



# The use of yellow mealworm (*T. molitor*) as alternative source of protein in poultry diets: a review

L. Selaledi<sup>1,2</sup> · C. A. Mbajorgu<sup>1</sup> · M. Mabelebele<sup>1</sup> 

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## Abstract

Protein sources are known to be the second largest component in the poultry sector. Traditionally, fish and soya-bean meals are known to supply very good protein; however, these are restricted in supply and more expensive than energy sources. The prices of soya-bean meal are currently high and tend to fluctuate with changes in climatic conditions and social situations in the countries where it is produced. Developing countries like South Africa have made enormous investments in soya-bean production, despite that the country still imports considerable volumes of this crop and is not self-sufficient. This then means that there is an urgent need to seek for alternative and cost-effective protein sources that can provide the same nutrients as soya-bean and fish meal for poultry production. *Tenebrio molitor* L. which is commonly known as yellow mealworm has a huge potential to substitute commonly used protein sources in poultry diets. Mealworms are easy to breed and do not require large area for production. Moreover, they have high nutritional value comparable to that of soya-bean and fishmeal. However, the only limiting nutrient for mealworms is calcium which can be easily supplemented in the diets. Therefore, this review sets out to explore the importance of replacing soya bean with mealworms in poultry diets. Furthermore, the life cycle of meal worms will also be discussed.

**Keywords** Edible insects · Mealworms · Nutritional value · Chickens · Protein

## Introduction

The major factors that affect the high cost of poultry feeds are the scarcity of feed ingredients soya-bean and fishmeal (Adeniji 2007). These ingredients, soya-bean and fishmeal, are mainly used in the poultry feed because they are palatable and rich in protein. However, due to their dependency on its import and high cost, most researchers are seeking an alternative protein sources that will replace soya-bean and fishmeal in the poultry diets. Recently, there is an interest in the utilisation of insects such as black soldier fly larvae, maggot meal, earthworm and mealworm as potential replacement of soya-bean and fishmeal as protein source in poultry ration

(Van Huis et al. 2013; Khan et al. 2016). Therefore, the presence of insects' meals in poultry diets is expected to lower the price of feeds, consequently contributing to the cost-effectiveness of small-scale poultry farms (Moreki et al. 2012). Insects have high-quality protein concentration due to the presence of all the essential amino acids in the rations (Collavo et al. 2005). The inclusion of black soldier flies larval meal as a replacement of fishmeal in the diet of guinea fowl impacted positively the growth performance (Wallace et al. 2018). According to Bovera et al. (2016), insects in general and mealworm can be used as a replacement of soya-bean meal in the diets of chickens without affecting growth and diet palatability.

There are three species of mealworm: *Tenebrio molitor* L. (yellow mealworm), *Zophobas atratus* (giant mealworm) and *Alphitobius diaperinus panzer* (lesser mealworm). Mealworms are the larval stage of *Coleoptera Tenebrionidae* (darkling beetles). Mealworms are a harmful pest of stored grains; however, its larvae are commonly used as pet food in many countries. According to Ramos-Elorduy et al. (2002), *T. molitor* is also found in food storage facilities and is a pest of flour and grain. However, its larvae are rich in protein. They

✉ M. Mabelebele  
mabelebelem@gmail.com

<sup>1</sup> College of Agriculture and Environmental Sciences, University of South Africa, Florida Campus, Johannesburg, South Africa

<sup>2</sup> Department of Zoology and Entomology, Mammal Research Institute, Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria, South Africa

are already produced in commercial scale as feeds for pets such as reptiles and birds. Mealworms are inexpensive and easy to raise with less harmful effects on the environment (Wang et al. 2012). Therefore, many studies have been conducted on *T. molitor* to determine its potential uses in poultry farms.

