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Review

Worming the Circular Economy for Biowaste and Plastics: *Hermetia illucens*, *Tenebrio molitor*, and *Zophobas morio*

Zhi-Jue Kuan [1], Barnabas Kuan-Nang Chan [1] and Samuel Ken-En Gan [1,2,3,4,*]

[1] Bountifood Pte Ltd., Science Park II, Singapore 117610, Singapore; zhijue.intern@bountifood.com.sg (Z.-J.K.); barnabas.chan@bountifood.com.sg (B.K.-N.C.)
[2] APD SKEG Pte Ltd., Katong, Singapore 439444, Singapore
[3] James Cook University, Aljunied, Singapore 387380, Singapore
[4] Antibody & Product Development Lab, EDDC-BII, A*STAR, Biopolis, Singapore 138672, Singapore
* Correspondence: samgan@apdskeg.com

Abstract: The negative impact of the modern-day lifestyle on the environment was aggravated during the COVID-19 pandemic through the increased use of single-use plastics from food take-aways to medical supplies. Similarly, the closure of food outlets and disrupted supply chains have also resulted in significant food wastage. As the pandemic rages on, the aggravation of increased waste becomes an increasingly urgent problem that threatens the biodiversity, ecosystems, and human health worldwide through pollution. While there are existing methods to deal with organic and plastic waste, many of the solutions cause additional problems. Increasingly proposed as a natural solution to man-made problems, there are insect solutions for dealing with the artificial and organic waste products and moving towards a circular economy, making the use of natural insect solutions commercially sustainable. This review discusses the findings on how some of these insects, particularly *Hermetia illucens*, *Tenebrio molitor*, and *Zophobas morio*, can play an increasingly important role in food and plastics, with a focus on the latter.

Keywords: polystyrene; polyethylene; worms; *Hermetia illucens*; *Tenebrio molitor*; *Zophobas morio*; plastic waste; food waste; circular economy

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1. Introduction

The COVID-19 pandemic has indirectly disrupted food services, logistics, and daily operations to augment the food delivery market, which is expected to grow at a compounded annual rate of 8.2% from 2020 to 2024 globally [1]. However, this increase is detrimental to the environment because of increased food wastage [2] and the plastic containers used in take-aways. Panic buying and increased food delivery together with reduced business and overbuying contributed to food wastage in diners and at home [2]. These have severely set back the third target of United Nations (UN) 17 Sustainable Development Goals (SDGs), particularly SDG 12, aiming to reduce food waste by 2030 at retail and consumer levels [3]. One-third of the food produced in the world for human consumption every year, an estimated 1.3 billion tons, was already lost or wasted [4] during pre-pandemic times. In parallel, it should be noted that 49 million tonnes of plastic is already used per year in Europe alone, with 40% for packaging [5].

Given their inherent resistance to natural biodegradation, most plastics end up in landfills or as litter on streets and seas. Since the beginning of the global plastic industry, from the first synthetic plastic in 1907 to the rapid expansion in the 1950s, the annual production of plastics has increased more than 200-fold to 367 million tons in 2020 [6]. Made through a polymerisation or polycondensation process, plastics are polymers of the liquid hydrocarbon found in petroleum. They are lightweight, sturdy materials with good insulation and low thermal conductivity. With their low cost and ease of manufacturing, plastics support economic efficiency and marketing. Given the scale of the plastic problem, it is likely that a multipronged approach in addition to the current use of landfills is sorely needed. The space to bury persistent plastic waste is rapidly exhausted, as expanded polystyrene cups and polyethylene bags require at least 500 years to degrade [7] and are disposed of in large amounts worldwide. Less than 4% of the plastic waste today is recycled [8], leaving 300 million tons of plastic waste for the oceans [9]. Burning the unrecycled plastic to save the oceans would contribute to the production of greenhouse gases. Notably, the problem is compounded by the greenhouse gas more potent than carbon dioxide [8], methane, which is produced during food waste decomposition and can occur on food-contaminated plastic materials.

Amid these increasing problems with incomplete solutions, nature provides solutions to both organic and artificial plastic wastes in the form of insects, which would function in a possible zero-waste circular economy. The zero-waste approach incorporates the aim of keeping waste out of the environment, while the circular economy step regenerates the environment towards greater sustainability.

