

# Sustainable Mealworm Farming: A Circular Approach to Food Production

Mohan Kumar G<sup>1</sup>, Kungumapriya R<sup>2\*</sup>

<sup>1</sup>Research Scholar, Department of Zoology, Pachaiyappa's College, Chetpet, Chennai-600 030, India

<sup>2\*</sup>Assistant Professor, Department of Zoology, Pachaiyappa's College, Chetpet, Chennai-600 030, India

Orcid ID: <sup>1</sup>0009-0001-2500-592X, <sup>2\*</sup>0009-0004-1995-8195

<sup>1</sup>mohanph.d2022@gmail.com, <sup>2\*</sup>drkungumapriya@gmail.com

---

## Abstract

The rising food needs of our growing population need better methods for making food in a safe way and caring for food waste properly. The yellow mealworm (*Tenebrio molitor*) serves as an excellent example which transforms biodiverse waste into protein-storage while delivering considerable protein content together with essential dietary components. The conversion of various organic waste by mealworms into vital circular bio-economy products happens through waste management of agro-industries and food waste operations. Yellow mealworm serves as an advantageous biological component because it maintains optimal production conditions and forms food items and animal feed through waste biological conversion processes. The nutritional significance of mealworm substances stems from the presence of vitamins and fatty acids and essential minerals which enhance human diet foods and animal feeds. Frass obtained from worms proves beneficial in improving soil as a fertilizer. A research-based sustainable mealworm farm needs ongoing development of feed management systems which preserve microbial safety while maximizing output volume. The research demonstrates that mealworms work as sustainable food system materials because their waste management converts proteins into valuable products that simultaneously protect natural environments.

*Keywords:* *Tenebrio molitor*, sustainable development, environment, waste-management, and bio-economy.

---

## INTRODUCTION

The expanding human population worldwide produces overwhelming stress on food availability together with resource infrastructure which requires immediate sustainable actions. Agricultural innovations should unite efficient natural resource management with new technological solutions and different food production methods (Makkar *et al.*, 2014). These approaches fail to fulfill the rising global food requirements particularly because of the lack of protein supply. The growing world population requires protein sources the food industry seeks to discover since this development will provide food security to consumers while minimizing food production's environmental damage. The world faces an important international issue concerning excessive food waste distribution. The substantial amount of annual food waste reaches 1.3 billion tons per year and accounts for 13.8 percent of the global food output thus urging scientists to find new ways of reducing food waste level. Different collective actions together create positive effects to achieve sustainable food security and future (Amicarelli *et al.*, 2021).

Comparatively, insects use greater feed conversion efficiency, need substantially less area than conventional cattle, reproduce much shorter time, and emit fewer greenhouse gases (Oonincx and De Boer, 2012). Besides, insects are nutrient- and energy-dense foods that contain fat, protein, vitamins, and minerals with bioavailability of essential amino acids. In addition, the latest studies have led to increasing interest in using insects as circular food products. Dealer *et al.* (2021) mention several clear and apparent sources for the rising importance of insects in CE. Insects have all the potential to help solve the food waste/food loss puzzle by efficiently converting organic matter to proteins. Besides, insects can help to diversify human and animal diets because they contain high amounts of nutrients. They are an alternative source of nutrients because they can convert organic residues and manure to helpful biomass.

Feeding the environment is a significant issue worldwide; fruits and vegetables are among the most wasted of these substances. Fifty-five percent of the waste is disposed of in landfills, where approximately 1.3 billion tons of food waste are produced yearly, of which fruits and vegetables contribute about 45%. This remains an environmental problem and, foremost, a failure to address the topic of food scarcity. Introducing mealworms to cater to fruit and vegetable wastage is another ingenious idea that has proven

to decrease wastage and minimize its production by providing improved food production strategies. Reducing food waste here can come hand in hand with encouraging and informing people about safe food consumption and strengthening the food system. To increase the feasibility of this solution, efforts should be made to build educational programs, contribute to local undertakings, and invest in research. Greenhouse gas emissions from the decomposition of fruit and vegetable waste far exceed emissions from mealworm farming. Moreover, fermentation of 1 ton of food waste deposited in a landfill can produce between 400 to 500 kg of CO<sub>2</sub> equivalent. At the same time, using mealworms to process an equivalent amount of waste will produce significantly fewer GHG emissions. Namely, CO<sub>2</sub> equivalent emissions range from 2.7 to 4.1 kg/kg of produced mealworms. This evidence indicates the viability of incorporating the yellow mealworm into agro waste and particularly into the processing of fruit and vegetable waste to reduce the emission of GHG significantly. Such an action diffuses waste away from landfills while at the same time promoting the conversion of the waste to valuable proteins, all this without necessarily having negative consequences on the environment (Oonincx *et al.*, 2010; Van Huis, 2013).

Insects are increasingly exhibited as potential functional foods reported high protein-rich than those found in plant-based sources. Species such as wax worms, locusts, black soldier flies, yellow bran worms, has showed to alter a low-protein diet to produce high protein biomass (Ng WK *et al.*, 2002). Among these, the yellow mealworm, (*Tenebrio molitor* L.; Coleoptera: Tenebrionidae) emerges as the most suitable insect species for large-scale industrial manufacture. The farming industry produces *Tenebrio molitor* larvae as livestock feed for fishes along with others including reptiles and birds and small pets (Van Huis 2013; Huis *et al.* 2013). The protein-producing ability of mealworms differs from other insect species as they excel through their swift life stage duration and fast growth speed as well as their high reproduction rates. A female *Tenebrio molitor* produces approximately 160 eggs throughout her existence while her eggs quickly develop thus lowering demands on environmental resources (Oonincx and De Boer, 2012).

