Review

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

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Abstract: The negative impact of the modern-day lifestyle on the environment is aggravated during the COVID-19 pandemic through the increased use of single-use plastics from food takeaways 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 the organic and plastic waste, many of the solutions also cause additional problems. Increasingly proposed as a natural solution to man-made unnatural problems, there are insect solutions for dealing with the artificial and organic waste products towards a circular economy, making the use of natural insect solutions commercially sustainable. This review discusses the findings and how some of these insects, particularly the *Hermetia illucens*, *Tenebrio molitor*, and *Zophobas morio*, can play an increasing important role in food and plastics, with a focus on the latter.

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

1. Introduction

The Covid-19 pandemic had indirectly disrupted food services, logistics and daily operations to augment the food delivery market that is expected to grow at a compounded annual rate of 8.2 % from 2020 to 2024 globally [1]. Yet this increase is also detrimental on the environment due to increased food wastage [2] along with the plastic containers used in take-aways. In fact, the panic buying together with increased food delivery contributed to the food wastage in food diners and at home [3] through reduced business and overbuying. These have severely set back the third target of United Nations (UN) 17 Sustainable Development Goals (SDG) 12 aiming to reduce food waste by 2030 at retail and consumer levels [4] given that one-third of the food produced in the world for human consumption every year at an estimated 1.3 billion tons are already lost or wasted [5] during pre-pandemic times. It should also be noted that 49 million tonnes of plastic are already used per year use in Europe, with 40 % for packaging [6].

Given the 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 followed by the rapid expansion in the 1950s, the annual production of plastics increased more than 200-fold to 367 million tons in 2020 [7]. Made through a polymerization or polycondensation process, plastics are polymers of the liquid hydrocarbon found in petroleum to be a lightweight, sturdy material with good insulation and low thermal conductivity. With its low cost and ease of manufacturing, plastics supported economic efficiencies and marketing. Given the scale of the plastic problem, it is

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likely that a multi-pronged approach in addition to the current use of landfill given the insufficiency of space to deal with the persistent plastic waste where expanded polystyrene cups and polyethylene bags requires at least 500 years or more to degrade [8]. The alternate in burning to address the less than 4% of the plastic waste recycled [9], leaving 300 million tons of plastic waste for the oceans [10] would only contribute to the production of greenhouse gases. Methane, a greenhouse gas more potent than carbon dioxide [11] is also produced also during food waste decomposition and can occur on the food-contaminated plastic wrappings.

In the midst of these increasing problems, nature provided solutions to both organic and man-made plastic wastes in the form of insects. In one example, cockroaches are highly efficient machines to clear organic waste with their insatiable appetites. While generally culturally unacceptable, cockroaches are protein diet food sources in some communities, and it is with better understanding in entomology that further solutions for both food and plastic waste in black soldier fly (*Hermetia illucens*), superworm (*Zophobas morio*) and mealworm (*Tenebrio molitor*) have emerged.

An upcoming solution for organic waste, the *H. illucens* larvae have been gaining interest worldwide as a more acceptable food waste solution and in generating valuable biomass for the circular economy [12–14]. As a 13-20 mm long fly in the insect family *Stratiomyidae* native to the Neotropics but found across all zoogeographic regions due to anthropogenic factors, *H. illucens* can be bred all year round in the tropics and in warmer months in colder areas [15,16]. The larvae typically hatches three to four days after oviposition and develops for approximately two weeks through six larval instars, including a prepupal stage turning from dull white to black in colour [17]. *H. illucens* larvae can also aid in the rapid removal of manure, reducing odour. The microbial infestation, the type of feed, pH, moisture content, temperature, and rearing container size can influence its development time to prolong the prepupal larvae stage for continued waste consumption. Before proceeding to the next stage, the prepupa finds a safe, dark, and dry area to start its pupal development, after which the mouthless adult fly emerges about 14 days later purely for mating and laying of eggs.