One example of the zero-waste circular economy using insects is cockroaches, which are highly efficient machines for clearing organic waste with their insatiable appetites. While generally culturally unacceptable, cockroaches are protein diet food sources in some communities. Furthermore, it is with a better understanding in entomology that other solutions for both food and plastic waste in black soldier flies (*Hermetia illucens*), superworms (*Zophobas morio*), and mealworms (particularly the yellow *Tenebrio molitor*) have emerged.

Starting with organic waste, *H. illucens* larvae are mentioned before the other two insects in the plastic section.

Hermetia illucens is gaining interest worldwide as a food waste management solution and in generating valuable biomass for the circular economy [10–12]. As a 13–20 mm long fly in the insect family *Stratiomyidae* native to the Neotropics but found across all zoogeographic regions because of anthropogenic factors, *H. illucens* can be bred year round in the tropics and in warmer months in colder areas [13,14]. The larvae typically hatch three to four days after oviposition and develop for approximately two weeks through six larval instars, including a prepupal stage in which they turn from dull white to black in colour [15]. *Hermetia illucens* larvae can also aid in the rapid removal of manure, reducing odour. The microbial colonisation, type of feed, pH, moisture content, temperature, and rearing container size can influence their development time to prolong the prepupal larva stage for continued waste consumption [16]. Before proceeding to the next stage, the prepupa first finds a safe, dark, and dry area to start its pupal development. The mouthless adult fly emerges about 14 days later purely for mating and laying eggs.

2. Factors Affecting the Growth of *Hermetia illucens*

The *H. illucens* larva solution has a small environmental footprint through reduced greenhouse and ammonia emissions, low water requirements, and high feed conversion efficiency. Able to deal with both food waste and manure [17], *H. illucens* larvae are nature's bioreactors that convert the waste into frass, which has natural fertiliser applications [11]. With further optimisation of the growth conditions for the various scales [16], *H. illucens* can process tonnes of organic waste on an industrial scale and even be adopted in smaller setups [16] for more decentralised deployment in backyards and garages. Easily performed optimisations include attempts to extend the larval stage and improve the rate of weight gain, worm nutrition content, and rearing density, among many others [18]. The factors that affect the growth of *H. illucens* are as shown in Table 1.

Table 1. Factors that affect the growth of *Hermetia illucens* larvae.

Factors	Description
Feed	Various organic wastes, such as manure, food waste, and industrial organic byproducts, have different compositions and may require varying fermentative preprocessing actions and chemoattractant treatment for *H. illucens*.
pH	The acidity and alkalinity of the organic waste affects the microbiota, thereby affecting the potential preprocessing or fermentation that can influence the development of *H. illucens*.
Moisture	The moisture content of the feed can affect the rate of consumption. The larvae of *H. illucens* lack teeth and have preferred moisture levels. Excessive moisture influences microbial growth as well as the larval growth rate. Moisture plays a more important role in the development and survival of *H. illucens* than the protein and carbohydrate content of feed. Larvae were found to be unable to develop on diets with 30–40% moisture content, with most larvae dying within 13 days [19,20].
Temperature	The environmental temperature affects the survival rate and growth rate/metabolism of *H. illucens* and microbes, in turn affecting the speed of consumption and digestion. A favourable temperature is 30 °C.
Size of Container	Overcrowding can negatively impact the developmental stages and survival of *H. illucens*. In a small container, there was an overall 28.8% lower survivorship than in a large rearing tray at 24.7%, with the larvae also growing to a larger sizes in the larger tray. However, the bioconversion rate in the large tray was only 2.7% higher than that in the smaller container [21].
Species strain	The strain of *H. illucens* underpins its developmental time and ability to reduce dry matter [21]. A comparison of three strains (Texas strain; Guangzhou strain; Wuhan strain) showed that they reduced poultry manure by 56.8%, 31.8%, and 61.7%, respectively.
Severe food limitations	The most substantial food limitation at high density (200 and 400 larvae consumed 0.09 and 0.06 g per larva, respectively) kept *H. illucens* at the prepupal stage for 45 days. Overcrowding delayed metamorphosis, perhaps because of nutrient limitations. Comparisons between batch and daily feeding showed daily feeding to provide better weight gain but result in a longer prepupal stage [22]. Furthermore, severe food limitations were found to prolong or pause larval development time.
Microbial environment	Bacterial species isolated from *H. illucens* eggs and from the larval gut that were further inoculated into chicken manure with pre-existing *H. illucens* larvae independently promoted *H. illucens* larval growth. Larvae reared in manure with the species *Kocuria marina, Lynsinibacillus boronitolerans, Proteus mirabilis*, and *Bacillus subtilis* had higher weight gain and manure reduction rates compared to the control without supplementation [23]. Supplementation with *Bacillus subtilis* was also found to lead to faster manure processing [24].