*T. molitor* Linnaeus (Coleoptera: Tenebrionidae) can be used as an interdisciplinary method to learn science at school level (Harrell and Bailer 2004); it can be used as bio-indicators (Simon et al. 2013) and can be included in chicken feed (Bovera et al. 2016). Mealworms are also used for human consumption with nearly two billion people globally consuming insects (Van Huis et al. 2013). In China, the yellow mealworm is a popular dish for local people (Li et al. 2013). According to Li et al. (2013), mealworm can also be used in a bio-regenerative life support system in space, by providing an efficient system for treating plant waste and providing protein for Astronauts. Mealworms are considered as potential ingredients for fish diet Rainbow trout (Iaconisi et al. 2017).

The detrimental environmental effects such as global warming, loss of biodiversity and land degradation are relatively associated with conventional livestock production (Steinfeld et al. 2006). Insects are poikilothermic and as such they do not invest energy in keeping a constant body temperature. Instead, this energy is invested in growth and development and thus, they require less feed to gain mass (Nakagaki and Defoliart 1991). Mealworms produce much less greenhouse gas and require much less land, as compared to livestock production such as cattle, chickens and pigs (Oonincx and De Boer 2012).

The conventional chicken feed ingredients such as fishmeal and soya-bean are expensive sources of protein. According to Mupeta et al. (2003), chicken feed costs account for over 70% of the total production costs. Insects' meal displays a great potential for being a suitable ingredient in animal feeding, because of the high quality of protein (Ramos-Elorduy 1997). Therefore, the objective of this work is to provide practical knowledge on the production of mealworms and create awareness of their nutritional value as sources of protein in poultry diets. It also provides a background on the safety and environmental risk of mealworms as compared to conventional livestock.

## The biology and lifecycle of mealworms

The life cycle of mealworms has four stages: adult darkling beetles lay eggs, tiny larvae emerge from eggs and larval stage begins, the larva turns into pupa before it becomes an adult beetle. The entire process takes place in the same ecosystem. The environmental conditions such as diet, relative humidity, temperature and population density are key factors that contribute to the developmental stages of darkling beetle

mealworm. Figure 1 describes the lifecycle of the mealworm, and the entire cycle can take up to 60 days before a new beetle is born; however, the environmental conditions determine how fast the developmental stages take place.

### Adult darkling beetles

*T. molitor* is a species of the Tenebrionidae family, commonly known as darkling beetles. The adult darkling beetle female lay an average of 400–500 eggs in a substrate at the bottom of the container where they are bred (Spencer and Spencer 2006). The young adult can start oviposition in just 3 days after emerging from the pupa stage (Manojlovic 1987). During the mating period, females produce pheromone 4-methyl-1-nonanol to attract males (Tanaka et al. 1986). According to Pölkki et al. (2012), females are also attracted to odours produced by outbred males, suggesting that inbreeding reduces the desirability of sexual signalling. The adult stage of darkling beetles that emerge as white beetles and gradually darkening is reported to last from 16 to 173 days (Miryam et al. 2000). The duration of adult life is shorter when beetles were exposed at 30 °C as compared to 20 °C or 25 °C respectively (Fiore 1960). The offspring of young beetle parents was reported to have longer adult life than the offspring of adult beetle parents (Tracey 1958).

### Mealworm eggs

The incubation period of eggs varies between periods of 4 days at 26–30 °C and 34 days at 15 °C (Kim et al. 2015). Mealworm eggs have above 70% hatching rate at 17.5 to 27.5 °C; the egg hatching period takes 5–7 days in 25–35 °C. The larvae emerge from the eggs and the larval stage begins. According to Fiore (1960), the weight of the egg and the duration of the egg stage are not affected by the parental age. However, egg hatchability is affected by parental age of mealworm beetle.