2. Factors affecting growth of *Hermetia illucens*

The *H. illucens* larvae solution has a smaller environmental footprint through reduced greenhouse and ammonia emissions, reduced water requirement, and high feed conversion efficiencies. Able to deal with both food waste and manure [18], they are nature's bioreactors to convert these waste into frass which have natural fertilizer applications [13]. With further optimization of the growth conditions that would differ between small-scale and industrial scale [19], the easily reared *H. illucens* can easily process tons of organic waste in industrial scale and even be adopted in smaller set-ups [19] for more decentralized deployment in backyards and garages. Easily performed optimizations include attempts to extend the larvae stage, improve the rate of weight gain, worm nutrition content, rearing density, amongst many others [20]. The factors that affect the growth of *Hermetia illucens* are as shown in Table 1.1.

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

Factors	Description
Feed	Various organic waste: such as manure, food waste and industrial organic byproducts have different composition and may require varying fermentative actions and chemoattractant for the *H. illucens*.
pH	The acidity and alkalinity of the organic waste affects the microbiota thereby affecting the potential pre-processing or fermentation that can influence the development of the *H. illucens*.
Moisture	The moisture content of the feed can affect the rate of consumption. The *H. illucens* larvae lack teeth and have preferable moisture levels. Excessive moisture has influences on the microbial growth as well as the larvae growth rate. Moisture played a more important role on

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	the development and survival of *H. illucens* more than protein and carbohydrate content of feed. Larvae were found to be unable to develop on diets at 30-40 % moisture content with most larvae dying within 13 days [21,22].
Temperature	The environmental temperature affects the survival rate and the growth rate/metabolism of the *H. illucens* and the microbes, in turn affecting the speed of consumption and digestion having a favorable temperature of 30 °C.
Size of Container	Overcrowding can negatively impact their developmental stages and survival. In a smaller container, there was an overall 28.8 % lower survivorship than in the large rearing tray at 24.7 % with the larvae also growing to a larger size in the larger tray. However, the bioconversion rate in a large tray is only 2.7 % more than in the smaller container [23].
Species strain	The strain of *H. illucens* underpins their developmental time, ability to reduce dry matter [23]. The comparison of three strains (Texas strain; Guangzhou strain; Wuhan strain) showed the reduction of poultry manure at 56.8 %, 31.8 %, and 61.7 %, respectively.
Severe food limitations	The most substantial food limitation at high density (200 and 400 were consumed at 0.09 and 0.06 grams per larvae, respectively) kept the *H. illucens* at prepupal stage for 45 days. Overcrowding delayed metamorphosis, perhaps due to nutrient limitations. Comparisons between batch and daily feeding showed daily to provide better weight gain but also resulting in longer prepupa stage [24]. Furthermore, severe food limitations were also found to prolong or pause larvae 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. The 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 [25]. The supplementation of *Bacillus subtilis* were also found to lead to faster manure processing [26].

From the summary table 1.1, the *H. illucens* larvae are found to be fastidious in their growth condition.

3. *Hermatia illucens* in organic waste treatment

H. illucens biowaste treatment had garnered increased attention over the last few decades [27,28]. The biowaste treatment facility consists of waste pre-processing, biowaste treatment by *H. illucens* larvae, separation of larvae from the process residue, and refinement of the larvae and residue into upcycled marketable products [29]. The whole process involves killing, cleaning, sterilizing, drying, and fractionating (proteins, lipids, and chitin), followed at times by composting or anaerobic digestion [28]. The constancy of *H. illucens* larvae supply for biowaste treatment from the healthy adult plays a crucial role in the sustainability and economical [13,29] continued operations. As a natural process, this treatment system could potentially be more sustainable and profitable than other treatment technologies, making it suitable for low- and middle-income countries.