Feeding the system with mealworms using agro-waste high in moisture and possessing high liquid content is also challenging. This can be done by subjecting the waste to processing to enhance it to a form conducive to consumption by the mentioned (Musembi *et al.*, 2024). According to the study, debarking, drying, or aggregating the agro waste with other materials can reduce its moisture level enough to ensure the safe feeding of mealworms. Air drying or mechanical dehydrating dried the excreta to a required level and retained nutrient contents for the subsequent growth of mealworms. Dried fruit peels or spent grains can also be added to preprocessed agro-wastes to increase the protein level of the larval diet and to improve the yield of mealworm protein, but without the risk of pathogenic growth (Moruzzo *et al.*, 2021). Also, the proposed system of utilizing agro-waste for mealworm rearing minimizes food wastage and has economic implications. To a certain extent, this characteristic of mealworms meets the objectives of the circular economy and sustainable farming (Kotsou *et al.*, 2024). This review points out that transforming agro-waste into a better feed and managing pathogen risks will positively aid in achieving high protein yield and generate better survival rates for the mealworm.

#### **Mealworm lifecycle**

*Tenebrio molitor* known scientifically as yellow mealworms experiences complete metamorphosis through successive life cycle stages of egg followed by larva then pupa finally leading to adulthood. The mating process allows female darkling beetles to produce up to 500 adhesive eggs which forms bean-shaped structure. The eggs incubate into larvae after a time span of 4 to 8 weeks which depends on the nature of environmental factors. Newly born yellow mealworm larvae possess a brown hue with dimensions of 0.12 inches. The developmental stage comprises the consumption of decaying plants along with dead insects combined with multiple molts reaching between 10 to 20 stages of development. The larvae complete their transformation into pupae during 3 to 30 days although the period depends on environmental factors like temperature and humidity. Ludwig *et al.* (1960) reported during the pupal stage of beetle, develops its wings and legs but its wings will remain unusable while flight is impossible. The lifespan of adult beetles extends from 3 to 6 months at a length that falls between 0.49 to 0.71 inches

#### **Nutritional benefits of mealworms**

Mealworms (TM) are gradually recognized as a profitable and efficient human and animal food product because of their high protein, vitamin, and mineral content. In discovering the thought-provoking features that feed mealworms may have and their capability to be an efficient source of animal protein. The present article seeks to discuss mealworms as a nutritious food source, along with current scientific information on the makeup of mealworms, the potential health benefits, and the viability of mealworms as an increasingly popular food category.

#### **Protein-Rich Source**

Houben *et al.* (2020) recounted that mealworms possess one of the highest protein levels, and mealworm protein profiles range from 46 to 55% of dry matter. This protein is also free of unsaturated bonds and videos, all nine essential dietary amino acids for human and animal necessities. It is equivalent to other superior food materials such as beef, chicken, and fish. It was also observed that the protein in mealworms has bioactive profiles, whereby some peptides showed antimicrobial, antioxidant, and immunomodulatory effects. Such peptides can elevate immune response, reduce susceptibility to infections, and be a natural substitute for antibiotic growth promoters, particularly for animals. For instance, bioactive peptides obtained from mealworms can inhibit bacteria such as *E.coli* and *Salmonella* spp. Optimally, synthetic antibiotics should be minimized for use in livestock farming. Moreover, the results showed that the mealworm protein could reduce the incidence factors of heart disease by suppressing some enzymes, such as ACE, which regulate blood pressure.

#### **Healthy Fats**

The nutritional content of insects contains abundant health-promoting fats that include PUFAs and MUFAs according to Mariod (2020). Eating saturated fats and trans fats offers cardiovascular benefits because they lower LDL cholesterol while raising HDL cholesterol levels. Linoleic acid represents one of the crucial fatty acids contained in mealworms because it preserves cellular lipids while supporting skin health and serves as a component for inflammation responses. According to Berggren *et al.* (2019) mealworm presents superior lipid composition in comparison to traditional livestock fats. The nutritional value of mealworm resembles how supplemental fish and plant oils would enhance healthy fats within a dish.

#### **Micronutrients**

It earns the names 'the human diet,' 'the poor man's food,' or the 'man of the soil' food because several researchers have also revealed that mealworms are rich in micronutrients that are vital for a wide range of physiological processes in the human body. They are a good source of iron, which is necessary for oxygen transportation and energy production. In composition, the mealworms contain nearly 10% protein, about four times the quantity in vegetables, and richness in iron, closely resembling red meat, making them suitable for people with anemia or those prone to iron weakness. On the same note, mealworms are a rich source of zinc in the same percentage as other animal meat, which is very rich in DNA synthesis and immunity boosting. Also, the availability of Magnesium and Potassium in the mealworm adds nutritional value to the mealworm as the two minerals vital in muscular contraction, neuronal signal transmission, and blood pressure regulation, respectively. Besides these base minerals, they are equally rich in vitamin B12, which is used in the health of our nerves and is essential in DNA synthesis. These things hint at the possibility of mealworms being a valuable substitute for people who choose plant-based diets with low access to elemental nutrients, in this case - B12 (Mariod 2020).

#### **Fiber and Chitin**

The mealworms have chitin fiber in their body cover. Though chitin is not digested in humans, it has some positive effects on the gut and enhances the growth of good bacteria, thus making it suitable for the gut. However, chitin has demonstrated capability as a cholesterol modulator and improves immunity. However, further investigation is necessary to reveal more about the therapeutic values of such an approach (Jankauskienė *et al.*, 2024).

