Chapter

# The Insects as a Workforce for Organic Fertilizers Production – Insect Frass

*Regina Menino and Daniel Murta*

## Abstract

Following the evolution of composting technology, the process of digestion of a biological substrate by insects (entomocomposting) represents the last stage; however, from its initial context of producing an organic fertilizer, the role of entomocomposting has been imposing itself (due to increasing demographic pressure) mainly in the safe disposal of organic waste (in rampant growth) and in the breeding of insects for food and feed, for the sake of food security. Both these last goals converge in the first, as the safest disposal of the compost is its use as organic fertilizer; but the organic substrates are of a diversified nature, as are the species of insects which have already proved themselves in entomocomposting; hence, for each of the purposes in view, the choice is vast and, in the same way, the entomocompost composition is wide-ranging. Furthermore, various types of organic substrates, in addition to a microbial flora with symbiotic effects, may sometimes be able to transmit to the frass a harmful load of heavy metals and/or, depending on the composting insect agents, the presence of microorganisms harmful to crops and to humans and animals; in these situations, the former should be encouraged, and the latter counteracted through appropriate composting technology. Directives and legislation in this area, if properly considered, constitute a fundamental basis for ensuring the appropriate use of this particular kind of organic fertilizer. Apart from the production of insects for food and feed, where the choice of which insect is determined at the outset, the preference for the insect to be used in entomocomposting should be considered according to its proficiency in biological digestion of the organic substrates available for this purpose and the fertilizing quality of the frass produced. Although a multitude of species have been evaluated, to date, for the digestion of organic substrates, most have been used in assessing their specific potential for certain functionalities of frass related to crop nutrition and health, but there are few which, either by prolificacy, proficiency or rapidity in digesting substrates, exhibit capacity to compete in rural environment; nevertheless, new species could be evaluated in the framework of the research of competitors for entomocomposting of all or each substrate type and for each of the main anticipated objectives, meanwhile, genetic improvement to obtain new strains specialized for different organic substrates has already started to take its first steps. In addition to the binomial "insect x substrate" the composting technology constitutes the third fundamental factor for the efficiency of the process. Insects use as a composting agent has been suggested several decades ago, but it was only in the last decade that this process grown from the garden to the factory. Within rural areas, entomocomposting could play a key role within a circular economy, where recycling and reusing potentially polluting wastes safely returns to the land the enduring fertility that enables the sustained production that generated them, requiring no particularly upscale installations, equipment or technical training; it can, therefore, be adapted to any size of agricultural holding, from smallholdings to large industrial holdings, on the other hand, and in order to obtain a controlled production and high quality entomocompost, it is needed to implement industrial technologies and the composting unit can achieve a very high production per square meter, comparing with traditional composting methods. However, whether from the perspective of agriculture, livestock or forestry, the production of waste for entomocomposting always falls far short of the necessary scale, and therefore always requiring the use of biodigested organic waste from agricultural industries, provided that the necessary precautions are taken; in any case, it always constitutes added value, due to the products it generates, in addition to the inestimable value of the productive disposal of potentially polluting products. Despite all the advantages mentioned above, the controversy over the organic vs. mineral fertilizer option persists, often fuelled by myths on both sides, but the successes already achieved with insect entomocomposts, such as the black soldier fly (*Hermetia illucens* L.) or the mealworm (*Tenebrio molitor* L.), in field trials, which are gradually adding up, anticipate an important role for insects in safeguarding global food and environmental security.

**Keywords:** soil fertilizers, biodigestion, entomocompost, insect frass, sustainable agriculture

## 1. Introduction

The first alternative to the traditional aerobic composting of organic waste was vermicomposting; however, according to Čičková *et al*. [1], Lindner already in the second decade of the last century (1919) had proposed the use of insects (in accordance to his experiments with the house fly (*Musca domestica* L), to recover nutrients (especially fat) from organic waste; this could have been the threshold for entomocomposting research, nevertheless, it is only a few decades later that some experimental work appears in the context of the disposal of potentially polluting organic waste.

Nowadays, suitable technologies have already been developed for a diverse range of target functionalities of entomocomposting, namely:

- The treatment of polluting organic waste for safe disposal, from the point of view of environmental safety;
- The production of insects (in the larval, pupal or imaginal stage), from the perspective of food and feed security;
- and the production of an organic fertilizer, from the perspective of rationalizing sustained agricultural production and reducing to minimum the environmental impact of agricultural activity, without prejudice of the optimum levels of the potential production in each "soil-climate-culture" interaction process.

Whatever the main objective is, the entomocompost will always provide invaluable added value (as produced or, possibly, after suitable treatment) for safeguarding food security and the environment, due to its potential in the immediate and deferred fertilization of agricultural soils, so as in the recovery of exhausted soils and even in the inclusion of new unproductive land, as, for example, in the case of abandoned mining sites.

But when we talk about entomocompost we are referring to a product with a very diversified physical, chemical and microbiological composition, depending on the nature of the substrate to be digested and the species used to produce it; thus, the option to obtain an organic fertilizer by entomocomposting for pre-defined main purposes, requires taking the following into consideration, as regards the elements of the above mentioned "substrate-insect" interaction: On the one hand, knowledge of the nature of the substrates to be biodigested and the more adequate species to do the job; on the other hand, the eventual treatment of the substrate that may enhance more efficient bio-digestion and/or specific qualities of the frass, and the choice of the best insect species (or genotype within the elected species) in order to obtain most efficiently the entomocompost that is more suitable for fertilizing the soil and the crop for which it is intended.

This would be ideal, and to some extent feasible, at rural level, however, the production of entomocompost for crop fertilization is still in short supply, even counting on the compost obtained in a different context.

Organic bio-digestion by insects for the production of entomocompost also requires the choice of technology to be adopted, both for industrial production and for medium-scale production in rural areas (either at cooperative scale or at farm level), and in the case of agricultural and livestock holdings, it evokes the choice of a circular economy system.

This chapter deals with the knowledge that informs the decision to be taken for all the aforementioned options, by the some other, concluding with a compilation of the experimental results that we consider most relevant with regard to the relative fertilizing potential (immediate and deferred) for specific situations of the "soil–plant-fertilizer" triad interaction. Some notes on insects regarding food and feed are anticipated, as they are inextricably linked to the production of the entomocompost.

## 2. Insects as food and feed

The present COVID-19 pandemic has shown how Europe is hostage of the international feed market, and as far as nutrition is concerned, protein is a huge problem to be solved. However, society continues to waste food products, contributing to a very inefficient agriculture vale chain in which more than 25% of food products can be lost.

Based on a one hundred percent circular economy-based approach, vegetable by-products can be converted into high valuable nutrient sources for both animals and plants. Insects can be the key for the transformation of this otherwise lost nutrients into new nutritional solutions not only for both humans and animals, but also for plants.

In a very short period, insects can convert a very large range low value by-products into high value insect protein and oil for animal and human nutrition and insect frass, and organic fertilizer for plants. With this process, now completely industrialized and at a full-scale level, it is possible to reduce the Europe dependency from the international feed and food markets, contributing to a local and more sustainable food production.

