Insect frass in the development of sustainable agriculture. A review

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Abstract

Given the current rate of human population growth, the mass breeding of insects for feed and food is in full industrial development, as a more efficient and effective alternative to conventional livestock for the production of animal protein. In these industries, the production of insect excreta (frass) represents one of the main outputs of the process, being up to 40 times greater than the production of animal biomass, which is why its use as organic fertilizer to replace the use of agrochemicals is considered a viable alternative in the development of sustainable agriculture and a circular economy. Through a review of all the existing literature, this article highlights the following benefits of the use of insect frass as organic fertilizer in sustainable agriculture: (1) contribution of nutrients to the soil, mainly nitrogen, easily assimilated by plant tissues; (2) addition of biomolecules and microorganisms that promote plant growth; and (3) increased tolerance to abiotic stresses and resistance to pathogens and pests due to the presence of different compounds and microorganisms. Therefore, insect frass from the mass breeding of insects for feed and food represents an important source of effective organic fertilizer for use in sustainable agriculture.

Keywords Insect frass · Fertilizer · Sustainable agriculture · Nitrogen · Plant growth · Mealworm

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1 Introduction

The world population has increased very rapidly in the last century, from 1.6 billion people in 1900 to 7.0 billion in 2011. In this context, it is estimated that in 2050 the world population will reach 9.7 billion, with a consequent increase in the demand for resources such as water, food, and energy. Given this scenario, food production will need to increase by roughly 70% by 2050 and double or triple by 2100, while trying to decrease the environmental impact of food production activity (Chen et al. 2016; Crist et al. 2017).

Food systems can have serious environmental effects, such as land degradation, deforestation, loss of habitats and biodiversity, depletion of natural resources, and contamination of air, soil, and waters. They account for about one-quarter of anthropogenic greenhouse gas emissions, and agricultural production accounts for 70% of global freshwater withdrawals. There is also the use of synthetic fertilizers and pesticides in agriculture and the chemical pollution of marine and terrestrial ecosystems with contamination of food products and ecosystems that in turn may have severe health consequences (Lindgren et al. 2018). The ecological impact of food production is widely demonstrated; therefore, production must be increased without losing more biodiversity and converting additional natural areas to cultivated land. This

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requires a sustainable intensification of agricultural production, by increasing yields on agricultural lands already in production, increasing efficiency in freshwater use, applying fertilizers and pesticides through more cautious methodologies, and genetically modifying crops to produce higher yields or to tailor them to specific challenges (Foley et al. 2011). Moreover, a reduction of meat consumption in the developed world, because meat is ecologically costly to produce, should be carried out. This can be accomplished by consuming plant protein rather than animal protein, or by changing the animal's protein source, such as insects. Through such agronomic adjustments, efficiency gains, and perhaps consumer shifts, researchers are hopeful that food supplies can meet demand without added biodiversity losses and further environmental damage (Crist et al. 2017).

The increasing risk of agro-environment from crop production in future can threaten the sustainability of agricultural land use. Post-green revolution intensification of agriculture has resulted in soil degradation in the form of compaction, erosion, loss of organic matter, pesticide contamination, low biodiversity, increased soil salinization and waterlogging, etc. (Turpin et al. 2017). Therefore, sustainable agriculture should be able to restore soil quality by the use of nonchemical fertilizer and pesticides (organic fertilizers, biofertilizers, and biopesticides) and crop rotation with increased diversity to match global food production with sustainable environment and soil health (Farooq et al. 2019). Application of organic fertilizers instead of chemical fertilizers is economically feasible and one of the environmentally sound long-term approaches to sustainable agriculture. However, organic fertilizers can have less direct effects than chemical fertilizers, since their effect on crop yield is slow and variable in the short term, and their use needs more labor and monetary input (Wang et al. 2018). However, organic sources of nutrients are proposed as a sustainable strategy for producing safe, healthy, and cheaper food and for restoring soil fertility and mitigating climate change. Therefore, there is a clear need in the search for new organic sources of nutrients for use as fertilizers in the development of sustainable agriculture (Timsina 2018).