#### **Sustainability of Mealworms**

Jeon *et al.* (2016) expanded their previous findings to include additional information about both nutritional value and sustainability of mealworms as food. When measured against the production of

protein the amount of space water and feed required by mealworm farming remains significantly lower than what pigs and cattle and poultry businesses need. The production of mealworms as food results in decreased emissions of greenhouse gases which exceeds regular meat products in environmental friendliness. The nutritious protein produced by mealworms results from their ingestion of kitchen waste organic material while avoiding both waste generation and environmental damage. Urban areas can implement large-scale mealworm farming because their farms operate using vertical farming methods which minimize demands on agricultural land. Research indicates that mealworms transform feed into protein at better efficiency levels compared to conventional fish feed sources mainly based on grain and water. The food-scarcity areas obtain valuable significance from this efficiency because mealworms could serve as an accessible localized nutrient-dense food source.

#### **Enhancing animal health:**

In a simple breakdown of the food value per 100 g, Rumpold and Schlüter (2013) explained the nutritional value of the mealworms in a way that was not exclusive to human consumption. The effectiveness of the feed constituents was pointed out for feeding livestock, poultry, and fish. In particular, the availability of mealworms as a high protein replacement for regular feeds for animals, including soy and fish, can considerably enhance the growth and health of farm animals. Many types of research have proved that animals fed on mealworm-based diets experience increased growth, immune responses, and overall health. In addition, the facts confirmed that if the consumed proteins are of mealworm origin, then the indicated bioactive compounds can reduce the need for antibiotics in animal farming, enhancing sustainable agriculture.

#### **Safety and Allergenicity**

In addition, the fact that, as a kind of food, they contain valuable nutrients should be stressed, but at the same time, possible concerns for safety measures should also be noted. Another important factor to acknowledge is the dietary allergenicity of these insects, which is owing to their phylogenetic kinship with allergenic food products such as shrimp and lobster. Current research is directed toward establishing the extent and seriousness of the civilized's allergy to mealworms. Moreover, there is a thrust for the formulation of food safety regulations to ensure that mealworms are produced and prepared safely and cleanly, minimizing the possible presence of contaminants that are dangerous to human consumption. Since the demand for edible insects is rising, it is essential to look after the quality of the soy mealworm products to adopt it. Mealworms are an option food source that is favorable for humans and animals and can be easily farmed. These include ingredients such as proteins, health and essential body fats, vitamins, and minerals, as well as the low impact on our environment compared to traditional animal proteins. Ongoing studies on mealworms' macronutrient and safety profile suggest that this food could go a long way in solving multiple food crises that threaten global food security, not to mention its role in improving more modern and efficient farming practices (Finke, 2002).

Kotsou et al. (2024) stressed the advantages of mealworm farming through their observations about utilizing agro-waste combined with organic co-products as feed. Traditional livestock needs specific high-value diets but mealworms efficiently convert various waste materials including fermented grains and fruit and vegetable scraps into consumption sources. This efficient utilization results in both lower nutritional expenses and reduced organic waste amounts through transforming unused organic materials into protein products. The transmission of zoonotic diseases through mealworms presents less risk for animal feed manufacturing than raising traditional livestock thereby making insect farming a safe animal feed production method. The speedy generation development of mealworms should receive priority since they reproduce quickly due to their shorter life cycle in comparison to pigs and cattle. Fast-growing conditions allow the development of dependable sustainable animal protein production systems which will suffice demand increases in the global animal protein market. The ethical issue of animal mistreatment in substantial livestock operations ceases to exist within insect farming thereby permitting manufacturers and consumers worldwide to choose mealworms for their protein requirements. The characteristics of mealworms establish them as beneficial, nutritious, low-cost protein sources for animal feed to decrease animal farming risks. Through harnessing mealworms into protein supplies the practice minimizes waste materials which otherwise persist within the market.

### **Waste Management in Mealworm Cultivation**

Mealworm farming for waste management has gained significant public attention because the mealworm (TM) ranks highest in its efficiency in recycling organic waste products into valuable products, including protein feed, chitin, and bio-fertilizers. These biological processes give them a unique solution to reduce the effects of pollution on the environment and produce sustainable outputs. Therefore, this paper aims to provide a detailed analysis of waste management using mealworms.

### **Organic Waste Bioconversion**

The nutritional needs of mealworms are fulfilled through organic waste processing that leads to fertility products and protein production. The worms have eaten organic waste materials including agricultural produce remains along with food garbage and human waste. The supplementary growth of mealworms underwent research by Liu et al. (2020) after the researchers added vegetable waste material to their diets. The investigators revealed the potential applications of this substance because it functions both as animal feed protein and raw material for chitin production. The authors reported that through mealworm integration organic waste quantity could be minimized by percentages ranging from 60 percent to 80 percent based on the particular waste composition. The practice shows potential to reduce waste in organic materials while producing circular animal feed for agricultural cycling.

### **Mineral Nutrient Recycling and Manufacture of Chemical Fertilizers**

The biomass rich in proteins is mealworm frass which serves as excrement and represents a relatively new organic manure element. Plant fertilization requires Frass as an effective fertilizer because it contains Nitrogen, phosphorus and potassium (NPK). Niu et al. (2021) demonstrated in their study that facilities using mealworms boost agricultural field soil fertility along with enhanced properties of chemical composition and physical aspects. The waste products of mealworm culture are composed of their droppings along with their discarded exoskeletons. Research confirmed that Frass from standardized mealworms contains beneficial elements that promote soil growth and carbon sequestering abilities when applied to the ground. The conversion of dinner tea waste into biofertilizer increases their contribution to sustainable waste management since they become a usable product supporting agricultural sustainability.