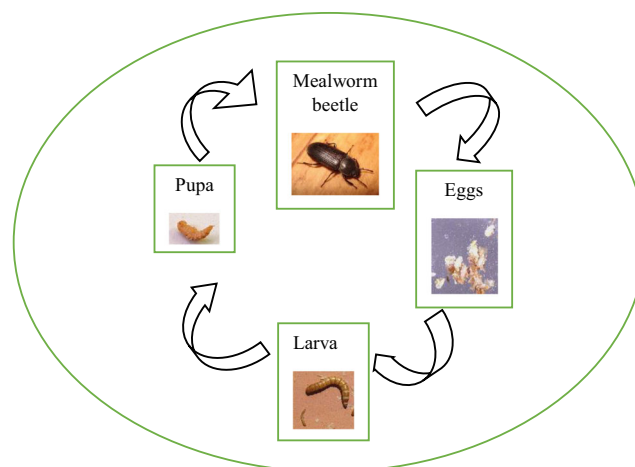


Fig. 1 The lifecycle of the mealworm

## Larvae

The tiny larvae emerge from the eggs and the larval stage begins. According to Park et al. (2014), mealworm larval stage goes through instar stages where the old skin is removed by a new one; the process can take 17 instars before it becomes a pupa. During this process, the body length gradually increases with each successive instar. However, the body length after 17th instar starts to decrease (Park et al. 2014). The length of the larva can be between 12 and 32 mm (Hill 2002; Hardouin and Mahoux 2003). The larvae of the yellow mealworm are white with the first instar; it gradually turns brown after the 2nd instar. After the larval stage, the larvae begin a short period of inactivity gaining a “C” shape before turning into a pupa, the process which is called metamorphosis. A larva is a good source of protein for chickens and other captive animals (Biasato et al. 2016). Larvae from young parents grow faster as compared to larva from old parents (Fiore 1960). However, different results were reported by Tracey (1958) who found that larvae from old parents grow faster than larvae from young parents.

## Pupae

The pupa has no mouth or anus so does not eat; it continuously turns its helpless body. The duration of the pupal stage varies between 6 and 20 days before it becomes a beetle (Kim et al. 2015; Cotton 1927). Therefore, the duration of the pupal stage is not affected by the parental age of mealworm beetle (Tracey 1958).

## Housing requirements for mealworms

*T. molitor* (TM) lives in flour, bran and similar products and is reasonably resistant to dryness; however, it shows different reactions to relative humidity (Pielou and Gunn 1940). The feed conversion efficiency, development and growth of mealworms are affected by diet variability (Van Broekhoven et al. 2015). According to Fraenkel (1950), mealworms require 80 to 85% of carbohydrates; the rate of growth is also influenced by the relative humidity. Mealworm produces the heaviest larvae when grown in a diet containing wheat bran only (Van Zyl and Malan 2015). Adding water to mealworm food may accelerate growth (Fiore 1960). Mealworm larvae grow fastest on 70% relative humidity, slow at 30% and hardly proceeding at 13% relative humidity (Fraenkel 1950). The temperature also contributes on the larval growth. According to Fiore (1960), the maximal larval weight (175 mg) was recorded when the temperature was 30 °C and 100 mg was recorded when the temperature was 20 °C. However, the higher temperature (30 °C) is reported to increase larval moults to 19 (Ludwig 1956). Table 1 shows different factors

**Table 1** Environmental factors for rearing mealworm (*T. molitor* L.)

| Factors           | Adult beetles                                                 | Mealworm eggs | Larvae                                                        | Pupae                 |
|-------------------|---------------------------------------------------------------|---------------|---------------------------------------------------------------|-----------------------|
| Temperature       | 25 °C                                                         | 25–27 °C      | 25–28 °C                                                      | 25–28 °C              |
| Relative humidity | 90–100                                                        | 60–75         | 60–70                                                         | 70–75                 |
| Light             | 12:12 or darkness                                             | Darkness      | 14:10                                                         | Darkness              |
| Diet              | Wheat bran/flour and water source: vegetable (carrot/-potato) | N/A           | Wheat bran/flour and water source: vegetable (carrot/-potato) | N/A (pupa do not eat) |

