









Review

# Black Soldier Fly (*Hermetia illucens*) Meal as A Promising Feed Ingredient for Poultry: A Comprehensive Review

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**Abstract:** Insects could be a potential replacement of protein-rich ingredients in poultry diets. Among these insects, black soldier fly (BSF), *Hermetia illucens*, has a high content of protein and fat, which reinforces the potential of using it in poultry feed formulation and makes it one of the most promising insect species for commercial production. Protein content as well as amino acid profile in *H. illucens* larvae is comparable to those in many protein-rich feedstuffs such as fish meal and soybean meal. BSF can convert organic wastes into a precious source of nutrients, such as proteins, lipids, and chitin, which contribute to reducing the environmental burden and pollution potential arising from organic waste accumulation. This review emphasizes the significance of this insect as a “green” technology in the extremely variable recycling of organic waste and generates a sustainable protein source as well as the importance of its use as a substitute of protein-rich feedstuff in poultry feed manufacturing.

**Keywords:** black soldier fly; nutritional value; poultry; growth performance; digestibility

## 1. Introduction

Poultry is by far the largest livestock group. However, the demand for animal protein is expected to increase in the near future with the continuous growth in the human population, which may reach

9 billion in 2050 [1], particularly in terms of poultry products, which have the lowest carbon and water footprint compared with other types of animal protein [2]. In addition, quality and quantity of animal feedstuff such as maize and soybean meal, major ingredients in poultry feed, may be influenced by global warming and climate change, as well as increasing feed and energy costs, thereby influencing global food security [3]. For example, soybean meal as a protein source is one of the most frequently used ingredients in feed formulations for poultry. However, in recent years, the high price of this ingredient has become a serious issue for the economic sustainability of poultry production, particularly in developing countries [4]. In short, the rapid decrease of areas suitable for agricultural production present a serious global challenge [5], which is different from anything we have faced before. These new challenges require revolutionary solutions to cope adequately in the pursuit to find the way towards sustainability of global food production [5] as much as possible. However, the competition for food and fuel at the same time for the same resources may exacerbate the situation. Under these conditions, the investigation for alternative feed resources is a must [6].

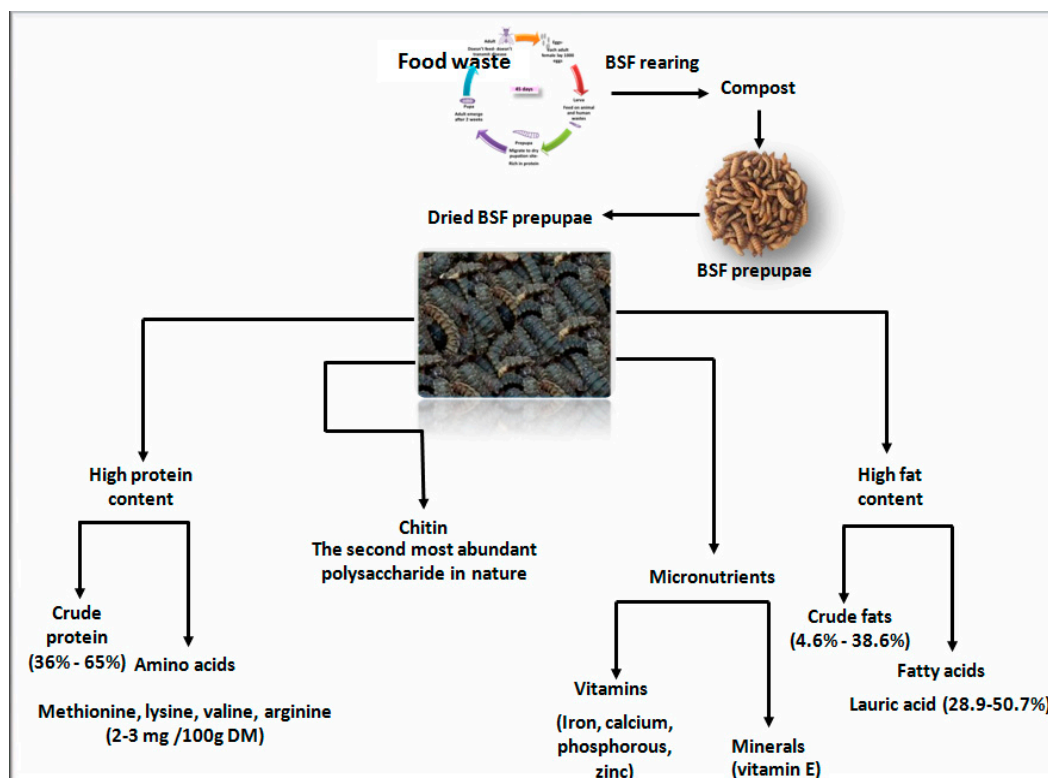
There is a growing amount of literature and experts that recognize that using insect meals in feed formulation could be a novel way to improve feed and food security [7,8]. Insects have been used as food for humans since the ancient era and are nowadays consumed as human food in many parts of the world [9]. However, utilization of insect meal in poultry feeding is more acceptable for consumers rather than direct consumption by humans since in some societies there is a degree of distaste for their consumption [10]. Recent developments in the field of animal nutrition have led to a renewed interest in utilization of insects as ingredients for animal feeds [11,12]. It is now well established from a variety of studies that edible insects have a high content of protein, essential amino acids, minerals, and vitamins [13]. Several studies have demonstrated that insect meals can be used as food or a feed source, which can eventually contribute to the solving of the global food problem [6,7,9,11]. There have been a number of longitudinal studies that have shown interesting findings regarding the appropriateness of some insect meals as feed ingredients for livestock animals (pigs, poultry, and fish) [14–18].

Besides using insects as feedstuff, they also can be used directly to treat organic waste-associated problems, which is produced in large amounts and may represent an environmental burden [19]. In addition, it has been investigated that non-pest flies species can decrease wastes of nitrogen and phosphorus by up to 75% and the mass of manure by 50% in poultry and swine farms [20,21]. The potential of insect meal for use as feedstuff may also have beneficial environmental effects—insect rearing requires less energy and an insignificant amount of land area, which results in a lower environmental footprint [6,11,22]. Therefore, the use of black soldier fly (BSF) grown on farms and household wastes in poultry feed manufacturing could contribute to the reduction of environmental pollutants generated from the accumulation of organic waste [23]. In addition, it has been demonstrated that the rearing of black soldier larvae leads to a significant reduction in waste moisture, waste volume, offensive odor, and pollution potential, as well as the elimination of house fly, *Musca domestica* L. and lesser house fly, *Fannia canicularis* [24,25]. Hence, their last larvae has unique characteristics that make it one of the most promising insect species for commercial and industrial production [26]. For example, their last larval stage—the so-called prepupa—has a high content of protein and fat, containing up to 47% crude protein and 35% ether extract on a dry matter basis [11,18,27,28], making them a suitable feed ingredient for pigs, poultry, and also fish. However, insect rearing farms should be operated under very controlled and healthy conditions. The same evidence from a number of experimental studies has established that use of black soldier fly larvae as a part of a complete feed promoted the growth of commercial fish [18,20], poultry, and pigs [28,29]. Insect meal from black soldier larvae, *Hermetia illucens*, is included in the European Union Feed Material Register, and the insect industry moves quickly, being fueled by the authorization to use protein derived from seven insect species including BSF in aqua feed in 2017, and thus we now stand prepared for a next step—insect meal approval for poultry and pig diets. Insect meal is close to being an appropriate ingredient and is believed to be realistic in the short term for feed manufacturing of pigs and poultry [11,17].

Although insects represent a part of the natural feed of poultry, recent studies indicate that the sustainability of the poultry supply chain may be enhanced by using insect meals in feed formulation. However, to date, data from insect digestibility trials in poultry is rare, and this limits the design of adequate insect-based diets for poultry [30]. This review aims to draw the attention of industrial stakeholders and scientists to the nutritional value of BSF and the feasibility to use it as a novel protein alternative source in poultry diets, as well as its contribution in terms of the bioconversion of organic waste into protein biomass by BSF, thereby contributing to mitigating environmental pollution.

## 2. Nutritional Values

The nutritional value of insects, with emphasis being placed on protein and fat content, has been discussed in several research studies [8]. Black soldier larvae meal has a rich content of protein and fat, which reinforces the potential of using it in animal feedstuff [31]. The chemical composition of insect meals can be affected by their diet [32] and their developmental life stage [33,34]. In the study of Oonincx et al. [35], four types of diets composed of food manufacturing byproducts were used to estimate the effect of diet content of protein and fat on the chemical composition of BSF. Little variation was found in the chemical composition of BSF. Their content of dry matter and crude protein ranged between 33 and 36%, and 38 and 46%, respectively, whereas total fatty acid content was not affected. The nutritional values of BSF are shown in Figure 1.



**Figure 1.** Nutritional and chemical composition of black soldier fly (BSF).

### 2.1. Crude Protein and Amino Acids

When reviewing the importance of the nutrient composition of insects, the focus should be on protein content as one of the most expensive nutrients in poultry nutrition (Table 1). In terms of recent evidence, drastic variations have been found in the nutritional composition of BSF used as chicken feed throughout the different stages of development. Crude protein content in larvae increased just after hatching, and then it gradually decreased from 4–12 days of larval development, with a minimum concentration of 38% crude protein (CP) at larval phase followed by a further increase of 39.2% in

mature larvae on day 14. In the later development stages, there was a steady increase in CP content to reach a peak concentration of 46.2% CP at the early pupa stage. Interestingly, at the post-mortem adult stage, CP content reported the highest level (57.6%) [33]. In addition, defatted BSF larvae meal provides higher protein values and probably surpasses those in soybean meal [36]. The partially defatted BSF larvae meal showed CP content of 55.3%, while the highly defatted BSF larvae meal recorded 65.5% CP [37]. These values of CP of the defatted black soldier larvae meal are close to the crude protein content of meat and fish meals [38].

On the basis of the lowest measured CP level in BSF (36%) [39], the BSF larvae meal showed CP content similar to or slightly higher than some plant-based protein, such as linseed meal, sunflower meal, cottonseed meal, lupins, wheat distillers' grains, or faba beans [11,38]. Finke [40] estimated the value of protein recovery and calculated it as the sum of the amino acids plus taurine divided by crude protein (nitrogen times 6.25). Data from their work showed a high value of protein recovery in BSF larvae 98% (as is) basis, suggesting that amino acids make up the majority of nitrogen in BSF larvae while a slight amount comes from chitin (Table 1).

