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The effects of black soldier fly (*Hermetia illucens* L.) on the sustainable poultry nutrition production systems

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ABSTRACT

The rapid increase in humans' population, changing dietary patterns, and increasing competition between food and feed production spotlight the crucial need for the search of new sustainable food production chains. Intensive research has been carried out on the use of different protein sources as in the livestock diets, however, there are still limits on the suitability of amino acid profiles, nutrient availability, and yield. Consequently, there is a necessity for new, sustainable, and easy-to-produce substitute protein sources for the modern industry production. Insects do not compete with humans for resources, and they efficiently utilize organic waste to grow. Recently, insect products have gained increasing attention as a new animal's protein and fat alternative for the animal's feed. In this line, the black soldier fly (BSF) meals have been highlighted as a solution in the livestock, particularly, poultry production. In the poultry feeding systems, BSF could be directly incorporated in diets as larva, powder, or oil to improve the general health conditions of birds. Therefore, this article was designed to investigate the different impacts of adding BSF to the diets of poultry regarding the performance, carcass traits, gut health, mortalities, blood parameters, immunity, as well as the oxidant and microbial status of the fed birds.

Introduction

In the last decade, there has been an increase in the demand of the animal source foods due to the global population expansion. Besides, increasing the consumption of animal's foods origin requires different sources of protein to feed livestock (Alexandratos and Bruinsma, 2012). Thus, searching for organic or natural alternative sources of nutrients, particularly proteins, became an urgent issue.

The insect products recently offered functional and nutritional significant characters, making them one of the best and the most important alternatives in poultry diets (Van Huis *et al*., 2020). Moreover, insects feed addition could increase the livestock sustainability (Barragan-Fonseca *et al*., 2017; Dicke, 2018; Saatkamp *et al*., 2022). The different forms of insects' meals range from living (Veldkamp and Van Niekerk, 2019) or dried (Bejaei and Cheng, 2020) larvae; non-defatted (Maurer *et al*., 2016), partially defatted (Schiavone *et al*., 2017), and full defatted (Schiavone *et al*., 2017), as well as oil (Kim *et al*., 2020).

The black soldier fly (BSF) (*Hermetia illucens* L.) (Diptera: Stratiomyidae) has a wide importance for the management of wastes (Banks *et al*., 2014) and production of high-quality proteins. The larvae of BSF are sometimes used in the different food industry end-products substrates (Diener *et al*., 2009; Tschirner and Simon, 2015). Moreover, the produced lipids in the defatted process of meals could be used for the biodiesel production (Leong *et al*., 2016).

The larvae of BSF are adapted to grow in wide ranges of environmental conditions (25-30°C) and preferred habitats rich in decomposing organic matter. It has been reported that the production of BSF larvae shows a lower environmental impact and requires less land and energy/kg protein compared to the traditional sources of protein (Bosch *et al*., 2019). So, BSF has crucial roles in sustainable agriculture and wastes management (Ee *et al*., 2022; Pazmiño-Palomino *et al*., 2022). Furthermore, the BSF larvae contain high concentrations of crude protein, amino acids, fats, fatty acids, and carbohydrates profiles which are essential for livestock nutrition (Veldkamp and Bosch, 2015; Gold *et al*., 2020). Accordingly, soybean meal, fishmeal, and soybean oil meals could be replaced by BSF meals (Dorper *et al*., 2021). In addition, fat originated from BSF larvae meal is used during diets formulation as a substitution for lipid sources to improve the digestibility, beneficial microbial community, immune and physiological status, and final product quality of animals (Gasco *et al*., 2019), poultry (Sypniewski *et al*., 2020), and aquaculture (Kumar *et al*., 2021). Beside the distinguished surge in the rearing and utilization of BSF as feed substitutes for the livestock production systems (Lu *et al*., 2022), it shows promising results in poultry production sector (Heuel *et al*., 2012; Gold *et al*., 2018; Smetana *et al*., 2019; Dorper *et al*., 2021).

Despite BSF meals are used for fish and pet's nutrition in Europe, their usage in poultry feed is still under some restrictions. Moreover, the feed substrates that are used to feed larvae are not regulated in some regions of the world (EFSA Scientific Committee, 2015; Pinotti *et al*., 2019). The further incentives to use BSF larvae in poultry feed are relies on the health-related benefits.

