




The role of insects in promoting the health and gut status of poultry

E. Malematja¹ · T.G. Manyelo¹ · N.A. Sebola¹ · M. Mabelebele¹ 

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Abstract

The structure and functionality of digestive system and gastrointestinal microbiota composition play a crucial role in the development of the gastrointestinal tract and gut morphology. A well-developed gastrointestinal tract will have a proper balanced proportion between the beneficial and harmful microbes; therefore, this balance will promote nutrient utilization and stimulate the development of immune system. The gut microbiota living in an animal's gastrointestinal tract can be modulated through the feeding of prebiotic or probiotic compounds which have effects on the animal's humoral immunity, hence improving the nutrient utilization and thus improving growth performance and the overall health condition of the animal. Therefore, this review aimed to provide a comprehensive understanding and recent reports on the role of insect meal in poultry feed aimed at improving health condition and gut status in poultry production. A literature search was performed with an electronic database of Directory of Open Access Journals (DOAJ), Research gate, Web of Science, Science Direct, Google Scholar, and PubMed. In addition, recently published manuscripts were selected, and the citations included in articles from the databases were used to search for other relevant articles. The studies were evaluated, and the level of evidence varied with insect types, inclusion levels, and the supplementing method. Extensive research has shown that insects can be safely used in poultry feeds to modulate the development of digestive and immune system without compromising the production parameters and the quality of the produce. Insects can be directly fed to chickens or can be processed into insect meals and supplemented in the diet. Nonetheless, most literatures done on the effects of insect meal are focused commercial chicken breeds and little attention is given to other poultry species; therefore, more studies are recommended to ascertain these findings.

Keywords Insect meal · Gut morphology · Microbiome · Humoral immunity

Introduction

Growth performance, reproduction traits, and health condition of chickens are affected by factors which are plane of nutrition, ambient temperatures, and diseases; however, the plane of nutrition and ambient temperature can be manipulated through proper management (Bedford 2000; Goodarzi et al. 2014). Pathogens are microorganisms that cause diseases in animals and the common ones include bacteria, viruses, and fungi which are everywhere in feeds, water, and the environment and hence difficult to mitigate (Bedford 2000). The pathogens interfere with the digestive

functioning by causing inflammation in the gut and imbalance between the beneficial and harmful microbes and thus disturbing nutrient digestion and absorption as well as affecting the overall health condition of birds (Cross et al. 2007), and hence reducing growth and productivity of the chickens. This leads to the introduction of synthetic antibodies and the pathogens have become resistant to the synthetic antibodies (Nasir and Grashorn 2006). To counteract the risk of the emergence of drug-resistant microorganisms and drug residuals in chicken meat and meat products (Burgat 1999), attempts are being made to identify novel antimicrobial agents to improve chicken performance and overall health condition. The use of insects in poultry feeds is gaining popularity due to their high nutritional content, and feasibility to grow fast and production (Józefiak and Engberg 2015). Therefore, it is evident that the colony of microbiota living in the intestinal tract of chickens can be modulated through the feeding of prebiotic or probiotic compounds which in

✉ M. Mabelebele
mabelm@unisa.ac.za

¹ Department of Agriculture and Animal Health, College of Agriculture and Environmental Sciences, University of South Africa, Florida 1710, South Africa

turn stimulate the development of humoral immunity (Gasco et al. 2018), hence improving the nutrient utilization and thus improving growth performance and the overall health condition of the animal.

Polysaccharides in chitin from the exoskeleton of insects have a positive effect on the functioning of the immune system (Food and Agriculture Organization 2017). Insects are regarded as a good source of protein with good amino acid composition and contain numerous bioactive compounds, chitin, antimicrobial, and lauric acid (Gasco et al. 2018), with proven antibacterial and immunomodulatory effects, hypolipidemic efficiency, and growth promoters (Hossain and Blair 2007; Bovera et al. 2015). Several studies have shown that among the potential insects, yellow mealworm (*Tenebrio molitor*), housefly (*Musca domestica*), black carp (*Mylopharyngodon piceus*), super mealworm (*Zophobas morio*), and black soldier fly (*Hermetia illucens*) have positive effects on the gut microbiota of the animals and could be used in poultry industry without compromising the production (Food and Agriculture Organization 2017; Gasco et al. 2018). Therefore, it is evident that polysaccharides in chitin in the exoskeleton of insects have a positive effect on the immune system functioning when fed to livestock (Food and Agriculture Organization 2017). The addition of black soldier flies into chickens' diets may alter gastrointestinal tract through the alteration of gut microbiota (Detilleux et al. 2022). Biasato et al. (2018) investigated the effect of yellow mealworm on gut and microbiome modulation and observe no effect on gut morphometrics in free-range chickens. Gastrointestinal microbiota has a tremendous effect on the well-being of animals, and it is of great importance to manipulate the microbiota populations and improve the overall health condition in birds.