### **Waste-to-Protein Conversion**

The protein content of mealworms demonstrates value as food commodities because it helps secure both food needs and national stability. Other species use these worms as animal feed while humans occasionally eat them. Research demonstrates the capacity of mealworms to function in biological waste processing because they convert ordinary waste into protein. The study conducted by Ravzanaadii et al. (2012) measured the proximate composition and nutrient content of mealworms through which researchers learned these insects contained essential amino acids on par with fishmeal and solid proteins. Organic waste-fed mealworms represent an ecological alternative protein feed in animal diets thus becoming suitable for replacing protein sources that generate significant environmental influence. We start with the idea of transforming residual items into protein-based products. Such protein transformation plays two simultaneous roles by decreasing landfill waste while minimizing environmental hazards associated with conventional protein foods. Isolation of chitin from the mealworm outer shells. Among the possible rewards of growing mealworms stands chitin which exists as the protective structure outside the larvae. The agricultural and pharmaceutical sectors along with water treatment systems utilize chitin and chitosan as versatile materials. The main purpose of Guo et al. (2021) throughout their research involved extracting chitin from mealworms. The study authors confirmed that high-purity chitin derived from mealworms demonstrates capability in water pollution cleanup by extracting heavy metals. The extraction along with chitin demonstrates another profitable aspect for mealworm farming that helps waste management operations. Chitin research focused on creating biodegradable plastics as it serves to increase waste minimization processes while contributing to the development of bio-based circular economies.

Sustainable waste management through mealworm culture:

However, several challenges associated with the cultivation of mealworms may affect the use of this species in waste management. These are increasing the waste-to-biomass conversion efficiency, avoiding the accumulation of wastes, contaminants, or pathogens in the mass-rearing systems of mealworms, and

enhancing commercial production. Enhancement of plastic degradation by mealworms by modifying either the gut microbiome or even genetically to degrade Plastics at a faster rate and using mealworms to investigate digestion of other kinds of hard-to-break-down trash. Establish large-scale production platforms for the bio generation of valuable co-products that will convert organic waste streams and interface with different waste streams and agricultural production systems. Research on the growth of the mealworm has pointed out areas on how waste management can be made sustainable. These capabilities of breaking plastic, converting organic waste into protein sources, and generating additional high tonics such as chitin and biofertilizers make them inevitable components of future waste management systems. If large industries adopted these three practices of mealworm cultivation and consumption, it would only be possible to decrease the environmental impact and enhance the circular economy.

Nutritional and economic potential of mealworms in sustainable food system:

The chemical composition within vegetable and fruit waste favors the development of mealworms by improving their growth and biomass. The research determined that materials consisting of carbohydrates and proteins at medium levels generate optimal growth speeds using moderate amounts of produced gases (Rumpold and Schlüter, 2013). Makkar et al. (2014) validated that potato peel or carrot scrap vegetable waste which is readily accessible serves as a standardized dietary requirement for larval development. The growth of mealworms in limewater residues can be supported by additional nitrogen supplementation according to Oonincx et al. (2015). Research shows that mealworms fed a varied diet of various waste types will produce biomass with better protein and fat content suitable as protein sources (You et al., 2015). The development timing of mealworms differs based on what raw waste items they consume as a food source. The research from van et al. (2013) demonstrated that mealworms fed apple and potato waste demonstrated better health than those eating grain-based diets since they exhibited increased speed of growth together with extended larval development and reduced larval duration. Growth efficiency benefits highly from creating supportive environmental factors which include maintaining a temperature at 27°C while maintaining a relative humidity of 60%. The life cycle of mealworms becomes shorter when operated at best conditions thus boosting bioconversion efficiency.

Through mealworms study, they are seen to help increase the efficiency of organic waste to biomass conversion. You et al. (2015) classified the mealworm biomass as resource-efficient because 1 kg of vegetable waste can produce 0.3 food kg of the worms. That not only decreases the amount of organic waste but also brings back many nutrients to the system of an ecosystem. As a result, mealworm bioconversion entails considerably reduced cases of greenhouse gas emissions compared to such strategies as composting or landfilling (Bautista et al., 2019). Another factor of sustainable food production is methane and carbon dioxide emissions, which are relatively low given the investment in mealworm rearing. Nonetheless, several constraints must be met to ensure a more efficient bioconversion of wastes into valuable products for a more elaborate advancement of mealworms as waste-managing insects. There is a degree of cross-sensitivity to the growth rates due to the variability in the composition and quality of the vegetable and fruit waste fed to the fungus (Van Broekhoven et al., 2013). Science has helped solve these problems by including other ingredients, such as extra proteins or minerals in the wastes, which act as the food source for larvae (Park et al., 2017).

#### **Diverse Waste Substrates for Mealworms**

Organic waste substrates are characterized by different qualities in terms of nutrient composition, moisture, and possible contamination when serving as a diet for mealworms. Some of the frequently used substrates are Food waste (kitchen residues, vegetable/fruit peels, used bakeries), agri-waste (bran, rice hulls, straws, and many others), Brewery and coffee residuals, milch animal droppings, compost, and Blended waste, where there is a combination of all the above with proper distribution of nutritive value. Many nutrients that are present in food waste substrates make provision for optimum growth for mealworms. In a study done by Musembi et al. (2024), The authors thought that the biomass of mealworms that received the mixed food waste had a higher value than those reared on a single source of substrate in the experiment, pointing to the fact that growth could be optimized. This assures that mealworms need proteins, fats, and carbohydrates essential to their growth and development. Thus, high-fiber agricultural byproducts such as wheat bran may enhance the growth rates provided it combines

the right proportion of protein and fat unless the fiber depresses the growth more than it stimulates without additional nutrient support, which has been observed by Møller *et al.* (2021). For example, Brewery spent grain is reported to provide reasonable growth rates, and critters effectively feed on it, as Oonincx *et al.* (2019) reported.