Accordingly, the present article was purposed to investigate different impacts of adding BSF to the diets of poultry regarding performance, carcass traits, gut health, mortalities, blood parameters, immunity, as well as the oxidant and microbial status of the fed birds.

Health benefits of BSF in poultry nutrition

Table 1 shows the different effects of BSF larvae on the performance parameters of broilers and layers.

Broilers performance

The investigation into performance parameters offers valuable insights into the health status of poultry. The effects of using BSF on the broiler's performance vary from positive, neutral, to negative (Dabbou *et al*., 2018; Velten *et al*., 2018; Schiavone *et al*., 2019; Attivi *et al*., 2020; Ipema *et al*., 2020; Bellezza Oddon *et al*., 2021; DeJong *et al*., 2021; Heuel *et al*., 2022). Most of studies indicated that the addition of low concentrations of insect larvae meal to poultry diets induced the best performance parameters. The early study of Cousins (1985) indicated that at 10-day-old broilers received BSF-based starter diet showed daily body weight gain (BWG) similar to those received fish meal control diet. Moreover, the dietary combination of both BSF larvae oil and larvae meal products improved the FCR (Facey *et al*., 2023).

However, no changes were observed in daily or final BWG during the grower phase of broiler quails fed either a BSF larvae meal diet or a control diet (Cullere *et al*., 2016). Similarly, the recent results of Dorper *et al*. (2024) showed that the dietary addition of BSF larvae oil led to a 3.6% lower BWG of broiler chickens compared to birds fed on BSF larvae meal. The authors attributed these results to the negative impacts of dietary BSF larvae meal on gut architecture particularly when inoculated into poultry diet at high levels.

The discrepancy in the results of BSF larvae on the performance of broilers depends on using of unprocessed or processed insects and the dietary inclusion level of the insect's products. The unprocessed insect's products have the most nutrients components, while processing by drying or separation of fat and protein could change the nutrient properties, structure, abundance, and function of the product (Veldkamp *et al*., 2021; Hurtado-Ribeira *et al*., 2023; Son *et al*., 2023).

Carcass traits

The study of Cullere *et al*. (2016) revealed that quails fed on a diet supplemented with 10% BSF larvae meal showed heavier and tenderer cooked breast muscles than those supplemented with 15% BSF diet or even control birds. However, no difference in the carcass and breast muscles weight, breast meat yield, and dressing percentage in comparison with birds supplemented with a control diet. However, the dietary inoculation of BSF larvae had no adverse effects on meat yield, carcass characteristics, or meat quality of broiler chickens (Schiavone *et al*., 2017). In addition, the sensory tests including flavor, odour, and texture of quail's breast muscles were not affected after feeding on dietary BSF larvae meal (Cullere *et al*., 2018).

No changes in the fatty acids' composition of broiler's meat when BSF meal was added (Neumann *et al*., 2018; Schiavone *et al*., 2018). It has been found that increasing the dietary inclusion level of BSF larvae led to an increase in the concentrations of saturated fatty acids but not the polyunsaturated fatty acids (Schiavone *et al*., 2017; Cullere *et al*., 2019). Moreover, the crude protein and the total essential amino acids (lysine and tryptophan) contents of breast muscles were higher in broilers fed on BSF diet than birds fed on soybean-based diet (Hwangbo *et al*., 2009).

Broilers quails fed on defatted BSF at inoculation level of 15% increased the total saturated fatty acids and the total mono and polyunsaturated fatty acids (Cullere *et al*., 2016). Higher levels of calcium (Ca) and lower potassium as well as increasing the contents of contents of some proteins such as alanine, glutamate, aspartate, serine, tyrosine, and threonine have been found in the breast meat of BSF treated birds than non-treated groups (Cullere *et al*., 2018).