**Table 1.** Crude protein and amino acids contents in black soldier fly (BSF).

References	CP %	CF %	Ash %	Amino Acids % DM					
				LYS	MET	THR	ARG	VAL	ILE
Spranghers et al. [13]	39.9–43.1	21.8–38.6	2.7–19.7	2.34–2.57	0.71–0.87	1.54–1.68	1.99–2.03	2.41–2.82	1.72–1.91
St-Hilaire et al. [18]	43.6	33.1	15.5	2.62	0.74	1.78	2.65	2.79	2.03
Barroso et al. [39]	36.2	18	9.3	2.75	0.54	1.95	2.98	2.28	2.1
Barroso et al. [39]	40.7	15.6	19.7	2.9	1.3	2	3.27	2.6	2.17
De Marco et al. [11]	36.9	34.3	17.3	2.23	0.9	1.52	1.94	2.2	1.72
De Marco et al. [11]	55.3	18	9.9	2.1	0.65	1.7	2.2	2.7	1.9
Cullere et al. [41]	54.8	15.6	7.7	2.1	0.66	2.04	1.73	3.8	2.34
De Marco et al. [11]	65.5	4.6	9.3	2.5	0.86	2.2	2.7	3.5	2.4
Marono et al. [42]	62.7	4.7	8	4.14	1.33	2.37	-	5.13	3.18
Mwaniki et al. [43]	57.5	7	-	3.3	0.92	2.32	2.79	3.47	2.44

CP = crude protein, CF = crude fat, LYS = lysine, MET = methionine, THR = threonine, ARG = arginine, VAL = valine, ILE = isoleucine.

## 2.2. Amino Acids

In relation to poultry feedstuffs, amino acid profiles and ileal amino acid digestibility are the main measures of protein quality. In a previous digestibility trial, it has been suggested that BSF larvae meal, on the basis of content of amino acids, makes it a good source of protein in pigs' diets [28]. Nowadays, a poultry diet is formulated on the basis of plant protein sources. Cereal protein is the core component of worldwide diets. In addition, lysine, methionine, and threonine are major limiting essential amino acids in cereal-based diets for pigs and poultry. Overall, insects have high levels of these essential amino acids [13,44,45] and have a better amino acid profile compared with that of soya bean meal and most of the common conventional protein sources (Table 2) [46]. Moreover, corn gluten meal (60%) is one of the conventional protein sources in poultry feed. Content of essential amino acids in BSF larvae meal is overall better than content in corn gluten meal (60%); they are similar in valine, while BSF larvae are higher in lysine and arginine, and lower in methionine, threonine, and isoleucine [13,33]. However, the most represented essential amino acids AAs in the BSF larvae meal are leucine and lysine [11]. Although de-fatting decreased histidine concentration from 154 to 125% (relative to lysine), it was still about four times higher than that in fishmeal (30%) [47]. It has been observed that the BSF larvae meal content of methionine and lysine is consistent or slightly less than those of meat meal [11,48]. As far as non-essential amino acids are concerned, protein content in BSF larvae showed higher levels of alanine, proline, and tyrosine than protein of fish meal and soybean meal [49].

**Table 2.** Crude protein and amino acid contents in BSF and common conventional protein sources.

Protein Source *	CP %	CF %	Amino Acids % DM					
			LYS	MET	THR	ARG	VAL	ILE
BSF	49.47	18.11	2.71	0.87	1.95	2.47	3.11	2.21
Soybean meal	44.0	0.80	1.00	0.60	1.05	2.30	1.60	1.00
Herring fish meal	72.3	10.0	5.47	2.16	3.07	4.21	3.90	3.23
Corn gluten	62.0	2.50	1.03	1.49	2.00	1.82	2.78	2.45
Sunflower meal	32.0	1.10	2.69	0.62	1.72	3.14	2.07	1.96
Canola seed meal	38.0	3.80	1.94	0.71	1.53	2.08	1.76	1.37
Sesame seed meal	43.8	6.50	0.91	1.22	1.40	4.68	1.91	1.51

\* Values of nutrients of BSF are the average of their values presented in Table 1 while the values of the rest of the protein sources are according to the National Research Council (NRC) [50]. CP = crude protein, CF = crude fat, LYS = lysine, MET = methionine, THR = threonine, ARG = arginine, VAL = valine, ILE = isoleucine.

The content of amino acids in BSF varies throughout their lifespan, for example, BSF content of lysine was relatively abundant throughout their lifespan from egg to adult (19.0–29.8 g/kg) [33]. Evidence from a recent experimental study reported that every growth phase of the black soldier fly lifespan has a variety of synthesized essential amino acids. In addition, amino acid profile in BSF appears to be related to its CP content as the highest level of amino acids contents was mostly expressed in the early stages of larval development (4th–6th day), then gradually decreased until the larva maturation stage, followed by a stable phase of amino acid levels at a late stage of BSF life cycles such as prepupa and pupa. However, in dry matter (DM), the adult stage of larvae was characterized by the highest content of amino acids (g/kg) [33]. Among the most prevalent essential amino acids in the prepupal stage were methionine [33], lysine, valine, and arginine, with levels between 20 and 30 g/kg DM [13,33]. It has been demonstrated that BSF larvae reared on pig manure showed a content of essential amino acids similar to soybean meal content in terms of lysine, leucine, phenylalanine, and threonine, being higher in methionine, histidine, valine, and tryptophan, and lower in isoleucine and arginine. However, their amino acid profile will be improved through removing the chitin [19]. These data from numerous studies conclude that larvae meal of BSF can be used as a valuable replacer for soybean products in poultry diets.

### 2.3. Crude Fat and Fatty Acids

Insect fatty acids are an interesting potential feed ingredient for poultry and other animals and may be a suitable alternative to less eco-friendly fat sources (i.e., soybean, palm kernel, and fish oil) without any detrimental effect on growth performance, apparent digestibility, gut mucosa traits, and health [51,52]. As mentioned above, the nutritive composition of BSF may be altered during different stages of life. Previous research found that crude fat content was 4.8% on one-day post-hatch of larval age, followed by a dramatic increase throughout the progress in larval development to reach its maximum level 28.4% at 14 days [53]. BSF fed on chicken feed demonstrated satisfactory concentrations of essential fatty acids [33]. Ooninx [35] estimated the fatty acid in four insect species reared on four types of diet with different levels of protein and fat. There was no butanoic acid (C4:0), hexanoic acid (C6:0), octanoic acid (C8:0), undecanoic acid (C11:0), or (Z)-docos-13-enoic acid (C 22:1n9) detected in black soldier fly or other species (Argentinean cockroaches (AC), yellow mealworms (YM), and house crickets (HC). Moreover, decanoic acid (C10:0) was not detected in these species, except in BSF, which presented 0.8–1.3% of total fatty acid content. In black soldier fly, dodecanoic acid (C12:0) contributed 28.9–50.7% of total fatty acids, while this was ≤0.5% in the other species. Thus, this indicated the impact of species-specific fatty acid profiles. Moreover, BSF showed a higher tetradecanoic acid (C14:0) content compared with AC, YM, and HC by 422.7, 23.7, and 228.6%, respectively. In contrast, in terms of BSF used as chicken feed as a rearing substrate, hexanoic acid (C6:0) was detected with low concentration (0.4) at the early phase of larval development [33]. These different findings in fatty acids may be due to the fact that previous research focused on the nutritional composition only at the last stage of larval and prepupal development.

Fatty acids, especially essential fatty acids, are gaining importance in poultry nutrition for improving the health and productivity of birds [54]. However, BSF fats are deficient in essential fatty acids as a main source in poultry diets. Therefore, great attention should be paid to the fat content and its fatty acid composition in the case of regular inclusion of their larvae male and pre-pupae oil as an ingredient in poultry diets [55,56]. BSF in every phase of their life cycle showed adequately high content of essential fatty acid, including linoleic (C18:2) and  $\alpha$ -linolenic acid (C18:3). As mentioned above in the previous study, the main fatty acid in BSF is dodecanoic acid (C12:0). The concentration of dodecanoic acid (C12:0) increased gradually from the fourth day of larval development and reached maximum at pupa stage. Excluding the first week-old larvae, it showed a high contribution of 34–70% of the total fatty acid content.

Although the ratio between saturated to unsaturated fatty acid of most insect meals is less than 40%, as compared to animal products, some insects have a higher concentration of polyunsaturated fatty acids (linoleic and linolenic acids) [2]. It is well established that in poultry diets a minimum quantity of linoleic acid is required for optimum egg production and egg quality [50]. Ratios of linoleic to  $\alpha$ -linolenic acid in the range of 5–15 to 1 is recommended in humans and infants [46,47]. This recommendation relies on the average ratio observed in breast milk. Nevertheless, the average ratio in breast milk has a tendency to be high (up to 15) [46]. Ratios of linoleic to  $\alpha$ -linolenic acid in BSF have been found to be in the same range (6.1:1–11.1:1). These variations of n6/n3 ratio in black soldier fly reflected diet content of n6/n3 ratio (4.9:1–13.5:1). However, among four species of insects, black soldier fly had the lowest n6/n3 ratios [26]. Varying content of unsaturated fatty acids was found at an early stage of BSF larvae development; this content gently declined after the prepupal stage [28]. In a recent study [28], researchers estimated linoleic acid (C18:2) and  $\alpha$ -linolenic acid (C18:3) in different development stages of BSF. High level of linoleic acid (C18:2) and  $\alpha$ -linolenic acid (C18:3) were detected on the sixth day of development (31.4% and 1.6%, respectively). In addition, the mature larval stage content of linoleic acid (C18:2) and  $\alpha$ -linolenic acid (C18:3) were 7.2% and 0.4%, respectively, while those of the prepupal phase were 9.6% and 0.6%, respectively [33].

BSF has a satisfactory level of oleic acid (C18:1) in the range of 10.3% to 15.9%, according to feed composition [35]. Furthermore, a maximum level of oleic acid (C18:1) 36.4% was detected on the 4th day of larval development followed by a gradual decrease to reach 10.4% and 7.8% on 12th day and 14th day of larval development, respectively [33]. Interestingly, there is a competitive interaction in metabolism between oleic acid and the indispensable fatty acids (linoleic acid and  $\alpha$ -linolenic acid). Therefore, a high concentration of oleic acid may affect the metabolic processing of essential fatty acids [57]. In addition, profiles of fatty acid in larvae reared on manure showed little amounts of long-chain unsaturated fatty acids [18]. However, the concentration of omega-3 fatty acid eicosapentaenoic acid (20:5n-3) increased in those grown on a seaweed included-diet [58].