2 Mass insect breeding industry

In recent years, the use of insects as food and feed is receiving more and more interest, increasing the numbers of scientific publications and private enterprises engaged in producing insect products. The number of companies in the world working on insects as food and feed, not including insect industry organizations and insect advocacy organizations, was estimated in April 2019 to be more than 250 (Van Huis 2020). Scientifically, the use of insects as food and feed provides hundreds of publications each year, being constantly reviewed by various authors (Sogari et al. 2019; Tang et al. 2019; da Silva-Lucas et al. 2020).

The design and operation of a mass insect breeding industry requires the adaptation of industrial processes to the lifecycle of the insect to be multiplied, although there are aspects common to all of them noted by several authors (Dossey et al. 2016; Ortiz et al. 2016; Cohen 2018). A very important part of the mass rearing process is the production of frass (insect excreta) by insects, which supposes an important end product within the system. For this reason, in these industrial systems, frass has been considered as an organic fertilizer and even as food for other livestock farms (Ortiz et al. 2016). To get an idea of the amount of frass that this type of industry can accumulate daily, it has been determined that yellow mealworm (*Tenebrio molitor*) can consume 220 g of food in the form of corn and carrots, supposing an insect biomass production of 4 g and 180 g of frass and residues, respectively (Wang et al. 2017).

3 Insect frass and gut microbiota

The presence of certain microorganisms in organic agricultural fertilizers is of great agronomic and economic importance. These microorganisms are known as bioprotectants, biocontrollers, biofertilizers, or biostimulants, because they are able to promote plant growth, increase their tolerance to abiotic stresses, and decrease the damaging effect of biotic stresses (de Souza-Vandenberghe et al. 2017). Therefore, the microorganisms present in insect frass intended for use as agricultural fertilizer must be studied (Fig. 1).

In contrast to mammals, the microbial diversity in insect digestive tracts is generally low and rarely exceeds a few tens of species. This is due to insects having developed physical barriers to separate the microbes from the host, by the formation of a specific organ or by the existence of an acellular structure that effectively separates the microbes from the host tissues, as the peritrophic membrane, which does not allow the passage of microorganisms and contains them in the gut lumen (Pernice et al. 2014). Furthermore, this microbial diversity can vary very significantly due to factors such as environmental habitat, diet, developmental stage, and phylogeny of host (Yun et al. 2014).

The microorganisms in insect guts can include protists, fungi, archaea, and bacteria, which are responsible for various functions in their hosts (Hongoh 2010). The presence of insects in ecological niches with a reduced capacity for nutritional contribution is possible due to the bacterial communities present in their gut and the advantages that they provide. Due to their enzymatic capacity, they are able to break down the cellulose present in plant tissues and allow insects to assimilate simple sugars (Prem Anand et al. 2010). In addition, the microbiota can provide its hosts with nutrients that it synthesizes and releases to the environment, such as vitamins and essential amino acids. Closely related to its nutritional role is the ability of the microbiota to eliminate toxic compounds that could be present in the food consumed by its hosts, such as insecticides or defensive

Fig. 1 Infographic on the use of insect frass from mass breeding of insects for feed and food as an organic fertilizer in sustainable agriculture, indicating the benefits of its use

plant compounds. The gut microbiota can also have systemic effects on the growth and development of its host by modulating its hormonal signals, such as those involved in the synthesis of chitin that allows insects to molt and grow (Engel and Moran 2013). They even play a key role in inter- and intraspecific communication, since some of the volatile chemical components used can be totally or partially synthesized by the gut microbiota (Engel and Moran 2013).

The great metabolic and physiological diversity of the gut microbiota of insects has led to the development of important biotechnological and industrial applications due to its knowledge. Both isolated microorganisms and their enzymes are used for cellulose and xylan hydrolysis, plastic degradation, vitamin production, nitrogen fixation, metabolism of phenolic compounds, antimicrobial compounds production, or signaling compounds (Krishnan et al. 2014; Singh et al. 2019; Jang and Kikuchi 2020).