Layers performance

Several studies showed successful using of defatted BSF meals as a source of protein in hen's diets (Heuel *et al*., 2012; Maurer *et al*., 2016; Marono *et al*., 2017; Secci *et al*., 2018; Mwaniki *et al*., 2020). The combined positive effect of both fish and maggot meals as a source of protein in 50-week old laying hens was evaluated. Agunbiade *et al*. (2007) demonstrated that the inoculation of equal proportion of fish meal and maggot meal into the diet of 50-week-old laying hens resulting in 70.83% egg production with 2.78 FCR compared with 67.43% egg production percentage and 3.04 FCR of those that received 100% fish meal. In the same study, 100% substitution of fish meal by maggot meal showed no effect on the egg weight, egg shape index, yolk color, and yolk index with a slight affection of the shell weight and shell thickness. The authors referred these results to the differences in Ca and phosphorus (P) levels

Table 1. The different effects of BSF larvae on the performance parameters of broilers and layers.

Level of dietary BSF larvae meal	Type of birds	Effects	References
5%, 10%, 15%, and 20%	Broiler chickens	Improved BWG and FCR Increased the dressing and breast muscle weight	Hwangbo *et al*. (2009)
10 g/kg feed	Layer chickens	Improvement in the sensory profile of eggs*	Al-Qazzaz *et al*. (2016)
50%	Layer chickens	No effects on health, meat yield, and egg's weight and quality	Maurer *et al*. (2016)
10% and 15%	Layer quails	No effect on sensory profile of eggs* High feed off-flavor	Cullere *et al*. (2018)
15%	Broiler chickens	Improved BWG and FCR	Dabbou *et al*. (2018)
8%	Broiler chickens	Slight improvement of weekly BWG Improvement of the sensory traits of muscles No effect on the carcass yield, breast muscle, drumstick, thigh weight, and the weights of internal organs	Moula *et al*. (2018)
7.50%	Layer chickens	Increased BWG Poor FCR Increased eggshell thickness. No change in egg's weight, egg mass, and Haugh unit Pale egg yolk color	Mwaniki *et al*. (2018)
9%	Muscovy ducks	No difference in daily BWG and FCR	Gariglio *et al*. (2019)
10%	Layer chickens	No differences in performance parameters	Kawasaki *et al*. (2019)
10% 15%	Broiler chickens	No adverse effects on carcass traits and muscle's quality traits High redness index muscles	Schiavone *et al*. (2019)
50%	Layer chickens	*Enhanced the sensory profile of eggs	Bejaei and Cheng (2020)
50%, 75%, and 100%	Broiler chickens	Decreased FI and BWG	Murawska *et al*. (2021)
5%-15%	Broiler chickens	Sustained BWG Reduced feed costs	Zaid *et al*. (2023)

*Sensory profile of eggs= Acceptance, appearance, texture, and taste. BWG: Body weight gain; FI: Feed intake; FCR= Feed conversion ratio in fish and maggot meals. Additionally, Marono *et al*. (2017) showed that the complete substitution of soybean-based meal of layers with BSF larvae induced a lower FCR compared with the soybean-based control feed. But the study of Borrelli *et al*. (2017) demonstrated that the full replacement of soya-bean meal with BSF larvae meal for 21 weeks reduced the BW of laying hens (2.09 versus 1.89 kg, respectively).

Partial and complete replacements of soya-bean based meal with BSF for 64-74-week-old laying hens were corresponded to the breed standards of 84.4% and 83.4%, respectively (Maurer *et al*., 2016). Moreover, the partial replacing of soya-bean meal by BSF-based diet did not affect the egg's weight, egg's shell, and albumen and yolk parameters, while the total replacement of soya-bean meal lowered the eggs albumen by 7.5% (Maurer *et al*., 2016). Feeding of layer chickens on BSF larvae meal for 6 weeks resulting in 91.6% egg production percentages versus 82.8% for control birds (Ruhnke *et al*., 2018). Moreover, higher egg weights (>67 g), paler yolk color, and significant lower eggshell thickness (by 6.3%) were measured in eggs produced by hens fed BSF larvae meal than those produced by control non-treated birds.

On the other hand, the full replacement of soya-bean by BSF larvae meal in the diet of layer chickens for more than 21 weeks had no effect on egg weight and shell weight (Secci *et al*., 2018). Marono *et al*. (2017) demonstrated that feeding of Lohmann Brown Classic laying hens on BSF larvae meal for 21 weeks to totally replace the soya-bean meal induced a greater reduction in laying rate and average eggs weight, higher percentage of abnormally sized eggs, and lower egg weight and egg mass than those fed on soya-bean meal.

