Mopane Worm (Gonimbrasia belina Westwood) Meal as a Potential Protein Source for Sustainable Quail Production: A Review

Caven Mguvane Mnisi 1,2,*, Chika Ethelbert Oyeagu 3 and Ozinel Ruzvidzo 4*

1 Department of Animal Science, School of Agricultural Science, North-West University, Mafikeng 2745, South Africa
2 Food Security and Safety Focus Area, Faculty of Natural and Agricultural Science, North-West University, Mafikeng 2745, South Africa
3 Department of Agriculture, Faculty of Applied Science, Cape Peninsula University of Technology, Wellington 7654, South Africa; oyeaguc@cup.ac.za
4 Department of Botany, School of Biological Sciences, North-West University, Mafikeng 2745, South Africa; oziniel.ruzvidzo@nwu.ac.za
* Correspondence: 23257539@nwu.ac.za; Tel.: +27-18-389-2738

Abstract: 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. However, there are limited studies on the effect of partial or complete replacement of conventional protein sources with mopane worm meal (MWM) in quail diets. This paper reviews the nutritional profile and use of the MW as a protein source, as well as its potential future prospects in poultry diets. Finally, we postulate that mass production of this insect-based protein source and its sustainability would be an inventive strategy to develop a profitable quail business.

Keywords: food security; insect meal; mopane worm; protein sources; quail; sustainability

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 [1–4]. 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 authors 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 [13–15]. 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. Thus, this paper seeks to review the utility of MW as a potential source of protein for sustainable quail production. Furthermore, we compare the nutritional composition of MWM to those of other conventional protein sources such as fish and soybean meals. We postulate that mass-rearing MW for use as a protein source in quail diets would be an inventive strategy to improve quail performance, health, and meat quality, and thus usher in a sustainable and profitable quail business.

2. Quail Production and Nutrient Requirements

High-input quail production integrates highly advanced processing units with high-performing birds and electrical machinery [18]. In this system, quail are reared in enclosures without access to the outdoor environment, and feed containing the required nutrients to satisfy their daily requirements must be available ad libitum. Musundire [19] claimed that intensive rearing of poultry aims to establish the optimum temperature and lighting conditions and to manipulate the daytime length to maximize yield. This is in response to the great demand for animal protein in most non-industrialized nations due to their growing urban populations [20]. Nonetheless, sustainable intensification of quail production relies heavily on the protein and energy levels of the feed, which is mostly generated from soybean and maize grains. Indeed, high productivity can be achieved by feeding quail a nutritionally balanced diet designed to meet their nutrient requirements [21].

Like any other poultry bird, quail require a well-balanced diet with highly digestible AA and nitrogen to synthesize non-essential AA [2]. To achieve this, quail diets should be formulated to meet the requirements of AA digestibility instead of crude protein (CP) content [22]. This is mainly because birds generally utilize AA attained from dietary proteins for various structural and protective tissue functions, such as the development of feathers, skin, ligaments, and bone matrix, together with soft tissues including organs and muscles [23]. Therefore, the AA constituent to be used in quail diets must come from a high-quality protein source with highly digestible AA content [24]. Thus, it is worth evaluating MWM as a potential protein source in quail feeds because of its high CP content (54–59%) and an AA profile comparable to those of fish and soybean meals [25]. The MW has notably higher amounts of lysine, methionine, valine, threonine, tryptophan, and phenylalanine than soybeans [26]. According to the National Research Council (NRC) [23],
quail should be reared on a high protein diet with 24% CP during the growing phase and 20% CP in the production phase, as shown in Table 1. However, it is worth noting that these recommended protein levels are suitable for quail that are reared in temperate regions [23].

Table 1. Nutrient requirement (g/kg dry matter) of quail in different production stages.

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Starter and Grower</th>
<th>Breeder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>240</td>
<td>200</td>
</tr>
<tr>
<td>Lysine</td>
<td>13.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Histidine</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Glycine + serine</td>
<td>11.5</td>
<td>11.7</td>
</tr>
<tr>
<td>Arginine</td>
<td>12.5</td>
<td>12.6</td>
</tr>
<tr>
<td>Methionine</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Leucine</td>
<td>16.9</td>
<td>14.2</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>9.8</td>
<td>9.0</td>
</tr>
<tr>
<td>Threonine</td>
<td>10.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Tryptophan</td>
<td>2.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>9.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Phenylalanine + tyrosine</td>
<td>18.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Methionine + cysteine</td>
<td>7.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Valine</td>
<td>9.5</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Sources: National Research Council [23].