As mentioned, nowadays, feed producers face several significant global challenges to find suitable resources to produce compound feed for livestock, aquaculture, and pets. On the one hand, the growing demand for animal products, and thus for animal feed, associated with the need to find resources with reduced environmental impact, has led to the development of novel feed ingredients, and moves to decrease dependency on common resources, such as soybean meal, maize and fishmeal. The current use of these resources is assessed as being unsustainable therefore driving the need for alternative ingredients to maintain the balance between food, feed and biofuel industries. Land degradation, water deprivation and drastic climate change are additional challenges impacting on livestock production, aquaculture and the pet food industry.

On the other hand, recent events have illustrated the need to reduce our dependency on imported resources, specifically from other continents, strengthened by consumer opinion exerting pressure to provide more 'natural' food production for humans, livestock and pets. Accordingly, the development of novel sustainable raw materials plus improved efficiency of resource use play, and will continue to play, a vital role in ensuring the sustainability of feed manufacture.

Significant relevance is now placed on the development of new feed resources based on environmentally friendly approaches, circular economy solutions, and the use of natural resources. However, it is not likely in the near future to be feasible to completely replace existing feed ingredients with novel ones, leading to a focus in the sector on improving efficient use of existing ingredients, thus decreasing demand.

Some novel food and feed ingredients have the significant advantage of making use of available agri-food co-products and transforming them locally into new nutrient sources. Insects are one such ingredient that has the capability to convert low value vegetal co-products into a high value nutritional solution, while also aligning with the environmental drivers that are prompting the food and feed revolution.

It has been estimated that food waste accounts for 23% of arable land and 24% of freshwater resources used for crop production [2]. Thus, it is relevant to evaluate the use of insects in feed from a circular economy point of view. Insect rearing can potentially be used to upgrade low-value organic food waste streams increasing the efficiency of natural resource use and animal production.

Several livestock production companies in the world operate vertically, producing feed for the animals, raising and processing them before market. Co-products include manure and other animal and vegetable co-products as well as former foodstuffs. Insects could be an invaluable tool for such organizations, as they can provide a perfect link between nutrient loss in vegetable co-products, and the protein supplement needed for animal feed.

Therefore, insects have a perfect spot in certain value chains, where, more than creating value, they contribute to natural resource use efficiency through nutrient bioconversion. This might be the greatest contribution of insects to the food value chain, as they have the capability to be integrated perfectly in present day market chains, whilst also converting wastes and less desirable co-products into high value nutrient resources. When applied with the right infrastructure, such systems could contribute to animal production efficiency, environmental sustainability, and supply chain profitability. Furthermore, insects, as for other novel food and feed ingredients, offer the potential to decrease dependency upon foreign products imports, creating new local products, and thus helping to shorten supply chains.

Thus, there is growing interest regarding the use of insects as an alternative ingredient source for both food and feed production. The use of alternative ingredients in animal diets can be optimized in terms of their nutritional characterization, their safety and technological quality, in order to achieve better performance as well as facing the challenges of increased feed demand in volume as well as quality and sustainability factors.

Insects can supplement traditional feed sources such as soy, maize, grain and fishmeal, with several different species of insects considered for use as a partial or total substitute of traditional feed sources [3–6]. Many trials have been conducted with different animal species, both terrestrial and marine, with the challenges associated with the use of insects in these animals changing, dependent not only on the animal species being fed, but also on the insect species being used, and the rearing substrate on which it was grown. However, it has also been demonstrated that different organic substrates can be used to rear insects, such as Black Soldier Fly (BSF), without significantly affecting its amino acid composition, the profile of which has been shown to be similar to that of fish meal and soybean meal [3, 7]. By contrast, when considering fat and ash composition, both can differ substantially according to the rearing substrate [8]. Thus, insect nutritional and technological properties are linked to the species, rearing system adopted and especially to the substrate used [8].

On the other hand, the so produced novel plant nutritional source, entomo-compost, can contribute to a wide range of soil solutions, from drought resistance and plant nutrition to even pest control and sprouting promotion.

However, this novel sector still faces several challenges, from legal to consumer acceptance and to industrialization and growth. Although the legal framework is changing and adapting to this new reality, consumers still have to prepare for it, and insect producers have a lot to learn from other livestock and industrial sectors. Besides that, the use of insects as a tool to other applications is still in its infancy, as insects can be used from bioremediation in garbage disposal systems, to the production of new plastic solutions.

## 3. On the substrate to be composted

If initially the use of uncontrolled composting of organic agricultural wastes may have been motivated by obtaining a fertilizer for crops, as in the case of the use for this purpose of animal bedding and manure slurry, the fact is that subsequently, with the exponential growing production of industrial and urban organic waste, the emphasis has shifted to the disposal of polluting waste.

Within this last context, controlled composting methods have been developed [9], including in its motivation for the production of arthropods and worms for food and feed, and not least for the production of organic fertilizers; in fact, food security is no less relevant, and to this end the resilience of agricultural soil fertility, the restoration of depleted soils and even the acariation for agricultural production of infertile soils hitherto ignored for this purpose, without compromising environmental security, is urgently needed.

But fertility is an ambiguous concept when applied in relation to the productive capacity of agricultural soils. Actually, boosting the full productive capacity of a given plant species (or even of a given genotype of the same species), depends on rigorously reconciling its physical and chemical requirements with the soil and climate conditions in which it is located, and these can be very diverse – in poor soil conditions, a primitive variety has more yield potential than a variety improved for yield capacity [10, 11].

However, that above-mentioned objective, of full productive capacity, will not always be the most appropriate if it is not based on economic, environmental and ethical considerations, because maximizing production does not always lead to greater financial return, it frequently translates into an environmental burden and it often forgets the responsibility of the agricultural sector in the context of global food security.

With regard to soil fertilization, which underlies the subject of this Communication, the above considerations are also valid: Soil fertilizers should be required to provide an advantageous cost–benefit balance, to cooperate in protecting the environment, and to increase the resilience of soil fertility as a basis for long-term food security. According to these requirements there seems to be difficult to find a perfect type of fertilizer.

As with the majority of organic fertilizers, the main virtue of entomocompost lies in their action in correcting the physical, chemical and microbiological properties of soils (a fundamental factor in their deferred fertility) and in supplying the mineral elements necessary for each crop, in each specific situation (an important factor for their immediate fertility) [12]. Furthermore, entomocomposting can be a relevant factor in recycling exhaustible plant nutrient resources; an example of this is mentioned by Zhang *et al*. [13], when they observe the accumulation of phosphorus in the frass of grasshoppers as a function of the stoichiometric homeostasis of the N:P ratio in their bodies.

Any entomocompost is, however, more than the frass obtained from a given substrate; apart from the frass, it contains the remainder of the substrate and residues from the metamorphosis of pupae into adults (if not the pupae themselves). This is not entirely true in the case of biological digestion by the BSF larvae, which evidences the unique behavior of abandoning the compost at the pre-pupa stage, a phenomenon with obvious advantages in pupal harvesting and which is referred to in the bibliography as self-harvesting. For this reason, for the entomocompost obtained from BSF was proposed [14] the acronym CASH (Compost After Self Harvesting).

But the constraints on the more generalized use of entomocomposts are not limited to those mentioned above. They range from lack of definition of the exact formulation of their composition, to lack of knowledge of the mineralization rate (for formulations of its fertilizing elements that can be directly assimilated by the plants) in the soil and climate situations in question, to logistical and scale limitations to supply. In reference to this latter setback, Timsina [15] states that "considering the current organic sources of nutrients in developing countries, organic nutrients alone are not enough to increase crop yields to meet global food demand".

