Black Soldier Fly Larvae Nutrients Digestibility and Bioavailability

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The black soldier fly (BSF) is a distinct member of the Stratiomyidae family within the Diptera order. BSF, primarily thriving in South America, has adapted to a wide range of climates including temperate, subtropical, and tropical regions, with its ideal living conditions being temperatures between 25 °C and 30 °C. Outside of industrial production, they cannot live in northwestern Europe and locations with temperatures below 5 °C due to their inability to withstand the cold. Today, the BSF is estimated to inhabit over 80% of the world, particularly between latitudes 46 N and 42 S. Incredibly prolific in humid tropical areas, the BSF is drawn to regions abundant in decomposing organic materials.

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1. Introduction

By 2050, the world's population is anticipated to reach 10 billion, leading to a rise in global food requirements by about 35% to 56% from 2010 levels, as reported by Van Dijk et al. [1]. Animal products currently account for nearly 70% of worldwide food consumption, a figure projected to grow, primarily due to changing dietary preferences and rising economic status, particularly in regions with lower incomes [2]. To accommodate this surge in demand for animal-based products, the global poultry industry needs to enhance its productivity and adopt more eco-friendly practices. Sustainable feeding practices are essential for the poultry sector to achieve environmental and economic sustainability. The choice and management of animal feed play a pivotal role in this process, influencing the overall impact of livestock production on the environment and its economic viability. The high cost of poultry feeds is primarily influenced by the scarcity of critical ingredients like soybean and fishmeal [3]. These components are favored in poultry diets due to their palatability and high protein content. However, their reliance on imports and the associated high costs have prompted researchers to explore alternative protein sources that could substitute soybean and fishmeal in poultry feeds.

In recent years, the quest for sustainable and environmentally friendly alternatives within the animal feed industry has led to a growing interest in black soldier fly larvae (BSFL), scientifically known as *Hermetia illucens* (L.) (Diptera: Stratiomyidae) [4][5][6][7]. This species, originating from South America, and its larvae have demonstrated remarkable adaptability across various climates, including temperate, subtropical, and tropical regions. Thriving

best in temperatures of 25 °C to 30 °C, BSFL can also grow in a range of environmental conditions, showcasing their resilience. Their natural inclination toward habitats rich in decomposing organic material, coupled with this adaptability, highlights their pivotal role in sustainable agriculture and waste management, suitable for diverse geographical locations [8][9][10]. These larvae, which can grow up to 27 mm in length and weigh approximately 220 mg, are nutritionally dense, with a composition rich in proteins and fats [11][12][13][14][15][16][17]. This makes them an invaluable source of nutrients compared with conventional feed ingredients, suitable for a range of animals including poultry [18][19][20][21][22][23], aquaculture species such as fish [24][25][26][27], and swine [28][29][30]. Furthermore, BSFL significantly reduces waste volume by rapidly eating organic waste, providing a practical substitute for conventional landfill disposal techniques. This contributes to reducing methane emissions, a potent greenhouse gas frequently emitted by decomposing organic matter in landfills, and waste accumulation [31][32][33].

In the field of animal nutrition, BSFL have emerged as a highly viable and sustainable source of protein. They present an environmentally friendly alternative to conventional feed ingredients such as soybean meal and fishmeal, which are often linked to environmental challenges like deforestation and overfishing. Additionally, traditional feed components like soybean meal and fishmeal with other feed ingredients can account for up to 70% of total poultry production costs [34]. The nutrient-dense nature of BSFL, which is rich in proteins and lipids, makes them an excellent solution to the growing need for quality feed in chicken raising. The fact that BSFL can feed on various organic wastes not only demonstrates their sustainability but also contributes to significant waste reduction. The dual role of BSFL in delivering vital feed while reducing waste has piqued the interest of the animal feed industry. Their efficient waste conversion into usable biomass adheres to circular economy concepts, establishing BSFL as a trailblazer in advancing sustainable poultry farming operations. The nutritional benefits of BSFL have been shown to be the most appealing to the feed business, with a balanced amino acid composition and a high concentration of protein, energy, and mono- and poly-unsaturated fatty acids [35].

BSFL have been used as a potential alternative source of animal feed, especially for poultry, due to their high digestibility and bioavailability of nutrients.