Gut health

The dietary supplementation of poultry with BSF larvae meals mostly induced a significant positive impact on the gut health, as evidenced by changes in intestinal morphology. These changes indicate the possible alterations in the digestion and adsorption functions of the gastro-intestinal tract and highlight the complex effects of BSF larvae meals on the gut's health and function. Less than 15% of BSF larvae meal in the feed of broiler chickens could improve the intestinal morphology, while higher inclusion levels led to shorter villi and shallower crypts, along with a decreased villus height: crypt depth ratio (Dabbou *et al*., 2018). In the same context, Cutrignelli *et al*. (2018) found that an addition of BSF to the diet of laying hens increased the intestinal villus height (VH) of the duodenum but decreased the highest of the jejunum and ileum. Besides, the crypt depth (CD) was higher in the ileum without changes in the duodenum or jejunum. An analogous finding was reported by Chen *et al*. (2022) who observed an increase in VH of the jejunum after incorporation of the broilers diet with BSF oil larvae oil, however, there was no significant differences in VH and CD of the duodenum between the control and treatment groups. A meal containing soybean with 50% BSF larvae could increase the VH in the ileum and improve the surface absorption without significant differences in the CD, the VH to CD ratio, villus width, and villus areas among treatments (Kim *et al*., 2020). The study of Biasato *et al*. (2020) revealed that an incorporation of broiler chickens' diet with 5% BSF larvae meal resulted in an enhancement of mucin layer of the intestinal villi, and consequently boosting the mucus barrier and the gut's microbiota.

Nevertheless, half or total substitution of soybean-based oil with BSF larvae meal in the diet of broilers had no effect on the intestinal histology (Schiavone *et al*., 2018). Similarly, a dietary BSF larvae meal didn't affect the intestinal histological traits of Muscovy ducks (Gariglio *et al*., 2019). Also, Kawasaki *et al*. (2019) demonstrated that meals of layers containing 10% BSF larvae and 10% pre-pupa had no positive effects on the VH and CD of small intestine when compared with a control diet supplemented with corn-soybean. A dietary concentration of 10% and 15% BSF larvae meal reduced the intensity of mucin staining, decreased mucus production, and increased the intestinal degradation (Biasato *et al*., 2020).

Regarding the possible effects of the dietary BSF larvae inoculation on the gut microbiota, the findings vary between beneficial and harmful impacts. For instance, the dietary addition of 5% BSF larvae meal furthered the beneficial bacteria, while a level of 15% reduced the microbial complexity and increased the mucolytic bacteria which harm the gut health (Biasato *et al*., 2020). A broilers diet containing 75% BSF larvae significantly increased the beneficial lactic acid bacteria count and enhanced the gut microbiota diversity (Ndotono *et al*., 2022). Additionally, chickens fed on BSF pupae showed a more decrease in Salmonella and increase in *LactoBacillus* spp. caecal counts compared with the control group (Attia *et al*., 2023). De Souza Vilela *et al*. (2023) reported that a dietary inoculation with 20% BSF larvae resulted in a certain decrease in Enterococcus and Christensenellaceae but increase in *Roseburia* and *Dehalobacterium* butyrate-producing bacterial abundance. Similarly, incorporating BSFL at a level of 50% reduced the pathogenic caecal bacteria such as *Enterobacteriaceae*, *Bacteroides-Prevotella*, *Bacillus* spp., *Clostridia leptum*, and *Clostridia coccoides-Eubacterium rectale* (Kiero´nczyk *et al*., 2021).

There were no differences in the total coliform, *Escherichia coli*, and *Clostridia* spp. counts among groups of broilers fed on fish meal, BSF larvae, and BSF pupae at both 3% and 5% inclusion levels during the starter and grower-finisher phases (Attia *et al*., 2023). However, the high inoculation levels of BSF larvae meal could increase the pathogenic *Clostridia* and *Campylobacter* spp. (Ndotono, 2023).

Mortalities

The addition of insect meal to bird's diets has a positive effect on the health status of layers and broilers. Absence of any signs or mortalities in layers supplemented with of BSF indicates the positive impact on the health conditions (Borrelli *et al*., 2017; Marono *et al*., 2017). Generally, the products of insects have bioactive components including antimicrobial peptides, lauric acid, and chitin which may help in improving the health of broilers (Gasco *et al*., 2018).