3.1 Challenges in implementation of *Hermatia illucens* biowaste treatment

While beneficial, the potential of *H.* illucens is not without challenges, and a summary of these are shown in Table 1.3

Table 3. Challenges in implementation of *H. illucens* treatment at full scale

No.	Challenge
1	Precision, reliability, and efficiency of operating the *H. illucens* nursery to maximize young larvae production for higher survival rates.
2	The economical scale of technologies [13,14,29] where 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 to animal feed and the frass to be sent to nearby farms and agricultural land may be a logistic challenge.
3	Missing benchmarks for products: the full benefits of *H. illucens* larval-based feeds and the frass have yet been extensively demonstrated and benchmarked, thereby facing market penetration challenges.
4	Incomplete or restrictive local regulations on its use: Several countries have started allowing the use of *H. illucens* larvae for the production of feeds under certain strict conditions (registration, processing, animal specificity) [13], however, some countries may still prohibit its use as feeds for livestock that are meant to be consumed by humans [29]. Given its general novelty, there may be regions with blanket prohibition from the lack of established guidelines.
5	Infestation and control of *H. illucens* larvae.
6	*H. illucens* larvae consumption rate can vary between different biowaste types. Most experiments are performed in small-scale and may have problems with scalability and sustainability [29]. With each batch of biowaste that comes in for *H. illucens* larvae treatment, these compositions in the waste can vary significantly.

3.2 Potential dangers in biowaste processing of *Hermatia illucens* larvae

Since biowaste often have a highly diverse specimen of microbes and that even manures can contain pharmaceutical products, some biowate may be laced with mycotoxins, pesticides, heavy metal contents, and other toxins such as dioxins, polychlorinated biphenyls (PCB), and polyaromatic hydrocarbons (PAHs) [29]. With potential effects of entomopathogens on humans such as *Beauveria* spp. and Arboviruses [10,30], care needs to be taken that some pathogens from the waste do not transfer to make the larvae vectors for human pathogens.

3.3 *Hermetia illucens* as a feed for livestock

Poultry is by far the most prominent livestock group [31]. The demand for animal protein is expected to grow together with the global population. With plant-based feed influenced by global warming and climate change aggravated by feed and energy costs, global food security [32] is increasingly unstable. Currently, poultry feed is predominantly plant-based, where the increases in prices affect human food supply as well as sustainability, particularly in developing countries. The current conventional feed constituents of soya bean and fishmeal are generally unsustainable, opening the opportunities for insects to convert biowaste that would otherwise not be suitable as animal feed.

Yet in all these, 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 less land area, leaving a lower environmental footprint [32].

In boosting its nutritional value, the type of feed for the larvae will affect the nutrition content of the larvae. Table 1.4 illustrates the type of organic waste used for treatment by *H. illucens* larvae.

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Table 4. Type of organic waste suitable for *H. illucens* larvae treatment

Organic Waste	Origin
Human manure	Fecal 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 industry dried distiller grains, wheat, bran, billed grains and grinding dust
Poultry feeds	Uneaten feeds used for poultry

4. *Hermetia illucens* in the management of dead bodies

H. illucens is a detritivore commonly 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 interval (PMI) based on the life cycle of the *H. illucens* with one example in northern Brazil [33]. Given its natural presence, *H.* illucens can play a natural solution of carcasses and corpses apart from the commonly used method of incineration/cremation.

Studies on swine carcasses found the female *H. illucens* to lay 620-700 eggs per posture in concealed cranial cavities with about 93 % of the eggs hatching. The larvae were found under the swine skin and on bones. Interestingly, the *H. illucens* did not seek out drier sites for pupation after feeding but burrowed deeper into the carcass instead. Pupae were observed as of the 60th day after death with the *H. illucens* lifecycle taking ~53-82d to complete when compared to manure and food waste. 11 % of the *H. illucens* in the carcass reached adult stage [34] with room for further optimization for such applications.

5. *Zophobas morio* & *Tenebrio molitor* in the circular economy

Also voracious eaters but at a much lower rate than the *H.* illucens, the *Z. morio* and *T. molitor* can also contribute to a circular economy of food waste in a significant way. Interstingly, their value comes in dealing with plastic waste, particularly polystyrene (PS) and polyethylene(PE). It is their ability of consuming and mineralizing PS & PE [16,35] that would be the focus of their contribution to the circular economy of plastic waste.