Source: Temp: Kim et al. (2015), Siemianowska et al. (2013); relative humidity: Hardouin and Mahoux (2003), Manojlovic (1987), Spencer and Spencer (2006), Punzo and Mutchmor (1980); light: Kim et al. (2015), Oonincx et al. (2010); diet: Oonincx et al. (2015), Van Broekhoven et al. (2016)

affecting the growth of *T. molitor*. A 12% relative humidity results in an advanced loss of water from the egg; it will then become dry and result in a loss (Punzo and Mutchmor 1980). Moreover, the development of the embryo is more rapid at 35 °C; it takes only 15 days as compared to 19 days under 25 °C. The egg and larvae are not immune to extreme temperature and relative humidity as compared to the pupa. The pupae are the most resistant developmental stages in the lives of *T. molitor* (Punzo and Mutchmor 1980). According to Berggreen et al. (2018), the highest output of larvae was recorded from beetles that were overpopulated; they seemed not to be affected by that condition. The life cycle of yellow mealworm differs according to the growth stage. The pupae and eggs seem to be fine in a dark cycle period, the larvae require light (14:10) and adult beetles can also be kept in a 12:12 light period or darkness.

## Nutritional value of mealworms

The nutritional composition of mealworms has already been studied extensively (Finke 2002; Ravzanaadii et al. 2012; Bovera et al. 2016; Khan et al. 2017). Nutritional value of mealworms varies depending on species and developmental stage. These worms are rich in protein, fats, essential amino acids, and vitamins or minerals (Rumpold and Schlüter 2013). Insects, in general, contain a higher amount in lysine and threonine which are deficient in most commonly used cereal wheat, rice, cassava and maize but have the lower amount of amino acids, methionine and cysteine (Deforliart 1992). Mealworm larva also contains poor sources of calcium, but rich in phosphorus; nevertheless, the excreta and exuvium components were reported to have the highest elements of

**Table 2** Nutrient profile of dried mealworm larvae from different researchers

| Nutrient composition | Khan et al.<br>(2017) (%)    | Ravzanaadii et al.<br>(2012) (%)         | Hussain et al.<br>(2017) (%)    | Bovera et al.<br>(2015) (%)                 |
|----------------------|------------------------------|------------------------------------------|---------------------------------|---------------------------------------------|
| Crude protein (%)    | 53.0                         | 46.4                                     | 45.8                            | 51.9                                        |
| Crude lipid (%)      | 3.6                          | 32.7                                     | 34.2                            | 21.6                                        |
| Crude fibre (%)      | 3.1                          | 4.6                                      | 4.0                             | 7.2                                         |
| Ash (%)              | 26.8                         | 2.9                                      | 2.5                             | 4.7                                         |
| Moisture             | ND                           | 5.3                                      | 5.8                             | ND                                          |
| Dry matter           | ND                           | ND                                       | ND                              | 93.9                                        |
| Elements             | Khan et al.<br>(2017) (g/kg) | Simon et al.<br>(2013) (g/kg) 1st larvae | Hussain et al.<br>(2017) (g/kg) | Ravzanaadii et al.<br>(2012) (g/kg) samples |
| Sodium (Na)          | ND                           | 65                                       | ND                              | 36.4                                        |
| Calcium (Ca)         | 2.7                          | 7.4                                      | 3.8                             | 4.3                                         |
| Potassium (K)        | ND                           | 14.6                                     | 8.5                             | 9.4                                         |
| Phosphorus (P)       | 7.8                          | 6.5                                      | 7.0                             | 7.1                                         |
| Magnesium (Mg)       | 2.3                          | 1.9                                      | ND                              | 2.0                                         |
| Zinc (Zn)            | 1.2                          | 1.7                                      | 1.0                             | 1.0                                         |

calcium as compared to larva and beetle (Ravzanaadii et al. 2012). Exclusive feeding of mealworm to chickens can cause calcium deficiency and symptomatic metabolic bone disease. Therefore, it is recommended that calcium is supplemented when mealworms are used.