Herbivores possess diverse microbes in their digestive systems, and recent research has demonstrated that these gut microbes can modify plant–insect interactions. For example, when an insect feeds on the leaves, there is contact between plant cell receptors and the insect's saliva. In this situation, the bacteria present in their saliva are recognized by the receptors of the plant cells, activating a defensive response mediated by salicylic acid (SA). This defensive response is antagonistic to the specific defense pathway against insects, mediated by jasmonic acid (JA) (Casteel and Hansen 2014).

However, with the greater affinity between plants, we find the close functional relationship between insect gut and plant roots. Guts and roots are inhabited by many different

microorganisms; have large surface areas, with microvilli and folds or root hairs in some parts; and are structured, non-homogenous habitats with pH, nutrient, water, and oxygen differential levels or gradients. In both cases, the microbiome is acquired from the environment: in the roots, the microorganisms are acquired from the soil using active strategies such as the secretion of nutritive exudates; in insects, they are acquired orally or anally after birth. Regarding their functions, they also have many things in common (Ramírez-Puebla et al. 2013). Both microbiota are rich in catabolic enzymes that specialize in the release of nutrients from different substrates to be absorbed by the host, for example: sugar hydrolases or phosphate solubilizers, they produce vitamins such as B12 and essential amino acids, suppress pathogens through competition or antibiosis, and regulate gene expression in both types of hosts (Ramírez-Puebla et al. 2013). Through the insect frass, both microbiomes interrelate, so a significant contribution of microorganisms to the roots from the insect gut through this pathway is expected, since the gut and frass microbiota are very similar (Osimani et al. 2018).

Behaviors associated with defecation in many groups of insects go well beyond the simple elimination of waste materials and fall squarely into an ecological arena, affecting interactions between insects and their biotic and abiotic environments. Microbes on, in, and around insects and their waste products probably play an important and almost entirely unexamined role in ecological interactions involving defecation (Weiss 2006).

Finally, it is important to note that just as the insect frass transmits symbiotic microorganisms between insects in contact

(Paniagua-Voirol et al. 2018), it can transmit entomopathogens (Osimani et al. 2018). It is also used as a transmission strategy by different plant pathogens, such as *Erwinia tracheiphila*, the causal agent of the bacterial wilt of cucurbits, transmitted by the excrement of the striped cucumber beetle (*Acalymma vittatum*) (Mitchell and Hanks 2009).

4 Insect frass and agriculture

Currently, more and more specialist industries are being established and specializing in the mass breeding of insects for food and feed. This causes, in turn, the production of a massive amount of frass from these insects, which can become a serious environmental problem. To avoid this, different uses for frass have been proposed, such as the elaboration of bio-char, a solid product from biomass pyrolysis (Yang et al. 2019; He et al. 2020).

4.1 As a source of nutrients and compounds of interest for plant growth

In nature, insect frass is included in the nutrient cycle, forming a fundamental part of the exchange between plant material and soil. In this context, insect frass can be used to monitor the diversity of insects present in a specific place (Sweetapple and Barron 2016). The presence of a lot of nutrients in insect frass has raised its possible use in fish feed, such as frass from *Hermetia illucens* in the channel catfish (*Ictalurus punctatus*) or hybrid tilapia (*Oreochromis niloticus* x *O. mozambique*) diets (Yildirim-Aksoy et al. 2020a, b). As far as plants are concerned, insect frass presents nutrients easily assimilated by the roots due to the insect's own physiological mechanisms to shape its body waste. Occasionally, plant tissues on which herbivores feed present nutrients such as nitrogen or phosphorus in greater amounts than the insects need to consume to maintain their body N:P stoichiometric homeostasis. This means that they must regulate in a very controlled way the excretion in their frass of these types of nutrients, promoting high concentrations (Zhang et al. 2014).