Recent studies reported the possibility of replacing soybean oil with BSF fats in rabbit diets without affecting consumer acceptance. Moreover, the results showed that the meat of the rabbits fed the diets containing insect fat (average for BSF and *Tenebrio molitor* diets) was less susceptible to oxidation (0.24 vs. 0.39 mg malondialdehyde/kg meat in the control group [52]).

#### 2.4. Micronutrients

Micronutrients such as minerals and vitamins have a main role in the nutritional value of poultry feed. Although most of the previous studies focused on protein and fat content of insects, there are also significant contents of essential micronutrients found in insects, such as iron, calcium, phosphorous, zinc, and vitamin E, which also have significant importance [33]. Nevertheless, the accumulation of undesirable substances such as toxic metals may occur and should be monitored during production. Therefore, further investigations are required to estimate the bioavailability of minerals such as iron, zinc, and cadmium obtained from insects [57].

Liu et al. [33] estimated the content of minerals and vitamins in BSF chicken feed at commercial phases (mature larvae at 14th day and early prepupa). Their results showed rich content of vitamin E in

both commercial stages. However, the concentration of vitamin E in early prepupa (3.26 mg/100 g) was lower than that in the mature larval stage (6.68 mg/100 g). They also reported that most micronutrients were found in the last stages of larval development. The prepupal stage showed higher content of some minerals compared with the mature larval stages, such as phosphorus and calcium. For example, results showed that in the early prepupa phase, phosphorous content (620 mg/100 g) was almost twice that of mature larvae on the 14th day (350 mg/100 g), whereas the content of some other minerals such as sodium, iron, and zinc were higher in the mature larval stage on the 14th day. In BSF larvae reared on horse manure, phosphorous content was higher and reported a value of 920 mg/100 g DM, while the rest of the minerals content was 4.43% calcium, 1.56% potassium, 0.41% magnesium, and 0.3% sodium on a DM basis. [59].

### 2.5. Chitin

Chitin, the second most abundant polysaccharide in nature, is commonly found in lower organisms such as fungi, crustaceans, and insects, but not in mammals [60]. Black soldier fly represent an effective way to convert waste into a precious source of nutrients, such as proteins, lipids, and chitin [61]. Chitin (the main component of the arthropod exoskeleton), chitosan (produced by deacetylation of chitin), and chitooligosaccharides (degraded products of chitosan or chitin) have gained tremendous attention due to their biological and great economic values [60,62–64]. Chitin and its derivatives have various applications: food, cosmetics, pharmaceuticals, textile industries, waste water treatment, and agriculture [62]. Recent studies demonstrated that chitin and its derivatives have an enhancing effect on the responses of each innate and adaptive immune system, including recruitment and activation of innate immune cells and generation of cytokine and chemokine [60,64]. Moreover, in light of potential use of chitin as a feed supplement, various studies have reported other biological effects of chitin such as antibacterial activity [65–71], antifungal activity [72–74], and antiviral activity [75–78] against various types of bacteria, fungi, and viruses. In addition, the importance of chitin and its derivatives as feed supplements in poultry and pig nutrition has been reviewed and investigated in several studies [79–82]. For example, a recent study reported that chitosan oligosaccharide supplementation improved the growth performance of poultry via promoting the antioxidant status and immune responses, as well as intestinal development [81,83].

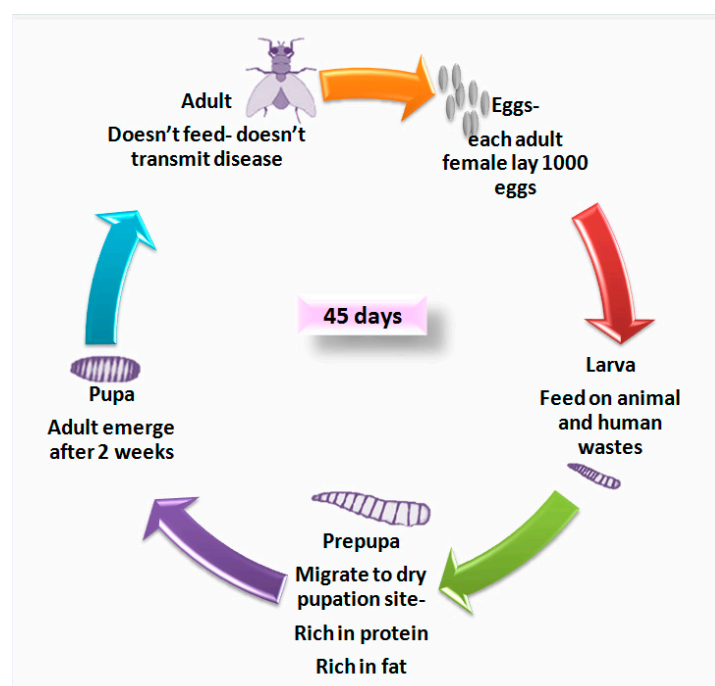
According to the conclusion of the World Economic Forum (WEF) 2013, arguably the greatest risk to human health comes in the form of antibiotic-resistant bacteria. We live in a bacterial world where we will never be able to stay ahead of the mutation curve. A test of our resilience is how far behind the curve we allow ourselves to fall [84]. Insect products demonstrate interesting characteristics, making them potentially one of the best alternatives to the excessive usage of antibiotics in poultry feed [8]. Although chitin is a source of non-protein nitrogen in insect-included diets, the content of chitin in the larval stage is very small relative to total nitrogen [28].

## 3. Production of Black Soldier Fly

BSF originates from the southern USA [85] and has spread throughout tropical and warmer temperate regions between about 45 °N and 40 °S [86]. Its larvae feed on organic waste; however, no food is required for the adult fly. Moreover, this insect has no attraction to human food or habitat; hence, it has no potential to transmit any disease or cause a nuisance [7,87,88].

For reproductive purposes, *Hermetia* pupae stage is used. The priority of adults is on mating and laying eggs after they come out of their pupal states. Mating and oviposition occur throughout the year [88]. Sixty-nine percent of mating occurs 2 days after eclosion, while 70% of oviposition occurs at 2 days after mating. Mating has an association with daytime and lighting, and oviposition has a strong correlation with time of day, temperature, and moisture [89]. Adults initiate mating on the wing. Females usually lay an egg number of around 500 and prefer to oviposit in a dry crevice near the selected larval medium [21] in temperature ranges between 27.5 and 37.5 °C [31], humidity >65% [90]. The eggs of BSF require 102–105 h (4.3 days) to hatch at 24 °C [31]. After the preparation of the rearing

substrate, larvae will colonize the substrate. The nutritive composition of organic waste used in larvae rearing determines the amount of introduced larvae [90]. The last stage in larval development is the prepupa, a migratory stage. At this point, the BSF prepupal gets ready to store a great amount of fat to supply energy for their migration and pupation into an adult. This stage with the maximal stored fats is the desired stage to harvest for feedstuff [21]. Black soldier larvae develop through five larval stages; upon reaching the last stage (prepupal stage), the larvae detach from the rearing substrate in search of a dry pupation site to complete the pupation into an adult. During this dispersal phase, separation of larvae from the manure becomes easy [90]. In the course of this scattering stage, prepupae can easily be harvested by simply directing their search for pupation sites into collection bins [21,87,91], and a portion of the colony should stay to produce a new stock of pupae to sustain the production chain [90]. A schematic diagram for the life cycle of the black soldier fly (BSF) is illustrated in Figure 2.



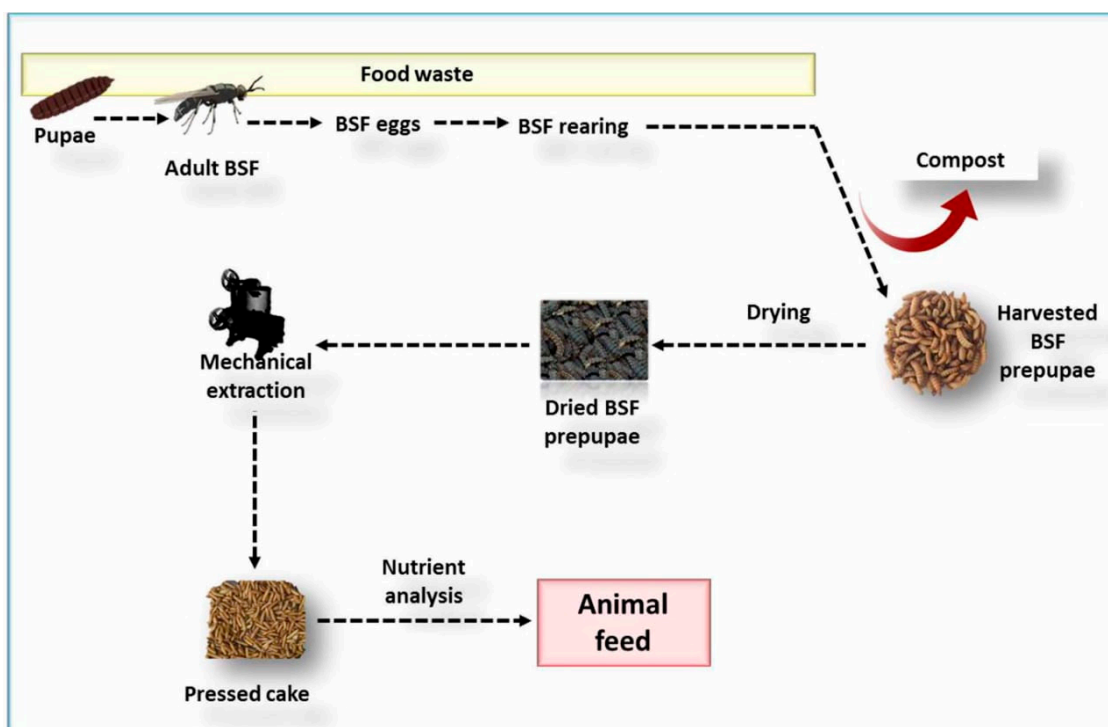
**Figure 2.** Schematic diagram for the life cycle of the BSF.

For rearing and production, eggs should be collected from cracks and crevices near the larval substrate and gathered in carton flutes. BSF larvae are most easily reared on layer wastes in concrete basins under caged layers [24]; a 100,000-bird caged layer house gives a yield of 42.26 tons of live weight of prepupae for June through August, which is suitable for livestock feeding [21]. BSF larvae convert large amounts of organic wastes such as spoiled animal feed into protein mass and soil fertilizer. Schematic presentation of food waste bioconversion to animal feed via insect farming is illustrated in Figure 3.