The low calcium content can only be a problem if there is no alternative source of calcium in the diet given in captivity. Mealworms are not the only insects that have a low calcium content, according to Bilby and Widdowson (1971) the calcium content of earthworms is related to calcium level in the soil that they consumed. Nevertheless, *T. molitor* is a very good source of nitrogen. According to Martin et al. (1976), the nitrogen in mealworm is present as D-acetylglucosamine, an amino acid sugar of which chitin is a polymer. It is reported that chitin passes through the alimentary canal of most vertebrate species undigested. Mealworms are not only beneficial to poultry, but they can also be protein source for white shrimp; however, the diet should be supplemented by methionine to meat shrimp amino acid requirements (Panini et al. 2017). It is also reported that body lipid levels of shrimp increased when fed mealworm meal. According to Martin et al. (1976), "Mealworms that were freshly extracted and those that were extracted after storage at -20 °C contain up to one-third of the lipid as free fatty acids." This suggests that mealworms contain a lipase that is activated or not activated by freezing, such changes make it inadvisable to attempt to keep surplus mealworms frozen.

*T. molitor* contains a high amount of protein, fats, amino acids and mineral content; as a result, it can easily be included in the poultry ration (Aguilar-Miranda et al. 2002). It can convert wheat bran into high-quality protein (Makkar et al. 2014). According to Dreyer and Wehmeyer (1982), indigestibility of protein that is in insects is known to be the lower

efficiency of protein conversion product than protein from vertebrate animals. Chitin found in insects reduces the protein digestibility in chickens (Khempaka et al. 2011). Nonetheless, the existence of chitin in insects' meal has the potential to improve poultry health because it decreases populations of intestinal *Escherichia coli* and *Salmonella* spp. it could also increase intestinal *Lactobacillus* spp. Khan et al. (2017) reported that mealworms are the best insect meal option as compared to maggot and silkworm; they improve broiler performance and meat quality. The concentration of elements such as calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), sulphur (S), strontium (Sr) and zinc (Zn) plays a critical role during the metamorphosis stages of mealworms (Simon et al. 2013). The essential inorganic compounds that play a key role in the functioning of cells are Ca, Mg, Na, phosphate and chlorides; therefore, their concentration in the diet of insects is vital (McFarlane 1991). Tables 2, 3 and 4 summarise different concentrations of mealworm composition from different researchers. The large variation in composition may be due to the differences in processing or production method and environmental factors. According to Table 2, the crude protein content of mealworms varies from 45.8 to 51.9% and the calcium content varies from 2.7 to 7.4 g/kg. Table 3 summarises the amino acid profile of mealworms. The amino acid profile can be used to measure protein quality (Bukkens 1997).

Table 5 provides a summary of the different percentages of crude protein from three different types of commonly used poultry feeds: mealworm, soya-bean and fishmeal. According to Bovera et al. (2015), mealworms contain 51.93% of protein with higher protein content than soya-bean (44.51%) and lower than fishmeal which is 60.2%.

**Table 3** Essential amino acids of mealworms from different researchers

| Essential amino acids | Finke (2002) (g/100 g) | Khan et al. (2017) (g/100 g) | Hussain et al. (2017) (g/100 g) | Bovera et al. (2015) (g/100 g) |
|-----------------------|------------------------|------------------------------|---------------------------------|--------------------------------|
| Isoleucine            | 2.5                    | 4.6                          | 4.5                             | 2.6                            |
| Leucine               | 5.2                    | 8.6                          | 5.3                             | 4.5                            |
| Lysine                | 2.7                    | 5.4                          | 4.5                             | 1.7                            |
| Methionine            | 0.6                    | 1.5                          | 1.3                             | 1.6                            |
| Phenylalanine         | 1.7                    | 4.0                          | 1.5                             | ND                             |
| Threonine             | 2.5                    | 4.0                          | 1.6                             | 2.7                            |
| Tryptophan            | 0.4                    | 0.6                          | ND                              | 1.7                            |
| Valine                | 2.9                    | 6.0                          | 4.4                             | 3.7                            |

ND not detected

These results are in line with those of Barker et al. (1998) who reported that the crude protein values of mealworms are between 45 and 68.9%.

### Food safety and carbon emission of mealworms

The demand for animal protein is increasing because of the human population and its nutritional requirements are continuously rising. Therefore, conventional livestock production as one of the factors that are associated with climate change, loss of biodiversity and land degradation need to be addressed at local, national and international level (Steinfeld et al. (2006). Ooninx and de Boer (2012) reported that insects as compared to conventional livestock emit fewer greenhouse gases per unit of growth; they require less space to be produced, can be fully grown on organic by-products and convert it into a protein source.