Through bio-digestion by insects, the formulation of the substrate is largely altered in its physical, chemical and microbiological composition, with decisive consequences on the fertilizing potential of the entomocompost; it, therefore, plays a relevant role in the quality of the compost. As referred by Poveda *et al*. [16], by modifying the insect diet, not only do you get different nutritional content in the frass, but also significant changes in the actual microbiota, both aspects relevant to its ability to be used as organic fertilizer.

As an extreme situation, regarding the nature of the substrate, Koh *et al*. [17] reports that polystyrene, when digested by the coleopteran *Zophobas morio*, produced a starch-rich frass, which promoted the growth of *Hylocereus undatus* plants from both the aerial and root parts.

An entomocompost of a substrate of agroindustry origin, or of remnants and residues from agricultural production, is not seen as a threat of chemical or microbiological contamination of agricultural soil. On the other hand, a compost obtained by insect bio-digestion in industrial urban waste plants, requires analysis and possible remediation if chemical and microbiological substances harmful to soil fertility are found to be present, as for instance in the case of houseflies, with high levels of lead and arsenic in the frass [18].

Entomocompost derived from manure and slurry does not normally pose the danger of soil contamination of any kind, however, in the context of insect production for feed or for food, is not at all suitable, and is subject to severe restrictions. To overcome these constraints, which are mainly dictated by the nature of the substrates, some progress has already been made.

Thus, although the use of unsafe wastes as substrate for entomocomposting can be done with efficiency, as this technic is mainly applied for food and feed purposes, it is quite uncommon to see full-scale insect rearing units using such substrates. In fact, the majority of entomocomposting units, or insect farms, are using vegetable coproducts as substrates for insect production, being its main purpose the production of insects as a protein source and the insect frass a co-product of this process. Nevertheless, and as previously demonstrated, entomocompost is a high valuable product with very good effects in soil fertility and plant health.

This way, entomocomposting should not only be considered as a process to produce food and feed, but also to produce the entomocompost as a main objective, opening the use of other, unsafe, wastes that cannot be used when the produced insects are intended for the food chain. However, such approach will require studies to evaluate food safety concerns in a one health approach, evaluating from environmental impacts and benefits, to possible impacts in the soil and plants. The so produced insects cannot be intended for the food cahin but might well find an economic value as a raw material for biorefineries such as fuel and plastic, or to be also used as fertilizers.

The use of entomocomposting technics to convert unsafe substrates such as urban organic wastes, manure or sewer sludge, is being tried in several R&D projects. Such is the case of NETA project (POCI-01-0247-FEDER-046959), a project in which a new manure and sewer water is being treated with a novel process and the sludge is being tested as a substrate for entomocomposting. This produced insect frass is being tested in vegetable and olive oil production, while the larvae are being evaluated in terms of safety, evaluating both chemical and microbiological contaminants, and being used for industrial purposes.

In order to be possible to produce insects for food and feed purposes with organic wastes as substrate, what would unlock the entomocomposting potential as a bioremediation tool, one should first show if such approach is safe. However, before proving its safety, one of the main challenges in entomocomposting organic wastes is that if we used the same insect species as for the production of food and feed, it will not be possible to differentiate insect products produced with safe or unsafe substrates. Thus, one possibility would be to develop the entomocomposting process of unsafe substrates, such as organic wastes, manure and sewer sludge, with insect species not being used for food and feed purposes. That would allow to differentiate the obtained insect product with DNA testing and would unlock a very beneficial tool for the treatment of high environmental impact organic wastes, transforming them into novel products and returning lost value to the value chain, while contributing to both economic growth and sustainability in a 100% circular economy approach.

Thus, it should be highlighted that using insects for nutrient production is not a goal in itself but can be an instrument to achieve goals in biowaste reduction and conversion, improving sustainability and optimizing the food value chain. Insects should be evaluated as a tool to increase the efficiency of resources use and to increase income, and thus, one must evaluate them beyond their nutrient value as a feed ingredient.

For example, BSF are a rich source of lipids which can be industrially extracted to obtain a pure oil with several different potential uses, from feed and food, to biodiesel and cosmetics. It has been shown that BSF fat could be a useful alternative for other commonly used fats, with specific technological properties in common with palm and coconut oils, which are increasingly associated with negative environmental impacts. In particular, the melting and crystallization behavior of BSF larval fat seems to allow replacement for traditional fats [19].

In addition, the insect exoskeleton can be processed to obtain chitin and chitosan, and its industrial scale production could offer a potential source of prebiotic oligosaccharides for pet, animal, and human nutrition [20]. Applications for chitin and chitosan go beyond nutrition, as chitosan is characterized by non-toxicity, biodegradability, film-forming capacity, antimicrobial and antioxidant properties and good barrier properties of packaging films against oxygen [21–23]. Thus, the potential for the use of insect derived chitosan to produce biodegradable plastics is being evaluated for a variety of applications, ranging from agriculture to food packaging.

Chitin-derived products have also been shown to be toxic to plant pests and pathogens, inducing plant defenses and stimulating the growth and activity of beneficial microbes. Chitin-based treatments augment and amplify the action of beneficial chitinolytic microbes [24]. Such properties prompted the development of novel crop fertilizer and crop protection products, which can be used in conjunction with one of the main insect products, the insect frass. In natural conditions, it is well known that frass deposition to soil has a great impact on soil fertility due to its high nutrient and labile carbon content and, therefore, several companies have already started to sell frass as a fertilizer [25].

## 4. Insects as agents to produce organic fertilizers

With all the economic and environmental advantages in the search for agricultural production that is compatible, in a sustainable way, with global demand, entomocomposts have been affirming themselves as an important alternative for reducing (if not replacing, in some cases) synthetic mineral fertilizers. To this end, several insect species have been evaluated for their proficiency in composting organic substrates.

In a careful literature review, Poveda [26] presents two thorough lists of studies on the use of insect frass as fertilizers, indicating, for each case, the plants, the benefits and the mechanisms by which these benefits were expressed.

In addition to providing the necessary mineral nutrient elements for plants, the benefits provided by adding insect frass to the soil are diverse in nature, such as: increased germination, sprouting, growth and nutritional content of plants; increased tolerance to abiotic stress; activation of the plant's defense mechanisms against pathogens and pests; increased nitrogen in plant tissue; reduced oviposition of pest insects and; increased microbial activity in soils.

However, these advantages are not all concentrated in a single species so, although frass from various species may have a relevant role as a complementary fertilizer in specific situations, few species have shown the potential to produce an entomocompost with the potential to be an alternative to avoid completely mineral fertilization in all situations. One of this specie contradicts the thesis of Lardé [27], supported by Smetana *et al*. [28], that one species cannot be suitable for the huge diversity of organic substrates - BSF has proven to be quite "cosmopolitan", living comfortably in any type of organic substrate experienced so far [29–33]. Note, however, that even in cases - in experimental situations - where entomocompost shows the potential to provide a reduction in synthetic mineral fertilizer, the fertilizing effect of entomocompost can still be enhanced if associated with appropriate soil handling technology. In this context, Dulaurent *et al*. [34], in a pot trial with frass, reports a significant increase in nutrient content in the plant by the addition of earthworms (*Lumbricus terrestris*), by promoting an acceleration of the recycling of fertilizing elements from the frass.

