increased the breast yield by more than 10% (Onsongo et al., 2018). Similarly, broiler chickens fed BSFM (14.5% in starter phase followed by 11.9% in grower phase) exhibited greater carcass yield compared to other dietary treatments (Altmann et al., 2018). Similar results were reported by Mohammed et al. (2017) in broiler chickens fed 4% BSFLM compared to those fed diets without BSFLM. In some studies, increased carcass and parts yields might be due to the increased availability of dietary amino acids for greater protein accretion and muscle growth. Interestingly, a study reported a reduction in carcass, breast, and thigh yields in broiler chickens fed 5, 7.5, and 10% BSFLM (Dahiru et al., 2016).

Adverse effect on carcass and parts yield might be attributed to the chitin in BSF larvae indigestible by monogastric animals (Sánchez-Muros et al., 2014) that can negatively affect protein digestibility (Longvah et al., 2011) thus protein deposition and muscle growth of broiler chickens. The difference in the findings at higher inclusion levels of BSFM in the above experiments might be linked with the difference in the nutritional composition of insect at various life stages like larvae, pupa and adult, divergent rearing materials, and insect processing to obtain meal (Sánchez-Muros et al., 2014).

Table 4. Summary of literature data on the effect of black soldier flies on the changes of carcass characteristics in broilers

Inclusion level (%)	Optimal (%)	Age (d)	Carcass (g)	Breast (g)	Thigh (g)	Liver (g)	Heart (g)	Reference
0, 5	5	38	–0.64	–1.04	–0.97	+4.16	+6.67	Bellezza et al. (2021)
0, 2, 4, 6, 8	6	56	ND	ND	ND	+4.73	ND	Attivi et al. (2020)
0, 5, 10, 15	10	35	+0.80	+2.56	+0.63	–4.14	–12.50	Schiavone et al. (2019)
0, 5, 10, 15	15	35	+1.78	–3.61	+3.15	ND	ND	Pieterse et al. (2019)
0, 2, 4, 6, 8, 10	8	42	ND	+4.36	ND	–4.57	ND	Kareem et al. (2018)
0, 5, 10, 15	10	35	ND	ND	ND	NF	ND	Dabbou et al. (2018)
0, 5, 10, 15	15	49	ND	+11.88	ND	+9.36	+17.83	Onsongo et al. (2018)
0, 11.9	11.9	34	+6.53	–1.92	ND	ND	ND	Altmann et al. (2018)
0, 3.3	3.3	56	ND	+10.61	–5.21	ND	ND	Mohammed (2017)
0, 4	4	49	+0.40	ND	ND	–6.59	+6.27	Mohammed et al. (2017)
0, 5, 7.5, 10	5	26	–7.30	–18.48	–17.01	+14.41	ND	Dahiru et al. (2016)
0, 5, 10, 15	10	35	+1.65	-4.54	+8.69	+3.19	+1.85	

ND = not determined; +/– = positive/negative change at optimal inclusion level.

Fatty acid composition of breast meat

Fatty acid (FA) composition of diet greatly influences the FA composition of breast meat in broiler chickens. Even though FA composition of breast meat depends on other factors like genotype, sex, age at slaughter, diet is considered as the most important factor that determines the FA composition of meat in poultry (Schiavone et al., 2007, 2010). Breast meat also contains essential FA like eicosapentaenoic acid (EPA; C20:5 n3) and docosahexaenoic acid (DHA; C22:6n3) well known for their beneficial biological activities in humans (Rymer and Givens, 2005). The BSF contains 58–72% saturated fatty acids (SFA) and 19–40% mono (MUFA) and polyunsaturated fatty acids (PUFA) of the total fat content (Makkar et al., 2014). Replacement of soybean oil with insect fat resulted in decreased saturated fatty acids and increased monounsaturated fatty acids (Kierończyk et al., 2018). Inclusion of insect fat in broilers diet as a substitute for soybean oil resulted in medium-chain fatty acid increment like lauric acid (Cullere et al., 2019) that might be due to the high lauric acid concentration in BSF prepupae (BSFPP) (Danieli et al., 2019). Diets with BSF fat increased the oleic acid (Cullere et al., 2019; Loponte et al., 2019), increasing dietary BSFDM-enhanced oleic acid, lauric acid, myristic acid, and MUFA while decreasing PUFA (Schiavone et al., 2019) in breast meat of broiler chickens. Contrarily, dietary 0, 5, 10, and 15% BSFPP meal (BSFPPM) did not affect oleic acid while a decreasing trend of SFA, MUFA, and PUFA was noted in the cooked meat of broiler chickens (Pieterse et al., 2019). The difference in the FA composition of breast meat might be due to the differences in the used BSF or its products in addition to the FA composition of BSF and derived products that is dependent on the substrate used to grow the BSF. Taken together, it can be suggested that soybean meal/oil can be replaced with BSFL meal/oil up to 10% without any negative influence on FA composition of breast meat of broiler chickens.