3. Mopane Worm

Mopane woodlands are found in semi-arid regions of Southern Africa and host one of the most valuable larvae, _G. belina_ [27]. 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 [28]. 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 [26,28]. The worm is consumed in significant quantities as part of family diets and as a food source in rural areas [28]. 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 [29].

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) [29]. 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 [30]. 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 [29]. 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 indigesed material [29]. 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 [31]. 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 [31].
4. 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 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 [32]. Indoor and/or semi-outdoor insect farming in a monitored or controlled ecosystem ensures successful insect mass production [33]. 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 [34]. 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 [35]. 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 [35] demonstrated that a captive breeding population of MW could be established and sustained for over three years.

5. 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 [36]. 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 [31].

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 [30]. 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 [37]. 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 [38]. 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.

6. Chemical Components of Mopane Larvae

The nutrient content of insect worms such as the MW is comparable to those of fish and soybean meals [39], as indicated in Table 2. The supplemental protein level in poultry diets needs to be considered when working around feed protein sources [13]. The MW contains higher protein, fat, carbohydrate, and mineral contents than chicken and beef meat [38]. The fact that mopane leaves have a high protein content of 50% may explain the
increased protein content of the worm [40]. Moreover, removal of gut contents from the worms improves their protein concentration by 10% [41]. Lautenschläger et al. [42] added that the removal of gut contents creates a relative increase in the remaining protein and fat. Furthermore, Madibela et al. [41] reported changes in acid detergent fibre (ADF), neutral detergent fibre (NDF), and lignin in degutted MW samples.

Table 2. Chemical composition (%) of mopane worm, fish, and soybean meals.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mopane Meal</th>
<th>Reference</th>
<th>Fish Meal</th>
<th>Reference</th>
<th>Soybean Meal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein</td>
<td>55–60 b, c, e, f</td>
<td>65.6</td>
<td>d</td>
<td>40.2–46.9 a, d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>6.8–10.5 b, c, e, f</td>
<td>17.0</td>
<td>d</td>
<td>6.14 d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NDF</td>
<td>28.8 a</td>
<td>5.8</td>
<td>g</td>
<td>14.6 d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADF</td>
<td>17–59.4 b, e, f</td>
<td>0.5</td>
<td>g</td>
<td>9.6 d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADL</td>
<td>5.4</td>
<td>b</td>
<td>0.2</td>
<td>g</td>
<td>1.5 h</td>
<td></td>
</tr>
<tr>
<td>ADIN</td>
<td>0.9</td>
<td>b</td>
<td>4.9</td>
<td>g</td>
<td>2.1 h</td>
<td></td>
</tr>
<tr>
<td>Fat</td>
<td>13.9–16.8 b, c, e, f</td>
<td>13.0</td>
<td>d</td>
<td>18.3–21 a, d</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.1. Protein and Amino Acids in Mopane Worms

Protein is an essential component of the edible MW, as it contains about 30–65% crude protein (CP) on a dry matter basis. However, the quality of protein is determined by its amino acids (AA) and digestibility, given as a percentage of the “ideal” protein [48]. The balance between essential and non-essential AA is vital [13], because imbalanced uptake can cause serious harm to quail growth and production [49]. It is important to note that MWM has an increased content of some essential AA, such as phenylalanine, valine, tryptophan, and threonine, compared to soybean and fish meals [50]. Thus, the supplementation of quail diets with MWM may offer an opportunity to balance and/or enhance the level of essential AA. Some essential AA such as lysine and methionine found in MWM are comparable to those found in fish meal [51]. Table 3 shows that MWM contains all the essential AA needed by quail, which demonstrates that MWM has the potential to replace soybean and fish meals in quail diets. This could reduce the over-reliance on costly fish and soybean meals. However, more studies should be carried out to evaluate the actual protein feed value and the cost-effectiveness of including MWM in quail diets.

Table 3. The essential amino acid profile (g/kg) of mopane worm, fish, and soybean meals.

<table>
<thead>
<tr>
<th>Amino Acid</th>
<th>Mopane Meal</th>
<th>Reference</th>
<th>Fish Meal</th>
<th>Reference</th>
<th>Soybean Meal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Histidine</td>
<td>1.9–3.5 a, b, e</td>
<td>1.6–4.3 a, d</td>
<td>1.5–1.9 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isoleucine</td>
<td>2.6–3.5 a, b, e</td>
<td>2.6–2.7 a, d</td>
<td>2.2–2.6 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leucine</td>
<td>3.8–7.6 a, b, e</td>
<td>4.7–8.4 a, d</td>
<td>3.49–3.5 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lysine</td>
<td>3.8–4.9 a, b, e</td>
<td>5.0–11.1 a, d</td>
<td>2.9–3.1 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methionine</td>
<td>1.6–2.4 a, b, e</td>
<td>1.6–2.5 a, d</td>
<td>0.7–0.9 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>2.5–5.1 a, b, e</td>
<td>2.9–5.52 a, d</td>
<td>2.4–2.6 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threonine</td>
<td>2.7–7.3 a, b, e</td>
<td>2.7–5.4 a, d</td>
<td>1.8–2.0 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tryptophan</td>
<td>0.9–1.4 a, c, e</td>
<td>0.8–1.3 a, d</td>
<td>0.7–0.8 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valine</td>
<td>3.2–4.1 a, b, e</td>
<td>3.22–3.1 a, d</td>
<td>2.3–2.4 a, d</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.2. Mineral Profile of Mopane Worms