Both PS & 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, but the efforts are often unsustainable in terms of cost, and with the very harsh chemicals themselves becoming environmental problems. While plastics do not occur naturally, nature has a solution to man's artificial problem in the insects. These biological expertise include: *Tenebrio molitor* [36–38], *Zophobas morio* [35,36,39] and waxworms (*Galleria mellonella L.)* [40,41] to utilize PS and PE for mineralization [35,36,39–41] as a carbon source. Fully digested, their frass can be utilized as natural fertilizers.

5.1 Polyethylene (PE)

Among the myriad of commonly used plastics, PE is the most chemically simple, comprising of just carbon and hydrogen bonds, yet its molecular make-up makes it resistant to natural degradation. Compared to PS, PE is of higher density and ultra-high molecular weight, making it more impact-resistant and durable. PE is resistant to chemicals, UV light, and moisture, with it easily made into sheets, films, and other fibrous forms.

Given its thermostability up to 122 °C with 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.

Despite being completely recyclable, the sheer volume of PE products as construction and packaging discarded daily had largely overwhelmed the recycling capabilities, resulting in wastes. Compounding this problem is the issue of food waste contamination for most of these packaging waste.

5.1.1 Biodegradation rate of PE by *Tenebrio molitor*

T. molitor can live solely on a diet of low-density polyethylene (LDPE) [42]. Three strains of *T. molitor* (Guanzhou, Tai'an, and Shenzen) tested showed the rates to be 172.2 μg, 102.7 μg, and 138.6 μg per day per larvae respectively [43]. When the feed comprised solely of PE and when PE was mixed with wheat bran mixed in, 226.6 μg and 286.5 μg of feed were consumed respectively per day per larvae [44]. In the examples, PE were successfully metabolized *T. molitor* although there had yet a rate of consumption of PE apart from high-density polyethylene (HDPE).

5.1.2 Biodegradation rate of PE by *Zophobas morio*

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

5.2 Polystyrene (PS)

Contrary to PE, PS is not a biodegradable plastic and is resistant to acids, bases, and photolysis and is not easily recyclable. The expanded polystyrene (XPS) is rigid, and its porous nature prevents pressure buildup. PS is commonly available in sheets, films, and form foams at low prices with it being low cost with its high thermostability of up to 200 °C. Given its easily shape, PS a popular option within the food industry.

5.2.1 Biodegradation rate of PS by *Tenebrio molitor*

The average consumption rate of PS for each *T. molitor* was reportedly 0.12 mg of PS per day per larvae [16]. 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 at a rate doubled when compared to PS alone [44–46]. *T. molitor* showed increased consumption of PS when they are of lower density 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 [36].

5.2.2 Biodegradation rate of PS by *Zophobas morio*

PS was reportedly consumed at the rate of 0.58 mg of PS per day per larvae[16], four times more than that of *T. molitor*. A parallel study normalizing by per gram of worm, reported the rate to be at 1.04 mg of PS was consumed per day for each gram of worm. With the additions 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 present, respectively [36].

5.3 Challenges in plastic waste treatment by larvae

The rate of digestion of PS by these worms occurs at a rate slower than *H. illucens* for organic material requiring around a week an 3,000 to 4,000 *T. molitors* to completely eat and digest one XPS coffee cup [48]. Even after digestion, there remains uneaten microplastics and plastic monomers in the frass [16,49,50] requiring re-eating and further digestion. *Z. morio* & *T. molitor* are also unable to consume high-density PS & PE, requiring them to be processed to mediate easier consumption. Thus, there remains a lot of optimizations prior to large-scale processing of plastic waste such as:

1. Prolonged incubation with the worms, given that PS/PE degradation by these worms requires some time [49]. The advantage is that the worms are low maintenance, can eat food-contaminated plastics, and do not fly, making containment easier.
2. To decrease the microplastic content excrement by having multiple layers of worm feeding chambers where lower levels of worms will consume the frass and reduce microplastic and monomer content [36].
3. Depolymerization of PS/PE into smaller fragments such as dimer, trimer, *etc.*, resulting in a decrease in its density and molecular weight for easier consumption by the worms.