In summary, *H. illucens* larvae are fastidious in their growth condition requirements.

3. *Hermetia illucens* in Organic Waste Treatment

Hermetia illucens biowaste treatment has garnered increased attention over the last few decades [25,26]. The process consists of waste preprocessing, biowaste treatment by *H. illucens* larvae, separation of larvae from the process residue, and refinement of the larvae and residue into upcycled marketable products [27]. The whole process involves killing, cleaning, sterilising, drying, and fractionating (proteins, lipids, and chitin) followed by composting or anaerobic digestion [26]. The constancy of the *H. illucens* larva supply for biowaste treatment from the healthy adult plays a crucial role in the operational sustainability and economy of the process [13,28]. This treatment process could potentially be more sustainable and profitable than other treatment technologies, making it suitable for low- and middle-income countries to adopt widely.

3.1. Challenges in Implementation of Hermetia illucens Biowaste Treatment

While beneficial, the potential of *H. illucens* is not without challenges, and a summary of these is shown in Table 2.

Table 2. Challenges in implementation of *H. illucens* treatment.

No.	Challenge
1	Precision, reliability, and efficiency of operating the *H. illucens* nursery to maximize young larva production for higher survival rates.
2	The economical scale of technologies [11,12,27]—the supply chains for the input of waste and distribution of extracted products and frass for various industries are still lacking. For example, the processing of animal feed in one location and the sending of the frass to nearby farms and agricultural land may be a logistical challenge.
3	Missing benchmarks for products—the full benefits of *H. illucens* larval-based feeds and frass have still to be extensively demonstrated and benchmarked, therefore facing market penetration challenges.
4	Incomplete or restrictive local regulations on usage—Several countries have started allowing the use of *H. illucens* larvae for the production of feeds under certain strict conditions (registration, processing, animal specificity) [11]. However, some countries still prohibit its use as feeds for livestock that are meant for later consumption by humans [27]. Given the general novelty of this approach, there may be regions with blanket prohibitions on it from the lack of established guidelines.
5	Containment of *H. illucens* to prevent escape—this is challenging because the adult fly is able to escape by flying away, requiring that a more secured containment area.
6	*Hermetia illucens* larva consumption rate can vary between different biowaste types. Most experiments have been performed in small scale, with unknown scalability and sustainability for larger applications [27]. With each batch of biowaste that comes in for *H. illucens* larva treatment having different compositions, the results of experiments can vary significantly.

3.2. Potential Dangers in Biowaste Processing of Hermetia illucens Larvae

Since biowaste often has a highly diverse population of microbes, and since even manures can contain pharmaceutical by-products, some biowaste may be laced with mycotoxins, pesticides, heavy metals, and other toxins such as dioxins, polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs) [27]. With the potential effects of entomopathogens such as *Beauveria* spp. and Arboviruses [9,29] on humans, care needs to be taken that pathogens from the waste and harmful chemicals do not transfer to make the larvae vectors for human toxins and pathogens.

3.3. Hermetia illucens as a Feed for Livestock

Poultry is the most prominent livestock group [28], with the demand for animal protein expected to grow together with the global population. With plant-based feed being easily influenced by global warming and climate change and aggravated by feed and energy costs, global food security [30] is increasingly unstable. Currently, poultry feed is predominantly plant-based; thus, the price increases affect human food supply and sustainability, especially in developing countries. The current conventional feed constituents of soya bean and fishmeal are generally unsustainable, opening opportunities for insects.

However, despite all of this, there remain questions on the safety and cleanliness of the insects, especially if they feed on manure or potentially hazardous waste, that can threaten the benefits of insects requiring less energy and land area and thus leaving a lower environmental footprint [30].

