Mopane Worm

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Fast-growing and highly adaptable avian birds such as quail (Coturnix coturnix) possess great potential to meet the growing demand for animal protein by the rapidly increasing human population, and would contribute immensely to global food production and nutritional security. However, overreliance on conventional protein sources such as fish and soybean meals during the formulation of quail diets is economically and environmentally unsustainable. Alternatively, insect-based protein sources such as Gonimbrasia belina, commonly known as mopane worm (MW), can be used to increase quail production due to their high biological value and low feed-food competition. Indeed, MW is highly nutritious, with an average protein content of 55% and a well-balanced amino acid profile. Thus, its incorporation in quail diets could provide great potential to alleviate nutritional deficiencies in quail production and allow for their sustainable intensification.

Keywords: food security ; insect meal ; mopane worm

1. Introduction

Quail (*Coturnix coturnix*) farming is currently gaining global recognition as a source of high-quality animal protein in the form of meat and eggs [1]. These products can improve human nutrition and contribute towards achieving food and nutritional security as well as achieve the sustainable development goals set by the United Nations [2]. Quail have high adaptability, fast growth rates, strong resistance to avian diseases, and high feed efficiency [3]. They require minimal space for their production, meaning a large flock can be reared even under landless production systems [1][3]. These birds have very short generation intervals, can reach sexual maturity by six weeks of age, and the hens can produce over 100 eggs in their first production cycle [1][2][3][4]. For optimum quail production, high-quality feeds containing high levels of energy and protein should be provided to the birds daily. Unfortunately, these conventional feedstuffs have become unsustainable due to their high market prices and high demand by livestock, humans, and the biofuel sector [2]. Indeed, fish and soybean meals have been strongly criticized for their high market prices [5].

Moreover, soybean production generates high land-use competition and incurs high variable costs due to the use of pesticides, fuel, chemical fertilizers, and machinery at the farm level, which, in turn, contributes to the emission of greenhouse gases that have detrimental effects on the environment [2][5]. These aspects have prompted researchers to look for alternative protein sources, whose production does not affect the environment [6]. The use of already-known insect protein sources (*Musca domestica, Hermetia illucens*, *Bombyx mori*, and *Tenibro molitor*), as well as new and lesser-known alternatives such as the mopane worm (MW) (*Gonimbrasia belina*) can be a worthy solution. Gahukar [7] pointed out that edible insects are renewable natural feed sources that provide nutritional, economic, and ecological benefits. Indeed, several researchers confirmed that insects are essential sources of proteins, amino acids (AA), carbohydrates, lipids, vitamins, and some minerals [8][9]. For instance, caterpillars, to which MW belongs, contain high levels (50–60% dry weight) of highly digestible (77–98%) crude protein [10]. Thus, the utilisation of MW in quail diets can complement both crop and animal food production systems because their production does not rely on the use of arable land and gallons of water [11].

Moreover, the use of insect meals in quail diets is desirable due to better feed conversion efficiency, low greenhouse gas emission, low risk of transmitting zoonotic infections, and low water requirements with little or no animal welfares issues [12]. Due to the high cost of conventional protein sources (fish and soybean meal), several scholars have reported the potential of insect (worm) meals as an alternative protein source in animal feeds [13][14][15]. Notably, the MW has been used as a protein source in Jumbo quail [2], indigenous chicken hens [16], and broilers [17] with good results. However, there is a paucity of information on the use of dietary mopane worm meal (MWM) in various quail breeds.

2. Mopane Worm

Mopane woodlands are found in semi-arid regions of Southern Africa and host one of the most valuable larvae, *G. belina* [18]. Mopane trees grow on nutrient-rich clay soil at a preferred altitude of 300 to 900 m, where they receive an average annual rainfall of 550 mm [19]. Mopane worm is a species of the emperor moth, native to the tropical parts of Southern Africa. Its sizeable and edible caterpillar feeds primarily on mopane tree leaves and, to a lesser extent, on other tree leaves within the mopane woodland [19][20]. The worm is consumed in significant quantities as part of family diets and as a food source in rural areas [19]. However, MW consumption has religious restrictions on a large part of the population in South Africa, making it an ideal protein source for quail. On average, a MW life cycle takes about 4 to 6 weeks and is divided into five growing stages, known as instars [21].