But if the possibility of biotic associations or of physical or chemical corrections of entomocompost for preferential purposes (within the versatility of its benefits in crop nutrition and soil fertility resilience) is a proven reality in the experimental and commercial field, in the field of genetic enhancement of insect species for entomocomposting only the first steps have been taken.

Advances in this field are predictable and particularly desirable, notably when it comes to insects with the ability to adapt to a wide diversity of substrates. This is the case of BSF, which is able to efficiently biodigest manure from various livestock species (from polygastric, monogastric or fish species) as well as residues and remnants from crops or from agroindustry.

The methodologies for this could be very diverse, but the simple continuous selection of pupae fed on the digestion of specific substrates can lead (as it has happened with the generality of animal and plant species already submitted to human-induced selection) to the differentiation of specialist genotypes more competent than generalists, probably because it should be anchored in an evolution towards more targeted physiological mechanisms that are necessarily less energy-demanding; this option, which would certainly not meet with the disagreement of the detractors of transgenics, would only require, as an additional effort, the separation of breeding facilities for flies, even though it may be slower in results, but "constant dripping wears the rock away".

## 5. Entomocomposting technologies

Insect production has grown a lot in the last decade. This new sector emerged with the support of FAO-UN who first referred to this field in the beginning of the decade and started an insect rush in several countries, with the development of new business. However, by then, both the business and the process where not mature yet and it took several years of development to see the first full-scale insect rearing unit being built by a handful of companies. However, the legal framework had not grown at the same rhythm, what promoted a lower growth. At this point, different companies have developed their entomocomposting technics in parallel, and even using the same insect species and substrates the processes can follow completely different approaches.

Besides that, although several approached have been made to create technologies to produce insects, and entomocompost, at a small scale, and although it can be applied at the farm level, it is only economically relevant at a large and controlled scale, ensuring both food safety and traceability.

Large scale insect production is an industrial sector in which several tons of vegetable by-products are converted by insects every day. Contrary to most composting technologies, insect production generally does not use piles of by-products. It processes them into controlled mixes of raw-materials ready to be digested. This raw material processing allows a steady rhythm of conversion and production. In most cases insects are thus reared inside plastic boxes of different sizes in large controlled environment warehouses. The time needed for composting and the number of insects to be used to convert each ton of by-products change from insect specie to insect specie and between companies. The main insect species to be used for food and feed are *Tenebrio molitor* and *Hermetia illucens* (BSF), however the last one is more prone to be used as an entomocomposting tool, as it have a large range of vegetable by-product conversion capabilities. BSF can convert decaying by-products in as few as 7 days, depending on the technology used, and some of the already existing BSF production units can convert as much as 100 tons of vegetable by-product every day into 20 tons of insect frass, while also producing 17 tons of insect larvae. However, this numbers and process greatly change between companies, which all apply different technologies, even when producing the same insect species.

Therefore, insect production has not only to achieve economically viable production at scale, investing in new full-scale insect production units, but it must also be standardized, to obtain a steady production and uniform product. Standardization is key not only in relation to a single production unit, but also between different producers. Insects as a food and feed resource, and also as a plant nutrition source, would greatly benefit from standard quality and nutritional values when considering the same insect species and product. This would increase farmers trust in this novel fertilizer. However, different insect producers may use different insect species and rearing substrates, as well as different production and processing techniques. This results in different products, with different nutritional values and properties, entering the market.

Nevertheless, as the insect rearing industry is only in its infancy, we believe that in the future the production and processing of insects and frass will tend to be more similar between operators, as different production processes and technologies attain relevance in the sector. One opportunity to increase standardization and quality of insect products might be technology transfer between companies, enabling rapid growth of this novel sector and allowing investors and new operators to enter the market without the need to invest in the development of processing technologies. Technology transfer from other companies and research institutes that have spent recent years in R&D will have processes providing the most suitable solutions, avoiding the need for new producers to start from scratch, costing time and money as well as decreasing the chances of success for new businesses.

## 6. The role of entomocomposting in the context of a circular economy in rural areas

For Zink & Geyer [35] "the proponents of the circular economy have tended to look at the world purely as an engineering system and have neglected the economic part of the circular economy"; to this assertion, the facts have been demonstrating, convincingly anchored in science, that the linear economy alternative, in turn, blatantly belittles the environmental part.

The circular economy is "a new economic model operating in closed circuits, catalyzed by innovation throughout the value chain" [36], and, within the agrarian economy, whether in plant or animal production, entomocomposting is an innovative alternative, more efficient than traditional composting, to reduce the import of feed and fertilizers and energy losses, with added advantages in terms of safeguarding the environment.

This is how the entomocomposting of crop remains and residues, so as livestock production wastes, is a multifaceted pivotal factor of the greatest relevance to different circularities within farms, as shown in **Figure 1**.

The circularities represented in the diagram are multiple and interlinked and are not necessarily closed. In fact, there will always be a need for outsourcing, both for supplementation of feed and fertilizer, in quantities compatible with optimizing the efficiency of the entomocompost and the feed value derived from pupae.

The protagonist in this diagram is BSF, for the peculiarities that distinguish it, in a positive way, from the other composting agents, namely:

- High prolificacy;
- High proficiency and speed in biodigestion;
- Widespread range of organic substrates that have the potential to digest;
- Efficiency in the elimination of potentially harmful microorganisms;

*DOI: http://dx.doi.org/10.5772/intechopen.100144*

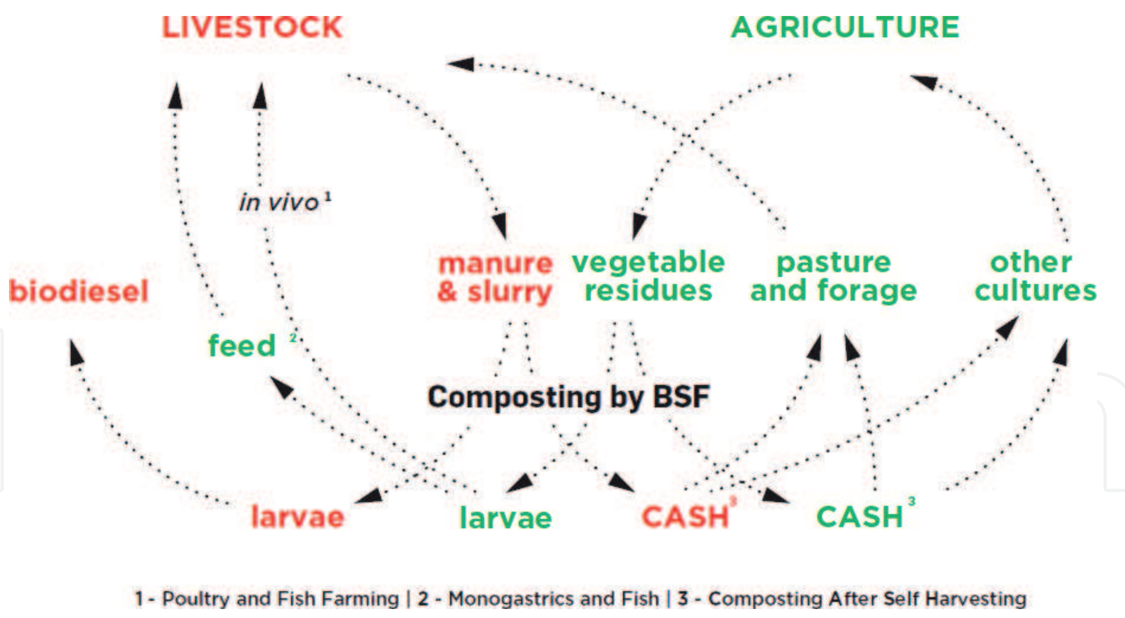


**Figure 1.**
*Multiple circularities driven by BSF on farms.*

- The ability to drastically eliminate housefly multiplication during digestion processes;

- Capacity to provide the presence of plant growth factors in the CASH.