### 3.1. Larvae Feed and Rearing Substrates

The larvae grow on organic wastes such as spoiled animal feed, vegetables, and food waste. In nature, manure is the main rearing substance of many insects, particularly BSF larvae [19]. In addition, black soldier larvae can be grown on organic materials that are unusable for humans, for example, kitchen waste and spoiled feed [37,92]. However, it has previously been observed that manure of laying hens is a perfect substrate for rearing black soldier fly larvae, and there is no requirement for special facility or extra energy [21]. With respect to feed/substrate for insects, the European Union Legislation prohibits the use of certain materials such as manure in their feeding.





**Figure 3.** Schematic presentation of food waste bioconversion into animal feed via insect farming.

Restaurant waste is one of the most widely available wastes, which considers an environmental pollutant in case of the absence the appropriate disposal. However, there are large amounts of this waste accumulated every hour, especially in highly populated cities. For example, in Wuhan, China, more than 1000 tons of restaurant waste is generated daily [93]. Restaurant waste is usually rich in starch, fat, protein (approximately 20% protein, 20% fat, and 57% carbohydrate) [92]. Restaurant waste alone or mixed with other organic wastes can be used for rearing the black soldier larvae.

There is currently significant environmental and economic push to reduce pollution caused by industrial operations waste, such as rich nutrient content. For example, more than 85% of the total by-products of the brewing industry are wet brewers' spent grain, which contains 17% cellulose; 28% non-cellulosic polysaccharides, chiefly arabinoxylans; and 28% lignin. It is also rich in protein and fibers (around 20 and 70% dry basis, respectively). Brewers' spent grain is available with low or no cost over the year [94]. Additionally found among these forms of industrial waste is soybean curd residue, called okara, a cellulosic by-product of the soy milk and tofu (soypaneer) industry [95]. The main components of okara are ruptured cotyledon cells and the soybean seed hull, which has a high content of cell wall polysaccharides. It also includes high levels of protein, oil, fiber, and minerals, along with unspecified monosaccharides and oligosaccharides [96].

Merging such by-products together in a combination can create optimal diets for insects. The economic and environmental advantages of the combination depend on the effectiveness of the production insects in converting it into body mass. According to a previous study [87], one meter squared of a BSF larvae production unit could produce 145 g dry prepupal biomass daily. Optimum daily feed intake per larva was 100 mg of wasted poultry feed (60% moisture content), which resulted in an optimum trade-off between waste reduction efficiency (41.8%) and biomass generation (prepupal dry weight: 48.0 mg) [87]. Finally, the waste treatment scheme must fulfill two goals: (1) achieving high effectiveness in waste disposal, and (2) peak production of biomass [87].

### 3.2. Growth Performance and Survival

Rearing substrates can present a wide variability in their chemical composition, affecting in turn the composition and the growth performance of BSF larvae. Protein, carbohydrate, and moisture

content have a great effect on growth performance. However, moisture has a greater influence on development and life history traits than protein and carbohydrate contents; a diet with 40% moisture content failed to provide adequate development to BSF larvae through their life cycle, including the fact that 70% moisture accelerated the rate of development through all life stages [97]. This finding could suggest that other diet components (e.g., associated microbes) play a role in the development processing of BSF larvae [97]. Black soldier flies reared on a protein and fat-rich diet could develop faster (3 weeks), whereas extended development was associated with low protein (5 weeks) [35]. This period may be reduced more to only 2 to 3 weeks in cases of feeding on an ideal diet (high moisture, high protein, and high fat) [21,98]. For instance, the diet at 70% moisture, with a protein level of 21% and carbohydrate level of 21%, gave the highest growth performance and the lowest mortality rate in comparison with other investigated diets [97]. Six diets were investigated to assess the effect of diet types on larvae development rate: control poultry feed, liver, manure, kitchen waste, fruits and vegetables, and fish rendering. The highest growth performance was obtained by kitchen waste, and the poorest was found in larvae fed manure, while those fed fish had almost 100% mortality at the adult stage [99].

Although insects are cold-blooded and the energy content of the diet is not required for maintaining body temperature, energy content is very important for growth performance. However, larvae development and duration of the feeding stage essentially depends on dietary protein more than energy content [35].

### 3.3. Conversion Efficiency

Black soldier flies that have received a suitable diet have a feed conversion efficiency better than most conventional production animals [35]. BSF can convert 50% of the dry matter content of organic wastes into insect biomass rich in protein and fat content (42% and 35%, respectively) [21]. Moreover, this species can convert feed more efficiently than other species of insects, such as yellow mealworms and house crickets [35]. The primary factor determining feed conversion effectiveness in a specified insect species is dietary composition [100]. Moreover, converting diets into insect biomass was greatly affected by the quality and composition of the diet (the nitrogen content, the ratio of nitrogen to acid detergent fiber content, and the content of crude fat) [101]. According to Ooninx et al. [35], dietary protein is the key determinant for the efficiency of feed conversion. However, they reported no significant effect of diet composition on the nitrogen conversion efficiency of black soldier larvae.

### 3.4. Waste Reduction Index and Environmental Efficiency

A potential pollution problem can rise due to the accumulation of organic wastes. BSF can use a great variety of organic waste and convert it to a protein source for livestock. BSF larvae can also remove house fly breeding, a major vector of diseases [21,25,98,102]. It is supposed that an interspecific chemical communication prevents oviposition of the house fly, *Musca domestica* L., around poultry manure containing larvae of BSF [103]. Furthermore, it has previously been observed that larvae of BSF have the ability to dispose and inactivate bacteria or diseases such as *Escherichia coli* in dairy manure [104], and *Salmonella enterica* and *Escherichia coli* O157:H7 in chicken manure [105,106]. Decontamination may happen due to the release of some compounds that have a bactericidal effect in larvae secretions [107–109]. It has been suggested that in an inherent reaction to elevated bacteria concentrations, larvae secrete antimicrobial substances with a broad spectrum of activity [110]. This ensures sufficient safety in terms of the use of the residual in crop cultivation as an organic fertilizer [111]. Organic waste is considered completely treated when it has been digested by larvae in one cycle of digestion. The residue compost has great value for agriculture as a soil fertilizer [87].

Waste reduction efficiency is calculated using the overall degradation (D) Equation (2). Taking into consideration the time that larvae need to recycle this waste quantity, waste reduction index (WRI, Equation (1)) is a measure used to evaluate the capacity of black soldier larvae to recycle and

convert the waste in a specific time. Good reduction efficiency is indicated by high values of waste reduction index [87].

$$WRI = D/t \times 100 \quad (1)$$

$$D = [W - R]/W \quad (2)$$

where  $W$  is the total quantity of organic waste used for larvae feeding during the time  $t$ , and  $R$  is the residue after harvesting time  $t$ .

Diener et al. [87] used chicken feed with different levels of daily feed consumption in order to estimate the optimum daily feed intake for the bioconversion system. The highest value of waste reduction efficiency was 43.2% with 50 mg daily feeding rate, while the value of WRI was 3.1. However, the best value of WRI was 3.8 for the optimum feed intake of 100 mg larva<sup>-1</sup> day<sup>-1</sup>. In a study by Salomone et al. [90], BSF were grown on food waste from different sources. Thirty tons of food waste per day produced 930 kg/day dry weight of prepupal biomass, which can be utilized as a sustainable protein source in poultry feeding and residue (9990 kg/day) and can be used for bio-fertilization. They showed a value of 66.7% waste reduction efficiency. To the best of our knowledge, these authors reported the highest value of waste reduction efficiency.

## 4. Effects on Poultry Performance

### 4.1. Feed Intake

Soybean cake substitution by either partially or fully defatted BSF larvae meal in hen diet had no adverse effects on feed intake in comparison to the standard given by the breeder (Lohmann) for the same age [112]. These results are in line with a recent study comparing the effects of replacing soybean meal and oil with 10% (*w/w*) dried BSF larvae and 10% (*w/w*) dried pre-pupae raised on experimental household organic waste in corn–soybean-based control diet. Twenty-four-week-old laying hens received the experimental diets for 5 weeks. They did not observe significant differences in feed intake between treatments [55]. Similar findings were obtained by Cullere et al. [41], who estimated the performance of broiler quails receiving different levels of dietary BSF larvae meal as a partial substitution of soybean meal (16.1% and 24.8%) during the grower phase.

As for broiler chickens, dried house fly larvae meal and soybean-based control meal were used as a feed of broiler chicken in a 0–3 and 4–5 three-phase feeding system (0–3 weeks, 4–5 weeks, and 0–5 weeks) without significant differences in feed intake [113]. This finding was consonant with a recent study, in which local poultry (Ardennaise chickens) were fed a standard commercial diet with 8% replaced by de-frozen BSF larvae corresponding to 2% on a dry matter basis, from 30 to 80 days of age without being statistically different compared to control diet [59]. It has been demonstrated that the complete replacement of soybean meal by BSF larvae meal in Lohmann Brown Classic laying hens feeding over 21 weeks led to a significant reduction in feed intake by about 13% [42,114]. This reduction in feed intake might be attributed to the color and flavor of BSF meal [114]. Short-chain fatty acid content in larvae might also be the reason behind this, since they may work as essential signaling molecules between gut microbiota and host physiology [115]. In this sense, it has been observed that the growing level of circulating acetate in rodents led to appetite suppression via central hypothalamic mechanisms [116]. In addition, the insect meal administration also increased the levels of propionate, produced as a result of fermentative activity of gut microbiota during fiber degradation [117], which was found to cause satiety after insect meal administration [114]. For instance, recent evidence from human studies indicates that propionate may also play a key role in appetite modulation [117]. This study was followed by another study that suggested that increasing propionate concentration may contribute to attenuation reward-based eating behavior by a lowering of the response to high-energy food via striatal pathways, independently of modulating satiety-related hormones in the blood [116].

In contrast, adding defatted BSF larvae meal in laying hens' diet significantly increased their feed intake [118], while no differences were found in feed intake when ISA brown laying hens were fed

15 g/day BSF larvae meal over 6 weeks in an on-range choice feeding system [119] or when Muscovy Ducks were fed up to 9% dietary BSF larvae meal over 7 weeks [120]. Furthermore, compared to the inclusion of 25% fish meal-based control diet, the inclusion of 25% house fly larvae meal in a broiler diet showed higher feed intake while feeding either 10% fishmeal or 10% *Musca domestica* larvae meal did not observe significant differences [121]. These results indicate that inclusion of BSF in poultry diets in a whole or in the defatted form as well as other techniques of BSF processing may significantly affect the feed intake, which requires further investigation.