The production of MW involves two generations each year, with outbreaks occurring first in early summer and again in late summer. The males follow chemical pheromones secreted by the females during mating, after which the mated female lays a cluster of 50–200 eggs around twigs and leaves of host plants. The eggs hatch after about 10 days to produce tiny black larvae (caterpillars) [21]. The larvae pass through five stages (instars) during their growth phases; each stage lasting for not more than a week. During instar stages I–III, the caterpillars cluster together in groups of 20–200, whereby they feed on leaves of mopane trees and other trees that grow close to the mopane woodlands [22]. When the larvae pass stage IV, they moult and displace from the unit. At this stage, they are now referred to as mopane worms (caterpillars) and can grow to approximately 80 mm long [21]. During this phase of growth, the MW ceases feeding and begins to descend the tree trunk to burrow through the soil and form pupae. This last stage of growth (instar V) before pupations is the most favourable period for harvesting because the gut does not contain any indigested material [21]. Mopane worms that are harvested undergo a series of separate processing stages. The first stage of processing is to degut the worms. This is done by pushing from the head towards the anus in-between two fingers to remove the undigested material in the gut [23]. The second stage involves boiling the worms in brine for 20–60 min, followed by sun-drying for 2–4 days. These two last steps of processing are essential for removing spines, which extends the shelf life of the worm up to a year [23].

3. Mass Production of Mopane Worms

Successful utilisation of MW as a potential protein source in quail diets would require mass production to maintain a sustainable and continuous supply of the worms [13]. Most insects utilized by man as food or feed exist naturally in the environment, where they are collected. However, to a lesser extent, insects with economic value have been domesticated for commercial production. The concept of insect farming is a relatively a new venture of diversification that encompasses rearing insects in a confined area (i.e., a farm) and controlling their rearing conditions, diet, and food quality. Insects farmed in captivity are isolated from their natural communities [24]. Indoor and/or semi-outdoor insect farming in a monitored or controlled ecosystem ensures successful insect mass production [25]. In addition, commercializing insects of the *Lepidoptera* genus, such as MW and mulberry silkworms, could be an economically viable business because these worms are prolific.

The intensive production of MW to ensure continuous availability has been investigated in Zimbabwe, South Africa, and Botswana [26]. Large-scale, industrial worm production coupled with sustainable worm breeding and processing technology can ease the challenges of worm availability and reduce the selling price of MW [27]. Indoor and semi-outdoor worm production aims to increase production and protect the worms from viral and parasitoid infection. Twigs or leaves that carry eggs should be covered with a white sleeve to protect eggs from parasitoid infections, or eggs can be stored in a white container until they hatch. Gardiner [27] demonstrated that a captive breeding population of MW could be established and sustained for over three years.

4. Sustainability in Harvesting Mopane Worms

Overexploitation is one problem that could limit the efficient utilisation of MW in quail diets. Over-harvesting manifests when there is a food shortage or increased returns from the general sale of the worms [28]. The collection of MW has also increased due to lack of regulations. Consequently, this has increased competition between local people and outsiders at the expense of the lifecycle and sustainability of the worm. Some harvesting practices literally hinder the sustainability of MW production. Destruction of mopane trees by chopping off branches to make the worm reachable, incorrect timing, and a prolonged harvesting period are some practices that hinder the sustainability of MW production. Further, harvesting too many under-aged larvae and harvesting beyond the carrying capacity of the area pose serious threats to the sustainability of MW production. Trampling by harvesters, firewood collection, and litter also hinder MW production [23].