However, due to genetic improvements of chickens and everchanging climate conditions, insect inclusion levels for optimal performance change. Therefore, this review aimed to provide a comprehensive understanding of nutritional composition and bioactive compounds of potential feeder insects as feed additives and mechanisms in which insects modulate the overall health condition in birds as well as reports on the effects of using insects for gut health and status, immune system modulation, and overall growth performance in poultry as well as the recommended level and effective methods of supplementation.

Nutritional composition of potential insects

The nutritional values of insects are high enough to substitute many conventional protein sources such as soybean meal, fishmeal, or bonemeal (Govorushko 2019). Khusro et al. (2012) reviewed published literature on the nutritional composition of insect meals and observed that insects have

high good quality nutrients such as protein, crude fat, crude fiber, minerals, and vitamins. Apart from having high nutritional content, insects are best known for their utilizable protein, lipids, carbohydrates, vitamins, and minerals (Payne et al. 2016). The summary report on the global status of insects as food and feed source stated that most insects have a well-balanced nutrient content and good amino acid profile and are rich in micronutrients such as copper, iron, magnesium, and zinc (Govorushko 2019). Similarly, Nogales-Mérida et al. (2019) referred to insect meal as a useful source of crude protein, crude fat, crude fiber, and fatty acids. Given the reasons mentioned above, insects appear to be one of the best-suited feedstuffs to address the issue of protein sources and certain health problems in poultry industries. The researchers are currently focusing on the larvae stage of yellow mealworm (*Tenebrio molitor*), black soldier fly (*Hermetia illucens*), the maggot, and pupae of the housefly (*Musca domestica*) as they are being regarded as a novel food due to their relatively high protein, vitamins, and mineral values and source of chitin compared other insect growing stages (Józefiak and Engberg 2015; Nowak et al. 2016; Zhao et al. 2016). Edible insects such as yellow mealworm (*Tenebrio molitor*) and black soldier are gaining popularities in animal food industries, used as a source of protein and chitin for growth promoter and immune-modulatory as well. Proximate analysis of raw larvae of these insects indicates that they contain protein content that varies between 40 and 60% (Józefiak and Engberg 2015), with an amino acid profile that is comparable to traditional protein sources (Finke 2002). Carbohydrates are contained in chitin, ranging from 5 to 20% of the dry weight (Chen et al. 2009). DiGiacomo and Leury (2019) investigated the nutritional composition of the black soldier fly and reported that raw larvae have about 20–44% dry matter content, protein content of 37–63%, and fat content ranging from 7 to 39%. The nutritional composition values depend on the life stage at which the insect is harvested, the rearing composition, and the type and quality of feeds ingested (Ghaly and Alkoaik 2009). For instance, larvae grown on pig manure result in higher protein content than that fed ruminant manure (DiGiacomo and Leury 2019); feeding insects spent grain will result in higher protein content and crude fat content (Oonincx et al. 2015). Furthermore, the nutrient content of most common insects is determined by the processing method, and thermal processing results in better nutrient content (Bordiean et al. 2020). Reports on the nutrition composition of common edible insects are summarized in Table 1.

The amino acid composition determines the protein quality and the nutritional values of the feedstuff (Ghaly and Alkoaik 2009). It is evident that insect meals are a good source of amino acids than most meal types and some of the essential amino acid content is higher than those of plant or animal origin (Nogales-Mérida et al. 2019). Although

Table 1 Nutritional composition of dried various insects (per 100 g)

Insect species	Nutrient composition									Author
	DM	CP	Crude fat	Crude fiber	Crude ash	Lysine	Methionine	Ca	P	
<i>Hermetia illucens</i>	95.9	59	11		5	3.09	0.98	0.98	0.63	Maurer et al. (2016)
	-	17.5	14	-	3.5	1.19	0.34	0.02	0.24	Finke (2013)
<i>Tenebrio molitor</i>	95.95	47.82	31.69		2.61	-	-	-	-	Fontes et al. (2019)
	97.02	53.81	7.53		6.99	2.748	0.667	0.35	6.80	Sedgh-Gooya et al. (2021)
	93.9	51.9	21.6	7.2	4.7	1.4	1.6	4.3	7.1	Bovera et al. (2015)
	-	45.8	34.2	4.0	2.5	4.5	1.3	3.8	7.0	Hussain et al. (2017)
	-	53	3.6	3.1	26.8	5.4	1.5	2.7	7.8	Khan et al. (2017)
<i>Zophobas morio</i>	-	19.7	17.7	-	1.0	1.0.3	0.21	0.02	0.32	Finke (2013)
<i>Acheta domesticus</i>	-	20.5	6.8	-	1.1	1.10	0.30	0.04	0.30	Finke (2013)
<i>Galleria mellonella</i>	-	14.1	24.9	-	0.6	0.79	0.22	0.02	0.20	Finke (2013)