In boosting its nutritional value, the type of feed for the larvae affects the nutritional content of the larvae. Table 3 illustrates the types of organic waste treated by *H. illucens* larvae.

Table 3. Type of organic waste suitable for *H. illucens* larvae treatment.

Organic Waste	Origin
Human manure	Faecal sludge from sewage
Animal manure	Farms with poultry, cow, or swine
Fruit wastes	Discarded/rotten fruits from food companies or markets
Vegetable wastes	Spoilt/rotten vegetables from farms, food companies, or markets
Municipal organic solid wastes	Food scraps from households, restaurants, markets, malls, companies, and public institutions
Millings and brewery side streams	From the milling and brewery industries, dried distiller grains, wheat, bran, billed grains, and grinding dust
Poultry feeds	Uneaten feeds used for poultry

4. *Hermetia illucens* in the Management of Carcasses and Corpses

Hermetia illucens is a detritivore commonly found in the late stage of decomposition of carcasses and corpses. The insect is often used in forensic entomology for the occasional estimation of post-mortem intervals (PMIs) based on the life cycle of *H. illucens*, with one example in northern Brazil [31]. Given its natural presence, *H. illucens* can constitute a natural solution for carcasses and corpses through natural consumption, apart from the commonly used method of incineration/cremation.

A study using swine carcasses [32] found that the *H. illucens* female could lay 620–700 eggs per posture in concealed cranial cavities, with about 93% of the hatching. The larvae were found under the swine skin and on bones. Interestingly, *H. illucens* did not seek out drier sites for pupation after feeding but burrowed deeper into the carcass. Pupae were observed at the 60th day after death, with the *H. illucens* lifecycle taking ~53–82 days to complete. Of the *H. illucens* in the carcass, 11% reached the adult stage, leaving room for further optimisation for such applications.

5. *Zophobas morio* and *Tenebrio molitor* in the Plastic Waste Circular Economy

Also voracious eaters, but at a much lower rate than *H. illucens*, *Z. morio* and *T. molitor* can contribute to a circular economy of food waste in a significant way. Interestingly, their value comes in dealing with plastic waste, particularly that of polystyrene (PS) and polyethylene (PE). Their ability to consume and mineralise PS and PE [14,33] would be the focus of their contribution to the circular economy of plastic waste.

Both PS and PE are among the most used plastics and are thus major contributors to plastic waste. Various physical and chemical means have been attempted to address these plastic polymers. Still, these efforts are often unsustainable in terms of cost, and the very harsh chemicals involved themselves becoming environmental problems. While plastics do not occur naturally, nature has a solution to man's artificial problem in insects. These include *T. molitor* [34–36], *Z. morio* [33,34,37], and waxworms (*Galleria mellonella* L.) [38,39], which utilise PS and PE for mineralisation [33,34,37–39] as a carbon source. After full digestion, their frass can be used as natural fertiliser. At the point of writing this review, the pathway of plastic degradation by the gut microbiome in these insects have yet to be fully characterised, with only some bacteria identified for PS degradation in *Z. morio*, such as *Pseudomonas aeruginosa* [33]. Thus, while the degradation can involve the gut bacteria, the present review focuses only on plastic consumption, specifically of PS and PE, at the insect level.

5.1. Polyethylene (PE)

Among the myriad of commonly used plastics, PE is the most chemically simple but resistant to natural degradation [40]. Compared to PS, PE is of higher density and higher molecular weight, making it more impact-resistant and durable. PE is resistant to chemicals, UV light, and moisture and can be easily made into sheets, films, and other fibrous forms. Given their thermostability at up to 122 °C and high plasticity, both low-density and high-density PE are fully recyclable. PE is principally used in packaging film, trash and grocery bags, agricultural mulch, wire, and cable insulation.

Though PE is completely recyclable, the sheer volume of PE products as construction and packaging discarded daily has largely overwhelmed recycling capabilities, resulting in it becoming waste. Compounding this problem is the issue of food waste contamination for PE is widely used for packaginge, thus reducing its recyclability without preprocessing.