Although mineral levels vary across different feed ingredients, the mineral content of the MW mainly depends on its diet [55]. Rapatsa and Moyo [34] reported mineral element levels in MWM that are similar or higher to those in fish or soybean meals, as indicated in Table 4. Furthermore, MWM has high concentrations of sodium, which is due to the salt added during processing. The high iron concentration in MWM can also be attributed
to the iron-rich alkaline soils onto which mopane trees grow [56] and has been reported to be higher than that of plant-based feed sources [39]. Notably, no research to date has identified the type of iron found in insect worms. ‘Haem’ iron, found in animals (animals with blood circulatory systems and haemoglobin), has a higher bioavailability than the other known types of iron. It is absorbed more uniformly in the human body than the ‘non-haem’ iron found in plants [57]. Insects do not have a circulatory system and, therefore, do not use haemoglobin. Thus, their iron availability is, ironically, unknown, although their iron bioavailability is somewhat more similar to that of animals rather than plants [39].

Table 4. Mineral profile (g/kg) of mopane worm, fish, and soybean meals.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mopane Meal</th>
<th>Reference</th>
<th>Fish Meal</th>
<th>Reference</th>
<th>Soybean Meal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>0.8–17</td>
<td>b, d, e</td>
<td>3.8</td>
<td>c</td>
<td>3.14</td>
<td>c</td>
</tr>
<tr>
<td>Iron</td>
<td>11.8–12.9</td>
<td>b, d, e</td>
<td>0.3</td>
<td>c</td>
<td>1.07</td>
<td>f</td>
</tr>
<tr>
<td>Magnesium</td>
<td>4.3–36.3</td>
<td>b, d, e</td>
<td>0.0</td>
<td>c</td>
<td>2.81</td>
<td>c</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.46–14.8</td>
<td>b, d, e</td>
<td>2.7</td>
<td>c</td>
<td>6.59</td>
<td>c</td>
</tr>
<tr>
<td>Potassium</td>
<td>1.2–36.5</td>
<td>b, d, e</td>
<td>0.6</td>
<td>c</td>
<td>19.78</td>
<td>c</td>
</tr>
<tr>
<td>Sodium</td>
<td>26.9–33.5</td>
<td>b, d, e</td>
<td>0.9</td>
<td>c</td>
<td>0.19–0.5</td>
<td>a, c</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.9–2.3</td>
<td>b, d, e</td>
<td>0.0</td>
<td>c</td>
<td>0.12</td>
<td>f</td>
</tr>
</tbody>
</table>

6.3. Fatty Acid Profile of Mopane Worms

There is limited information on the lipid and essential fatty acid requirements for quail. However, MWM has the potential as a lipid source to provide the essential fatty acids required by the birds. For example, the ratio of total unsaturated fatty acid to total saturated fatty acid in MW is 55:48, and its α-Linolenic acid content is comparable to that of fish and soybean meals (Table 5). Furthermore, Yeboah and Mitei [59] reported high concentrations of α-Linolenic and palmitic acids in MWM, which can help alleviate coronary heart disease and chronic ailments. There are several health benefits of having higher unsaturated fatty acids, including their ability to reduce the concentration of low-density lipoprotein (LDL) and cholesterol that cause heart-related diseases, stroke, and other disorders [60]. According to Maitane et al. [61], unsaturated fatty acids stabilize heart rhythms and build stronger cell membranes in the body.

Table 5. Fatty acid composition (g/100 g) of mopane worm, fish, and soybean meals.