Microbiological data of edible insect's safety is scarcely available (Vandeweyer et al. 2017); besides, there are few studies available containing microbiological data. Insects are known for many different purposes such as functioning

as vectors that are spreading zoonotic diseases, carry and transmit infective and non-infective micro-organisms. Therefore, for edible insects to be considered as an alternative animal feed or food, one needs to develop and implement operational decontamination measures (Rumpold et al. 2014). The presence of spore-forming bacteria is considered a possible risk of edible insects; unlike enterobacteria, it is difficult to eliminate by using boiling water without any other substance (Klunder et al. 2012). For that reason, a thermal treatment at 90 °C has shown a promising results in terms of reducing the total mealworm microbial count. It has also been reported that starvation and rinsing of mealworm larvae are common procedures used to enhance microbial quality. However, Wynants and Crauwels (2017) reported that starvation and rinsing of mealworm did not show differences in the microbial numbers. Diseases that are caused by insects have been reported, such as seasonal ataxia; the disease is caused by ingestion of roasted larvae of *Anaphe venata* Butler, an alternative protein source consumed in western Nigeria (Moyo et al. 2014). The Codex Alimentarius Commission has developed and adopted the hazard analysis and critical control point system as preventative measures of food safety (CAC/GL 2008).

**Table 4** Fatty acids profile of mealworm from different researchers

| Fatty acids profile | Ravzanaadii et al. (2012) (g/100 g) |         |       | Finke (2002) (g/100 g) dry matter |       | Iaconisi et al. (2017) (g/100 g) |      | Belforti et al. (2015) (g/100 g) dry matter |  |
|---------------------|-------------------------------------|---------|-------|-----------------------------------|-------|----------------------------------|------|---------------------------------------------|--|
| Myristic acid       | 3.05                                | C14:0   | 0.76  | Lip #14:0                         | 2.15  | C14:0                            | 0.51 | C14:0                                       |  |
| Palmitic acid       | 16.72                               | C16:0   | 6.01  | Lipid #16:0                       | 16.69 | C16:0                            | 3.43 | C16:0                                       |  |
| Palmitoleic acid    | 2.67                                | C16:1n7 | 0.92  | Lipid #16:1                       | 1.56  | C17:1n7                          | 0.40 | C16:1                                       |  |
| Stearic acid        | 2.49                                | C18:1n0 | 1.02  | Lipid #18:0                       | 3.46  | C18:0                            | 0.64 | C18:0                                       |  |
| Oleic acid          | 43.17                               | C18:1n9 | 14.15 | Lipid #18:1                       | 31.56 | C18:1n9                          | ND   | ND                                          |  |
| Vaccenic acid       | 0.03                                | C18:1n7 | ND    | ND                                | 0.56  | C18:1n7                          | ND   | ND                                          |  |
| Linoleic acid       | 30.23                               | C18:2n6 | 9.13  | Lipid#18.2                        | 36.42 | C18:2n6                          | 6.97 | C18:2 N6                                    |  |
| γ-Linolenic acid    | 0.05                                | C18:3n6 | 0.37  | Lipid# 18:3                       | 0.09  | C18:4n3                          | ND   | ND                                          |  |
| Linolenic acid      | 1.36                                | C18:3n3 | ND    | ND                                | 2.43  | C18:3n3                          | 0.27 | C18:3n3                                     |  |
| Eicosenoic acid     | 0.24                                | C20:1n9 | ND    | ND                                | 0.39  | C20:1n9                          | 0.31 | C20:0                                       |  |

**Table 5** Comparison of nutritive value of mealworms, soya bean and fishmeal

| Protein sources | Crude protein (%) |
|-----------------|-------------------|
| Mealworm        | 51.93             |
| Soya bean       | 44.51             |
| Fishmeal        | 60.2              |