The growth of IML can be sustained by properly controlling either residual alcohol or the byproducts accumulated during the processing stage. According to research the survival rates reach a significant level with properly balanced food waste substrates which confirms the importance of different nutrients for mealworm survival. Using manure-based substrates in agriculture leads to complications since ammonia concentrations are off scales while pathogens might exist. Dossey *et al.* (2016) state that both composting methods and substrate treatment procedures regulate basic safety risks which makes it possible to use manure-based substrates for mealworm cultivation. High survival rates exist in brewery-spent grains waste but practitioners must manage antinutritional factors and substrate moisture content in these types of industrial substrates. According to Evans *et al.* (2015) both a wide range of nutritious food ingredients and their availability simultaneously boost mealworm reproduction and extend their lifespan. The reproductive ability and life expectancy of mealworms fed with food can reach its peak when they have access to different nutrient sources.

In particular, mealworms from generation or culture on protein-rich substrates-devoured wastes or spent grains are generally observed to inculcate a higher protein component than their conventional counterparts, improving their worth as a protein source. Desirable fat profiles in the substrates contribute to the mealworms' proportional fat deposition, which is essential for their energy storage and well-being. Oonincx *et al.* (2015) similarly showed how substrate content can be changed to control the feeding profile of mealworms for purposes of animal feed and consumption by humans. Different microbial contents affect the health of the mealworm in its substrate in various ways, and substrates containing hazardous pathogens can result in infections that consequently decrease health. Dossey *et al.* (2016) are also right to stress substrate sanitation to avert illnesses in mealworm colonies. Some wastes may contain pollutants such as heavy metals that can be toxic to the mealworms. When raised on contaminated substrates, mealworms display signs of stress and diminished health, making it necessary to choose and process wastes appropriately. In addition to improving waste recycling, using organic waste in the rearing of mealworms decreases the environmental impact of insect production. Green *et al.* (2015) performed a life cycle assessment that proved that mealworm production using waste substrates reduces the emission of greenhouse gases and the utilization of resources compared to conventional protein sources.

#### Environmental impact of mealworm

Insects for human food and animal feed have numerous advantages in as much as the effects of their presence on the environment. This can be attributed to lower emissions of greenhouse gases and ammonia, low demands for water and land, and the ability to utilize organic side streams into valuable commodities. Thus, the effects mentioned above should inform the required assessment since insect production may impact the environment directly and indirectly. This accountability is best done by a life cycle assessment (LCA). Most works used the attributional LCA approach based on mealworms, where only one product life cycle is considered. Therefore, both the feed type and the assessment modeling played a key role in configuring the environmental impact of insects. The flows and frequencies of by-products, the substitutability of by-products, and waste scenarios determined the ecological implications of food processing by-products, food waste, and manure (Van *et al.*, 2021).

The mealworms are a rich source of protein with an abundance of essential amino acids that are part of proteins and thus can be used as substitute feed for livestock, poultry, cattle, and fish. The research shows that mealworms are leveled off in a feed conversion ratio much lower than livestock and needs much less space, water, and feed to yield the same proteins. However, the research of Oonincx *et al.* (2010) shows that mealworms occur more favorable in the emission of greenhouse gases and are relatively efficient in occupying land and energy to become a better option. This is so especially with everyday discovery showing that normal meat production is detrimental to the environment; there is a need for tasty protein sources. However, mealworms can consume various species of organic waste, including agricultural residues and some plastics, including polystyrene, as discussed by Yang *et al.* Such capability, however, puts mealworms

in a crucial position in performing waste disposal and ecological rehabilitation functions. By processing organic waste products to obtain high protein biomass, these mealworms help solve the waste problem while supplying proper feed to livestock, aquaculture, and pet industries. In addition, the scientific literature has investigated the possible application of insect mealworms in animal nutrition in detail. The consumption of mealworm meals has been considered a replacement for fishmeal and soybean meals for poultry and fish-feeding programs. Makkar *et al.* (2014) have also identified the potential application of *C. lunula* as a protein source for fish and poultry diets: mealworm larvae are highly nutritious and increase the growth rate of animals. This substitution may decrease the utilization of heavily depleted sea products and large-scale monocultural crop production like soybeans, significantly impacting the environment.

As the newly awakening global market for edible insects appears ready for a meal, so does it look ready to be served a dish of mealworms. Research such as van Huis (2013) shows the potential of the mealworm in provisions, specifically, the skeletal composition, which boasts of vitamins and minerals as well as healthy fats. The use of insect-derived protein in processed foods, protein bars, and flour has gained popularity across various markets, especially in Europe and Asia, so there could be higher commercialization and equivalent food security impact worldwide. Specifically, the application of mealworms in a circular economy is advanced towards gradually inserting waste streams in mealworm production. It delivers additional food waste outputs such as protein, fats, and fertilizer. Thus, a cross-section of industries can see the effective use of resources that entails producing economic value and overall sustainability.

Researchers have analyzed the production efficiency of the mealworms (TM). The mealworms provide an effective answer to address the world's current challenges which include population feeding as well as ecological sustainability together with sustainable animal protein sources. These organisms serve as both nutritional protein sources and fat resources containing essential elements while processing difficult-to-digest resources into practical animal-feed components better than typical livestock food. Researchers discovered that farming mealworms demand fewer resources of farmland and freshwater and feed than what is needed to sustain cattle, pigs, or poultry. According to van Huis *et al.*'s research, mealworms use their feed efficiently which produces an FCR of 1.7 to 2.2 and beef requires an FCR of 8. The optimized mealworm feed conversion system enables producers to decrease production costs which makes the farming enterprise profitable.