In addition, on-site processing of the worms with fire leads to patches of the veld being burnt, reducing the grazing capacity of the veld. With the existing challenges facing MW production, local and/or traditional regulations may need to be employed. The regulations would monitor caterpillar development and abundance, and the harvesting of giant, more mature worms rather than smaller, young ones. Furthermore, the increased demand for the worm calls for government legislation and permits to control harvesting [22]. The regulations in communal areas may involve managing the number of harvesters, the number and size of MW, and the number of days spent harvesting [29]. Non-harvest areas should also be established as nature reserves, which will serve as sacred and rotational harvesting sites. This is vital since the population of MW not picked in one period would lead to abundance in the next period [30]. It is also essential to recognize property rights, whereby locals will be allowed to manage and control their land, which will help them protect their resources from outside harvesters.

5. Feed Value of Mopane Worm Meal

Achieving a balanced diet for growth and productivity of quail remains one of the most significant challenges in the poultry industry. Therefore, the associated protein source must be characterized by proper AA profiles with high digestibility and good palatability [31]. Moyo et al. [17] reported higher body weight gain in broilers fed with a diet containing 12% MWM than those in the control group. Similarly, indigenous chicken hens fed with a diet containing 18% MWM had increased average daily gains (ADG) with a lower (better) feed conversion ratio (FCR) [16]. A lower FCR points to high feed efficiency [32], which could be attributed to better ingredient combination, digestibility, and absorption of nutrients [33]. Contrary to these results, the feed consumption, ADG, FCR, and dressing percentage of guinea fowls fed with 4.5% MWM did not differ from those fed the control diet [34]. These variations in performance could be attributed to the involvement of different species as well as the age and sex of the birds, which are known to produce different results even when birds are offered the same feed [33].

Increased average weight gain remains one of the tools vital to monitoring the nutritional value of a specific diet and animal growth. Positive results have been reported when insect-based protein meals were used in poultry diets. For example, Radulovic et al. [35] and Pretorius and Pieterse [36] reported an increase in bodyweight gain in chickens fed with *M. domestica* meal and maggot larvae meal, respectively. Similar results were noted by Moyo et al. [17], Moreki et al. [37], Hwangbo et al. [38], and Schiavone et al. [39], where feeding chickens with insect-meal-containing diets improved overall growth performance compared to the control diet. Loponte et al. [40] also observed better feed efficiency and increased body weight in barbary partridges fed with insect (*T. molitor and H. illucens*) larvae meals rather than dietary soybean meal. The excellent nutritional profiles of the insect meals could have prevented nutrient dilution by supplying more of the required nutrients at a time, resulting in moderate feed consumption and increased weight gain with better FCR. This was supported by Hwangbo et al. [38], who concluded that the availability of vital and readily digestible protein in insect meals may explain the reason for better feed utilization.

Moyo et al. [17] observed that inclusion of MWM into chicken diets positively impacts the colour of breast meat, and results in meat pH values between 5.80 and 5.91 at 24 h post-mortem. Meat pH is essential to consider because it determines meat acid accumulation, which affects the colour and water-holding capacity of the meat [41]. Previous studies have shown that the presence of chitin, a fibrous substance in insects, has intrinsic antioxidant properties, with enzymatic reactions that increase the conversion of glycogen into lactic acid, resulting in the decline of pH immediately after slaughter [42]. The ultimate pH is affected by the degree of glycogen reserves in the meat of birds before slaughter. Another vital meat quality trait is meat tenderness, which is affected by diet, sex, strain, age, and the environment [43]. Tenderness is usually increased by post-mortem protein proteolysis, which is followed by the degradation of the myofibrillar protein [44]. Gunya et al. [45] reported a positive influence on breast meat tenderness of birds fed with dietary *Eisenia foetida* worm meal. Likewise, Moyo et al. [17] reported an increase in tenderness (low shear force value) for breast meat of broilers fed with dietary MWM.