#### 4.2. Daily Body Gain and Live Weight

A recent study on laying hens fed a diet supplemented either with whole (non-defatted) 10% BSF larvae meal or with 10% BSF pre-pupa meal for 5 consecutive weeks did not show significant differences among treated birds and those fed the basal diet consisting of maize grain, soybean meal, and soybean oil [55]. In another study, it was reported that broilers fed BSF-based starter diet showed daily gain and body weight at 10 days old, roughly similar to those fed the fish meal control diet (24.6 vs. 24.5 g/day, 286 vs. 285 g, respectively) [122]. These results were consistent with other studies that did not indicate any differences in daily gain or final weight during the grower phase in broiler quails fed either a control diet or BSF larvae meal diet [41] or in Muscovy Ducks fed up to 9% dietary BSF larvae meal [120]. Moreover, inclusion of 10% house fly larvae meal or 10% fish meal in broiler diet did not observe a meaningful differences in growth performance [121].

It has been observed that inclusion of 5–20% house fly larvae meal in broiler diet improved live body weight significantly when larvae meal diets were fed throughout the overall 5-week growing period. The highest value of body weight was recorded for the group fed 15% larvae meal diet with 1.785 kg vs. 1.638 kg for the control group, respectively [113]. Moreover, 30-day-old local chicken (Ardennaise chickens) fed 8% fresh BSF larvae meal that was included in the diet for 50 days recorded a weekly body weight that was slightly better than those of control chickens [59]. The same trend was demonstrated when 25% house fly larvae meal was included in broiler diets in three-phase feeding systems. Data from this study showed significantly increased daily gain and final slaughter weight compared to corn–soya oil cake diet [121]. Linear and quadratic responses were found in body weight and average daily gain during starter and growing periods due to the inclusion of BSF into the broiler chicken diets, while the average daily gain decreased linearly during the finisher stage, which may be attributed to some negative effects of dietary BSF larvae meal on gut morphology when administrated at a high level (10%) [123]. In laying hens, inclusion of 7.5% defatted BSF larvae meal into their diet from weeks 19 to 27 of age showed significantly higher body weight than other groups [43]. However, Borrelli et al. [114] reported that the complete replacement of soybean meal by BSF larvae meal in laying hens reduced their body weight (2.09 vs. 1.89 kg, respectively) after a 21-week feeding period.

#### 4.3. Feed Conversion Ratio

In a study by Agunbiade et al. [124], hens fed a diet containing maggot meal (50% of dietary animal protein supplied by fish meal, 12.5% of total dietary protein) in a cassava product-based layer diet showed the best feed conversion ratio (FCR) (2.78 kg feed/1 kg egg) compared with those fed fish meal as 25% of the dietary protein (3.04 kg feed/1 kg egg). However, increasing maggot meal concentration up to 100% fish meal replacement impaired the FCR without significant differences. These results indicate that the inclusion of the insect larvae meal at low concentration appears to be more suitable in poultry diets. As was evident from this study also, when house fly larvae meal was included (5–20%) in the first 3 weeks of broiler diet, the 5% supplemented group had the best FCR (1.33 vs. 1.40 for the control) compared to other treatments; however, the dietary treatments significantly improved the FCR during two-phase feeding systems (28–35 days and 0–35 days) compared to a soybean-based control diet [113]. This may have been due to the higher nutrient content of larvae meal diet compared to soybean meal, particularly essential amino acids (29.5 vs. 18.3%, respectively), and due to the higher digestibility values of crude protein and amino acids in maggot compared to soybean meal [113].

Moreover, when a complete replacement of soybean meal by BSF larvae meal was used in layer feed, researchers found a lower FCR compared with the soybean-based control diet [42]. In contrast, FCR significantly increased due to the inclusion of de-fatted BSF larvae meal into the laying hen diets [43]. The differences in responses between these studies could be ascribed to the age and strains of birds.

In a recent study on Muscovy ducks, no differences were observed in the feed conversion ratio when ducks were fed up to 9% dietary BSF larvae meal over 7 weeks [120], while linear and quadratic responses to increasing BSF larvae meal were found with a maximum correspondence in broiler fed up to 15% BSF larvae meal during all growing stages [123].

#### 4.4. Mortality and Diseases Signs

Mortality was zero in all hens either fed partly defatted meal from BSF larvae or soybean cake-based control diet [112]. Moreover, no mortality was reported in 50-week laying hens that were fed a diet including maggot meal as a partial or full substitution of animal protein (fish meal) [124]. Substitute soybean meal and oil with 10% (*w/w*) BSF larvae meal and 10% (*w/w*) pre-pupae meal in laying hen diets had no effect on mortality rate during the experiment period (5 weeks) [55]. On the same line, the inclusion of BSF larvae meal in the grower diet of broiler quails did not show adverse effects on the mortality rate [41,124]. Moreover, no pathological signs of common diseases were observed in broilers fed maggot-based diets [125,126]. No gizzard erosions or toxicity were observed due to the inclusion of house fly larvae meal in broiler diets [121]. These results indicate that inclusion of insect meal in poultry diets has no adverse effect on mortality rate.

It has been investigated that hens fed partly defatted dietary BSF larvae meal (12% and 24%) did not develop metabolic or health disorders [112]. Moreover, the absence of mortality and morbidity in laying hens fed a BSF-supplemented diet stated that the BSF larvae had no adverse impacts on the health status of laying hens [42,55,114]. As for Muscovy ducks, the cumulative mortality rates in Muscovy ducks fed different levels of partially defatted BSF larvae meal was 2.08% (for 3%, 6%, and 9% dietary BSF larvae meal groups) against 4.16% for the control group; however, no statistical effect of dietary BSF larvae meal was found for this parameter [120].

#### 4.5. Apparent Digestibility

In a study by Hwangbo et al. [113], 28-day-old male broilers were fed a diet with house fly larvae meal content of 30% or soybean meal for 1 week to estimate the apparent digestibility of crude protein and amino acids. The highest digestibility values of crude protein, essential amino acids, and nonessential amino acids in this study were recorded by house fly larvae meal (98.5%, 94.8%, and 94.7%, respectively) compared to the soybean group (98%, 92.4%, and 92.2%, respectively) [67]. In a similar study, house fly larvae and pupa meal were used in a broiler digestibility trial. The results showed a digestibility of 69% and 79% for crude protein for larvae meal and pupae meal, respectively [121]. Another study estimated the total tract apparent digestibility of crude protein, ether extract, and gross energy of BSF larvae meal for the broiler. The results showed 51% for crude protein digestibility, 99% for ether extract, 69% for gross energy, 53% for dry matter, and 66% for organic matter [11]. These results provide some insights with regards to the utility of BSF as a promising alternative of conventional feedstuff in poultry diets.

In contrast, Cullere et al. [41] examined a partial replacement of soybean meal and soybean oil with two levels of de-fatted BSF larvae meal (10% and 15%) in the grower diet (10–28 days of age) of broiler quails. Dietary inclusion of 10% BSF larvae meal was able to substitute 28.4% of soybean oil and 16.1% of soybean meal, whereas 15% BSF larvae meal replaced 100% of soya bean oil and 24.8% of soya bean meal. Apparent digestibility of crude protein (45.1, 42.9, and 34.0), starch (93.9, 95.7, and 95.7), dry matter (54.0, 58.9, and 55.2), organic matter (58.4, 62.9, and 59.1), and energy (62.0, 65.3, and 63.1) for control, 10% BSF, and 15% BSF diets, respectively, did not show statistical differences among groups, while digestibility of ether extract was lower in the 10% BSF inclusion level group

compared with control and 15% BSF. However, the 10% BSF group, numerically but not statistically, reported the highest values of apparent digestibility for dry matter, organic matter, starch, and energy. Although the crude fat content in the 15% BSF diet was the lowest (45.5 g/kg feed) as compared with 10% BSF and control diet (51.5 and 61.4 g/kg feed, respectively), the apparent digestibility of ether extract of 15% BSF birds was significantly higher than those of 10% BSF (89.6 g/kg vs. 82.5) but similar to the control (92.9 g/kg). Quails fed a diet including 15% BSF larvae meal showed a reduction of 24.6% in the apparent digestibility of the crude protein compared to the control group; due to statistical reasons, this reduction was found to be not statistically significant.

This reduction in protein digestibility, which was reported by many studies and ranged from 8 to 11%, may have been due to the presence of chitin cross-linked with proteins [11,41,127–129]. Chitin content of BSF larvae is approximately 5.41% DM [40] and 8.72% DM for prepupae [87]. However the average in partially defatted BSF larvae meal is 5, while in highly defatted larvae is 6.9% DM [37]. For this reason, when soybean or fish meal protein is replaced with either partial or total BSF prepupae, attention should be paid to the balance of dietary amino acids, the ideal amino acid profile for poultry, and reliable digestibility coefficients [127].

Chickens, mice, and Japanese nightingales were used in digestion trials to evaluate the apparent digestibility of purified and natural chitin. Digestibility of chitin ranged between 19% and 58% in mice, and 23% and 31% in broilers fed pure dietary chitin, and was 56.8% in Japanese nightingales that received mealworm larvae [130]. Chitinase can act as a protease-resistant digestive enzyme that dissociates chitin in the chicken gut, indicating that chitinase can be supplemented in poultry diets, especially insect-fortified diets, for improving their nutritional value [10]. Chicken chitinase mRNA level was extremely high and was the second most abundantly expressed transcript in the glandular stomach, exceeded only by pepsinogen A. These findings showed the importance of chitinase in the digestion of chitin-containing diets [10]. In chicken, oxyntic-peptic cells in proventriculus and hepatocytes expressed chitinase mRNA. Data showed that chicken gut chitinase was expressed more abundantly in the proventriculus than in the liver [131]. Moreover, results from an earlier study reported that chitinase could be secreted in the gizzard of broilers [132]. The first significant signals of chicken chitinase mRNA in the proventriculus were found at embryonic day 7, and the signals gradually increased in intensity with development until the hatching day, and then a drastic increase was seen around post-hatching day 2, manifesting in forms such as intensity in the adult bird.

Chicken chitinase has a robust activity at pH 2.0–2.3 [10,133], and thus its activity is high in the proventriculus, low in the duodenum, and negligible in the jejunum and ileum [128]. The earlier findings also reported the same finding that the functional significance of chitinase in the intestinal lumen is doubtful [131]. However, Tabata et al. [10] incubated mealworm shells in the stomach extract of white leghorn chicken for 1 or 16 h and reported that insect chitin was degraded to  $(\text{GlcNAc})_2$  by endogenous chitinase under the pH conditions of the stomach and intestine. Furthermore, it has recently been reported that feeding behavior affects chitinase expression levels as well as chitinolytic activity of the enzyme, determining chitin digestibility in different species [134]. However, a previous study indicated that the activity of mucosal chitinase in intestinal parts of the chicken was not improved with elongated chitin feeding period, suggesting that dietary chitin has no enhancing effect on mucosal chitinase activity [128].