But beyond these, two singularities, particularly relevant in agricultural and livestock holdings, distinguish them from other insects:

- Self-harvesting and;

- The fact that the adult does not have a developed mouth apparatus, feeding on the copious reserves accumulated in the larval stage, and thus does not bother (or even transmit diseases to) humans and animals.

Finally, and following the results reported by Yildirim-Aksoy *et al*. [37, 38] in trials with channel catfish (*Ictalurus punctatus*) and hybrid tilapia (*Oreocromis niloticus* x *O. Mozambique*), frass obtained by biodigestion by BSF of suitable substrates, more than an organic fertilizer, can be a feed in aquaculture.

Notwithstanding the fact that entomocomposting by BSF has already proven to be highly efficient in recycling and reuse capacity in the plant and animal production circuit, the deficit generated in the export of plant and animal products to the market means that feed and fertilizers have to be imported. To this end, in rural areas, initiatives (possibly of a cooperative nature) for the production, on an industrial scale, of entomocomposts and larvae (or pupae) for soil fertilization and feed, allow the circularity of the production system to be extrapolated from the individual sphere to the community sphere; With this type of initiative, the agroindustry will play a relevant role, with additional advantages in terms of capacity and fluidity of the system, broadening the scope of circularity at regional level.

## 7. Data in the context of the trinomial "soil x plant x fertilizer"

Most of the research on the role of insects in soil fertility has focused on specific aspects of the benefits of their frass, not necessarily obtained through the technological composting of organic waste but through their metabolism as part of the soil entomological fauna; with this last aim, numerous studies have been published, as it can be seen in the comprehensive listing by Poveda [26].

These *in situ* studies focus on the possible symbiotic effect of frass within the particular soil entomofauna, in different ecosystems, to assess their role in the ecological balance of the same, particularly with regard to nutrition and phytosanitary aspects of the crop species.

When it comes to the use of a compost derived from off-site insect digestion of organic waste, a more objective assessment of its fertilizing potential, although guided by scientifically well-founded theoretical considerations, should be further informed by evaluation in preliminary production trials in a conditioned environment, in accordance with the pre-defined end goal.

The fact that seldom these trials showed a decrease in production - as was reported by Alattar *et al*. [39], when comparing processed food waste via Microaerobic Fermentation and BSF larvae biodigestion as soil fertilizers in maize, or Gärttling *et al*. [40], with a BSF frass in a low nutrient potting soil - may not mean that, in the overwhelming majority of experimental trials, the results with entomocompost compete with mineral fertilizers; it should be noted that on the one hand, the implementation of field trials is often preceded by a prior study of the feasibility of the hypothesis and, on the other hand, that regrettably a large proportion of the trials that do not confirm the hypothesis are not reported.

Some pot tests have shown the potential of entomocompost, obtained from substrates of various kinds, to reduce mineral fertilization in several crops, as for instance: With mealworm (*Tenebrio molitor* L.) frass, in barley [25] and ryegrass [41], and with BSF frass, in basil and Sudan grass [42], chinese cabbage [43], yard-long bean [44], lettuce [45, 46], ryegrass [45, 47], maize [48] and swiss chard [49].

Also testing the potential fertilizer value of BSF frass from several origins and for different plant species, in pot experiment, comparing either with other organic composts or with commercial substrates, the results found by Newton *et al*. [42], Rosmiati *et al*. [50], Setti *et al*. [51] and Kawasaki *et al*. [52], were encouraging, resulting in yield increases when using frass in certain amounts.

Although these results are encouraging, the conclusive proof, which is specific to the conditions that characterize the experimental situations, can only be given in the light of the results of the field test. Trials of this nature are still scarce and will never allow abusive extrapolations, but they constitute the most valuable information on the fertilizing potential of entomocompounds in relation to mineral fertilization.

Notwithstanding the fact that Temple *et al*. [53] have not foud positive results in a field trial with beans, using a BSF EntomoCompost (BSFEC) from food waste, most of the field trials where entomocompost is used as a complement of the mineral fertilization, for contrasting with exclusive mineral fertilization, have shown an increased production for the mixt alternative. This was the case reported, among others: by Anyega *et al*. [54], in a 'acric ferralsol' trial with tomato, kale and fresh beans, with BSFEC from Brewer's spent grains; by Quilliam *et al*. [55] in a 'Ustic duraquert' trial with chili pepper and shallots, with an identical entomocompost, so as in the same soil, with maize; and by Temple *et al*. (*op. cit*.) in a 'Humic Gleysol' trial with bok choi, lettuce and potato, with BSFEC from Brewer's spent grains.

These results support the thesis that in the experimental situations tested to date, the percentage of CASH capable of competing with mineral fertilization alone, in what concerns the immediate fertilization for crops, is between 10% and 40% in volume. More optimistic results were seen, for example, in a demonstration field [56] with potato (*Solanum tuberosum*), comparing traditional mineral fertilization without and with CASH (from the digestion of agroindustrial waste of potato and onion), where a 9% increase in yield was recorded and, in addition, the tuber specific weight, and the percentage of dry matter were also higher when combining both fertilization approaches.

The arguments mentioned so far, based on experimental results endorsed in the literature, justify promising perspectives regarding the role of insects in the production of organic fertilizers capable of allowing a reduction of mineral fertilizers as far as the immediate fertilization of crops is concerned; nevertheless, more important than the immediate fertilization of crops is the deferred fertility of soils, both in the resilience or increase of their fertility and in the acariation of soils rendered unproductive by anthropogenic or climatic effects.

In any case, the medium- and long-term promotion and resilience of the fertility of the soils, which should be fostered by insect frass, would be translated, as for the generality of organic fertilizers, by the improvement of the structure of the soils and its capacity to retain water and crop nutrients and as well as by symbiotic interaction with the soil microbial flora and with the plant. Many knowledge within this perspective is still needed, but also a lot have been accumulated, allowing for hopeful evidences, such as: better use efficiency of P and K [57]; improved soil fertility and defense against pathogens [58]; suppression against *Pythium ultimum* [59]; influence on soil N availability [60]; stimulation of soil microbial activity and diversity [25]; not impairing hygienic properties of soils [47]; improvement of microbial activity [41]; increased dehydrogenase activity [61]; or increased enzyme activity (dehydrogenase and β-glucosidase) [46].

These data augur well, but medium and long-term field trials are indispensable for continued soil fertility management, since organic matter resilience is not its greatest virtue, particularly in tropical and sub-tropical climates.

Despite being still at the beginning of its career as a biodigester, for the production of organic fertilizers, and beyond the benefits of the utmost relevance in the perspective of safeguarding the environmental balance and food safety, research and experimental development has already given concrete proof of its potential as an indispensable partner in the resilience and recuperation of soils for agricultural production.