DM dry matter, CP crude protein, Ca calcium, P phosphorous

insects are considered to contain all the essential amino acids, compared to fishmeal, yellow mealworm has lower methionine concentration which is one of the limiting amino acids in poultry (Józefiak and Engberg 2015). Reports on amino acids of insect meal are summarized in Table 1.

Bioactive compounds of insects

Besides being a good source of protein, insects have been validated to contain bioactive compounds with characteristics that could have potential health benefits and modulate the immune system (Roos and Van Huis 2017). The exoskeleton of insects contains chitin, antimicrobial peptides, and lauric acid compounds having a subsequent effect on the animal's humoral immune when supplemented with diets (Montalban-Arques et al. 2015). Chitin is a bioactive compound found in the exoskeleton of crustaceans and insects (Finke 2007). Chitin contains hypolipidemic and hypercholesterolemic compounds which stimulate an innate immune response to various diseases in animals (Komi et al. 2018; Bovera et al. 2015). Among the livestock, neither poultry nor mammals synthesize chitin; therefore, insects are a potential target for chitin (Komi et al. 2018; Bovera et al. 2015). Insects have been categorized to have a tremendous diversity of bioactive peptides such as antimicrobial, antioxidant, and antidiabetic properties (de Silva Lucas et al. 2020), and recently, there are more than 150 insect proteins with antimicrobial properties which are classified as follows: α -helical peptides which include cecropin and moricin; cysteine-rich peptides such as insect defensin and drosomycin; proline-rich peptides which include apidaecin, drosocin, and lebecin; and glycine-rich proteins such as attacin and gloverin (Otvos 2000; Tonk and Vilcinskis 2017; Gasco et al. 2018; de Silva Lucas et al. 2020). According to Chernysh et al. (2015), insect antimicrobial peptides are effective in various

bacteria with fewer chances for the bacteria to become resistant. These insect antimicrobial peptides have proven to be effective in pigs and broiler chickens in terms of growth traits and gut health through enhanced intestinal microbiota and immune function (Wang et al. 2016).

Insects' mechanism/modes of action in promoting health and gut status of poultry

The larvae of insects have known to contain natural antibiotic, antipathogenic, and anti-inflammatory properties capable of modifying the microbial ecology in the gastrointestinal tract of the host animal and balancing the proportion between the beneficial and harmful microbe (Borrelli et al. 2017). Insects contain polysaccharides in the form of chitin, which is fermented by the microbiota in the large intestine balancing microbiota community as well as stimulating the development of immune system (Finke 2007). Maintained equilibrium between the host and gut microbial will benefit the host animal through modification of the development and function of the digestive and immune system (Pan and Yu 2014). Microbial modulates the digestive system through their positive effects on the development of villus height and crypt depth of the small intestine (Forder et al. 2007; Biasato et al. 2018). The villus height has direct positive effect on the rate of nutrient absorption in the small intestine (Montagne et al. 2003); therefore, it is evident that microbiota may stimulate mucin synthesis and modify its compositions (Forder et al. 2007). Mucin is a heavily glycosylated protein gel-like mucus layer produced in the epithelial tissues of the small intestines which serves as a medium in food digestion and absorption and defense against pathogens entering through the intestinal tract (Forder et al. 2007; Biasato et al. 2018). Microbiotas modulate mucin composition by colonizing the outer layer

preventing pathogenic microorganism from penetrating into the intestinal epithelium (Pan and Yu 2014). Modes of action in which bioactive compounds promote and modulate health and gut status and immune system of poultry are presented in Fig. 1.