Regarding protein quality, house fly larvae meal was noticed as a good source of limiting amino acids, particularly lysine and arginine, being comparable to fish meal and meat and bone meal, and superior to soybean meal [113,121]. Hwangbo et al. [113] also reported that house fly larvae meal can provide an adequate amount of all the essential amino acids, except for leucine and isoleucine, compared to soybean meal. It was also stated that since house fly larvae contain low percentages of methionine and cysteine, it is necessary to support diets that contain maggots with methionine since it is known that methionine has a sparing effect on cysteine [121].

As far as defatted BSF larvae meal is concerned, the 32-day-old broilers were fed corn–soybean basal diet supplemented with 250 g/kg of partially or highly defatted BSF larvae meal to estimate

the apparent digestibility. The feed trial lasted for 4 consecutive days after 6 days of adaptation. The average apparent digestibility was 62, 98, 61, 63, and 69% for crude protein, ether extract, gross energy, dry matter, and organic matter, respectively, in the partially defatted BSF larvae meal, while for the highly defatted BSF larvae meal, the value showed 62, 93, 50, 59, and 64% for crude protein, ether extract, gross energy, dry matter, and organic matter, respectively [37].

A significant reduction in apparent ileal digestibility in dry matter, organic matter, and crude protein was found in layers fed full replacement of soybean meal by defatted BSF larvae meal over 21 weeks by 3.76, 4.17, and 13.57%, respectively in comparison with control birds, while insignificant reduction (by 5.60%) was observed in digestibility of ether extract [135]. This reduction of the digestibility in this study was associated with the lower feed intake found in the BSF treatment group.

#### 4.6. Apparent Metabolizable Energy (AME) and Nitrogen-Corrected Apparent Metabolizable Energy (AMEn)

In order to better formulate poultry feed, the overall information about the feedstuff should be available, particularly apparent metabolizable energy (AME) and nitrogen-corrected apparent metabolizable energy (AMEn), which have great importance in this sense. De Marco et al. [11] estimated AME and AMEn in whole BSF larvae meal for broiler chickens, with their values being 17.38 MJ/kg DM and 16.60 MJ/kg DM, respectively. These findings of AME and AMEn values of the whole BSF larvae meal are equivalent or even higher than full-fat vegetable ingredients such as sunflower seed, linseed, soybean, and rapeseed [38].

In regard to defatted BSF larvae meal, broiler quails fed diets containing 10% and 15% defatted BSF larvae meal showed values of 12.2 and 12.8 MJ/kg DM, respectively, for AME compared to the control diet, which showed 11.8 MJ/kg DM [41]. In this context, corn and soybean-based diet with inclusion of 250 g/kg (*w/w*) partially defatted or highly defatted BSF larvae meal were used in a digestibility trial for estimating the AME and AMEn for 32-day-old broilers. The significantly higher values of AME and AMEn were recorded by the partially defatted BSF larvae meal at 16.25 and 14.87 MJ/kg DM, respectively, while the highly defatted BSF larvae meal showed 11.55 and 9.87 MJ/kg DM, respectively [37]. These significant differences in results were due to the variation in ether extract content for each source. These findings suggest the valuable and effective utilization of BSF larvae meal as a novel substitutional source of AME either whole or defatted.

#### 4.7. Apparent Ileal Amino Acid Digestibility

Evaluation of amino acid digestibility is very important for poultry feed formulation. It provides an indication of amino acid availability in feed ingredients. However, measurement of amino acid digestibility in excreta of poultry is not totally accurate due to the involvement of uric acid in feces and the probability of microbial protein contribution in the excreta. Therefore, using ileal amino acid digestibility is a more reliable method to estimate the digestibility of amino acids in poultry [39,136]. To the best of our knowledge, studies on ileal amino acid digestibility of BSF larvae meal are very limited.

De Marco et al. [11] estimated the apparent ileal digestibility of 17 amino acids of whole BSF larvae meal in broiler chicken. Thirty-two-day-old broiler chickens received a corn and soybean-based diet that included 250 g/kg larvae meal for 4 days after a 6-day adaptation period. The apparent ileal digestibility of the amino acids in BSF ranged from 42% to 89%, while the overall mean was 68%. The apparent ileal digestibility of methionine, isoleucine, and lysine showed the lower values in indispensable amino acids as 42%, 45%, and 46%, respectively, and higher values for arginine, histidine, and leucine at 83%, 81%, and 76%, respectively, whereas the most digestible values of dispensable amino acids were recorded for proline, alanine, and cysteine at 89%, 86%, and 82%, respectively, and the lowest value was recorded for tyrosine at 43%. All the aforementioned percentages of amino acid digestibility were lower than those of *Tenebrio molitor*, which was evaluated in the same study and under the same conditions. These differences in amino acid digestibility between BSF and *Tenebrio molitor* may have been due to the different levels of chitin content in the hard outer shell of insect larvae (4.62% and 5.40% as feed for *Tenebrio molitor* and BSF, respectively) [137].

As far as defatted black soldier fly larvae meal is concerned, it has been observed that the defatting process can improve the ileal digestibility of amino acids and can obtain values higher than those recorded for those of full-fat BSF, either partially or highly defatted. Thirty-two-day-old broiler chickens were used in digestibility trials to determine the apparent ileal digestibility of 17 amino acids. The broilers were fed a corn–soybean-based diet with a concentration of 250 g/kg (*w/w*) defatted BSF larvae meals either partially or highly defatted. The apparent ileal digestibility of these 17 amino acids was not influenced by the defatting levels, except for proline, which showed the value of 65% in the partial defatted meal vs. 82% for the highly defatted meal. The overall mean of indispensable amino acids were 80% and 81% for partially and highly defatted meals, respectively, with the highest value for valine being 90% and 91%, respectively, and lowest for histidine being 64% and 63%, respectively, while the average of dispensable amino acids were 74% and 79%, respectively, for partially and highly defatted meals with the highest values being for alanine (92% and 99%, respectively) and tyrosine (92% and 95%, respectively) and the lowest for cysteine (44% and 45%, respectively) [37]. The defatting process may be involved in the reduction of cysteine digestibility if performic acid oxidation was not performed prior to acid hydrolysis [40,138]. Apparent ileal amino acid digestibility in the defatted BSF larvae meals was higher than those obtained for certain animal protein sources such as meat meal, meat and bone meal, and feather meal, and were near to those reported for fish meal [48,139] and similar to those obtained for soybean [140]. These data showed an excellent value for the BSF larvae meal regarding its high content of amino acids with high ileal digestibility values.

#### 4.8. Palatability

A palatability trial was carried out by Cullere et al. [41] to estimate BSF larvae as a dietary supplement for quails. Quails were given a choice between soybean-based control diet and 15% BSF inclusion level in the diet, and they tended to prefer the diet that included 15% BSF larvae meal at a level of 53.8%, compared with 44.1% for the control diet. Furthermore, it was demonstrated that inclusion of *Tenebrio molitor* larvae meal up to 10% in a sorghum–soybean meal basal diet for first 14-day-old broilers had no negative effects on palatability [131].

#### 4.9. Blood Traits

To evaluate the effect of dietary BSF larvae and pre-pupa meal on serum content of Ca and P, 168-day-old laying hens were used in a feeding experiment (5 weeks) [42]. The results showed that a significant increase was measured in the level of serum Ca in hens fed a diet containing 10% prepupae meal. However, when all dietary soybean meal was replaced by BSF larvae meal in laying hen diet, the serum Ca was significantly higher when compared with birds fed the control diet [42]. In this sense, inclusion of BSF larvae meal up to 9% in Muscovy duck diets between 3 and 50 days of age did not affect serum levels of Ca and P [120]. However, regarding broiler chickens, increasing the level of BSF dietary meal increased the level of P, with the highest level at 10% dietary BSF larvae meal in comparison to other groups, although no effects were observed on Ca and other blood and serum parameters [123]. Although creatinine was reduced in the blood of hens fed the BSF diet when compared with the control group fed soybean meal diet [42,120], this did not affect Muscovy ducks fed up to 9% of BSF larvae meal [120]. Inclusion of BSF larvae meal up to 9% in Muscovy duck diets resulted in a linear increase for Fe and a linear decrease for Mg [120]. However, these findings are not consistent with several other studies that did not notice any significant changes in serum level of Fe and Mg in laying hens, broilers, or *Barbary partridge* that were fed BSF larvae meal [42,123,137].

Complete replacement of soybean meal by BSF larvae meal in laying hens did not alter glucose, total protein, and albumin in serum, whereas globulin was significantly higher and the albumin to globulin ratio was significantly lower in larvae meal-fed hens in comparison with those fed a control diet [42]. These findings regarding globulin and albumin to globulin ratio provided an overall increase of circulating immunoglobulines and demonstrated stronger resistance to disease and better immune function in larvae-feeding hens [42,141]. This effect may have been due to chitin content in a pre-pupa



meal, which has the ability to enhance the immune system [60,142,143]. In addition, significant and highly significant reductions were observed in serum cholesterol and triglycerides, respectively, in birds fed larvae meal [42,114], which may support the key role of short-chain fatty acids and chitin [114,144]. The same reduction in cholesterol and triglycerides were obtained by the inclusion of commercial chitin or BSF larvae meal in broiler diets in studies by Borrelli et al. and Hossain and Blair [114,145]. The hypocholesterolemic impact of chitin might be attributed to its derivative chitosan, which has a high anion-exchange capacity and consequently has a bile acid binding capacity, which may disturb the enterohepatic circulation and enhance both fecal triglycerides [146] and cholesterol excretion [147], which leads to a reduction in lipid absorption. Moreover, a linear decrease in serum triglycerides and cholesterol levels was found with increasing levels of dietary BSF larva meal up to 9% in Muscovy ducks, while serum protein was unaffected by dietary treatment [120].

#### 4.10. Antioxidant Status

Limited information is available in the literature in relation to the effect of BSF larvae meal on the antioxidant traits in poultry. The total antioxidant status in the plasma, the hemoglobin content, and the glutathione peroxidase (GPx, EC 1.11.1.9) activity in the blood were evaluated in male broilers fed dietary BSF larvae meal. Both total antioxidant status and the activity of GPx indicated a linear increase response to increasing the inclusion of dietary BSF larvae meal for up to 15% [123]. However, no significant effects were observed in levels of blood and plasma antioxidant enzymes (GPx and TAS) due to dietary BSF larvae meal inclusion levels in Muscovy duck diets [120]. On the other hand, dietary inclusion levels of BSF larva meal modulated the plasma oxidative metabolites malondialdehyde (MDA) and nitrotyrosine, and showed a linear decrease in their values as a healthy indicator of the antioxidant status [120]. The abovementioned results indicate that inclusion of BSF in poultry feed improves their antioxidative status, however, more investigations are needed to clarify this point.