2. Protein Digestibility

The utilization of nutrients from BSFL is typically efficient. Larval composition allows for the effective utilization of nutrients by broilers, leading to improved growth performance. The protein digestibility of BSFL in poultry is a topic of interest for many researchers and producers, as BSFL have a high protein content and a low environmental impact. The protein digestibility of BSFL in animals and poultry may vary depending on the larvae meal's age, processing method, and inclusion level. Some studies have reported that BSFL can be used as a partial or complete replacement for conventional protein sources in animal feeds, such as soybean meal, fish meal, or insect meal [36][37][38][39][40]. Recent studies on the protein digestibility of BSFL reveal that the dried larvae protein exhibits a digestibility of 48%, highlighting the need for efficient processing methods to enhance its nutritional value [41]. When the larvae biomass is defatted, the protein digestibility significantly improves to 75%, indicating the impact of fat content on protein availability [41]. The high protein content in BSFL, constituting up to 50% of their dry weight, positions them as a potential sustainable alternative to traditional protein sources in animal feeds [42]. BSFL full-fat

meal has a high protein content and is a good source of amino acids, which can further improve CP digestibility [43]. Another interesting recent study has investigated the relationship between inclusion level and nutrient digestibility by using the full-fatted BSFL in diets and found that a moderate inclusion (3%) of full-fatted BSFL in the diet significantly enhanced the digestibility of crude protein [37]. This indicated that these nutrients are better absorbed and used even at lower inclusion levels. The requirement for a balanced approach in feed formulation is shown by the adverse effects of more extensive BSFL inclusions (9%) on nutritional digestibility [37].

3. Fat Bioavailability

BSFL also contain significant amounts of lipids (fats), providing a source of energy for broilers. The fat bioavailability of BSFL in poultry refers to how effectively poultry can digest and utilize the fats present in BSFL as a food source. BSFL are increasingly recognized as a sustainable and efficient protein source for animal feed, including poultry diets. The concept of fat bioavailability is crucial in animal nutrition, as it influences the energy value of the feed and the health of the animals. The lipid profile of BSFL is a significant factor in determining their bioavailability as a feed ingredient, particularly in poultry diets. This profile is characterized by a high content of saturated fatty acids (SFAs), with lauric acid (C12:0) being the most abundant [44][45]. A study demonstrated that larvae with higher weight generally contain a higher percentage of saturated fatty acids and a lower percentage of unsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) [46]. Furthermore, research on the fatty acid composition of BSFL revealed a high content of saturated fatty acids, including a significant 58.9% concentration of lauric acid [47]. Incorporating BSFL fat into poultry diets has emerged as an innovative approach with multiple benefits, as evidenced by various studies. The dietary supplementation of BSFL oil has been shown to positively influence broiler health, suggesting its efficacy as an alternative fat source [48]. This is further supported by research on the inclusion of BSFL fat in finisher broiler chicken diets, which maintains growth performance while offering a sustainable alternative to conventional fat sources [49]. Additionally, evaluating low inclusion rates of full-fatted BSFL meal in chicken diets indicates improvements in growth performance, nutrient digestibility, and gut health [37]. This underscores the potential of BSFL as a comprehensive feed ingredient, as reviewed in studies highlighting BSFL meal's promise for poultry nutrition. The fatty acid composition of BSFL, notably influenced by the feed substrate, presents significant applications in the feed industry, offering a balanced and nutritious feed component [50]. Research also points to the possibility of BSFL meal and fat completely replacing soybean cake and oil in diets for laying hens, indicating a substantial shift in traditional poultry feeding practices [51]. The impact of BSFL larva fat on broiler diets extends to the quality of the chicken meat itself, particularly affecting breast meat quality [52]. Furthermore, modified BSF larva fat in broiler diets has been examined for its effects on performance, carcass traits, blood parameters, histomorphological features, and gut microbiota, demonstrating its comprehensive impact on poultry health and product quality [53]. Overall, the bioavailability of fat from BSFL in poultry diets presents a multifaceted opportunity. It not only aligns with sustainable feed production but also enhances the nutritional profile of poultry diets, thereby contributing to healthier poultry and potentially higher-quality poultry products.

4. Mineral Uptake

BSFL are known to be a good source of minerals and vitamins, contributing to the overall nutritional value of broiler diets. One of the main advantages of BSFL is their high calcium content, which can reach up to 9% of dry matter (DM) [36]. Calcium is essential for bone formation and eggshell quality in poultry, and its deficiency can cause rickets, osteomalacia, and poor production performance [54][55][56]. BSFL can provide sufficient calcium to meet the requirements of broilers and layers, and may even reduce the need for supplemental limestone or oyster shell in the diet [57]. Moreover, BSFL can enhance calcium absorption and retention in poultry, as they contain a natural form of calcium carbonate that is more soluble and bioavailable than the synthetic forms [58]. Another vital mineral in BSFL is phosphorus, which can range from 0.7% to 1.5% of DM [36]. Phosphorus is involved in many metabolic processes, such as energy production, nucleic acid synthesis, and acid–base balance. Phosphorus deficiency can impair growth, bone development, and egg production in poultry [59][60]. However, most of the phosphorus in plant-based feed ingredients is in the form of phytate, which is poorly digested and utilized by poultry and can also reduce the availability of other minerals, such as calcium, zinc, and iron. Therefore, poultry diets usually require supplemental inorganic phosphorus sources, such as monocalcium phosphate or dicalcium phosphate, which are costly and can have negative environmental impacts. BSFL can offer a more sustainable and efficient source of phosphorus for poultry, as they contain mainly non-phytate phosphorus that is highly digestible and bioavailable [58]. Furthermore, BSFL can improve phytate degradation and phosphorus utilization in poultry, as they contain phytase enzymes that can hydrolyze phytate and release its bound phosphorus [61]. Besides calcium and phosphorus, BSFL also contains other essential minerals, such as magnesium, potassium, sodium, iron, zinc, copper, manganese, and selenium, in varying amounts depending on the substrate and processing method [36]. These minerals play important roles in various physiological functions, such as enzyme activity, antioxidant defense, immune response, and blood formation. However, the optimal levels and ratios of these minerals in poultry diets are not well established, and their interactions with other dietary components may affect their absorption and metabolism. Therefore, more research is needed to determine the effects of BSFL on the mineral balance and status of poultry and to optimize the inclusion levels and combinations of BSFL with other feed ingredients.