Lautenschläger et al. [46] opined that such an effect might be due to the level of protein (53.7%) and fat (23.2%) content found in MWM. Teye et al. [47] reported improved appearance, juiciness, and tenderness of meat due to high dietary fat. Meat juiciness improves the meat texture, which is a function of the quality and composition of fat [48]. As such, MWM is an excellent dietary ingredient that can supply the needed composition and quality of fat. The total unsaturated fatty acid (FA) ratio to total saturated FA in MWM is 54:49, with increased α-linoleic and palmitic acids [49]. The α-linoleic and palmitic FAs are higher in dietary MWM and can be used to cure coronary heart disease and chronic ailments [50]. The ability of MWM to cure coronary heart diseases in humans is an indication that its proposed inclusion into the quail diet will further protect quail egg and meat consumers from such ailments, beyond the protein it offers them.

References

1. Mnisi, C.M.; Mlambo, V. Canola meal as an alternative dietary protein source in quail (Coturnix coturnix) diets A review. Acta Agric. Scand. Sect. A Anim. Sci. 2019, 68, 207–218.

2. Marareni, M.; Mnisi, C.M. Growth performance, serum biochemistry and meat quality traits of Jumbo quails fed with mo pane worm (Imbrasia belina) meal-containing diets. Vet. Anim. Sci. 2020, 10, 100141.
3. Ali, M.A.; Hmar, L.; Devi, L.I.; Prava, M.; Lallianchhunga, M.C.; Tolenkhomba, T.C. Effect of age on the haematological and biochemical profile of Japanese quails (Coturnix coturnix japonica). Int. Multidiscip. Res. J. 2012, 2, 32–35.
4. Mahlake, S.K.; Mnisi, C.M.; Lebopa, C.; Kumanda, C. The effect of green tea (Camellia sinensis) leaf powder on growt h performance, selected hematological indices, carcass characteristics and meat quality parameters of Jumbo quail. Su stainability 2021, 13, 7080.
5. Arru, B.; Furesi, R.; Gasco, L.; Madau, F.A.; Pulina, P. The introduction of insect meal into fish diet: The first economic a nalysis on European sea bass farming. Sustainability 2019, 11, 1697.
6. Van Huis, A. Potential of insects as food and feed in assuring food security. Annu. Rev. Entomol. 2013, 58, 563–583.
7. Gahukar, R.T. Entomophagy and human food security. Int. J. Trop. Insect. Sci. 2011, 31, 129–144.
8. Johnson, D.V. The contribution of edible forest insects to human nutrition and to forest management: Current status an d future potential. In Forest Insects as Food: Humans Bite Back, Proceedings of the a Workshop on Asia-Pacific Resou rces and Their Potential for Development, Chiang Mai, Thailand, 19–21 February 2008; Durst, P.B., Johnson, D.V., Lesl ie, R.N., Shono, K., Eds.; FAO Regional Office for Asia and the Pacific: Bangkok, Thailand, 2010; pp. 5–22.
9. Xiaoming, C.; Ying, F.; Hong, Z. Review of the nutrition value of edible insects. In Forest Insects as Food: Humans Bite Back, Proceedings of the a Workshop on Asia-Pacific Resources and Their Potential for Development, Chiang Mai, Tha iland, 19–21 February 2008; Durst, P.B., Johnson, D.V., Leslie, R.N., Shono, K., Eds.; FAO Regional Office for Asia and the Pacific: Bangkok, Thailand, 2010; pp. 85–92.