Source: mealworm and soya bean (Bovera et al. 2015); fishmeal (Wang et al. 2005)

According to a study conducted by Ravzanaadii et al. (2012), a microbiological analysis of mealworm showed that there were no detection of *E. coli* and *Salmonella* spp. in larvae, adult, exovium and excreta. Therefore, the results support the possibility of introducing mealworm in human food consumption or animal feed. However, to support risk assessment strategies, further research information on the infectious micro-organisms and quality of edible insects reared for animal feed are necessary. Many researchers mention the possibility for insects to contain pathogenic microorganism such as *Bacillus cereus*, *Campylobacter* spp., *Clostridium* spp., *Salmonella* spp. and *Staphylococcus aureus* (Crippen et al. 2012). Edible insects harbour a large amount of enterobacterial family containing foodborne pathogens. A study carried out by Roche et al. (2009) found that contaminated lesser mealworm larvae with *Salmonella* have the potential to transmit the pathogen to broilers when ingested as larva or beetle. The microbial load of mealworm can be reduced by heat treatment; this could prohibit the use of antibiotic during the production phase (Grau et al. 2017). The risk assessment of mealworm profile allergenicity is missing (Reckler 2015). A study conducted by Broekman et al. (2015) tested the allergenicity of *T. molitor* by heat processing fresh mealworm; it was found that the high temperature did not lower the allergenicity; however, the solubility of mealworm allergens was changed. Therefore, more studies regarding the allergenicity of mealworm need to be conducted.

According to Ooninx et al. (2010), *T. molitor* larvae do not emit ammonia excretion. Even though little data are available that support the notion that insects produce less greenhouse gas, Ooninx and de Boer (2012) studied the environmental impact of the production of mealworm; it was reported that *T. molitor* as compared to conventional livestock production produces much less greenhouse gas. Livestock production sector approximately produces 15% of anthropogenic greenhouse gas (Steinfeld et al. 2006). The water footprint per ton of beef is 3.5 times higher than that of mealworm (Miglietta et al. 2015).

Mealworm is easy to breed, inexpensive and produce less harmful effects on the environment (Wang et al. 2012). Van Huis (2010) studied the environmental impact of conventional livestock compared to insect production. It is reported that to produce 1 kg of meat, a 7.7-kg feed is required for beef, for sheep an enormous 6.3 kg and 3.6 kg for pork; chickens need

as little as 2.2 kg, and for insects' cricket meal, a slight 1.7 kg of feed is required to produce 1 kg protein. Therefore, insect production seems to be the eco-friendliest species in terms of protein production. According to Biasato et al. (2016), the inclusion of mealworm in poultry diets did not influence the physiological changes, thus suggesting that mealworm can safely be used in chicken diets.

## Impact of including mealworm meal in poultry diets

Free range chickens and wild birds, naturally they consume insects; many researchers have evaluated the feasibility of supplementing poultry diets using insects such as maggot meal or mealworm (Adeniji 2007; Ballitoc and Sun 2013; Bovera et al. 2016; Khan et al. 2018). The impact of mealworms in the diets of birds could be measured in terms of economic aspect, the animal welfare (health and production) or environmental effect. Feeding diet of low nutritive value to poultry results in an increase of intestinal length and intestinal weight (van der Klis and Jansman 2002). When broiler chickens fed 10% mealworm meal, it was found that the small intestine weight increased as compared to other intestinal tracts (Ballitoc and Sun 2013). However, Bovera et al. (2016) reported that the use of mealworm meal in poultry diet had no significant effect on growth performance, blood profile and carcass characteristics. As a result, mealworm meal in poultry diet does not affect the welfare of chickens (Biasato et al. 2016). Therefore, the presence of mealworm as the main protein source in the poultry diet would be the best suitable alternative. Furthermore, a study by Biasato et al. (2017) reported that increasing levels of dietary *T. molitor* meal inclusion in male broiler chickens may improve body weight and feed intake, but negatively affect feed efficiency and intestinal morphology, thus suggesting that low levels may be more suitable. However, no effect on haematochemical parameters, carcass traits and histological findings was observed in relation to *T. molitor* meal utilisation.