5.1.1. Biodegradation Rate of PE by *Tenebrio molitor*

Tenebrio molitor can survive solely on a diet of low-density polyethylene (LDPE) [41]. Three strains of *T. molitor* (Guanzhou, Tai'an, and Shenzen) showed consumption rates of 172.2 µg, 102.7 µg, and 138.6 µg per day per larva, respectively [42]. When the feed was composed solely of PE and when PE was mixed with wheat bran, 226.6 µg and 286.5 µg of feed were consumed per day per larva [43]. In these examples, PE was successfully metabolised. Recent evidence has shown *Tenebrio obscurus* (dark mealworms) to also be capable of biodegrading LDPE like *T. molitor.* While the degradation is gut microbe independent, it is enhanced by the microbes, which are in turn developed and shaped by the LDPE diets [44].

5.1.2. Biodegradation Rate of PE by *Zophobas morio*

Two different strains of *Z. morio* (Guangzhou, China: Strain G; Marion, Illinois, U.S.: Strain M) were tested for PE degradation at 25 °C. Within 33 days, strain G larvae ingested LDPE as their sole diet equivalent to 58.7 ± 1.8 mg per 100 larvae per day. Meanwhile, strain M required co-diet with organic material (bran or cabbage) for a consumption rate of 57.1 ± 2.5 mg per 100 larvae per day. Both strains G and M showed limited LDPE depolymerisation [45], leaving much to be further optimized here.

5.2. Polystyrene (PS)

Unlike PE, PS is not a biodegradable plastic. It is resistant to acids, bases, and photolysis and not easily recyclable. Expanded polystyrene (XPS) is rigid, and its porous nature prevents pressure build-up. PS is commonly available in sheets, films, and foams at low prices, with high thermostability of up to 200 °C. Given that it is easily shaped, PS is a popular option in the food industry.

5.2.1. Biodegradation Rate of PS by *Tenebrio molitor*

The average consumption rate of PS for *T. molitor* was reportedly 0.12 mg of PS per day per larva [14]. Testing two compositions of food waste at three different temperatures with seven PS waste types, the optimal temperature was found to be 25 °C using 10% PS and 90% bran; the rate of consumption was doubled compared with that when using PS alone [43,45,46]. *Tenebrio molitor* showed increased consumption with lower-density PS and at the optimal ambient temperature at 20 to 30 °C [46,47]. Rates of 1.40 mg of PS consumed per day for each gram of worm present could also be augmented by the addition of sucrose or bran to 3.55 mg and 2.14 mg of PS consumed per day for each gram of worm present, respectively [34]. With the second generation of PS-fed *T. molitor* showing more favourable PS degradation, there is room for selective breeding [43].

5.2.2. Biodegradation Rate of PS by *Zophobas morio*

PS was reportedly consumed at 0.58 mg of PS per day per larva [14], a rate four times faster than that of *T. molitor*. A parallel study normalising by per gram of worm reported that 1.04 mg of PS was consumed per day for each gram of worm. With the addition of small amounts of table sucrose or bran, the rate increased to 1.90 mg and 1.79 mg of PS consumed per day for each gram of worm, respectively [34].

5.3. Challenges in Plastic Waste Treatment by Larvae

The rate of PS consumption by these worms is slower than that of organic material consumption by *H. illucens*, requiring around a week for 3000 to 4000 *T. molitor* larvae to completely eat and digest one XPS coffee cup [48]. Even after digestion, uneaten microplastics and plastic monomers remain in the frass [14,49,50], requiring re-eating and further digestion. *Zophobas morio* and *T. molitor* are also unable to consume high-density PS and PE, requiring these materials to be pre-processed to mediate easier consumption. Thus, many optimisations are still required before large-scale processing of plastic waste, such as:

1. Prolonged incubation with the worms, given that PS/PE degradation by these worms is slow [49], though still millions of times faster than natural degradation of plastic. The advantage is that the worms require little maintenance, can eat food-contaminated plastics, and do not fly, doing away with cleaning and making containment easier to implement.
2. Multiple layers of worm feeding chambers to decrease the microplastic content. Lower levels of worms consume the frass to reduce undigested plastics, microplastics, and monomer content [34].
3. Depolymerisation of the PS/PE waste into smaller fragments such as dimers, trimers, etc., to decrease the density for easier consumption by the worms.