Nitrogen is often a limited resource for plants due to low soil nitrogen levels resulting from poor farming practices, biological processes such as denitrification and microbial competition, or soil erosion (Goulding et al. 1998). On an ecosystem level, insects can be an essential nitrogen source for plants, since they make up a nitrogen reservoir, being an integral part of the nitrogen cycle in soil (Behie and Bidochka 2013). The contribution of nitrogen to plants through insect frass represents the most widely studied mechanism in the possible use of this input as fertilizer in agriculture. Most of the studies have been carried out in the field, although it has also been verified in pots how frass from the cabbage moth (*Mamestra brassicae*) is capable of supplying nitrogen to the

soil, which promotes the growth of cabbage plants (*Brassica rapa* var. *perviridis*) and increases total nitrogen concentration, and accumulated inorganic nitrogen and ammonium nitrogen in the leaves in response to the application as fertilizer (Kagata and Ohgushi 2011, 2012a). Regarding its use in the field, we find numerous examples of defoliating insects whose droppings contribute nitrogen to the plants they feed on, such as the grasshoppers *Chorthippus curtipennis* and *Melanoplus borealis* that feed on grass (Fielding et al. 2013). In a 2-year cumulative study, the eucalyptus defoliating beetle *Paropsis atomaria* and the lepidopteran *Doratifera quadriguttata* were determined to be capable of producing between 160 and 270 kg/ha of frass, depositing 2 to 4 kg/ha of nitrogen (Gherlenda et al. 2016). This greater contribution of nitrogen to the soil in field leads to a promotion of plant growth and an increase in the amount of nitrogen present in plant tissues, as has been verified in various systems, such as the defoliation beetle *Trirhabda virgata* on goldenrod (Uriarte 2000); the defoliation moths *Malacosoma americanum* and *Orgyia leucostigma* on red oak (Frost and Hunter 2008); or the gypsy moth (*Lymantria dispar*) and the forest tent caterpillar (*Malacosoma disstria*) on trembling aspen (Madritch et al. 2007). In other cases, such as the defoliation moth *Lymantria monacha* on *Pinus sylvestris*, although soil nitrogen availability was increased via frass nitrogen input, trees did not respond with an increase in nitrogen acquisition but rather invested resources into defense by accumulation of amino acids and proteins as a survival strategy (Grüning et al. 2017). Moreover, the nitrogen contributed to the roots can appear in other forms, such as amides. In search of a circular economy of reconversion of the plastics used in agriculture, *Zophobas morio* beetle was fed with polystyrene, producing frass rich in amides, which promoted the plant growth in dragon fruit cacti (*Hylocereus undatus*) plants, both in terms of shoot height and root development (Koh et al. 2020).

Along with nitrogen, other nutrients are returned to the soil through insect frass in the field, such as carbon through frass from the defoliation moth *M. americanum* on red oak, increasing total carbon, total nitrogen, and ammonium in soil, also favoring the microbial activity in soil (Frost and Hunter 2004). This highlights the role insects play in the cycle of many other nutrients, thanks, for example, to feeding on dead wood and returning nutrients to the soil, as with various species of subterranean termites (Chen and Forschler 2016). Defoliating insects such as the mopane worm (*Imbrasia belina*), when feeding on *Colophospermum mopane* trees, contribute to the soil of the ecosystems of the savanna through its frass nitrogen, phosphorus, and potassium (de Swardt et al. 2018).

This contribution of nutrients has also been studied in the frass from one of the most widely used insects today in industrial breeding for food and feed, *T. molitor*. In 2019, using different feeds, Poveda et al. demonstrated how the nutritional content of frass and its possible capacity as a fertilizer is