6. Insects as a source of feed for monogastric animals.

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

6.1 Constitution and potential in *Hermatia illucens* larvae in the market

As *H. illucens* garners attention of livestock farmers due to its highly marketable as an animal feed, the focus of its nutritional content and how they can be improved gathers importance. Typically, the *H. illucens* larvae biomass contains 32-58 % proteins and 15-39 % lipids [19] which is suitable for the production of animal feeds including poultry, swine, fish, pets, and usage in biofuels [13,14,19,29,52]. The defatting of *H. illucens* larvae can increase their protein content to 55-65 % [53], and the already present lauric acid, chitin, and antimicrobial peptides makes them even more desirable as a feed constituent [29]. Given that micronutrients such as minerals and vitamins are important for poultry and also found in *H. illucens* larvae, they can fulfil this role in also providing iron, calcium, phosphorous, zinc, and vitamin E [54]. However, the potential of accumulating undesirable substances such as toxic metals should nevertheless be monitored [31]. *H. illucens* larvae are rich in vitamin E as mature larvae of the 14th day although this is lower in the early prepupa stages by more than two folds. Nonetheless, the prepupa stage compensated this by having higher minerals content than the mature larvae stages on phosphorous and calcium levels.

With a high feed conversion efficiency than most conventional production animal [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 the insects, the conversion of *H. illucens* is better than *Tenebrio molitor* and *Musca domestica* [18,55] that is primarily influenced by the dietary composition [56]. Table 1.2 describes the crude protein at various life-cycle stage of *H. illucens*.

Table 2. Crude protein percentage at different part of the life cycle of *H. illucens*

Life cycle sage	Crude protein percentage
Larval phase	~38 %
Matured Larvae (Day 14)	~39.2 %
Early pupae	~46.2 %
Post-mortem adult	~57.6 %

6.2 *Tenebrio molitor a*s 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]. *T. molitor* can be constantly produced [58]with the female *T. molitor* laying up to approximately 500 eggs that hatches after 3-9 days at ambient room temperature, 25 °C. The larvae of 2.0-3.5 cm or more [59] stage lasts 1-8 months and have a

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light yellowish-brown color before it pupates for 5-28 days at 18 °C. The adult stage lasts 2-3 months [58]. The approximate size of larvae spans.

T. molitor larvae have been successfully used as a feed ingredient in animal diets, including poultry and swine. Recently, it was approved in the EU as human food [60] especially at its larvae stage. The larvae are dried, grinded and the meal is produced from a by-product of oil extraction. Table 1.5 shows the composition of *T. molitor*.

Table 5. Composition of the composition of *T. molitor*

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

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

6.3 *Zophobas morio a*s an alternative source of protein

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

The *Z. morio* meal is a potential widely used as an alternative feed supplement for birds and fishes due to its protein content. The insect can be found widely in parts of the world, including Central and South America. As an identified alternative to fishmeal, *Z. morio* based diets can potentially be a promising project to evaluate whether the growth performances of fish can be on par with fishmeal-based diets [65]. Table 1.6 summarizes the analysis of fishmeal and *Z. morio* meal composition.

Table 6. Analysis of fishmeal and *Z. morio* meal composition

Composition	Fishmeal (%)	*Z. morio* Meal (%)
Dry Matter	89.24	92.49
Crude Protein	57.53	46.43
Crude Fat	4.75	40.01
Crude Ash	12.75	3.54

6.4 Concerns of larvae as feed

When using insects as animal feed, the insect chemical defences such as toxins produced by their endocrine glands [66] should be monitored. The *T. molitor* can secrete benzoquinone compounds from its glands [67]. Benzoquinone, a toxic metabolite for humans and animals, interferes with cellular respiration and has a carcinogenic effect while also causing kidney problems [68]. Typically, benzoquinone is continuously accumulated, so it increases as the *T. molitor* ages. However, it remains unclear how much benzoquinone stays in the larvae's body after processing for animal feeds and the tolerance levels in monogastric animals [58]. These larvae can also be contaminated by pathogens or mycotoxins from contaminated diets such as *Salmonella spp.* given their natural high bacteria load consisting of members of the *Enterobacteriaceae spp*. In the concerns of microbial safety, the insect gut is considered the primary habitat, with microbes found also on the body surface and mouthparts. Microbes are vertically transmitted from the ovary, eff capsule to spawning, as well are horizontally through the feed and environment [69,70].