## 8. Conclusions

The role of insects in the biological digestion of organic substrates, with a view to the fertilizing potential of entomocomposts, has raised a growing commitment from the scientific and technical community in the field of agriculture and environmental protection; however, despite the accumulation of positive results from the application of this type of fertilizer, significant progress is still expected in this sector, with the improvement of the genetic capacity of insects, of the pre-treatment of substrates and of the entomocomposting technology, so as the adequacy of fertilization techniques.

In the context of the organic fertilizers, entomocomposting takes precedence over other composting methods, mainly because of the speed of the organic waste digestion process, drastically reducing composting time and thus the risk of environmental pollution, besides advantages such as soil health, pest control, sprouting and germination potential.

Various insects have been tested for their potential in digesting substrates of a very different nature, giving rise to entomocomposts with positive results, in reduce mineral fertilizers, in crop production, or as correctors of certain chemical and/or microbiological deficiencies, not to mention physical soil deficiencies, for which any organic fertilizer is capable of dealing with.

Nevertheless, more results are expected with further research into entomocomposting technology, with the discovery of new insect species and their genetic improvement for the biodigestion of different organic substrates, and with new techniques for the enhancement of the fertilizing effect of composts, in order to make available suitable formulations for different "soil x plant x fertilizer" interaction situations.

Until now, as shown in the tests presented in this analysis, the greatest success in the contentious debate "organic vs. mineral" has been achieved in situations of compromise, where the organic fertilizer has the complementary role, by its relatively low and unbalanced nutrient content, notwithstanding its biological interaction with plant and soil microrganisms, its action in improving the soil's physical properties and its capacity to retain water and nutrients – so, as advocated by Ronald and Adamchak [62] or Amman K. [63], and as Saint Tomas d'Aquino said so well, '*in medio stat virtus*'.

Furthermore, although growing exponentially, increased production of organic waste for entomocomposting is unlikely to be sufficient to ensure global food security on its own, as it is a direct function of population growth; suggestions based on success rates reported in the literature for insect frass - ranging from 10 to 40% by volume - may be realistic to be expected, at least in the medium term. In fact, if the potential of the triple valence of entomocomposting (protection of the environment, food security and resilient soil fertility) can already be categorically stated, the use of entomocompost as a fertilizer still faces the major constraint of the lack of scale of its production.

Considering all these possibilities, insects must be recognized not only as a nutrient source but also as a tool. The value of insects can surpass the production of nutrients and the use of its by/co-products to increase its profitability. In the near future insects could be used in manure and household waste treatment approaches, decreasing the environmental impact of livestock production and landfill volumes [5, 64, 65]. This approach would open a completely new opportunity for insect rearing, that is distinct from insect production for animal nutrition which must comply with safety and hygiene regulations.

Increased sustainability of animal and food production can be delivered by insect use, not only through the development of new feed resources but also by contributing to the reduction and conversion of wastes into novel raw materials for bioindustry and biorefinery approaches.

There is still much to do in this regard but, in rural areas, the proposal of a circular economy system in the management of agricultural, livestock and forestry production, with circularities within private farms to be extrapolated (cooperatively) to the regional level with agroindustry and an industrial entomocomposting unit, deserved to be weighed up.

## Acknowledgements

This chapter was performed under the scope of the NETA project: New Strategies in Wastewater Treatment (POCI-01-0247- FEDER-046959) funded by PORTUGAL2020.

## Author details

Regina Menino[1] and Daniel Murta[2,3,4]*

1 Instituto Nacional de Investigação Agrária e Veterinária, IP (INIAV), Oeiras, Portugal

2 EntoGreen-Ingredient Odyssey SA, Santarém, Portugal

3 CiiEM-Centro de investigação interdisciplinar Egas Moniz, Caparica, Portugal

4 Myrtus Unipessoal Lda, Nisa, Portugal

*Address all correspondence to: daniel.murta@entogreen.com

## References

[1] Čičková H., Newton G., Lacy R. & Kozánek M. 2015. The use of fly larvae for organic waste treatment. *Waste Manag.*, **35**:68-80

[2] Kummu M., de Moel H., Porkka M., Siebert S., Varis O. & Ward P.J. 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Sci. Tot. Environm.*, **438**:477-489. doi.org/10.1016/j.scitotenv.2012.08.092

[3] Barroso F.G., de Haro C., Sánchez-Muros M.J., Venegas E., Martínez-Sánchez A. & Pérez-Bañón C. 2013. The potential of various insect species for use as food for fish. *Aquaculture*, 422-423, 193-201. doi: 10.1016/j.aquaculture.2013.12.024

[4] Tran G., Heuzé V. & Makkar H.P.S. 2015. Insects in fish diets. *Animal Frontiers*, **5(2)**:37-44. doi.org/10.2527/af.2015-0018

[5] van Raamsdonk L.W.D., van der Fels-Klerx H.J. & de Jong J. 2017. New feed ingredients: the insect opportunity. *Food Additives and Contaminants - Part A*, **34(8)**:1384-1397. doi.org/10.1080/19440049.2017.1306883

[6] Veldkamp T. & Bosch G. 2015. Insects : a protein-rich feed ingredient in pig and poultry diets. *Animal Frontiers*, **5(2)**:45-50. doi.org/10.2527/af.2015-0019

[7] Sprangers T., Ottoboni M., Klootwijk C., Ovyn A., Deboosere S., De Meulenaer B., Michiels J., Eeckhout M., De Clercq P. & De Smet S. 2017. Nutritional composition of black soldier fly *(Hermetia illucens)* prepupae reared on different organic waste substrates. *J. Sci. Food and Agric.*, **97**:2594-2600. doi.org/10.1002/jsfa.8081

[8] Pinotti L., Giromini C., Ottoboni M., Tretola M. & Marchis D. 2019. Review: Insects and former foodstuffs for upgrading food waste biomasses/streams to feed ingredients for farm animals. *Animal*, **13(7)**:1365-1375. doi.org/10.1017/S1751731118003622

[9] de Bertoldi M., Vallini G. & Pera A. 1983. The biology of composting: A review. *Waste Management & Research*, **1(2)**:157-176. doi:10.1016/0734-242x(83)90055-1

[10] Gusmão L., Mexia J.T. & Gomes M.L. 1988. Mapping of equipotential zones for cultivar yield patterns evaluation. *Plant Breeding*, **103**:293-298

[11] Gusmão L., Mexia J.T. & Baeta J. 1992. Trimmed Joint Regression: A new approach to the Joint Regression Analysis for cultivar relative performance evaluation. *Theor. Appl. Genet.*, 84:735-738

[12] Chen J.H. 2006. The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. *Int. Workshop Sustained Manag. Soil-Rhizosphere Syst. for Efficient Crop Prod. and Fertilizer Use*. Bangkok, 1-11

[13] Zhang Z., Elser J.J., Cease A.J., Zhang X., Yu Q., Han X. & Zhang G. 2014. Grasshoppers regulate N:P stoichiometric homeostasis by changing phosphorus contents in their frass. *PloS One*, **9**:e103697. doi.org/10.13 71/journal.pone.0103697