Additionally, the life cycle of mealworm production has the minimum output of greenhouse gas emissions. Ooninx *et al.* (2010) identified that mealworm farming releases up to 90 percent more emissions than the standard procedures of animal farming and, therefore, proves to be an efficient and profitable form of agriculture as the environmental standards and carbon cost continue to rise. Further, being able to feed on agro-industrial residues or food waste strengthens the later economic potential for the production of mealworms. For example, Rumpold and Schlüter (2013) showed that using waste materials in the feed also cuts the cost of feeds and uses waste as valuable protein, thus adopting a circular economy. Furthermore, they argue that circulating a mealworm is scalable and offers a strategic advantage to the farm. Due to increased automation, controlled environment, and vertical farming technologies, Mealworm production can quickly grow cheaply. For Morales-Ramos *et al.* (2020), large-scale elite mealworm rearing buoyed by modern-day automation would considerably reduce operating costs, labor, and energy and, therefore, can be deemed cost-effective animal protein sources.

## CHALLENGES AND LIMITATIONS

The mealworms (TM) are gradually gaining attention as a good source of protein and valuable bio-convertors of organic waste, particularly food waste. However, there is a need to manage the food waste substrate used in biomass production for human and animal feed because of contamination possibilities. Franken mealworms, in particular, bear several aerobic bacteria, enterobacteria endospores, yeasts, and fungi. Microbial transfer is likely to occur in animals and humans because they are swallowed whole and do not undergo gut elimination. Surprisingly, research shows that standard food poisoning germs such as *Salmonella* and *Listeria monocytogenes* are not readily present in mealworms. Moreover, there is a reduced microbial density when the larvae are left unharmed, probably because many microbial

inhabitants stay encapsulated in the gut. Most of this processing procedure involves low manipulation, which retains high bacteria reduction, including blanching. However, surface contamination is always an issue because the larvae are in contact with their surroundings, and more study is required to determine the best sterilization method (Grau *et al.*, 2017).

Since mealworms are a source of parasites like the rat tapeworm (*Hymenolepis diminuta*), which affects the health of rodents, livestock, and humans by delivering symptoms like enteritis, anorexia, and gut irritation (Grau *et al.*, 2017), they may also be infected by the single-cell parasite (*Gregarina niphandrodes*) that usually reduces the lifespan of adult beetles. While there is no proof of insect-specific prions, ingesting prions from contaminated food is possible for mealworms. In the large-scale production of the broiler species, there are high risks of diseases such as densovirus, microsporidia, and overcrowding, hence stressing the importance of humane husbandry practices to avoid high incidences of diseases. It is common knowledge that mealworms become toxic with time through the accumulation of these chemicals from the foods that they eat, and in addition to arsenic, cadmium, and lead, my experiment also revealed that these worms released arsenic into the medium even when they were transferred to uncontaminated foods. Although one-day fasting may help reduce pesticide levels, some pesticides are not well metabolized and expelled from the body. Thus, the appropriate control for these toxins is to pay attention to the quality of feed and the insect stocks from where they feed regularly. In the same way, those mealworms may also feed on food allergens that can harm allergic humans. Allergenic proteins can be transferred between species during rearing, so proper controls and labeling are required to protect the consumer during the use of the final mealworm product.

#### **Future Prospects**

The mass production of mealworms serves as a successful pathway to provide food for humans along with their companion animals. Since market demand for alternative protein sources has produced an urgent requirement for growing these mealworms. Research shows that automated rearing techniques like vertical farming need improvement to optimize the development of mealworms and related insects while saving resources to grow them optimally in controlled conditions (Van Huis *et al.*, 2020). Supplements together with feeding systems harvesting methods and monitoring methods reduce the need for work and create higher production benefits when applied to large-scale farming (Oonincx *et al.*, 2015). Scientists have demonstrated that mealworms can thrive when used to process organic waste streams which simultaneously lowers expense and environmental impact in feed production. The LCA study demonstrates that producing edible insects using mealworms stands as the most environmentally friendly method for human insect-based food production which supports the development of scalable sustainable food systems (Sogari *et al.*, 2019). Achieving the perfect outcome in MSW management requires more research and development to advance the field as well as path elimination and safety establishment for scaled-up facilities.

The practice of integrating mealworm production with sustainable farming finds promise as a solution for worldwide problems related to rising food security risks and environmental protection needs. The circular farming system benefits from TM through its strong ability to transform waste organic material into protein due to its ability to decrease agro-waste and recycle nutrients efficiently. Scientists confirmed through research that breeding mealworms on leftover crop materials together with food waste and farm waste allows protein production while also reducing environmental effects (Bertola and Mutinelli, 2021). The application of mealworm frass as organic manure leads to enhanced soil status and available nutrients according to studies conducted by Harsányi *et al.* (2020) which promotes sustainable and efficient agricultural practices. The mealworm has multiple advantages which include its low water and land needs for survival and its ability to use waste materials as food sources so manufacturers can integrate these features into resource-efficient systems designed to reduce environmental impact.

#### **CONCLUSION**

Mealworms provide value across various food supply needs as well as future environmental conservation requirements. The use of organic waste for quality protein production by mealworms provides dual solutions to reduce waste accumulation while meeting expanding market requirements. The combination

of low resource requirements and minimal GHG production and minimal space and water needs makes mealworms an improved alternative over traditional livestock. The nutritional essence of mealworms stands out since they contain essential amino acids together with vitamins and bioactive compounds suitable for animals and humans. Health support enabled by mealworms provides a sustainable feed solution that helps decrease the use of fishmeal and soy supplies which present sustainability problems. The circular economy receives positive prospects from mealworm farming because it turns agricultural waste and food waste into human consumption resources. Considerable challenges exist because of waste contamination management and converting waste into biomass. The fulfillment of these requirements depends on extensive research along with the creation of sustainable automation systems in farming techniques and intangible food safety regulations. The mealworm production industry advances its sustainability with each production improvement that leads toward securing food security on a global scale. The application of attention to safety protocols plus legislative guidelines makes mealworms indispensable for building sustainable food security infrastructure which brings dual benefits.