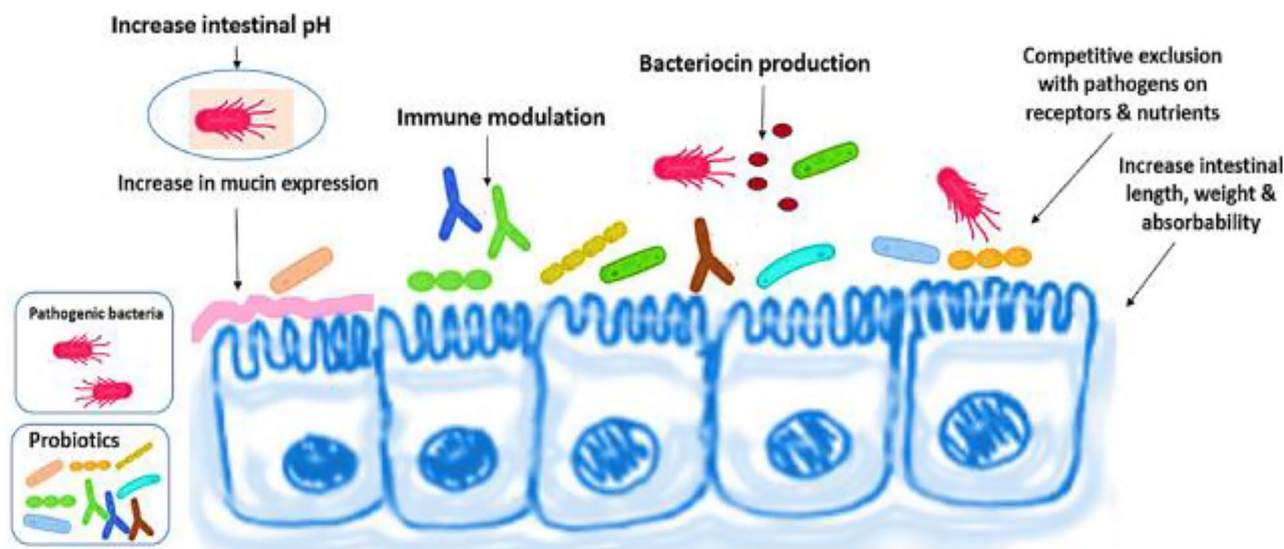
Reports on the effects of feeding insect-based diets on gut morphology of birds

The structure and functionality of gastrointestinal tract play a fundamental role in housing gut microbial population and balancing the proportion between the beneficial and harmful microorganisms colonizing the intestinal gut (Celi et al. 2017). The intestinal morphologies such as the length, muscle thickness, villus height, crypt depth, and villus height to crypt ratio are key factors contributing to intestinal development, health, and functionality, such as inducing nutrient digestibility and absorption (Wang and Peng 2008; Lei et al. 2015). The height of villus is directly proportional to the rate of absorption and the ratio of villus height to crypt depth is an indicator of nutrient absorption in the small intestine (Montagne et al. 2003). Therefore, the ideal gut morphology is characterized by long villus and shallow crypts (Biasato et al. 2018). Several studies demonstrated that feeding insect meal can improve the structure and functionality of gastrointestinal tract in chickens and subsequently improved the health status (Wang et al. 2016; Borrelli et al. 2017; Kim et al. 2021). Polysaccharides in chitin from the exoskeleton

of insects have a positive effect on the functioning of the immune system (Food and Agriculture Organization 2017). Kim et al. (2021) observed that the substitution of soybean meal with black soldier fly larvae meal (*Hermetia illucens*) improved intestinal morphology and enhanced nutrient absorption. Feeding insect meal, yellow mealworm in particular, has shown a positive effect villus height and crypt depth in Japanese quails (Zadeh et al. 2019). However, Sedgh-Gooya et al. (2021) reported no effect of yellow mealworm on gut morphology in broiler chickens throughout the experimental unit. Similarly, Biasato et al. (2018) observed that yellow meal supplementation in diets had no effect on gut morphometrics indices in free-range chickens. The same author suggested that yellow mealworm could be safely used in poultry diets to modulate the gut microbial ecology without compromising the gut morphology and mucin composition. Sedgh-Gooya et al. (2021) investigated the effect of replacing soybean and fishmeal using the levels 7.5, 15, 22.5, or 30 g per kg of diet on gut morphology of broiler chickens and reported no effect on gut morphology. Reports on the effect of supplementing insect meals in diets on gut morphology of poultry are represented in Table 2.

Role of insects on modulating gut microbiota composition of birds

Gut health is determined by the balance between the host, intestinal microbiota, and intestinal barrier to prevent harmful microbial (Biasato et al. 2018). Intestinal microbiota



Bioactive compounds mode of action

Fig. 1 Bioactive compounds' mode of action. Effects of bioactive compounds on gut health and status in birds (Abd El-Hack et al. 2022)

Table 2 Reports on the effects of feeding insect-based diets on gut morphology of birds