#### 4.11. Gut Microbiota

There is growing evidence that indicates that gut microbiota and its metabolites have a central role in host metabolism, health status, and growth performance [148]. Recent evidence has suggested that the antimicrobial potential of BSF could play a significant role when conventional dietary proteins are substituted with the whole prepupae in diets of monogastrics [149]. As mentioned above, dodecanoic acid (C12:0) is the major fatty acid in BSF, which contributes approximately 29–50% of the total fatty acid and has an antimicrobial impact on Gram-positive bacteria [149,150]. The lauric acid has the ability to convert into monolaurin, which can destroy the lipid membrane of bacteria [151]. The pKa of lauric acid is about 5.3, and thus the proximal small intestine at 4.0–6.0 pH is the target site for undissociated forms of medium-chain fatty acids [149]. By optimal hydrophilic lipophilic balance, undissociated forms of medium-chain fatty acids can destabilize the lipid membrane of the bacterial cells and penetrate it, subsequently dissociating within the cytoplasm into anions and protons. Sustaining functional macromolecules of bacterial cells requires maintaining a neutral pH cytoplasm, which forces bacteria to dispose of excess protons and subsequently leads to depletion of cellular energy [152].

On the basis of the outcome of an in vitro trial, significant antimicrobial activity of high levels of lauric acid was observed against D-streptococci (around 2 log fold reductions), while coliforms were not significantly affected, showing the potential effectiveness against Gram-positive bacteria and not against Gram-negative bacteria. Moreover, under in vivo conditions, feeding diets supplemented with BSF led to 0.5 log fold lowering in D streptococci in piglet gut, whereas no effects were found for the counts of coliforms and total anaerobic bacteria [149]. Regarding the *Bifidobacterium* and *Lactobacillus* population in laying hens, their population in the gut of hens fed BSF was significantly lower than in the control group [55]. This finding may be due to the antimicrobial effect of chitin or BSF saturated fatty acids such as lauric acid. Chitin and its derivative chitosan have remarkable antimicrobial activity through one or both of the following mechanisms: (1) their polycationic nature that interferes with

bacterial metabolism by electrostatic stacking at the cell surface of bacteria [153,154], and (2) their ability to prevent RNA transcription from DNA by adsorption of penetrated chitosan to DNA molecules [65].

Novel and statistical changes were found in cecal microbiota due to feeding of BSF larvae meal. Findings from previous studies demonstrated that inclusion of BSF larvae meal in laying hen diet throughout 21 weeks had a central role as a modulator of the gut microbiota and their metabolic products. 16S rDNA sequencing indicated high differences among the cecal microbial community for hens fed soybean and BSF larvae diets, both in type and relative abundance (unweighted and weighted  $\beta$ -diversity) of bacterial species. Moreover, in comparing bacterial communities by  $\beta$ -diversity analysis for hens fed larvae meal diet and those fed soybean meal diet, researchers found a diverse assortment in microbial species to be the major reason for variation between the treatments. Overall, the new microbiota detected in BSF treatment hens indicated a greater microbial abundance than in control birds [114]. A strong correlation was found between microbial community structure and cecal content of short-chain fatty acids (SCFAs) estimated during the experiment [114]. These findings were partially in line with previous research [55], wherein  $\alpha$ -diversity (Chao1 index: richness, Shannon index: evenness) and  $\beta$ -diversity (unweighted UniFrac distance) were compared in laying hens fed whole BSF larvae, whole BSF pre-pupa, and soybean-based control. Groups fed BSF larvae meals showed values of Chao1 index greater than in groups fed soybean meal, while no differences were observed in the Shannon index among treatments. As far as the  $\beta$ -diversity is concerned, statistical differences were found between groups fed BSF and soybean group. However, there were no statistical differences in weighted UniFrac distance among groups. On the other hand, unweighted UniFrac distances indicated significant differences among groups. These findings indicated that diet containing whole BSF larvae or prepupae meal has a positive impact on the cecal microbial community, especially for that containing BSF prepupae meal.

#### 4.12. Fatty Acids in the Ceca

Fermentation of indigestible nutrients in cecum generates SCFAs, mainly acetate, propionate, and butyrate, which are considered the most abundant [115]. Short-chain fatty acids suppress the expression of virulence factor of pathogenic bacteria [155] and play a key role in metabolism and gut physiology [114]. In addition, the inclusion of BSF larvae meal in poultry diet may modulate the concentration of SCFAs as fermentation end-products [114].

Estimation of cecal volatile fatty acid of laying hens receiving defatted BSF larvae meal as a full substitution of dietary soybean meal showed higher values of acetate and butyrate (increase of 36.1% and 62.6%, respectively; more than the values of the control), resulting in a 36.8% increase in total volatile fatty acid production higher than the control. However, no differences were observed between groups in their relative values as percentage of the total volatile fatty acid [135]. It has been reported that dietary supplementation with 10% (*w/w*) whole BSF larvae and 10% (*w/w*) pre-pupae in 168-day-old laying hens for 5 weeks had no significant effects on the levels of acetic acid, propionic acid, n-butyric acid, and total short-chain fatty acids in the cecum when compared to control diet, however, acetic acid values were 87.4, 110.2, and 95.4 ( $\mu\text{g/L}$ ) for control, larvae, and pre-pupa groups, respectively, while propionic acid recorded 41.7, 64.9, and 53.1 ( $\mu\text{g/L}$ ) for control, larvae, and pre-pupa groups, respectively, and the values of n-butyric acid were 204.9, 197.5, and 276.6 ( $\mu\text{g/L}$ ), respectively, for control, larvae, and pre-pupa groups. On the other hand, the total values showed the lower value of 334 ( $\mu\text{g/L}$ ) for the control group followed by the larvae group, which was recorded as 372.5 ( $\mu\text{g/L}$ ), whereas the highest concentration of 425.1 ( $\mu\text{g/L}$ ) was recorded by a pre-pupa group [55]. The authors suggested that these differences may be due to the microbial fermentation of indigestible nutrients obtained from BSF prepupae. According to diet composition in this study, those pre-pupa meals had a higher content of chitin than larvae meal while the control diet had no chitin.

As mentioned above, chitin is not a completely digested substance [130]. This indigestible amount of chitin might act as fermentable matter and may subsequently modulate the concentration of SCFAs in the cecum of hens. These results are in line with a previous study when total SCFAs, particularly

propionic acid and n-butyric acid, were greater in birds fed BSF larvae meal than in hens fed soybean meal diet [114]. The authors attributed this elevation in SCFAs levels to the improvement in the microbiota communities induced by the BSF-based diet. Black soldier fly larvae meal may have prebiotic functions, and chitin may be the most important player of this effect [114].

#### 4.13. Gut Morphometry and Histological Traits

There are a large number of published studies (e.g., [155–157]) reporting that medium-chain fatty acids could improve gut health through their positive effects on intestinal morphology. With regard to BSF larva fat, a study by Schiavone et al. [156] showed that 50% or 100% substitution of soybean oil with BSF larvae meal fat had no effect on the intestinal morphology of broiler chickens.

As far as whole BSF larvae and pre-pupa meals are concerned, villus height and crypt depth in small intestine parts (duodenum, jejunum, and ileum) were not affected by laying hens fed a 10% BSF larvae meal diet or 10% BSF pre-pupa meal diet compared to those fed a corn–soybean control diet [55]. However, villi height in the intestine of hens fed dietary BSF showed a higher value in the duodenum and lower value in both the jejunum and ileum when compared to the control group, while the crypt depth value was higher in the ileum of hens fed a BSF diet compared with the control, without differences in the duodenum or jejunum [135]. Increasing concentration of BSF larvae meals up to 15% in the diet of male broiler chickens negatively affected gut morphology, whereas the low level was more suitable [123]. As far as histological features are concerned, unfortunately, no more investigations related to these points are available in the literature. However, a recent study showed that no significant effects were found on the hematochemical or histological traits due to dietary BSF larvae meal in male broiler chickens [123] or in Muscovy ducks [120].

#### 4.14. Production Parameters of Layers

Regarding laying performance, dietary addition of BSF in Lohmann Selected Leghorn classic hens at the end of their laying period (64–74 weeks old) was investigated. Hens fed an isocaloric isonitrogenous BSF-based diet either partially or fully replaced with soybean was corresponded to breed standards of 84.4% and 83.4%, respectively, while the control group (soy-based diet) was 5% lower [112]. Fish meal and maggot meal (collected from poultry wastes) were used as an animal protein source for 25% of the total dietary protein in 50-week Isa Brown and Nera Black laying hens. Dietary inclusion of fish meal and maggot meal in equal participation as animal protein sources showed the highest egg production of 70.83% and best feed conversion of 2.78 kg feed/kg egg compared to the control group that received the protein source as 100% fish meal, which showed 67.43% for egg production and 3.04 for feed conversion [124], suggesting a complementary effect between amino acids profiles of both fish and maggot meals.

However, when the laying hens received a diet containing either 10% whole (non-defatted) BSF larvae meal or 10% dried BSF pre-pupa meal as a replacement of soybean meal and oil, the researchers observed no significant differences in egg production rate as compared to the corn-soybean control diet [55]. The same finding was obtained due to inclusion of 7.5% defatted BSF larvae meal into the hen's diet. However, 5% dietary defatted BSF reduced the egg production in comparison with other groups [43]. In contrast, the complete replacement of soybean meal by BSF larvae meal in laying hen diet for 21 weeks showed a significant reduction in lay percentage and the average egg weight. In addition, birds fed BSF larvae meal produced a greater percentage of abnormally sized eggs than birds fed soybean meal [42]. On the other hand, after 6 weeks of feeding on BSF larvae meal, the egg production was 91.6% and 82.8% for BSF hens and control hens, respectively. However, there were no statistical differences [119].

#### 4.15. Egg Physico-Chemical Quality

In 50-week laying hens, fish meal was used (6% in diet) as animal protein. One-hundred percent replacement of fish meal protein by maggot meal did not affect egg weight, egg shape index, yolk index,

and yolk color. However, both shell thickness and shell weight were slightly affected, and this deleterious effect may have been due to the variations in calcium (4.21% and 3.8%) and phosphorous (0.56% and 0.045%) levels in both diets in terms of fish and maggot meals, respectively [124]. On the other hand, 100% replacement of dietary soybean by BSF larvae meal over 21 weeks did not alter whole egg weight and shell weight [158].