<table>
<thead>
<tr>
<th>Fatty Acids</th>
<th>Mopane Meal</th>
<th>Reference</th>
<th>Fish Meal</th>
<th>Reference</th>
<th>Soybean Meal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lauric acid (C12:0)</td>
<td>0.3</td>
<td>c</td>
<td>0.2–0.40</td>
<td>b, d</td>
<td>0.2</td>
<td>d</td>
</tr>
<tr>
<td>Myristic acid (C14:0)</td>
<td>0.2</td>
<td>c</td>
<td>2.7–4.7</td>
<td>b, d</td>
<td>0.2–3.4</td>
<td>a, b, d</td>
</tr>
<tr>
<td>Palmitic acid (C16:0)</td>
<td>5.3</td>
<td>c</td>
<td>2.3–27.5</td>
<td>b, d</td>
<td>12.4–27.3</td>
<td>a, b, d</td>
</tr>
<tr>
<td>Searic acid (C18:0)</td>
<td>1.8</td>
<td>c</td>
<td>21.9–7.3</td>
<td>b, d</td>
<td>3.7–21.2</td>
<td>a, b, d</td>
</tr>
<tr>
<td>Arachidic acid (C20:0)</td>
<td>0.1</td>
<td>c</td>
<td>0.2</td>
<td>d</td>
<td>0.05</td>
<td>a</td>
</tr>
<tr>
<td>Palmitelaidic acid (C16:1)</td>
<td>0.1</td>
<td>c</td>
<td>0.42</td>
<td>b</td>
<td>0.02</td>
<td>d</td>
</tr>
<tr>
<td>α-Linolenic acid (C18:2n6c)</td>
<td>1.5</td>
<td>c</td>
<td>1.4</td>
<td>d</td>
<td>0.7–2.2</td>
<td>a, b</td>
</tr>
<tr>
<td>Linoleic acid (C18:2)</td>
<td>1.7</td>
<td>c</td>
<td>2.58</td>
<td>d</td>
<td>1.6–1.7</td>
<td>a, b, d</td>
</tr>
<tr>
<td>Oleic acid (C18:1n9c)</td>
<td>1.8</td>
<td>c</td>
<td>45.01</td>
<td>d</td>
<td>45.5</td>
<td>d</td>
</tr>
<tr>
<td>SFA</td>
<td>48</td>
<td>c</td>
<td>40.2–52.5</td>
<td>b, d</td>
<td>4.2–53.1</td>
<td>a, b, d</td>
</tr>
<tr>
<td>MUFA</td>
<td>18</td>
<td>c</td>
<td>18.6–45.0</td>
<td>b, d</td>
<td>8.5–45.5</td>
<td>a, b, d</td>
</tr>
<tr>
<td>PUFA</td>
<td>55</td>
<td>c</td>
<td>39.2</td>
<td>b</td>
<td>27.8–46.4</td>
<td>a, b</td>
</tr>
</tbody>
</table>

Reference: a–Van Eys et al. [62]; b–Gümüş [44]; c–Rapatsa and Moyo [34]; d–Romero-Bernal et al. [63]. PUFA–polyunsaturated fatty acid; MUFA–monounsaturated fatty acid; SFA–saturated fatty acid.

7. 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 [64]. 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 [65], which could be attributed to better ingredient combination, digestibility, and absorption of nutrients [66]. 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 [51]. 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 [66].

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. [67] and Pretorius and Pieterus [68] 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. [45], Hwangbo et al. [69], and Schiavone et al. [70], where feeding chickens with insect-meal-containing diets improved overall growth performance compared to the control diet. Loponte et al. [71] 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. [69], 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 [72]. 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 [73]. 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 [74]. Tenderness is usually increased by post-mortem protein proteolysis, which is followed by the degradation of the myofibrillar protein [75]. Gunya et al. [76] reported a positive influence on breast meat tenderness of birds fed with dietary *Eisenia fetida* 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. The authors attributed the improvements in meat tenderness to rigour resolution due to the enzymatic breakdown of collagen that keeps meat fibres together.

Lautenschläger et al. [42] 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. [77] 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 [78]. 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 [79]. The α-linoleic and palmitic FAs are higher in dietary MWM and can be used to cure coronary heart disease and chronic ailments [59]. 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.
8. Prospects and Conclusions

The continued over-reliance on soybean and fish proteins by feed compounders is unsustainable for large-scale quail intensification. MWM has the potential to be used as an alternative due to its intrinsic nutritional qualities such as high concentrations of protein, amino acids, fatty acids, and minerals, which are precursors of better poultry performance. Furthermore, MWM is an ideal protein source because its production requires no chemicals, less water and land, and has a lower carbon footprint. Mopane worms are overexploited during harvesting, and, as such, there is a need to enforce regulatory laws to sustain their production. Moreover, the possible use of MW in quail diets has not been thoroughly studied, with attention mostly directed to chickens. Thus, it is necessary to study the impact of dietary MWM on the performance, health, and meat and egg quality of quail. Further studies are required to ascertain the probable usefulness and cost-effectiveness of MWM as an alternative protein source on quail performance, health, and quality of meat and eggs.

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