5. Chitin as a Fiber Source

The digestibility of BSFL may be affected by the fibrous material called chitin. Although some research suggests that the chitin concentration may have an impact on how nutrients are utilized, overall effects appear to be beneficial. Recent studies have underscored the potential of chitin, a polysaccharide found in the exoskeleton of insects such as BSFL, as a sustainable and beneficial fiber source in poultry diets [62]. BSFL efficiently converts organic waste into valuable nutrients like proteins, lipids, and chitin, offering an environmentally friendly solution to waste management while providing nutrient-rich feed for poultry [63][64][65]. The chitin content in BSFL, which varies based on factors like rearing substrate and life stage, has been reported to range between 5.6% to 6.7% on a DM basis, as indicated in the study findings [66][67][68][69]. This variability is crucial for determining the nutritional impact on poultry. Several studies have explored chitin's role in enhancing nutrient digestibility in poultry. They suggest that a moderate inclusion level of this insoluble fiber stimulates the development of the gizzard and the production of digestive enzymes, thereby improving the digestion of starch, lipids, and other dietary components [70][71][72].

Additionally, chitin's impact on poultry gut health is notable. Chitin can modulate the intestinal microbiota, enhance immune responses, and strengthen the mucosal barrier, potentially increasing the population and diversity of beneficial gut bacteria [72][73][74]. This can lead to the production of short-chain fatty acids and a lower intestinal pH, thus inhibiting pathogenic bacteria growth. Moreover, the conversion of chitin into chitosan, its deacetylated form, has been shown to positively affect poultry plasma lipid profiles. Different studies have demonstrated that chitosan can reduce total plasma cholesterol and low-density lipoprotein (LDL) cholesterol concentrations, enhancing the high-density lipoprotein (HDL) to total cholesterol ratio in broilers [70][75][76][77][78]. These findings collectively suggest that chitin from BSFL could be a valuable component in poultry diets, potentially improving nutrient utilization, feed efficiency, gut health, antioxidant function, and lipid metabolism [78][79][80]. However, further systematic research is needed to fully understand the optimal conditions and mechanisms of chitin from BSFL action in poultry nutrition.

6. Factors Influencing Nutrient Utilization

Utilizing BSFL in poultry diets has garnered increasing interest due to their rich nutritional profile and sustainable production potential. The effectiveness of BSFL as a feed ingredient largely depends on their nutritional composition, which includes high levels of protein, essential amino acids, and lipids. These nutritional characteristics are influenced by the larvae's age and developmental stage, as well as their diet, which can vary significantly based on the substrates they are fed [14][81]. The processing methods applied to BSFL, such as drying or pelleting, also play a crucial role in determining their digestibility and nutrient availability [82]. Furthermore, the inclusion rate of BSFL in poultry diets needs careful consideration, as it can impact feed intake, nutrient absorption, and overall poultry performance. Studies have shown that while moderate inclusion rates can be beneficial, higher rates might lead to reduced palatability and intake [83]. Palatability itself is a significant factor, influencing poultry's acceptance of BSFL-based feeds. The texture and taste of the larvae can affect feed consumption patterns, which in turn impacts nutrient utilization [84]. Anti-nutritional factors present in BSFL, such as chitin, also warrant attention, as they can impede nutrient absorption and digestion [85]. The specific poultry species and age group being fed BSFL-based diets can exhibit varied responses due to differences in nutrient requirements and digestive capabilities. For instance, the dietary requirements of laying hens differ from those of broilers, which could affect how nutrients from BSFL are utilized [86]. The health status and gut health of the birds are also crucial, as they significantly influence nutrient absorption and overall feed efficiency [87]. Finally, environmental conditions like temperature and housing can affect feed intake, metabolic rates, and growth performance, thereby impacting the utilization of nutrients derived from BSFL [88][89][90][91]. Understanding these complex interactions is essential for optimizing the use of BSFL in poultry diets and ensuring the health and productivity of the birds. Ongoing research in this area is crucial to provide insights into maximizing the benefits of BSFL in sustainable poultry nutrition.

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