A partial or complete substitution of dietary protein with maggot meal induced no mortalities in layers (Agunbiade *et al*., 2007). Similarly, Maurer *et al*. (2016) showed that replacement of soybean cake-based diet of layer chickens with 12% and 24% BSF larvae meal had resulted in zero mortalities with no metabolic or health disorders. Moreover, the replacement of soybean meal and oil with 10% BSF larvae meal or 10% pre-pupae meal did not induce any mortality during 5 weeks experiment period (Kawasaki *et al*., 2019). Grower broiler quails supplemented with BSF larvae meal did not show any mortalities (Cullere *et al*., 2016). Similar studies in broilers didn't show clinical manifestations for any disease conditions after feeding of broilers on diets containing maggot (Koo *et al*., 1980; Atteh, 1990).

On the other hand, supplementation of Muscovy ducks with variable concentrations of dietary defatted BSF larvae meal (3%, 6%, and 9%) induced a cumulative mortality rate of 2.08%, while ducks supplemented with a control diet showed mortality rate of 4.16% (Gariglio *et al*., 2019).

Blood parameters

The impact of BSF larvae on the different blood parameters reflects the interaction between dietary components and the bird's physiology.

Feeding of 168-day-old hens on pre-pupa meal or BSF larvae for 5 weeks significantly increased the blood Ca level (Marono *et al*., 2017). However, 3 and 50-day-old Muscovy duck fed on diets with BSF larvae did not show any effect on serum levels of Ca and P (Gariglio *et al*., 2019). Dabbou *et al*. (2018) observed an elevation in serum P level without any significant effects on the levels of iron (Fe) and magnesium (Mg) after feeding of broilers on 10% dietary BSF meal. But, Gariglio *et al*. (2019) demonstrated that addition of 9% BSF larvae meal in the diet of Muscovy duck led to an increase in the serum level of Fe, but a decrease in Mg level. However, no significant modifications in Fe and Mg levels in the serum following chickens' supplementation with BSF larvae meal (Loponte *et al*., 2017; Marono *et al*., 2017; Dabbou *et al*., 2018).

The different dietary concentrations of BSF could influence the lipid metabolism and alter the high-density lipoprotein, cholesterol, and total cholesterol proportions in the blood (Kim *et al*., 2020; Aprianto *et al*., 2023). In the same context, a significant decrease in the blood levels of cholesterol and triglycerides was demonstrated in laying hens, broilers, and Muscovy ducks after inoculation of BSF larvae which was attributed to the high content of BSF larvae with chitin and short chain fatty acids (Hossain and Blair, 2007; Borrelli *et al*., 2017; Marono *et al*., 2017; Gariglio *et al*., 2019). Chitin has a bile acid binding and anion-exchange capacities that interrupt the enterohepatic circulation, enhance the excretion of triglycerides and cholesterol, and consequently decrease the lipid absorption (Bedford and Gong, 2018).

An enhancement in the liver functions and elevation of protein and albumin levels were also noticed in broilers supplemented with BSF (El-Kaiaty *et al*., 2022). Moreover, Dabbou *et al*. (2018) demonstrated no significant damaging effects of BSF on the liver functions in terms of normal activities of aspartate transferase and alanine transaminase. Nevertheless, an increase in the levels of alkaline phosphatase and uric acid were detected following feeding of chickens on higher BSF levels (Seyedalmoosavi *et al*., 2022). A reduced level of creatinine was observed in hens fed on BSF meal compared to a group fed on soybean meal diet (Marono *et al*., 2017; Gariglio *et al*., 2019).

Immunity

The BSF meals have a potential role in boosting both the local and humoral immune responses of the inoculated birds. Using of BSF larvae meal to replace dietary soybean meal from 24 to 45 weeks of age significantly increased the level of serum globulin (Ig) and consequently decreased the albumin to globulin ratio in laying hens (Marono *et al*., 2017). This indicated an increase in the circulating immuno-globulines and consequently the diseases resistance (Sturkie and Griminger, 1986). The presence of a high content of chitin in BSF larvae meal is the main cause of enhancing immunity (Elieh *et al*., 2018).