Insect species	Inclusion level	Breed type	Conclusion	Author
<i>Tenebrio molitor</i>	Supplemented in the diet at 5, 10, or 15% per kg DM	Boschveld chickens	Dietary treatments have significantly reduced the weight of gizzard (19 g) in chickens aged 60 days. However, the dietary treatments did not affect the weight of the small intestine and proventricular and the length of the intestine	Selaledi et al. (2020)
<i>Tenebrio molitor</i>	Supplemented in the diet at 5, 10, or 15% per kg DM	Boschveld indigenous chickens	Feeding indigenous chickens' insect-based diet did not affect small intestine pH after slaughtering	Selaledi et al. (2020)
<i>Tenebrio molitor</i>	Insect meal provided in basal diets at 7.5, 15, 22.5, or 30 g per kg of feed	Japanese quail	Dietary treatment increased villus height (32–36 µm), crypt depth (6–9 µm), and epithelial thickness (20 µm) in the jejunum; however, villus width (6.8–9 µm) was reduced at 35 days of age	Zadeh et al. (2019)
<i>Tenebrio molitor</i> or <i>Zophobas morio</i>	Insect meal was supplemented in the diet at a level of 0.4%	Broiler chicks	Insect meal supplementation into broiler diets did not affect the relative organ weight of broiler chicks aged 1 to 7 days, except for the reduced weight of the bursa of fabricius (0.13 g)	Islam and Yang (2016)
<i>Hermetia illucens</i>	Insect meal was supplemented in the diet at levels of 50 or 100%	Male broiler chickens	Dietary treatments improved the microscopic structure of the villus height (774.20 µm) of the ileum in male chickens aged 35 days	Kim et al. (2021)
<i>Tenebrio molitor</i> larvae	Insect meal was supplemented in the diet at 75 g/kg of feed	Female Label Hubbard hybrid chickens	Did not alter the physiological intestinal morphology at 97 days	Biasato et al. (2018)
<i>Tenebrio molitor</i> or <i>Hermetia illucens</i>	Basal diet plus live larvae distributed on 5% of expected daily feed intake	Ross 308 male broiler chickens	Did not affect mucin staining intensity in the small intestine at 39 days	Colombino et al. (2021)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at a level of 2.5 or 5%	Broiler chickens	The dietary treatment did not affect villus height, crypt depth, and the ratio of villus height to crypt depth of the small intestinal	Sedgh-Gooya et al. (2021)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at a level of 0.5%	Ross broiler chickens	Adding insect meal to the broiler diet increased the relative weight of the small and large intestines, caeca, gizzard, and crop of unsexed broiler chickens aged 34 days	Ballitoc and Sun (2013)

helps to digest low-quality feeds, thus improving nutrient utilization by the host animal and modulating the development and function of the digestive and immune system (Pan and Yu 2014). A proper proportion of beneficial and harmful microbiota modulates the growth performance and lowers the risk of infections (Józefiak et al. 2020). The gut microbiota living in an animal's gastrointestinal tract can be modulated through the feeding of prebiotic or probiotic compounds which have effects on the animal's humoral immunity (Gasco et al. 2018), hence improving the nutrient utilization and thus improving growth performance and the overall health condition of the animal. Several studies have shown that the potential use of insects in poultry diets has positive effects on the gut microbiota of the animals and could be used in the poultry industry without compromising production (Food and Agriculture Organization 2017; Gasco et al. 2018). Józefiak et al. (2020) reported that a small amount of insect meal in chickens' diet could stimulate colonization of beneficial microbes and reduce the population of harmful bacteria in the gastrointestinal tract. Insect meal supplementation had increased the proportion between intestinal beneficial and harmful microbes which resulted in better nutrient utilization in chickens (Biasato et al. 2018). The same author reported an increased in the abundance of bacterium populations which are known to promote growth and intestinal villus structure, with anti-inflammatory effects, and control antipathogenic properties. The dietary treatment containing black soldier fly larvae meal increased rich bacterial community in laying hens; furthermore, these microbes are associated with a healthy status (Biasato et al. 2018). Colombino et al. (2021) insect larvae altered microbiota composition in the intestinal gut of broiler chickens. Little information has been reported on the role of insects in modulating the microbial ecology of the gastrointestinal tract of poultry. Findings on the effects of insects in the diet on microbial modulation of poultry are summarized in Table 3.