closely linked to the feed received by the insect. By modifying the diet of the insects, they not only obtained different nutritional contents in the frass but also reported significant changes in the present microbiota, both aspects involved in its ability to be used as organic fertilizer. Poveda et al. obtained frass from mealworm with an NPK balance of 3-2-2 (g/100 g) and an iron content of 140 mg/Kg, which, in pots, was capable of promoting plant growth of chards, increasing the chlorophyll content of the leaves, the length of the stem, the width of the stem, and the fresh weight of the aerial part (product of economic interest) (Poveda et al. 2019). Subsequently, it has been determined that, due to its rapid mineralization and the presence of nutrient in a readily available form, frass from mealworm is an efficient natural NPK fertilizer that increases biomass and nutritional content in crops such as barley, thanks also to a stimulation of soil microbial activity (Houben et al. 2020). In barley, the application of frass from mealworm with an NPK balance of 5-2-2 increased plant biomass and the content of these nutrients in plant tissues. The addition of earthworms (*Lumbricus terrestris*) to the study pots was found to significantly increase the nutritional content of plants, because earthworm activity enhances the short-term recycling of nutrients from frass, improving the efficiency of frass use as fertilizer (Dulaurent et al. 2020).

Moreover, it has been verified how insect frass, in addition to nutrients, can provide plants with other compounds of importance for their development. Frass from saproxylic-cerambycid larvae of *Chlorophorus annularis* fed in the wood of dead twigs of *Acacia stenophylla*, brings sugars, alkaloids, and phenols to the soil, thanks, in part, to the presence of microorganisms, such as the beneficial fungus *Trichoderma hamatum*. In lettuce, it was verified how these compounds favor seed germination and seedling growth (Khan et al. 2016).

4.2 As a generator of tolerance to abiotic stress resistance to biotic stresses

The ability of insect frass to promote plant tolerance against different abiotic stresses has been described. In bean plants, the application of frass from mealworm increased the tolerance of the seedlings against drought, flooding, and salinity. The study describes, due to the sterilization of the frass, how this increase in tolerance is caused by the microorganisms present in the frass, identifying numerous bacterial and fungal isolates capable of fixing atmospheric nitrogen, solubilizing phosphates and potassium, and producing siderophores, auxins, and 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase (Poveda et al. 2019).

As far as the defense against pests and/or pathogens is concerned, there are several studies of direct action or activation of plant defense responses due to the use of frass as a fertilizer. The recognition by the roots of microorganisms and biomolecules present in insect frass may be involved in the activation of

plant systemic resistance through the SA and/or JA/ethylene (ET) pathways. This defensive response is based on the recognition by cellular receptors of molecular patterns associated with microorganisms and herbivores, such as chitin (Poveda 2020). In a study performed in a greenhouse, it was found that the excreta from different herbivorous insects were capable of activating the defensive responses of the plant mediated by SA and JA. For this, different interactions were used, such as cabbage looper (*Trichoplusia ni*) in cabbage, fall armyworm (*Spodoptera frugiperda*) in rice, and European corn borer (*Ostrinia nubilalis*) in maize and tomato fruit worm (*Helicoverpa zea*) in tomato (Ray et al. 2016b). The activation of defensive responses in the plant by the use of insect frass as fertilizer is due to the presence of eliciting molecules or of certain microorganisms. In 2015, Ray et al. indicated that the activation of plant defensive responses when in contact with insect frass was due to the presence of eliciting molecules that, in corn plants in contact with frass from *S. frugiperda*, produced the induction of pathogenesis-related expression (*pr*) defense genes against the pathogenic fungus *Cochliobolus heterostrophus* (Ray et al. 2015). One of these molecules can be chitin, which is part of the peritrophic gut membrane of insects and is present in their frass. In cowpea plants, it was possible to verify how frass from *H. illucens*, fed with brewery waste, was able to activate plant defense responses and reduce *Fusarium* wilt disease due to the presence of chitin (Quilliam et al. 2020). They can also be chitinase enzymes, necessary for the correct formation of peritrophic membrane. In maize plants in contact with frass from *S. frugiperda*, it was found that the chitinases present while suppressing herbivore defenses were able to induce pathogen defenses against *C. heterostrophus* (Ray et al. 2016a). Subsequently, it was demonstrated in the same system (*S. frugiperda* maize) that the insect frass is capable of activating plant defensive responses against chewing insects but not against sucking insects such as corn leaf aphid (*Rhopalosiphum maidis*) (Ray et al. 2020). Furthermore, microorganisms present in insect frass may be able to activate the defensive responses of the plant. Continuing with the *S. frugiperda* maize system, the bacterium *Pantoea ananatis* was isolated and identified in insect frass, demonstrating its ability to increase the expression in the plant of the gene that codes for the herbivore-induced maize proteinase inhibitor (*mpi*), which causes a decrease in the attack of the insect. Using tomato plants instead of corn did not achieve the same results of activation of plant defensive responses (Acevedo et al. 2017). It is noteworthy that with respect to the activation of defensive responses in plants against pathogens and/or pests, not all insect frass show the same results in all crops. In sugar beet and crew seedlings infected by the pathogens *Rhizoctonia solani* and *Pythium ultimum*, respectively, the application of frass from *H. illucens* did not decrease the diseases caused by pathogens (Elissen et al. 2019).