Chen *et al*. (2022) reported that high levels of BSF larvae meals significantly enhanced the immune markers including IgA and interleukin 2 (IL-2) and boosted the activities of the antioxidant enzymes without affection of the tumor necrosis factor-alpha levels. In the same line, 21-day-old chickens fed on a diet containing 75% BSF larvae showed an increase in the blood levels of clusters of differentiation (CD3) + CD4 + T cells, while a dietary level of 100% BSF larvae reduced the proportions of these cells and increased CD8a + T cells (Tykałowski *et al*., 2023). Besides, 42-day-old chickens exhibited a higher CD3 + CD8a + T cells and lower CD3 + CD4 + T cells levels in the blood and spleen samples following increasing the BSF larvae ratio in the diet (Tykałowski *et al*., 2023). The similar study of Lee *et al*. (2018) revealed that broilers fed on diets contains BSF larvae exhibited an increase in frequency of CD4 + T cells, improved activity of lysozymes in serum, and enhanced proliferation of lymphocytes in spleen.

Bongiorno *et al*. (2022) found decline in gamma-glutamyl transferase activity and white blood cell count, indicating the immunomodulatory effects of BSF. It has been found that BSF could convert wastes to proteins, lipids, and chitin (Gortari and Hours, 2013). Chitin is a polysaccharide constituent of the arthropod's exoskeleton (Muzzarelli, 2010). Deacetylation of chitin produced chitosan, while chito-oligosaccharides are products of chitosan or chitin (Swiatkiewicz *et al*., 2015; Liaqat and Eltem, 2018). Chitin and its derivatives showed activation of both innate and adaptive immune response in terms of generation of cytokine and chemokine (Lee *et al*., 2008).

Antimicrobial and antioxidant effects

The populations of the gut *Bifidobacterium* and *LactoBacillus* in laying hens were significantly higher in groups treated with BSF and this finding was attributed to the antibacterial effect of chitin or lauric acid (Kawasaki *et al*., 2019). Chitin has antibacterial (Sánchez *et al*., 2017), antiviral (Chirkov, 2002), and antifungal (Mei *et al*., 2015) activities. The significant antimicrobial effect of chitin and chitosan was attributed to the interference with the bacterial metabolism by electrostatic disturbance of bacterial surface (Je and Kim, 2006) as well as their ability to inhibit RNA transcription from DNA (Benhabiles *et al*., 2012). The fatty acid (lauric acid) could be changed to monolaurin that has the ability to destruct the bacterial lipid membrane (Srivastava *et al*., 2018). Moreover, feeding of weaning piglets on prepupae of BSF with high levels of lauric acid to replace the dietary proteins led to a potential antimicrobial activity by reducing Gram-positive bacteria such as *Streptococci* count in the gut (Spranghers *et al*., 2018). Fatty acids derived from BSF especially dodecanoic acid revealed a strong antimicrobial efficacy against Gram-positive bacteria (Skˇrivanová *et al*., 2005). Ricke (2003) demonstrated that non-dissociated forms of medium-chain fatty acids could disturb and penetrate the lipids in the bacterial membrane and consequently dissociated into anions and protons in the cytoplasm. Maintaining the neutral pH of the cytoplasm is important to the functional macromolecules of bacterial cells, so the bacteria get rid of excess protons with a depletion of cellular energy.

Limited data are available regarding the effects of the dietary incorporation by BSF on the antioxidant status of birds. The increase in the dietary inoculation level with BSF larvae meal for up to 15% was associated with the increase in the total antioxidant status and the glutathione peroxidase activity in blood of male broiler chickens (Dabbou *et al*., 2018). Moreover, Gariglio *et al*. (2019) found that BSF larvae meal in the diet of Muscovy ducks improved some plasma oxidative metabolites such as malondialdehyde and nitrotyrosine which are indicators of good health without significant effect on the antioxidant enzymes levels.

Conclusion

Despite the extensive research work that had been done on the various impacts of using BSF meals in the livestock production and particularly in the poultry production system, further investigations are essential to fully understand the mechanisms by which they can exert their effects. Besides, there is a further need to disentangle the complex relations between BSF and the gut microbiota and immunity which could offer deeper insights into improving poultry nutrition. Therefore, the optimum levels of BSF meal that can be integrated in poultry diets to guarantee optimal productive performance still needs to be recognized. Further work into standardizing insect and production methods should be prioritized.

Conflict of interest

The author declares that there is no conflict of interest.

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