Effects of feeding insect-based diets on humoral immune response of birds

Among the livestock, neither poultry nor mammals synthesize chitin; therefore, insects are a potential target for chitin (Komi et al. 2018; Bovera et al. 2015). It has been shown that modulating intestinal microbial through feeding of insects may influence antibody titers in birds (Bovera et al. 2015; Ido et al. 2015). Feeding insect meals to livestock has positive effects on gastrointestinal microorganisms which plays a significant role in the body's defense mechanisms through modulating the immune system and serving as a barrier to harmful microbes (Józefiak et al. 2020). The same author stated that the establishment of the proper balance

between beneficial and harmful microorganisms is a crucial factor for health improvements and insect meal offers viable bioactive compounds which could modulate gastrointestinal microbial activity. Khempaka et al. (2011) reported that feeding broiler chickens shrimp chitin inhibited the growth of foodborne pathogens and *Salmonella* in the intestine. Supplementing yellow mealworm (*Tenebrio molitor*) and super mealworm (*Zophobas morio*) in the diets reduced cecal *E. coli* and *Salmonella* spp. in broiler chicks (Islam and Yang 2017). Bovera et al. (2015) reported lower albumin to globin ratio which induced immune response and better disease resistance in broiler chickens fed diets containing yellow mealworm. The same author suggested that these effects could be due to the probiotic effects of chitin. Similar findings were found for laying hens fed diets having black soldier fly meal (Marono et al. 2017). In the study investigating the effects of replacing soybean with super mealworm on intestinal health and blood profile of broiler chickens, Kim et al. (2021) concluded that black soldier fly meal can be safely used to replace soybean meal in broiler diets without any adverse effects on chicken health. Similarly, yellow mealworm could be supplemented to free-range chickens as mode of modulating digestive system and intestinal microbiota without having adverse effects on the gut health of the birds (Biasato et al. 2018). In another study by Borrelli et al. (2017), the dietary treatment consisting of yellow mealworm did not affect health status of laying hens. Feeding fish chitin had reduced pathogens' growth by promoting the growth of beneficial intestinal microbiota with improved growth performance and health (Karlsen et al. 2017). Ido et al. (2015) reported a positive effect of housefly larval meal on the innate immune system activation against *Edwardsiella tarda* infection in red sea bream. The authors suggested that the immunomodulatory effects of insect-based diets could be linked to the presence of chitin in the exoskeleton of insects. Insect live larvae have no effects on mucin composition or immune response when fed to broiler chickens (Colombino et al. 2021). However, Mbhele et al. (2019) observed that black soldier fly larvae meal compromises autoimmunity in jumbo quails when included in higher levels. Reports on the effects of insect meal on humoral immune response of domesticated birds are summarized in Table 4.

Role of insects in promoting growth performance of poultry

The use of black soldier fly larvae in chicken feeds showed an improvement in terms of production performance, feed efficiency, and meat quality (DiGiacomo and Leury 2019). Studies by Maurer et al. (2016) and Nogales-Mérida et al. (2019) indicated that insect meal can partially or completely replace fishmeal and soybean cake in the diet of fish or layers

Table 3 Effects of feeding insect-based diets on microbial communities' modulation in poultry

Insect species	Inclusion level	Breed type	Conclusion	Author
<i>Tenebrio molitor</i> or <i>Zophobas morio</i>	Insect meal was supplemented in the diet at a level of 0.4%	Broiler chicks	Insect meal supplementation into broiler diets did not affect fecal microbiota content and fecal pH level	Islam and Yang (2016)
<i>Hermetia illucens</i> larvae	Insect meal was supplemented in the basal diet to replace soybean meal	Lohmann Brown classic laying hens	Altered the gut microbiota and attained a new equilibrium which was characterized by the significant increase of <i>Bacteroides plebeius</i> , <i>Elusimicrobium minutum</i> , <i>Alkaliphilus transvaalensis</i> , <i>Christensenella minuta</i> , <i>Vallitalea guaymasensis</i> , and <i>Flavonifractor plautii</i>	Borrelli et al. (2017)
<i>Tenebrio molitor</i> larvae	Insect meal was supplemented in the diet at 75 g/kg of feed	Female Label Hubbard hybrid chickens	The dietary treatment increased α - and β -diversity of cecal microbiota, indicating a good stability of intestinal microbiota	Biasato et al. (2018)
<i>Tenebrio molitor</i> larvae	Insect meal was supplemented in the diet at 75 g/kg of feed	Female Label Hubbard hybrid chickens	Increased <i>Firmicutes</i> and <i>Bacteroidetes</i> ratios, inducing the nutrient digestion as well as the host health	Biasato et al. (2018)
<i>Tenebrio molitor</i> larvae	Insect meal was supplemented in the diet at 75 g/kg of feed	Female Label Hubbard hybrid chickens	The dietary treatment increased the abundance of <i>Clostridium</i> , <i>Oscillospira</i> , and <i>Coproccoccus</i>	Biasato et al. (2018)
<i>Tenebrio molitor</i> or <i>Hermetia illucens</i>	Basal diet plus live larvae distributed on 5% of expected daily feed intake	Ross 308 male broiler chickens	Increased abundance of cecal microbiota <i>Clostridium</i> , <i>Saccharibacteria</i> , and <i>Vitvillaceae</i> at 39 days of age	Colombino et al. (2021)
<i>Zophobas morio</i>	Supplemented in the diet at levels of 0.2 or 0.3%	Ross 308 broiler chickens	Decreased the ratio of <i>Bacteroides</i> to <i>Lactobacilli</i> population, thus increasing intestinal health	Józefiak et al. (2020)