Table 1 Studies of the use of frass from insects as fertilizer in field

Insects	Crop/plant	Rate of application	Benefits	Mechanisms	References
Order	Species				
Blattodea	<i>Reticulitermes</i> sp.	-	-	Nutrients supply to soil	Chen and Forschler 2016
Blattodea	<i>Zootermopsis nevadensis</i>	-	-	Nutrients supply to soil	Chen and Forschler 2016
Coleoptera	<i>Anoplophora glabripennis</i>	-	Insect attack reduction	Parasitoid attraction for VOCs	Wei et al. 2013
	<i>A. swainsoni</i>				
	<i>Paropsis atomaria</i>	-	-	Nitrogen supply to soil	Gherlenda et al. 2016
	<i>Trirhabda virgata</i>	-	Plant growth promotion	Nitrogen supply to soil	Uriarte 2000
Diptera	<i>Hermetia illucens</i>	5 or 10 t/ha	Decreased Fusarium wilt disease	Activation of plant defensive responses by chitin presence	Quilliam et al. 2020
Lepidoptera	<i>Agrotis Ipsilon</i>	Potato	Reduction of oviposition of the insect pest <i>Phthorimaea operculella</i>	Presence of phenols and flavonoids	Ahmed et al. 2013
	<i>Doratifera quadriguttata</i>	Eucalyptus	-	Nitrogen supply to soil	Gherlenda et al. 2016
	<i>Imbrasia belina</i>	-	-	Nutrients supply to soil	de Swardt et al. 2018
	<i>Lymantria dispar</i>	Trembling aspen	Increased nitrogen content in plant tissues	Nitrogen supply to soil	Madritch et al. 2007
	<i>Lymantria dispar</i>	<i>Pinus densiflora</i>	-	Nitrogen supply to soil	Kagata and Ohgushi 2013
		<i>Quercus acutissima</i>			
	<i>Lymantria monacha</i>	<i>Pinus sylvestris</i>	Greater defensive capacity	Nitrogen supply to soil	Grüning et al. 2017
	<i>Lymantria monacha</i>	<i>P. sylvestris</i>	-	Nitrogen supply to soil	Grüning et al. 2018
	<i>Malacosoma americanum</i>	Red oak	Increased microbial activity in soil	Carbon and nitrogen supply to soil	Frost and Hunter 2004
	<i>Malacosoma americanum</i>	Red oak	Increased nitrogen content in plant tissues	Nitrogen supply to soil	Frost and Hunter 2008
	<i>Malacosoma disstria</i>	Trembling aspen	Increased nitrogen content in plant tissues	Nitrogen supply to soil	Madritch et al. 2007
	<i>Orgyia leucostigma</i>	Red oak	Increased nitrogen content in plant tissues	Nitrogen supply to soil	Frost and Hunter 2007
	<i>Orgyia leucostigma</i>	-	Increased microbial activity in soil	Carbon and nitrogen supply to soil	Hillstrom et al. 2010
	<i>Parasa Consocia</i>	<i>Salix gilgiana</i>	-	Nitrogen supply to soil	Kagata and Ohgushi 2012b
Orthoptera	<i>Chorhippus curtipennis</i>	-	-	Nitrogen supply to soil	Fielding et al. 2013
	<i>Melanoplus borealis</i>	-	-	Nitrogen supply to soil	Fielding et al. 2013