An added challenge to the application of worms in plastic waste treatment is the use of different additives, which can include colouring compounds in different plastic applications, even those centred around PS and PE. It is unclear how these possible additives for various applications could break down or accumulate in the insects, making them unsuitable for entering the food chain. The variety of these compounds is too diverse for discussion in this review, but indeed, more in-depth study on what they are, which products they are found in, how they accumulate, and their long-term effects on the worms and food chain must be conducted before full implementation to diverse plastic waste.

6. Insects as a Source of Feed for Monogastric Animals

With high protein and lipid content, the various insects have the potential to be used as feed for industrial animal production and aquaculture. An insect-based diet for farm animals has been investigated for swine, poultry, and edible fish [51].

6.1. Constitution and Potential of Hermetia illucens Larvae in the Market

As *H. illucens* garners the attention of livestock farmers because it is highly marketable as an animal feed, its nutritional content and how it can be improved are essential study topics. Typically, *H. illucens* larva biomass contains 32–58% proteins and 15–39% lipids [16], making it suitable for the production of feeds for animals including poultry, swine, fish, and pets, as well as for usage in biofuels [11,12,16,27,52]. The defatting of *H. illucens* larvae can increase their protein content to 55–65% [53]. The already-present lauric acid, chitin, and antimicrobial peptides make them even more desirable as a feed constituent [27]. Micronutrients such as minerals and vitamins are essential for poultry and are present in *H. illucens* larvae, including iron, calcium, phosphorous, zinc, and vitamin E [54]. However, the potential bioaccumulation of undesirable substances such as toxic metals should be monitored [28]. *Hermetia illucens* larvae are rich in vitamin E as mature larvae (14th day), although the amount is less than that in the early prepupal stages. Nonetheless, the prepupal stage compensates for this by having higher mineral content than the mature larval stages, particularly phosphorous and calcium content.

With a higher feed conversion efficiency than most conventional production animals [55], *H. illucens* can convert 50% of the dry matter content of organic wastes into insect biomass rich in protein and fat content at 42% and 35%, respectively. Even among insects, the conversion of *H. illucens* is better than that of *T. molitor* and *Musca domestica* [17,55]. This is primarily influenced by dietary composition [56]. Table 4 describes the crude protein at various life-cycle stages of *H. illucens*.

Table 4. Crude protein percentage at different parts of the life cycle of *Hermetia illucens*. Data summarised and adapted from previous publication [54].

Life Cycle Stage	Crude Protein Percentage
Larval phase	~38%
Matured larva (Day 14)	~39.2%
Early pupa	~46.2%
Post-mortem adult	~57.6%

6.2. *Tenebrio molitor* as an Alternative Source of Protein

The larvae of *T. molitor* are considered easy to breed and have a stable content of lipids regardless of their diets [57]. *Tenebrio molitor* can be constantly produced [58], with the female *T. molitor* laying up to 500 eggs that hatch after 3–9 days at ambient room temperature, i.e., 25 °C. Late-instar larvae become 2.0–3.5 cm long or more [59], and the larval stage lasts 1–8 months. Larvae have a light yellowish-brown colour before they pupate for 5–28 days at 18 °C. The adult stage lasts 2–3 months [58].

T. molitor larvae have been successfully used as a feed ingredient in animal diets, including those of poultry and swine. Recently, *T. molitor* was approved in the EU as a human food [60] in its larval stage. In this stage, it is dried and ground, and the meal is produced from a byproduct of oil extraction. Table 5 shows the composition of *T. molitor*.

Table 5. Composition of *T. molitor*. The data is summarized and adapted from a previous publication [58].

Composition of *T. molitor*	Description
Crude protein	The crude protein content of larvae is 52.4% in average and ranges from 47.0 to 60.2% [58]. *Tenebrio molitor* larvae have high quantities of high-quality amino acids and are thus a highly sustainable protein source alternative.
Crude fibre	The whole insect contains a variable amount of fibre, including crude fibre, acid detergent fibre, and neutral detergent fibre [61–63]. The crude fibre content of *T. molitor* larvae averages 7.43% and ranges from 4.19 to 22.35%. The average crude fibre content of the larvae is higher than that of fishmeal (0.26%) [58].

The inclusion of *T. molitor* larvae in 0–3% of diets fed to broiler chickens was found to improve chicken body weight gain (BWG), feed conversion ratio (FCR), and dressing rate [58,64].