## REFERENCES

- Makkar, H. P., Tran, G., Heuzé, V., & Ankers, P. (2014). State-of-the-art on use of insects as animal feed. *Animal feed science and technology*, 197, 1-33.
- Pöllinger-Zierler, B., Lienhard, A., Mayer, C., Berner, S., Rehorska, R., Schöpfer, A., & Grasser, M. (2023). *Tenebrio molitor* (Linnaeus, 1758): Microbiological screening of feed for a safe food choice. *Foods*, 12(11), 2139.
- Amicarelli, Vera, Giovanni Lagioia, and Christian Bux. Global warming potential of food waste through the life cycle assessment: An analytical review. *Environmental Impact Assessment Review* 91 (2021): 106677.
- Oonincx, D. G., & De Boer, I. J. (2012). Environmental impact of the production of mealworms as a protein source for humans—a life cycle assessment. *PLoS one*, 7(12), e51145.
- Derler, H., Lienhard, A., Berner, S., Grasser, M., Posch, A., & Rehorska, R. (2021). Use them for what they are good at: Mealworms in circular food systems. *Insects*, 12(1), 40.
- Ng, W. K., Liew, F. L., Ang, L. P., & Wong, K. W. (2001). Potential of mealworm (*Tenebrio molitor*) as an alternative protein source in practical diets for African catfish, *Clarias gariepinus*. *Aquaculture Research*, 32, 273-280.
- Huis, A. V., Itterbeek, J. V., Klunder, H., Mertens, E., Halloran, A., Muir, G., & Vantomme, P. (2013). Edible insects: future prospects for food and feed security.
- Van Huis, A. (2013). Potential of insects as food and feed in assuring food security. *Annual review of entomology*, 58(1), 563-583.
- Oonincx, D. G., Van Itterbeek, J., Heetkamp, M. J., Van Den Brand, H., Van Loon, J. J., & Van Huis, A. (2010). An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. *PLoS one*, 5(12), e14445.
- Musembi, J. P., Owino, E. A., Oyieke, F. A., Tanga, C. M., Beesigamukama, D., Subramanian, S., & Eguny, J. P. (2024). Efficient agri-food waste valorization using mealworm (Coleoptera: Tenebrionidae) into nutrient-rich biomass for food and feed. *Journal of Economic Entomology*, toae035.
- Moruzzo, R., Riccioli, F., Espinosa Diaz, S., Secci, C., Poli, G., & Mancini, S. (2021). Mealworm (*Tenebrio molitor*): potential and challenges to promote circular economy. *Animals*, 11(9), 2568.
- Kotsou, K., Chatzimitakos, T., Athanasiadis, V., Bozinou, E., & Lalas, S. I. (2024). Exploiting Agri-Food Waste as Feed for *Tenebrio molitor* Larvae Rearing: A Review. *Foods*, 13(7), 1027.
- Hasan, Z., & Lateef, M. (2024). Transforming food waste into animal feeds: an in-depth overview of conversion technologies and environmental benefits. *Environmental Science and Pollution Research*, 31(12), 17951-17963.
- Finke, M. D. (2002). Complete nutrient composition of commercially raised invertebrates used as food for insectivores. *Zoo biology: published in affiliation with the American zoo and aquarium association*, 21(3), 269-285.
- Rumpold, B. A., & Schlüter, O. K. (2013). Potential and challenges of insects as an innovative source for food and feed production. *Innovative Food Science & Emerging Technologies*, 17, 1-11.
- Jeon, Y. H., Son, Y. J., Kim, S. H., Yun, E. Y., Kang, H. J., & Hwang, I. K. (2016). Physicochemical properties and oxidative stabilities of mealworm (*Tenebrio molitor*) oils under different roasting conditions. *Food science and biotechnology*, 25, 105-110.
- Jankauskienė, A., Aleknavičius, D., Andrulevičiūtė, V., Mockus, E., Bartkienė, E., Juknienė, I., ... & Kabašinskienė, A. (2024). Nutritional composition and safety parameters of mealworms (*Tenebrio molitor*) reared on substrates derived from by-products. *Applied Sciences*, 14(7), 2744.
- Mariod, A. A. (2020). Nutrient composition of mealworm (*Tenebrio molitor*). *African edible insects as alternative source of food, oil, protein and bioactive components*, 275-280.
- Berggren, Å., Jansson, A., & Low, M. (2019). Approaching ecological sustainability in the emerging insects-as-food industry. *Trends in ecology & evolution*, 34(2), 132-138.
- Houben, D., Daoulas, G., Faucon, M. P., & Dulaurent, A. M. (2020). Potential use of mealworm frass as a fertilizer: Impact on crop growth and soil properties. *Scientific Reports*, 10(1), 4659.