[14] Menino R. & Murta D. 2021. BSF - time to change the flies. *Hort. Int. J.*, **5(3)**:114-117. doi: 10.15406/hij.2021.05.00215

[15] Timsina J. 2018. Can organic sources of nutrients increase crop yield to meet global food demand? *Agronomy*, **8**:214; doi:10.3390/agronomy8100214

[16] Poveda J., Jiménez-Gómez A., Saati-Santamaría Z., Usategui-

Martín R., Rivas R. & García-Fraile P. 2019. Mealworm frass as a potential biofertilizer and abiotic stress tolerance-inductor in plants. *Applied Soil Ecol.*, **142**:110-122. doi:10.1016/j.apsoil.2019.04.016

[17] Koh D.W.S., Ang B.Y.X., Yeo J.Y., Xing Z. & Gan S.K. 2020. Plastic agriculture using worms: Augmenting polystyrene consumption and using frass for plant growth towards a zero-waste circular economy. bioRxiv. doi.org/10.1101/2020.05.29.123521

[18] Zhu F.X., Yao Y.I., Wang S.J., Du R.G., Wang W.P., Chen X.Y., Hong C.L., Qi B., Xue Z.Y. & Yang H.Q., 2015. Housefly maggot-treated composting as sustainable option for pig manure management. *Waste Manag.*, **35**:62-67. doi.org/10.1016/j.wasman.2014.10.005

[19] Matthäus B., Piofczyk T., Katz H. & Pudel F. 2019. Renewable Resources from Insects: Exploitation, Properties, and Refining of Fat Obtained by Cold-Pressing from Hermetia illucens (Black Soldier Fly) Larvae. *Europ. J. Lipid Sci. Technol.*, **121(7)**:1800376. doi.org/10.1002/ejlt.201800376

[20] Song Y.-S.; Kim M.-W.; Moon C.; Seo D.-J.; Han Y.S.; Jo Y.H.; Noh M.Y.; Park Y.-K.; Kim S.-A.; Kim Y.W.; Jung W.-J. 2018. Extraction of chitin and chitosan from larval exuvium and whole body of edible mealworm, *Tenebrio molitor. Entomological Research*, **48**(3):227-233. doi: 10.1111/1748-5967.12304

[21] Aider M. 2010. Chitosan application for active bio-based films production and potential in the food industry: Review. *LWT - Food Sci. Technol.*, **43(6)**:837-842

[22] Kong M., Chen X.G., Xing K. & Park H.J. 2010. Antimicrobial properties of chitosan and mode of action: A state of the art review. *Int. J. Food Microbiol.*, **144(1)**:51-63

[23] Verlee A., MinCke S. & Stevens C.V. 2017. Recent developments in antibacterial and antifungal chitosan and its derivatives. *Carbohydrate Polymers*, **164**:268-283. doi.org/10.1016/j.carbpol.2017.02.001

[24] Sharp R. 2013. A Review of the Applications of Chitin and Its Derivatives in Agriculture to Modify Plant-Microbial Interactions and Improve Crop Yields. *Agronomy*, **3(4)**:757-793. https://doi.org/10.3390/agronomy3040757

[25] 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)**. doi:10.1038/s41598-020-61765-x

[26] Poveda, J. 2021. Insect frass in the development of sustainable agriculture. A review. *Agron. Sustain. Dev.*, **41**:5. doi.org/10.1007/s13593-020-00656-x

[27] Lardé G. 1990. Recycling of coffee pulp by *Hermetia illucens* (Diptera: *Stratiomyidae*) larvae. *Biological Wastes*, **33(4)**:307-310

[28] Smetana S., Palanisamy M., Mathys A. & Heinz V. 2016. Sustainability of insect use for feed and food: Life cycle assessment perspective. *J. Cleaner Prod.*, **137**:741-751. doi.org/10.1016/j.jclepro.2016.07.148

[29] Fowles T.M. & Nansen C. 2020. Insect-Based Bioconversion: Value from Food Waste. *In*: Närvänen E., Mesiranta N., Mattila M., Heikkinen A. (eds). Food Waste Management. Palgrave Macmillan, Cham. doi.org/10.1007/978-3-030-20561-4_12

[30] James M.T. 1935. The genus *Hermetia* in the United States (Diptera:

Stratiomyidae). Bull. Brooklyn Entomol. Soc., **30**:165-170

[31] Sheppard D.C., Newton G.L., Thompson S.A. & Savage S. 1994. A value-added manure management-system using the black soldier fly. *Bioresour. Technol.*, **50**:275-279. doi.org/10.1016/0960-8524(94)90102-3

[32] Singh A. & Kumari K. 2019. An inclusive approach for organic waste treatment and valorisation using Black Soldier Fly larvae: A review. *J. Environm. Manag.*, **251**:109569. doi:10.1016/j.jenvman.2019.109569

[33] Wang Y.S. & Shelomi M. 2017. Review of black soldier fly (*Hermetia illucens*) as animal feed and human food. *Foods, 6*(**10**):91. doi:10.3390/foods6100091

[34] Dulaurent A.M., Daoulas G., Faucon M.P. & Houben D. 2020. Earthworms (*Lumbricus terrestris* L.) mediate the fertilizing effect of frass. *Agronomy*, **10**:783. https://doi.org/10.3390/agronomy10060783

[35] Zink T. & Geyer R. 2017. "Circular Economy Rebound". *J. Ind. Ecol.*, **21(3)**:593-602. doi:10.1111/jiec.12545. S2CID 157110158

[36] Allwood J.M. 2014. "Squaring the Circular Economy". *Handbook of Recycling*, 445-477. doi:10.1016/b978-0-12-396459-5.00030-1. ISBN 978-0-12-396459-5

[37] Yildirim-Aksoy M., Eljack R. & Beck B.H. 2020a. Nutritional value of frass from black soldier fly larvae, *Hermetia illucens*, in a channel catfish, *Ictalurus punctatus*, diet. *Aquacult Nutr*, **26**:812-819. doi.org/10.1111/anu.13040

[38] Yildirim-Aksoy M., Eljack R., Schrimsher C. & Beck B.H. 2020b. Use of dietary frass from black soldier fly larvae, *Hermetia illucens*, in hybrid tilapia (Nile x Mozambique, *Oreochromis niloticus* x *O. Mozambique*) diets improves growth and resistance to bacterial diseases. *Aquacult Rep*, **17**:100373, doi.org/10.1016/j.aqrep.2020.100373

[39] Alattar M.A., Alattar F.N. & Popa, R. 2016. Effects of microaerobic fermentation and black soldier fly larvae food scrap processing residues on the growth of corn plants (*Zea mays*). *Plant Sci. Today*, **3(1)**:57-62. dx.doi.org/10.14719/pst.2016.3.1.179

[40] Gärttling D., Kirchner S.M. & Schulz H. 2020. Assessment of the N- and P-Fertilization Effect of Black Soldier Fly (Diptera: Stratiomyidae) By-Products on Maize, *J. Insect Sci.*, **20(5)**:1-11, doi.org/10.1093/jisesa/ieaa089

[41] Houben D., Daoulas G. & Dulaurent A.M. 2021. Assessment of the short-Term Fertilizer Potential of Mealworm Frass Using a Pot Experiment. *Front. Sust. Food Syst.*, **5**:714596. doi:10.3389/fsufs.2021.714596

[42] Newton G.L., Sheppard D.C., Watson D.W., Burtle G. & Dove R. 2005. Using the Black Soldier Fly, *Hermetia Illucens*, as a Value-Added Tool for the Management of Swine Manure. Animal and Poultry Waste Management Center, North Carolina State University, Raleigh, NC. http://www.organicvaluerecovery.com/studies/studies_htm_files/bsf_value_added.pdf

[43] Choi Y., Choi J., Kim J., Kim M., Kim W., Park K., Bae S. & Jeong G. 2009. Potential Usage of Food Waste as a Natural Fertilizer after Digestion by *Hermetia illucens* (Diptera: Stratiomyidae). *Int. J. Industr. Entomol., 19*:171-174.