6.3. *Zophobas morio* as an Alternative Source of Protein

In fish farming, nutrition composition is an essential contributor to 40–50% of the production costs [65]. Fishmeal is the primary dietary protein source based on its nutritional quality and palatability properties. However, increasing demand has led to a shortage in supply and thus the inflation of its price. Therefore, it is logical to search for alternative protein sources, as overdependence can lead to price hikes.

Z. morio meal could potentially become a widely used alternative feed supplement for birds and fish because of its protein content. This insect species can be found widely in parts of the world including Central and South America [66]. As *Z. morio* is an identified alternative to fishmeal, it could be a promising project to evaluate whether the growth performance of fish on *Z. morio*-based diets could be on par with that of fish on fishmeal-based diets [65].

6.4. Concerns about Larvae as Feed

When using insects as animal feed, insect chemical defences, such as toxins produced by their endocrine glands [67], should be monitored. *T. molitor* can secrete benzoquinone compounds from its glands [68]. Benzoquinone, a toxic metabolite for humans and animals, interferes with cellular respiration and has a carcinogenic effect while also causing kidney problems [69]. Typically, benzoquinone is continuously accumulated, increasing as *T. molitor* gets matures. However, how much benzoquinone stays in the larva's body after processing for animal feeds and the tolerated levels in monogastric animals [58] remain to be investigated. These larvae can also occasionally be contaminated by pathogens or mycotoxins from contaminated diets that are infested by *Salmonella* spp. For the concerns of microbial safety, the insect gut (mostly members of the *Enterobacteriaceae* spp.) is considered the primary habitat, with microbes also found on the body surface and mouthparts. Microbes are vertically transmitted from the ovary and horizontally transmitted through the feed and environment [70,71].

The microbiota ratio in the insect gut plays an essential role in insects being used as a food source. It contributes significantly to the total biomass at 1–10% of the insect body weight [72]. For this reason, it is not necessarily beneficial to remove the gut, apart from the obvious processing required. Nonetheless, one area of concern is the potential accumulation of heavy metals such as mercury, cadmium, and arsenic from the environment; these could be passed on in animal feed [73,74], requiring monitoring.

7. Entomophagy by Humans

In addition to these issues, consumer acceptance and regulatory issues need to be addressed. For the former, the consumer perspective toward insects as food, especially insects fed on plastic, is a challenge, to say nothing of the added approvals required from regulatory authorities.

In some cultures, insects are viewed as fallback foods associated with marginal environments [75], but they have been eaten by humans for thousands of years and are commonly part of modern-day gluten-free diets. Several projections suggest that the human population will reach over 9 billion by 2050 [76,77], requiring approximately double the current food production [78]. With global warming reducing food production worldwide [79], and with the recent COVID-19 aggravating waste production and resource shortages, several foods have been proposed as alternatives, with insects receiving the most attention [80,81]. With the COVID-19 pandemic expected to continue for most of 2022 and possibly beyond [82] and containment measures affecting food access by the poor and helpless, there is a need to examine alternative foods.

Today, sustainable insect farming can substantially increase food security, especially in areas vulnerable to environmental stochasticity [80,83–85]. The European Food Safety Authority (EFSA), finding no safety risk to human health, has authorised the placing on the market of dried *T. molitor* as a novel food. It is now up to consumers to decide.

8. Conclusions

The natural solution of insects for our artificial problems is an emerging yet lucrative field. We are now only scratching the surface, with plenty of untapped utility for both the environment and society left to be explored and adopt. The natural circular economy with *H. illucens* as a workhorse for biowaste treatments for private and public sectors can be augmented by other insects, with frass serving as a good fertiliser because of its NPK content. To complete the circular economy cycle, these insects can be fed to monogastric animals, fish, and even humans based on lipid and protein content beyond commercial extraction of other compounds, e.g., chitin for medical purposes and melanin for pigmentation and protection against damage from ultraviolet lights.

With the added ability of *Z. morio* and *T. molitor* to degrade PS and PE, one of the world's major issues has a natural solution. Through further research, these insects may one day be widely used as self-sustaining natural solutions in landfills and dumpsters to reduce food waste-contaminated plastic waste.

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