Yet, the microbiota ratio in the insect gut plays an essential part of being used as food sources given that it contributes significantly to the total amount of biomass at 1-10 % of insect body weight [71]. For this reason, it is not necessarily beneficial to remove the gut apart from the obvious labour required. Nonetheless one area of concern is the potential accumulation of heavy metals such as mercury, cadmium, and arsenic from the environment that could be passed on in animal feed [72,73] requiring monitoring.

7. Entomophagy by human

In addition to these issues, consumer acceptance and regulatory authorities need to be addressed. For the former, consumer's perspective toward insects as food, especially insects fed on plastic is a challenge, much less convincing for regulatory authorities.

In some cultures, insects are viewed as fallback foods associated with marginal environments [74], 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 [75,76] requiring approximately double the current food production [77]. With global warming is gradually reducing food production worldwide [78], and with the recent Covid-19 aggravating the waste and resource shortage, several foods have been proposed as alternatives, with insects receiving the most attention [79,80]. With the Covid-19 pandemic expected to continue throughout 2021, into 2022, and possibly beyond [83], and the measures affecting the access of food by the poor and helpless, there is a need to relook at alternative foods, but also to revisit historical foods.

Historically, the scarcity supply of sophisticated tools and hunting ability meant that ancient cultures were likely to consume insects frequently. Upon the introduction and development of agriculture and domestication of livestock, insect-eating habits have been disappearing in many regions [81]. The resultant abundance of food naturally could cause a decrease in the need for insect consumption [79]. With changing cultural conventions, insects have transitioned from a primary food source to snacks, exotic ingredients, and bait [82]. However, some countries have continued to use insects as ordinary food resources to this day.

Toay, sustainable insect farming can substantially increase food security, especially in areas vulnerable to environmental stochasticity [79,84–86]. The standing committee on plants, animals, food, and feed has adopted the regulation authorizing the placing on the market of the dried *T. molitor* as a novel food. *Novel foods* are defined as not having a significant history of consumption or is produced by a method previously used for food. Although there is informal evidence of insects consumed as food in the past, no member state has confirmed human consumption to a significant degree before 15 May 1997 for any insect species [51].

The approval was followed by a stringent scientific assessment by the European Food Safety Authority (EFSA). Through the assessment, scientific evidence suggested that it does not pose a safety risk to human health. The approval of such novel food is one of the final steps in allowing the commercial selling of these delicacies to the public [51,59,63]. However, it is entirely up to the consumers to decide whether they want to eat insects or not. Insects as an alternate source of protein are not new, and insects are regularly eaten in many parts of the world

8. Conclusion

The application of insects in treatments of environmental pollution is an emerging yet lucrative field. We believe that only a superficial layer of such technology has been touched, with plenty of untapped utility for both the environment and society. The application of insects is proved to be a viable opportunity in a circular economy with *H. illucens* as a workhorse for biowaste treatments for private and public sectors. This biowaste treatment system has potential to an alternate solution to current methods and in some sense more beneficial with their frass as good fertilizer for their NPK content. To complete the circular economy cycle for *H. illucens*, they can be used to feed monogastric animals and fishes based on lipids and protein content beyond extraction of other compounds e.g., chitin for medical purposes and melanin as pigmentation and protection against damage from ultraviolet lights.

With the promise of *Z. morio* and *T. molitor* to degrade PS and PE, one of the world's major issues has a natural solution. With further research on them, these insects may be able to join *H. illucens.* As farm animal feeds along with their frass as fertilizers. However, their speed is currently slow, but with their low maintenance, they can be self-sustaining natural solutions in landfills and dumpsters to reduce food waste contaminated plastic waste.

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