In a recent study, a BSF-based diet with partial soybean replacement did not adversely affect whole egg weight, albumen, yolk, and shell. However, in a fully soybean replacement diet, albumen was lowered by 7.5% [112]. Egg weight and egg mass were adversely affected by the total substitution of soybean meal by BSF larvae meal in Lohmann Brown Classic laying hens fed for 21 weeks [42]. Contrasting findings have been observed with the partial substitution of soybean meal. The findings showed that inclusion of 10% (*w/w*) of whole BSF pre-pupa meal in laying hen diet for consecutive 30 days improved egg weight and albumin weight significantly in comparison to control group or those fed a 10% (*w/w*) BSF larvae meal. However, no significant differences were observed among treatments in Haugh unit, egg yolk weight, and eggshell weight [55], whereas defatted BSF larvae meal at a level of 7.5% did not alter egg weight, egg mass, and Haugh unit [43]. An improving effect was found for the pre-pupa meal group with regard to eggshell thickness, with significant differences between pre-pupa meal and larvae meal groups, while the differences were not statistically different in comparison with the control group. Although eggshell strength in the group fed pre-pupa meal showed an increase of 16.9% and 18% higher than the control group and larvae meal group, respectively, the differences were not significant [55]. In this sense, significantly higher values of eggshell strength were recorded by using 5% defatted BSF larvae meal in hen diet as compared with other groups, while the level of 7.5% defatted BSF showed only numerically higher values for eggshell thickness than the control group [43]. These findings indicate that a BSF pre-pupa supplemented diet could enhance the absorption of dietary minerals, including Ca in laying hens, which may be a result of the higher content of cecal SCFAs in this group. This speculation has been supported by several studies that investigated the vital role of SCFAs and their derivatives in mineral absorption [146,147,159,160].

Eggs produced from hens fed BSF larvae meal in a choice feeding experiment over 12 weeks had significantly lower shell thickness (0.446 mm) than those produced from control birds (0.457 mm) [119]. No differences were observed among groups regarding shell deformation, albumen height, Haugh unit, and shell reflectivity. Shell weight was significantly lower by 6.3% than that in the control group as a result of significant lower egg weight in hens fed BSF as choice feeding; however, the average egg weights produced from treatment hens were >67 g [119]. Effect of 100% substitution of soybean meal with BSF larva meal in the diet of laying hens for 21 weeks was studied by Secci et al. [158]. Eggs obtained from hens fed BSF larvae meal had a greater proportion of yolk than those produced by the control group hens. Furthermore, the yolk of eggs produced from the BSF group were richer in  $\gamma$ -tocopherol, lutein,  $\beta$ -carotene, and total carotenoids and also were significantly more red-colored than those produced from the control group. The chemical composition (crude protein, total lipids, and ash) of yolk and albumen was unaffected by dietary treatments, while yolk content of cholesterol in BSF group was 11% less than the control group.

Furthermore, data from the study by Kawasaki et al. [55] indicated that feeding either BSF larvae meal or pre-pupa meal significantly improved both egg yolk color and albumin height. The same result was found regarding egg yolk color due to the inclusion of 5% and 7.5% defatted BSF larvae meal into the laying hen diets [43]. In contrast, free range laying hens fed BSF dried larvae in a choice feeding trail produced eggs with a significantly paler yolk color than those from the control group. However, there is no surprise in this result because artificial colorings were applied in the control diet, and their received levels in the BSF group were lower than in the control group [119].

#### 4.16. Carcass Dissection

Broiler quails that received a diet including BSF larvae meal did not show variations in carcass weight, breast weight, breast meat yield, and dressing percentage in comparison to those that received

a control diet [41]. On the contrary, broiler chickens fed different levels (5%, 10%, 15%, and 20%) of house fly larvae meal had a significant higher percentage of dressing and breast muscle weight than those fed on control diet [113]. Carcass traits of the broilers from different groups fed diets containing 10% *Musca domestica* larvae or 10% fish meal or control-based diet were compared. Carcass weight and breast muscle percentage were significantly higher in chicks fed diets that included either 10% house fly larvae meal or 10% fish meal than the control by 11.22% and 8.58% for carcass weight and 8.75% and 7.20% for breast muscle, respectively [121].

It has been observed that feeding a diet with 8% fresh BSF larvae meal to local chickens (Ardennaise chicken) from 30 to 80 days old (slaughter age) did not affect the carcass yield, pectoral muscle, drumstick, and thigh weight, nor the weights of internal organs [59]. It has been demonstrated that the inclusion of defatted BSF larvae meal up to 10% in broilers diets had no adverse effects on carcass traits or meat quality traits [161].

#### 4.17. Meat Quality

Data from a recent study by Cullere et al. [41] showed that cooked breast from quails fed 10% BSF diet was the heaviest and the most tender compared with 15% BSF and control diets, while no significant effect was observed in fresh breast meat yield. Moreover, no significant effect was observed in crude protein content nor in total essential amino acid composition of breast muscle in broiler chickens fed house fly larvae meal for 35 days. However, the values were higher for broiler fed a larvae meal diet than those fed a soybean-based control diet. Moreover, a significantly higher content of lysine and tryptophan and total amino acids were recorded in the larvae meal group than the control group [113]. The same trend was reported by Moula et al. [59], who estimated protein content, fatty acid profile, ash percentages, and omega 6/omega 3 ratio in the meat of Ardennaise chickens fed a diet supplemented with 8% fresh BSF larvae meal. No significant differences were observed between larvae-fed and control chicken regarding the color of breast [59] and thigh muscle or pH [121]. Moreover, proximate meat composition, cholesterol content, and oxidative status were not influenced by BSF administration [162].

Increasing the dietary defatted BSF inclusion up to 15% led to an increase in the breast meat content of the total saturated fatty acid, total monounsaturated fatty acid, and polyunsaturated fatty acid (PUFA) n-6/n-3, while a significant reduction was found in polyunsaturated fatty acids. These observations reflected the differences in the diet content of these nutrients. However, this finding indicates that increasing the dietary inclusion of BSF may lower the healthiness of bird meat [162]. Likewise, the breast fatty acid profile of broiler chickens was highly influenced by the BSF larvae fat inclusion level. With increasing BSF larvae fat inclusion rate, the proportion of saturated fatty acid increased to the detriment of the polyunsaturated fatty acid (PUFA) fraction. Moreover, the ratio of n-6/n-3 increased [163,164]. On the other hand, the biological value of the meat protein was increased, showing increased contents of aspartate, glutamate, alanine, serine, tyrosine, and threonine due to the diet being supplemented with 15% defatted BSF [162]. The same dietary inclusion (15%) of BSF larvae meal resulted in greater concentrations of Ca and lower K in breast meat than the control group, being a reflection of the diet content of nutrients [162].

The breast meat obtained from broilers fed 15% dietary BSF larvae meal showed higher redness (a\*) index, while birds that were fed 5% and 10% demonstrated intermediate values as compared to the control. These findings may be a result of pigments derived from larvae meal. On the contrary, a linear decrease was found for the yellowness value (b\*) with increasing BSF larvae meal content. This result may have been due to the low content of corn gluten in BSF diets [161].

#### 4.18. Sensory Traits

Unfortunately, the literature lacks enough information about the effects of insect meal on the sensory traits. However, in a previous study, according to a blind taste test, no differences were found in fish meat taste among groups fed BSF prepupae meal and a fish meal group. Average feedback of

participants in this test for fish meat from the BSF group was “milder taste” to “tastes fishier than the other” [127]. Sensory profile scores (odor, flavor, and texture) of breast meat from quails fed dietary defatted BSF larvae meal from 10 to 28 days of age remained unaffected by treatment [162].

The evaluation of sensory profile of the eggs is moreover definitely important when a novel feed ingredient is evaluated. In laying quails, inclusion of 10% and 15% defatted BSF larvae meal did not affect sensory profile, but eggs of birds fed 15% BSF diet had a higher feed off-flavor compared with a soybean meal-based control group. In another study, the BSF larvae meal was added to layer diets at 0, 50, and 10 g/kg feed as a source of protein. A significant improvement was observed in appearance, texture, taste, and acceptance of eggs of hens fed BSF larvae meal at 50 g/kg. Moreover, the odor was not affected by dietary treatments [165]. The significant improvement found in the sensory profile of eggs produced by hens fed BSF could have been due to the glutamic acid content being high in BSFL meal (6.85 g/kg). A recent study reported that partial substitution (50%) of soybean meal and oil with full-fat dried BSF larvae meal resulted in the production of eggs with a sensory profile comparable to control eggs [166].

## 5. Challenges of Using BSF in Poultry Feeding

With the aim of substituting protein-rich feedstuffs such as fishmeal and soybean meal, there will be a need to produce a large amount of insect biomass. However, large-scale production and use of insects meal in food and feed continue to face significant challenges, some related to legislation and the production system and others related to treatment design and utilization manner [87]. Although great research funds exist in this field, restrictive European laws regarding the utilization of insects in animal feed is still the major challenge in the development of insect production units [90]. Furthermore, the currently excessive cost of insect meal is not comparable with other conventional sources of protein. This is due to the lack of commercial production with a large scale of insect meals [135].

## 6. Conclusions

Insects as sustainable protein sources in the poultry diet might play a part in achieving food security and may participate in the solution of its problem, taking into account the precautions that prevent accumulation of some substances that are harmful to consumers in insect biomass. Using the organic wastes to feed the insects and using these insects in poultry feed may provide effective economic sustainability of the poultry industry. Simultaneously, the integration between the production of insect biomass as a feed ingredient and reduction of organic wastes such as restaurants waste, household organic waste, etc. can contribute to the reduction of the environmental burdens and add biological values to these forms of waste. In order to achieve this objective, there is a need to select suitable insects for large-scale production, high growth performance, high feed conversion, less mortality, good disease resistance, and protein quality. From this perspective, BSF is an excellent candidate. It has been observed from the most recent literature that insects represent a novel and promising feed ingredient for poultry diets and could potentially be used as substitution ingredients of soybean or fish meals in layer or broiler diets. However, further research should be done in order to assess the highest possible level of BSF larvae meal that may be applied to poultry diets, without a negative effect on growth performance, palatability, nutritional composition, or flavor of meat and eggs, taking into account the fatty acid composition and chitin content of the insect in line with the required health standards for poultry and consumers. Further research also is required to evaluate the effect of BSF larvae meal on the beneficial bacteria in the gut.

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