10. Kwiri, R.; Winini, C.; Muredzi, P.; Tongonya, J.; Gwala, W.; Mujuru, F.; Gwala, S.T. Mopane worm (Gonimbrasia belina) utilisation, a potential source of protein in fortified blended foods in Zimbabwe. A review. Glob. J. Sci. Front. Res. 2014, 14, 55–67.
11. Cassidy, E.S.; West, P.C.; Gerber, J.S.; Foley, J.A. Redefining agricultural yields: From tonnes to people nourished per hectare. Environ. Res. Lett. 2013, 8, 034015.
12. FAO. Edible Insects’ Future Prospects for Food and Feed Security; Forestry Paper 171; Food and Agriculture Organiza tion of the United Nations: Rome, Italy, 2013; Volume IX, pp. 9–12.
13. Sánchez-Muros, M.J.; Barroso, F.G.; Manzano-Agugliaro, F. Insect meal as renewable source of food for animal feedin g: A review. J. Clean. Prod. 2014, 65, 16–27.
14. Bovera, F.; Loponte, R.; Marono, S.; Piccolo, G.; Parisi, G.; Iaconisi, V.; Gasco, L.; Nizza, A. Use of Tenebrio molitor lar vae meal as protein source in broiler diet: Effect on growth performance, nutrient digestibility, and carcass and meat trai ts. J. Anim. Sci. 2016, 94, 639–647.
15. Dabbou, S.; Gai, F.; Biasato, I.; Capucchio, M.T.; Biasibetti, E.; Dezzutto, D.; Meneguz, M.; Plachà, I.; Gasco, L.; Schia vone, A. Black soldier fly defatted meal as a dietary protein source for broiler chickens: Effects on growth performance, blood traits, gut morphology and histological features. J. Anim. Sci. Biotechnol. 2018, 9, 49.
16. Manyeula, F.; Tsopito, C.; Kamau, J.; Mogotsi, K.K.; Nsoso, S.J.; Moreki, J.C. Effect of Imbrasia belina (westwood), Tyl osema esculentum (Burchell) Schreiber and Vigna subterranean (L.) Verde as protein sources on growth and laying pe rformance of Tswana hens raised under intensive production system. Agric. Adv. 2013, 2, 1–8.
17. Moyo, S.; Masika, P.J.; Muchenje, V.; Jaja, I.F. Effect of Imbrasia belina meal on growth performance, quality characteri stics and sensory attributes of broiler chicken meat. Ital. J. Anim. Sci. 2020, 19, 1450–1461.
18. Timberlake, J.; Chidumayo, E. Miombo Ecoregion Vision Report; Occasional Publications in Biodiversity No. 20; Biodiv ersity Foundation for Africa: Bulawayo, Zimbabwe, 2010; pp. 2–77.
19. Makhado, R.; Potgieter, M.; Timberlake, J.; Gumbo, D. A review of the significance of mopane products to rural peopl e’s livelihoods in southern Africa. Trans. R. Soc. S. Afr. 2014, 69, 117–122.
20. Madibela, O.R.; Seitiso, T.K.; Thema, T.F.; Letso, M. Effect of traditional processing methods on chemical composition a nd in vitro true dry matter digestibility of Mophane worm (Imbrasia belina). J. Arid. Environ. 2007, 68, 492–500.
21. Gondo, T.; Frost, P.; Kozanayi, W.; Stack, J.; Mushongahande, M. Linking knowledge and practice: Assessing options f or sustainable use of mopane worms (Imbrasia belina) in southern Zimbabwe. J. Sustain. Dev. Afr. 2010, 12, 281–305.
22. Dube, S.; Dube, C. Towards improved utilisation of macimbi Imbrasia belina Linnaeus, 1758 as food and financial resou rce for people in the Gwanda district of Zimbabwe. J. Sci. Technol. 2010, 5, 28–36.
23. Thomas, B. Sustainable harvesting and trading of mopane worms (Imbrasia belina) in Northern Namibia: An experienc e from the Uukwaluudhi area. Int. J. Environ. Stud. 2013, 70, 494–502.