*T. molitor* can be included in broiler starter diets without negatively affecting growth rate or showing signs of feed rejection because of palatability issue (Ramos-Elorduy et al. 2002). The potential advantage of using yellow mealworm is the lower conversion rate, thus reducing the overall feeding expense for farmers (Ballitoc and Sun 2013). Mealworm meal has proved to be the most promising diet for many species, not only chickens but aquatic species also, such as catfish, gilthead sea bream, rainbow trout and white shrimp (Ravzanaadii et al. 2012; Belforti et al. 2015; Panini et al. 2017; Piccolo et al. 2017). The larvae of a darkling beetle are also rich in fibre and fatty acids; thus, it improves digestion (Siemianowska et al. 2013). When fermented with probiotics, it can be used as an alternative to antibiotics in the poultry diet

(Islam and Yang 2016). A study conducted by Bovera et al. (2015) found that blood samples of broilers fed mealworm had a lower albumin-to-globulin ratio; therefore, it shows that mealworms have potential in improving the immune response of birds. This could be because of prebiotic effects of chitin.

The haematochemical parameters and carcass traits of female broiler chickens were observed when fed yellow mealworm larvae. It was discovered that when chickens were fed 1 % of ground yellow mealworms, the moisture content in the thigh region was significantly high; this can arguably be considered as good signs of development (Biasato et al. 2017). According to Khan et al. (2017), the meat of chickens fed mealworm was reported to be juicy and tender. Furthermore, it was noted that 10% inclusion of *T. molitor* produces heavier gizzard (Ballitoc and Sun 2013).

It is also important to consider the health of chickens that are fed mealworms, whether there are changes or not. Biasato et al. (2016) recorded a condition score of zero when assessing the footpad of chickens fed mealworm meal; therefore, it suggests that chickens that were fed mealworm at the time of the study did not show signs of footpad dermatitis. Footpad dermatitis is commonly used as a welfare indicator in poultry industry. A further research on assessing how mealworm meal affect footpad of chickens could be beneficial to poultry farmers.

The production cost of mealworm as compared to conventional protein sources such as soya bean meal could be lower (Ramos-Elorduy et al. 2002). Furthermore, mealworm supplementation in poultry diet improves feed utilisation efficiency and growth performance (Hussain et al. 2017). The economic production parameters of mealworms include less space needed, commercial production capability, high conversion efficiency and relative use of organic waste as a food source (Ramos-Elorduy et al. 2002).

## Conclusion

Protein is a vital nutrient in poultry diets; it plays many vital roles such as repairing and maintaining tissues to enable growth and development of organisms (Bondari and Sheppard 1981). Mealworms have demonstrated to be the most reliable, easy to breed insects that are rich in protein and meet the amino acid requirements for livestock. Mealworms are already produced at an industrial scale. Therefore, the same techniques that are used by mealworm commercial farmers can be transferred through the intervention of specialist Agricultural Extension officers (Entomologist) to small-scale poultry farmers. However, a cost-effective production method that would meet the needs of rural poor farmers should be developed. The process can include proper hygiene standard to prevent the spread of diseases. A constant training of poultry farmers and Agricultural

Extension officers and the public at large about the mealworm production is strongly recommended. A new method of gathering, producing and processing mealworms should also be investigated. An automated system should be developed where pupa is immediately separated from the adult beetles and larvae to prevent cannibalism; mealworm excrete automatically removed from the breeding box could improve efficiency in the mealworm breeding facilities.

The broilers brooder house which normally has high temperature and relative humidity should be tested if it can be a suitable environment to raise mealworms. This could help small-scale broiler farmers to reduce transactional costs by carrying out supportive projects simultaneously in the same environment. A study to evaluate the economics of utilising mealworm meal in small-scale poultry farms is also recommended. Furthermore, a consumer's perception about the use of mealworms in small-scale poultry farms should be investigated, whether the use of mealworms will affect sensory perception of consumers and influence their consumption.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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