[44] Anggraeni D. 2010. The effect of Bioconversion Fertilizer Palm Kernel Meal (BFPKM) as fertilizer for the growth of *Vigna unguiculata* L. Walp (yardlong bean) var. mutiara. Thesis for

S2 graduation. University of Indonesia, 95pp

[45] Kebli H. & Sinaj S. 2017. Potential agronomique d'un engrais naturel a base de digestats de larves de mouches. Recherche *Agronomique Suisse*, **8(3)**:88-95

[46] Esteves, C.F.M. 2020. Utilização do composto orgânico de larvas da *Hermitia illucens* como fertilizante em alface. Dissertação para obtenção de grau de Mestre. Instituto Superior de Agronomia (ISA), Universidade de Lisboa. 88pp.

[47] Klammsteiner T., Turan V., Fernández-Delgado Juárez M., Oberegger S. & Insam H. 2020. Suitability of Black Soldier Fly Frass as Soil Amendment and Implication for Organic Waste Hygienization. *Agronomy, 10*:1578. doi.org/10.3390/agronomy10101578

[48] Beesigamukama D., Mochoge B., Korir N.K., Fiaboe K.K.M., Nakimbugwe D., Khamis F.M., Subramanian S., Dubois T., Musyoka M.W., Ekesi S., Kelemu S. & Tanga C.M. 2020. Exploring Black Soldier Fly Frass as Novel Fertilizer for Improved Growth, Yield, and Nitrogen Use Efficiency of Maize Under Field Conditions. Front. Plant Sci. **11**:574592. doi: 10.3389/fpls.2020.574592

[49] Chirere T.E.S., Khalil S. & Lalander C. 2021. Fertiliser effect on Swiss chard of black soldier fly larvae-frass compost made from food waste and faeces. *J. Insects as Food and Feed*, **7(4)**:457-469. doi.org/10.3920/JIFF2020.0120

[50] Rosmiati M., Nurjanah K.A., Suantika G. & Putra R.E. 2017. Application of Compost Produced by Bioconversion of Coffee Husk by Black Soldier Fly Larvae (*Hermetia Illucens*) as Solid Fertilizer to Lettuce (*Lactuca Sativa* Var. Crispa): Impact to Growth. *Proc. Int. Conf. Green Technol.*, **8(1)**:38-44

[51] Setti L., Francia E., Pulvirenti A., Gigliano S., Zaccardelli M., Pane C., Caradonia F., Bortolini S., Maistrello L. & Ronga D. 2019. Use of black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae processing residue in peat-based growing media. *Waste Manag.*, **95**:278-288. doi:10.1016/j.wasman.2019.06.017

[52] Kawasaki K., Kawasaki T., Hirayasu H., Matsumoto Y. and Fujitani Y. 2020. Evaluation of Fertilizer Value of Residues Obtained after Processing Household Organic Waste with Black Soldier Fly Larvae (*Hermetia illucens*). *Sustainability*, **12(12)**:4920. doi.org/10.3390/su12124920

[53] Temple W.D., Radley R., Baker-French J. & Richardson F. 2013. *Use of Enterra natural fertilizer (black soldier fly larvae digestate) as a soil amendment*. Research Final Report, Enterra Feed Corporation, Vancouver, Canada. 34pp

[54] Anyega A.O., Korir N.K., Beesigamukama D., Changeh G.J., Nkoba K., Subramanian S., van Loon J.J.A., Dicke M. & Tanga C.M. 2021. Black Soldier Fly-Composted Organic Fertilizer Enhances Growth, Yield, and Nutrient Quality of Three Key Vegetable Crops in Sub-Saharan Africa. *Front. Plant Sci.*, **12**:680312. doi: 10.3389/fpls.2021.680312

[55] Quilliam R.S., Nuku-Adeku C., Maquart P., Little D., Newton R. & Murray F. 2020. Integrating insect frass biofertilisers into sustainable peri-urban agro-food systems. *J. Insects as Food and Feed*, **6(3)**:315-322. doi:10.3920/jiff2019.0049

[56] Matos S. & Murta D. 2019. Projeto ENTOVALOR e a valorização de subprodutos. *Revista Agrotejo*, **29**:

106-108. https://agrotejo.repo.pt/revista-agrotejo-29/

[57] Putra R.E., Hutami R., Suantika G. & Rosmiati M. 2017. Application of compost produced by bioconversion of coffee husk by Black Soldier Fly Larvae (*Hermetia Illucens*) as solid fertilizer to lettuce (*Lactuca sativa* Var. Crispa): impact to harvested biomass and utilization of nitrogen, phosphor, and potassium. Proc. Int. Conf. Green Technol., **8(1)**:466-472

[58] Choi S. & Hassanzadeh N. 2019. BSFL Frass: A Novel Biofertilizer for Improving Plant Health While Minimizing Environmental Impact. *Candian Sci. Fair J.*, **2**:41-46. doi: 10.18192/csfj.v2i220194146

[59] Elissen H., Schilder M., Postma J., van der Weide R. 2019. Disease suppression in cress and sugar beet seedlings with frass of the black soldier fly (*Hermetia illucens*). Stichting Wageningen Research, Wageningen Plant Research, Business Unit Field Crops

[60] Kagata H. & Ohgushi T. 2011. Positive and negative impacts of insect frass quality on soil nitrogen availability and plant growth. *Pop. Ecol.,* **54**(1):75-82. doi: 10.1007/S10144-011-0281-6

[61] Menino R., Felizes F., Castelo-Branco M.A., Fareleira P., Moreira O., Nunes R. & Murta D. 2021. Agricultural value of Black Soldier Fly larvae frass as organic fertilizer on ryegrass. *Heliyon*, Jan 2, **7(1)**:e05855. doi: 10.1016/j.heliyon.2020.e05855. PMID: 33426352, PMCID: PMC7785954

[62] Ronald P.C. & Adamchak R.W. 2008. *Tomorrow's Table: Organic Farming, Genetics and the Future of food*; Oxford University Press: NY, USA.

[63] Amman K. 2009. Why farming with high tech methods should integrate elements of organic agriculture. *New Biotech.*, **25**:378-388

[64] Li Q., Zheng L., Qiu N., Cai H., Tomberlin J.K. & Yu Z. 2011. Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production. *Waste Manag.*, **31(6)**:1316-1320. doi.org/10.1016/j.wasman.2011.01.005

[65] Surendra K.C., Olivier R., Tomberlin J.K., Jha R. & Khanal S.K. 2016. Bioconversion of organic wastes into biodiesel and animal feed via insect farming. *Renewable Energy*, **98**:197-202. doi.org/10.1016/j.renene.2016.03.022