Table 4 Effects of supplementing insects in poultry feed on humoral immune response of domesticated birds

Insect species	Inclusion level	Breed type	Conclusion	Author
<i>Tenebrio molitor</i> or <i>Zophobas morio</i>	Supplemented in diets at levels of 0.2 or 0.3%	Ross 308 broiler chickens	The induced immune system in broiler chickens	Benzerttha et al. (2020)
<i>Tenebrio molitor</i> or <i>Zophobas morio</i>	Insect meal was supplemented in the diet at a level of 0.4%	Broiler chicks	Increased IgG and IgA levels in broiler chicks aged 1 to 7 days. However, the IgM level was not affected by the dietary treatments as compared to the control group	Islam and Yang (2016)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at unspecified levels	Shaver brown broiler chickens	Insect meal inclusion in broiler diets did not affect hematological traits in male broiler chickens aged 62 days. However, the dietary treatment lowered the albumin to globulin ratio in the blood of broilers and this suggests a better disease resistance and immune response in chickens	Bovera et al. (2015)
<i>Zophobas morio</i>	Insect meal was supplemented in the diet at levels of 0.2 or 0.3%	Ross 308 broiler chickens	The dietary treatments stimulated cecal colonization and commensal bacteria, acting as a barrier to pathogenic microorganisms, thus inducing defense mechanism	Józefiak et al. (2020)
<i>Zophobas morio</i>	Insect meal was supplemented in the diet at levels of 0.2%	Ross 308 broiler chickens	Significantly increased abundance of genus <i>Lactobacillus</i> and <i>Bifidobacterium pseudolongum</i> and <i>Clostridia</i> class	Józefiak et al. (2020)
<i>Hermetia illucens</i>	Insect meal was supplemented in diets at levels 25, 50, 75, or 100%	Jumbo quail	Did not affect blood parameters, except for the albumin/globin ratio, which was reduced, thus reducing autoimmunity	Mbhele et al. (2019)
<i>Hermetia illucens</i>	Insect meal was supplemented in the diet at levels of 50 or 100%	Male broiler chickens	Lowered the concentration of lipase (111 U L^{-1}) in male broiler chickens	Kim et al. (2021)

Table 5 Effects of feeding insect-based diet on growth performance of chickens

Insect species	Inclusion level	Breed type	Conclusion	Author
<i>Hermetia illucens</i> larvae	Direct feeding of live larvae (12 g/h/day)	Dekalb White	Provision of live larvae reduced feed intake (123 g/h/day) of laying hens. However, the feed conversion ratio and body weight were not affected	Star et al. (2020)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at a level of 2.5%	Broiler chickens	Insect meal supplementation in broilers' diets improved feed conversion ratio (1.25 g/g), thus increasing body weight gain (186.2 g), during the starter period. However, the feed intake was not affected	Sedgh-Gooya et al. (2021)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at a level of 2.5 or 5%	Broiler chickens	The dietary treatments did not affect growth performance throughout the experimental period	Sedgh-Gooya et al. (2021)
<i>Zophobas morio</i>	Supplemented in diets at a level of 0.3%	Ross 308 broiler chickens	Dietary treatment improved feed intake (3304 g/35 days), feed conversion ratio (1.58 g:g), and body weight gain (2094 g/b) in female chickens aged 1 to 35 days	Benzertiha et al. (2020)
<i>Tenebrio molitor</i> or <i>Zophobas morio</i>	Insect meal was supplemented in the diet at a level of 0.4%	Broiler chicks	Insect meal supplementation in broiler diets had increased daily feed intake (1.18 g/day/b), average daily gain (5.07 g/b), and final body weight (74.89 g) of broiler chicks aged 1 to 7 days. However, the feed conversion ratio was negatively affected (0.29 g:g)	Islam and Yang (2016)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at unspecified levels	Shaver brown broiler chickens	Insect meal inclusion in broiler's diets did not affect the feed intake, body weight, and body weight gain in male broilers aged 30–62 days. However, adding insect meal into broiler's diets improved the feed conversion ratio in male broiler chickens aged 30–62 days	Bovera et al. (2015)
<i>Hermetia illucens</i>	Insect meal was supplemented in the diet to replace 50% of soybean meal	Ross 308 broiler chickens	Dietary treatment improved the live weight (2329 g) in male broiler chickens at the age of slaughter	Altmann et al. (2018)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at levels of 0.5, 1, 2, or 10%	Ross broiler chickens	Insect meal supplementation did not affect feed intake during the starter period. However, insect meal inclusion of 0.5% improved feed intake (172 g/day) and feed conversion ratio (1.7 g:g) in chickens aged 1 to 34 days	Ballitoc and Sun (2013)
<i>Hermetia illucens</i>	Insect meal was supplemented in diets at levels of 12 and 24 g/100 g	Leghorn laying hens	Dietary treatment did not affect feed intake and egg production	Maurer et al. (2016)