21. Yang, Y., Yang, J., Wu, W. M., Zhao, J., Song, Y., Gao, L., & Jiang, L. (2015). Biodegradation and mineralization of polystyrene by plastic-eating mealworms: Part 1. Chemical and physical characterization and isotopic tests. *Environmental Science & Technology*, 49(20), 12080-12086.
22. Liu, W., Zheng, X., Zhao, Y., & Chen, W. (2020). Conversion of vegetable waste by mealworms (*Tenebrio molitor*): Biodegradation rate and effects on life-cycle traits. *Scientific Reports*, 10(1), 1-9.
23. Niu, Y., Liu, Q., Lai, R., Zhu, Y., Song, X., Zhang, Z., & Gao, Y. (2021). Effects of mealworm frass on soil fertility and plant growth promotion. *Agricultural Research*, 10(2), 234-245.
24. Ravzanaadii, N., Kim, S. H., Choi, W. H., Hong, S. J., & Kim, N. J. (2012). Nutritional value of mealworm, *Tenebrio molitor* as food source. *International Journal of Industrial Entomology*, 25(1), 93-98.
25. Guo, W., Zhang, J., Xin, Y., & Li, Z. (2021). Chitin extraction from mealworm and its use in environmental applications. *Environmental Technology & Innovation*, 22, 101436.
26. Rumpold, B. A., & Schlüter, O. K. (2013). Nutritional composition and safety aspects of edible insects. *Molecular nutrition & food research*, 57(5), 802823.
27. Makkar, H. P., Tran, G., Heuzé, V., & Ankers, P. (2014). Stateoftheart on use of insects as animal feed. *Animal feed science and technology*, 197, 133.
28. You, S., Yang, H., Lee, S. K., & Kim, W. (2015). Mealworm (*Tenebrio molitor*) larvae as a sustainable protein source: Growth performance and nutrient conversion efficiency. *Journal of Insect Science*, 15(1), 125.
29. Bautista, M. G., Pirlo, R. K., Rao, C. V., & Saldaña, M. D. A. (2019). Environmental and economic assessment of mealworm (*Tenebrio molitor*) production on vegetable waste. *Journal of Cleaner Production*, 234, 11601170.
30. Van Broekhoven, S., Ooninx, D. G. A. B., van Huis, A., & van Loon, J. J. A. (2013). The role of mealworms in recycling of organic waste. *Sustainable Agriculture Research*, 2(1), 4559.
31. Park, H. W., Choi, S. W., Kim, H. J., & Kim, Y. H. (2017). Optimization of mealworm (*Tenebrio molitor*) rearing conditions for efficient conversion of organic waste. *Waste Management*, 59, 293301.
32. Sogari, G., Liotta, F., & Consoli, D. (2020). Largescale production of mealworms (*Tenebrio molitor*) on organic waste. *Journal of Insect Science*, 20(1), 12.
33. Musembi, J. P., Owino, E. A., Oyieke, F. A., Tanga, C. M., Beesigamukama, D., Subramanian, S., & Egonny, J. P. (2024). Efficient agri-food waste valorization using mealworm (Coleoptera: Tenebrionidae) into nutrient-rich biomass for food and feed. *Journal of Economic Entomology*, toae035.
34. Møller, C. O. D. A., Freire, L., Rosim, R. E., Margallo, L. P., Balthazar, C. F., Franco, L. T., & Oliveira, C. A. F. D. (2021). Effect of lactic acid bacteria strains on the growth and aflatoxin production potential of *Aspergillus parasiticus*, and their ability to bind aflatoxin B1, ochratoxin A, and zearalenone *in vitro*. *Frontiers in Microbiology*, 12, 655386.
35. Ooninx, D. G., van Broekhoven, S., van Huis, A., & van Loon, J. J. (2019). Correction: Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PLoS One*, 14(10), e0222043.
36. Ooninx, D. G., Van Broekhoven, S., Van Huis, A., & Van Loon, J. J. (2015). Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products. *PloS one*, 10(12), e0144601.
37. Dossey, A. T., Morales-Ramos, J. A., & Rojas, M. G. (Eds.). (2016). *Insects as sustainable food ingredients: production, processing and food applications*. Academic Press.
38. Evans, S. C., Roberts, M. C., Keeley, J. W., Blossom, J. B., Amaro, C. M., Garcia, A. M., & Reed, G. M. (2015). Vignette methodologies for studying clinicians' decision-making: Validity, utility, and application in ICD-11 field studies. *International journal of clinical and health psychology*, 15(2), 160-170.
39. Van Huis, A., Rumpold, B. A., Van der Fels-Klerx, H. J., & Tomberlin, J. K. (2021). Advancing edible insects as food and feed in a circular economy. *Journal of Insects as Food and Feed*, 7(5), 935-948.
40. Morales-Ramos, J. A., Rojas, M. G., Kelstrup, H. C., & Emery, V. (2020). Self-selection of agricultural by-products and food ingredients by *Tenebrio molitor* (Coleoptera: Tenebrionidae) and impact on food utilization and nutrient intake. *Insects*, 11(12), 827.
41. Grau, T., Vilcinkas, A., & Joop, G. (2017). Sustainable farming of the mealworm *Tenebrio molitor* for the production of food and feed. *Zeitschriftfür Naturforschung C*, 72(9-10), 337-349.
42. Sogari, G., Amato, M., Biasato, I., Chiesa, S., & Gasco, L. (2019). The potential role of insects as feed: A multi-perspective review. *Animals*, 9(4), 119.
43. Galvão, J. R. D. C. S. Paulo Brito· Filipe dos Santos Neves· Henrique de Amorim Almeida· Sandra de Jesus Martins Mourato· Catarina Nobre Editors.
44. Sangiorgio, P., Verardi, A., Dimatteo, S., Spagnoletta, A., Moliterni, S., & Errico, S. (2022). Valorisation of agri-food waste and mealworms rearing residues for improving the sustainability of *Tenebrio molitor* industrial production. *Journal of Insects as Food and Feed*, 8(5), 509-524.
45. Bertola, M., & Mutinelli, F. (2021). A systematic review on viruses in mass-reared edible insect species. *Viruses*, 13(11), 2280.
46. Harsányi, E., Juhász, C., Kovács, E., Huzsvai, L., Pintér, R., Fekete, G., & Gyuricza, C. (2020). Evaluation of organic wastes as substrates for rearing *Zophobasmorio*, *Tenebrio molitor*, and *Achetadomesticus* larvae as alternative feed supplements. *Insects*, 11(9), 604.
47. Ludwig, Daniel, and Carl Fiore. Further studies on the relationship between parental age and the life cycle of the mealworm, *Tenebrio molitor*. *Annals of the Entomological Society of America* 53.5 (1960): 595-600.