24. Van Huis, A.; Van Itterbeeck, J.; Klunder, H.; Mertens, E.; Halloran, A.; Muir, G.; Vantomme, P. Edible Insects: Future Pr ospects for Food and Feed Security; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013.
25. Gahukar, R.T. Edible insects farming: Efficiency and impact on family livelihood, food security, and environment compar ed with livestock and crops. In Insects as Sustainable Food Ingredients; Academic Press: Cambridge, MA, USA, 2016; pp. 85–111.
26. Rapatsa, M.M.; Moyo, N.A.G. Evaluation of Imbrasia belina meal as a fishmeal substitute in Oreochromis mossambicu s diets: Growth performance, histological analysis and enzyme activity. Aquac. Rep. 2017, 5, 18–26.
27. Gardiner, A.J. Internal Final Report: Mopane Woodlands and the Mopane Worm: Enhancing Rural Livelihoods and Res ource Sustainability, DFID Project No. R7822. The Domestication of Mopane Worms (Imbrasia belina); Veld Products R esearch and Development: Gaborone, Botswana, 2003.
28. Hope, R.A.; Frost, P.G.H.; Gardiner, A.; Ghazoul, J. Experimental analysis of adoption of domestic mopane worm farmi ng technology in Zimbabwe. Dev. S. Afr. 2009, 26, 29–46.
29. Mufandaedza, E.; Moyo, D.Z.; Makoni, P. Management of non-timber forest products harvesting: Rules and regulations governing (Imbrasia belina) access in the South-Eastern Lowveld of Zimbabwe. Afr. J. Agric. Res. 2015, 10, 1521–153 0.
30. Akpalu, W.; Muchapondwa, E.; Zikhali, P. Can the Restrictive Harvest Period Policy Conserve Mopane Worms in South ern Africa? A Bio-Economic Modeling Approach. Working Paper. Number 65. University of Pretoria/University of Cape T own/Götenborg University, South Africa. 2007. Available online: https://efdinitiative.org/sites/default/files/wp65.pdf (acce ssed on 9 March 2022).
31. Barrows, F.T.; Bellis, D.; Krogdahl, Å.; Silverstein, J.T.; Herman, E.M.; Sealey, W.M.; Rust, M.B.; Gatlin, D.M. Report of t he plant products in aquafeed strategic planning workshop: An integrated, interdisciplinary research roadmap for increa sing utilisation of plants feedstuffs in diets for carnivorous fish. Rev. Fish. Sci. 2008, 16, 449–455.
32. Haryanto, A.; Miharja, K.; Wijayanti, N. Effects of banana peel meal on the feed conversion ratio and blood lipid profile of broiler chickens. Int. J. Poult. Sci. 2016, 15, 27–34.
33. Oyeagu, C.E.; Mlambo, V.; Muchenje, V. Effect of dietary Aspergillus xylanase on nutrient digestibility and utilization, gr owth performance and size of internal organs in broiler chickens offered maize-soybean meal based-diet. Pak. J. Nutr. 2019, 18, 852–865.
34. Nobo, G.; Moreki, J.C.; Nsoso, S.J. Growth and carcass characteristics of helmeted guinea fowl (Numida meleagris) fe d varying levels of Phane meal (Imbrasia belina) as replacement of fishmeal under intensive system. Int. J. Agro Vet. M ed. Sci. 2012, 6, 296–306.
35. Radulovic, S.; Pavlovic, M.; Sefer, D.; Katoch, S.; Hadzi-Mili, M.; Jovanovic, D.; Grdovic, S.; Markovic, R. Effects of hou sefly larvae (Musca domestica) dehydrated meal on production performances and sensory properties of broiler meat. T hai. J. Vet. Med. 2018, 48, 63–70.
36. Pretorius, Q.; Pieterse, E. The Evaluation of Larvae of Musca domestica (Common House Fly) as Protein Source for Br oiler Production. Ph.D. Thesis, University of Stellenbosch, Stellenbosch, South Africa, 2011.
37. Moreki, J.C.; Tiroesele, B.; Chiripasi, S.C. Prospects of utilizing insects as alternative sources of protein in poultry diets in Botswana: A review. J. Anim. Sci. Adv. 2012, 2, 649–658.
38. Hwangbo, J.; Hong, E.C.; Jang, A.; Kang, H.K.; Oh, J.S.; Kim, B.W.; Park, B.S. Utilisation of house fly-maggots as feed supplement in the production of broiler chickens. J. Environ. Biol. 2009, 30, 609–614.
39. Schiavone, A.; Cullere, M.; De Marco, M. Partial or total replacement of soybean oil by black soldier fly larvae (Hermeti a illucens L.) fat in broiler diets: Effect on growth performances, feed-choice, blood traits. Ital. J. Anim. Sci. 2017, 16, 93 –100.
40. Loponte, R.; Nizza, S.; Bovera, F.; De Riu, N.; Fliegerova, K.; Lombardi, P.; Vassalotti, G.; Mastellone, V.; Nizza, A.; Mo niello, G. Growth performance, blood profiles and carcass traits of Barbary partridge (Alectoris barbara) fed two differen t insect larvae meals (Tenebrio molitor and Hermetia illucens). Res. Vet. Sci. 2017, 115, 183–188.
41. Bahadori, Z.; Esmaielzadeh, L.; Karimi-Torshizi, M.A.; Seidavi, A.; Olivares, J.; Rojas, S.; Salem, A.Z.M.; Khusro, A.L.; Opez, S. The effect of earthworm (Eisenia foetida) meal with vermihumus on growth performance, hematology, immunit y, intestinal microbiota, carcass characteristics, and meat quality of broiler chickens. Livest. Sci. 2017, 202, 74–81.
42. Veldkamp, T.; Duinkerken, G.; Van Huis, A.; Van Lakemond, C.; Ottevanger, E.; Bosch, G.; Boekel, M. Insects as a Sust ainable Feed Ingredient in Pig and Poultry Diets—A Feasibility Study; Wageningen UR Livestock Research: Lelystad, T he Netherland, 2012.
43. Abdulla, R.N.; Mohd Zamri, A.N.; Sabow, A.B.; Kareem, K.Y.; Nurhazirah, S.; Ling, F.H.; Sazili, A.Q.; Loh, C. Physico-ch emical properties of breast muscle in broiler chickens fed probiotics, antibiotics or antibiotic–probiotic mix. J. Appl. Ani