Gut morphology

It is understood that diet greatly impacts the intestinal framework of living organisms (Laudadio et al., 2012). Inclusion of dietary protein from insect sources in poultry diets has a positive influence on the overall performance (Makkar et al., 2014). However, there is an inadequacy of data on gut morphology and health. Use of insects as a source of protein is a hot topic to replace conventional protein sources. There is a dire need to explore this aspect with further research since gut morphology is directly linked with the overall performance of broiler chickens. Franco et al. (2006) stated that intestinal homeostasis mainly depends on villus height (VH) and crypt depth (CD). Absorption of nutrients largely occurs through intestinal villi. The higher the intestinal villi and the larger the villus area, the stronger the intestinal absorption and nutrient utilization (Guerreiro et al., 2016; Zhou et al., 2010). Shorter VH has adverse effects on the gut development since a shorter villus indicates reduced villus function leaving a decreased surface area for the absorption of nutrients (Caspary, 1992). In contrast, crypt depth indicates turnover of enterocytes in the intestine. Shallow crypts are indicative of healthy intestine whereas, deeper crypts designate the increased turnover due to an unhealthy gut ecosystem attributable to pathogenic invasion, and colonization of pathogens. In addition, thicker muscularis suggests the bacterial infections or inflammatory reactions due to infectious or non-infectious agents or vice versa (Chacher et al., 2017). An increase in VH following dietary BSFLM inclusion was reported by Yu et al. (2020) which suggests the suitability of insect meal utilization for positive effects on intestinal development and nutrient absorption. Similarly, an increase in VH and CD was noted in broiler chickens fed 10% BSFDM compared to those fed 0, 5, and 15% BSFDM (Dabbou et al. (2018). Velten et al. (2018) demonstrated that dietary 14.5% BSFM reduced the muscularis thickness in duodenum and cecum, and VH in jejunum

of broiler chickens while other traits remained unaffected in duodenum, jejunum, and cecum. Duodenum, the part of small intestine, is mainly responsible for the digestion of feed whereas jejunum and ileum are the main sites for the absorption of nutrients (Tasaki and Takahashi, 1966). Inconsistent results might be attributed to the fact the nutritional components of BSF and BSF derivatives do not usually belong to the class of ingredients that improve gut ecosystem and morphology. Moreover, the studies conducted so far have used isonitrogenous and isocaloric diets, thus, no or a little improvement in gut morphology was seen. This notion is further supported by the fact that the studies reporting such findings have also described that dietary BSF or its derivatives had no effect on the growth performance of broiler chickens.

Cecal microbiota

Chicken ceca that contain the highest variety and bulkiness of microbiota are principal sites for urea recycling, maximum time of digesta stay in the alimentary tract, and carbohydrate fermentation that ensure better intestinal health (Wise and Siragusa, 2007). The intestinal microbiota of chicken is greatly influenced by several factors like breed, age, sex, litter quality, biosecurity status, dietary composition, and feeding method used in poultry shed (Kers et al., 2018). Broiler chickens fed diets with 0, 5, 10, and 15% BSFLM had greater number of bacteria belonging to Bacteroidetes, Firmicutes and Proteobacteria (Biasato et al. (2020). *Helicobacter pullorum*, *Escherichia coli*, *Vibrio cholera* and *Salmonella* like infectious bacteria belong to the Proteobacteria phylum. Velten et al. (2018) reported an increase in the population of coliform bacteria, lactic acid bacteria and clostridia in broiler chickens receiving diets with 11.9% BSFM instead of soybean meal. Contrarily, cecal microbiota was not affected following diet consumption with 8% defrosted BSFL in broiler chickens (Moula et al., 2018 a). It is evident from the findings that more studies were conducted to evaluate the optimal level of BSF required for an improved population of beneficial bacteria and degrade undigested substances in caeca leading to improved performance of birds.

Conclusion

It is understandable from a direct or indirect collation of studies that partially or completely defatted black soldier fly larvae, prepupae, pupae, and meal can be added in broiler diets as a partial or complete replacement for conventional protein sources like soybean meal and fish meal. Studies have shown that black soldier fly can be added to broiler diets up to 5% without any negative influence on growth performance. In contrast, excessive inclusion may negatively affect the broilers' performance (slow growth). For optimal carcass characteristics, black soldier fly can be included in diets for broiler chickens up to 10% for 35 days trial. However, this level differs with the extension of the trial duration. Therefore, the inclusion level of black soldier fly is still an inconclusive matter in literature since there are no clearly mentioned levels of black soldier fly, which could lead to the optimal growth performance of broilers.

In the future, it is crucial to highlight the impact of black soldier fly inclusion on ileal and total tract digestibility of protein and immunity in broilers. The cost of meat produced from these alternative protein sources should be analyzed for economical meat production. Similarly, the influence of different rearing substrates on the organoleptic properties of the black soldier fly should be studied.

Disclosure statement

The authors declare that no competing interests may be construed as a potential conflict of interest.

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