Table 5 (continued)

Insect species	Inclusion level	Breed type	Conclusion	Author
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at levels 2, 4, or 8%	Ross 308 broiler chickens	Dietary treatment levels improved feed conversion ratio, body weight, and average daily gain of broiler chickens during the starter period	Elahi et al. (2020)
<i>Hermetia illucens</i>	Insect meal was supplemented in the diet at levels of 50 or 100%	Male broiler chickens	Insect meal supplementation in the diet did not affect the apparent digestibility of dry matter, crude protein, ether extract, and energy in male broiler chickens	Kim et al. (2021)
<i>Tenebrio molitor</i>	Insect meal was supplemented in the diet at levels of 1, 2, or 10%	Ross broiler chickens	Dietary treatment increased the average body weight (1484, 1470, and 1486 g, respectively) at slaughter age	Ballitoc and Sun (2013)

without affecting the production performance as well as the feed efficiency. There is evidence that the addition of yellow mealworm (*Tenebrio molitor*) in broilers' diets improved the growth performance of broiler chickens during the starter period (Sedgh-Gooya et al. 2021). Adding a small amount of yellow mealworm or super mealworm into broilers' diets can improve their growth performance traits (Benzertiha et al. 2020). These improvements could be due to increased daily feed intake which is be associated with the palatability of insect meal supplemented in the diet (Islam and Yang 2016). The addition of black soldier flies into chickens' diets may influence their growth performance traits through the alteration of gut microbiota (Detilleux et al. 2022). Yellow mealworm supplementation in the diets could improve growth performance in growing Japanese quails (Zadeh et al. 2019). Ballitoc and Sun (2013) observed positive effects of supplementing yellow mealworm on overall feed intake and body weight gain in broiler chickens. However, Selaledi et al. (2020) stated that yellow mealworm supplementation in the growing diet of indigenous chickens could not be considered a potential protein source. Results of the effects of insect meal on the growth performance of chickens are summarized in Table 5.

Conclusion

Poultry gut health has been a focus of many researchers since it is regarded as a major factor that determines the growth performance and health condition of the animal. However, the gut health condition depends on the features such as intestinal microscopic structures, dietary compounds, and balance between beneficial and harmful microorganisms' ratios and intestinal barrier. Intestinal microbiotas play a fundamental role in regulating metabolic processes of birds. Extensive research has shown that insects can be safely used in poultry feeds to modulate the development of digestive and immune system without compromising the production parameters and the quality of the produce. Edible insects are a good source of protein with good amino acid composition, and they have been regarded as a good source of antioxidants with antipathogenic properties and their results are two-fold. With these properties, insects are being targeted as an important future source of sustainable raw feed ingredients in the poultry industry, protein, and chitin in particular. Insects are promising feed additive for animals because they contain not only valuable nutrients but also bioactive compounds which are known to modulate the gut functionality as well as the gut microbiota, which could optimize the growth performance as well as the overall health condition of the birds. Insects can be directly fed to chickens or can be processed into insect meals and supplemented in the diet. Based on the recent literature, yellow mealworm and black soldier

fly larvae are the most used insects in poultry production and insect meal is more effective than larvae direct feeding and could serve as a promising protein and chitin source. Therefore, the addition of insect meal in poultry diets could promote gut microbiota community, development of gut, and immune system, hence improving growth performances of birds. Nonetheless, most of literatures done on the effects of insect meal are focused commercial chicken breeds; hence, more studies on the use of insect meal in poultry are recommended to ascertain these findings especially with other poultry species.

Source of data

The data used in this review article was acquired from recently published manuscripts from different journals. Databases were accessed using electronic data sources such as Directory of Open Access Journals (DOAJ), Research gate, Web of Science, Science Direct, Google Scholar, and PubMed. In addition, the citations included in articles from the databases were used to search for other relevant articles. The keywords “Insect meal,” “Edible insects,” and “poultry” were used in the search engines.

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Ethical approval This study requires no IRB/IACUC approval because there is no human and animal participants.

Informed consent For this type of study, informed consent is not required.

Consent for publication For this type of study, consent for publication is not required.

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