m. Res. 2017, 45, 64–70.

44. Lonergan, E.H.; Zhang, W.; Lonergan, S.M. Biochemistry of postmortem muscle—Lessons on mechanisms of meat tenderization. Meat Sci. 2010, 86, 184–195.
45. Gunya, B.; Muchenje, V.; Masika, P.J. The effect of earthworm Eisenia foetida meal as a protein source on carcass characteristics and physico-chemical attributes of broilers. Pak. J. Nutr. 2019, 18, 657–664.
46. Lautenschläger, T.; Neinhuis, C.; Kikongo, E.; Henle, T.; Forster, A. Impact of different preparations on the nutritional value of the edible caterpillar Imbrasia epimethea from northern Angola. Eur. Food Res. Technol. 2017, 243, 769–778.
47. Teye, G.A.; Baffoe, F.; Teye, M. Effects of Moringa (Moringa oleifera) leaf powder and dawadawa (Parkia biglobosa), on sensory characteristics and nutritional quality of frankfurtertype sausages—A preliminary study. Glob. Adv. Res. J. Agric. Sci. 2013, 2, 29–33.
48. Muchenje, V.; Chimonyo, M.; Dzama, K.; Strydom, P.E.; Ndlovu, T.; Raats, J.G. Relationship between off-flavor descriptors and flavor scores in beef from cattle raised on natural pasture. J. Muscle Foods. 2010, 21, 424–432.
49. Moyo, S.; Masika, P.J.; Muchenje, V. The potential of Imbrasia belina worm as a poultry and fish feed. A review. J. Anim. Feed Sci. 2019, 28, 209–219.
50. Yeboah, S.O.; Mitei, Y.C. Further lipid profiling of the oil from the mophane caterpillar, Imbrasia belina. J. Am. Oil Chem. Soc. 2009, 86, 1047.