Table 2 Studies of the use of frass from insects as fertilizer in vitro, in a growth chamber, and in pots

Insects	Crop/plant	Experiment conditions	Rate of application	Benefits	Mechanisms	References
Order	Species					
Coleoptera	<i>Chlorophorus annularis</i>	In vitro	10 g/100 ml of water	Increased germination and plant growth	Sugars, alkaloids and phenols supply	Khan et al. 2016
	<i>Tenebrio molitor</i>	Pots	2% v/v	Plant growth promotion	Nutrients supply	Poveda et al. 2019
		Pots	2% v/v	Increased tolerance to abiotic stresses	Presence of microorganisms promoting plant tolerance	
	<i>Tenebrio molitor</i>	Pots	10 Mg ha ⁻¹	Increased plant growth and nutritional content	Nutrients supply	Dulaurent et al. 2020
Diptera	<i>Tenebrio molitor</i>	Pots	10 Mg ha ⁻¹	Increased plant growth and nutritional content	Nutrients supply to soil	Houben et al. 2020
	<i>Zophobas morio</i>	Pots	-	Plant growth promotion	Stimulated soil microbial activity	Koh et al. 2020
	<i>Hermética illucens</i>	Pots	7.5 and 15 g frass/kg of soil	Non decreases disease caused by pathogens <i>Rhizoctonia solani</i> and <i>Pythium ultimum</i>	Amides supply to soil	Elissen et al. 2019
	<i>Helicoverpa zea</i>	Pots	-	Activation of plant defenses against pathogens and pests	-	Ray et al. 2016b
Lepidoptera	<i>Mamestra brassicae</i>	Pots	10% w/w	Increased nitrogen content in plant tissues	Nitrogen supply to soil	Kagata and Ohgushi 2011, 2012a
	<i>Ostrinia nubilalis</i>	Pots	-	Activation of plant defenses against pathogens and pests	-	Ray et al. 2016b
	<i>Phthorimaea operculella</i>	In vitro	10 g/ml	Reduce oviposition of the pest insect	VOC emissions	Zhang et al. 2019
	<i>Spodoptera frugiperda</i>	Pots	100 g per plant	Activation of plant defenses against pathogens	Presence of eliciting molecules	Ray et al. 2015
	<i>Spodoptera frugiperda</i>	Growth chamber	-	Activation of plant defenses against pathogens	Presence of chitinases	Ray et al. 2016a
	<i>Spodoptera frugiperda</i>	Pots	-	Activation of plant defenses against pathogens and pests	-	Ray et al. 2016b
	<i>Spodoptera frugiperda</i>	Pots	-	Activation of plant defenses against pests	Presence of plant defense inducing bacteria	Acevedo et al. 2017
	<i>Spodoptera frugiperda</i>	Pots	-	No effect against aphid attack	Presence of chitinases	Ray et al. 2020
	<i>Trichoplusia ni</i>	Pots	-	Activation of plant defenses against pathogens and pests	-	Ray et al. 2016b

Insect frass can have direct effects on pest behavior. In potato plants, it has been proven that frass from the black cutworm (*Agrotis ipsilon*) presents phenols and flavonoids that reduce oviposition of the potato tuber moth (*Phthorimaea operculella*) (Ahmed et al. 2013), also with its own frass, due to the presence of the volatile organic compound (VOC) pentacosane (Zhang et al. 2019). The emission of different VOCs by insect frass and their benefits in agriculture requires further study. In *Salix babylonica*, frass from the beetles *Anoplophora glabripennis* and *Apriona swainsoni*, destructive woodborers of many species of deciduous hardwood trees, emits VOCs capable of attracting the parasitoid *Dastarcus helophoroides*, specifically the (S)-(-)-limonene in *A. glabripennis* frass and the (+)- β -pinene in *A. swainsoni* frass (Wei et al. 2013).

5 Conclusions

The current rates of population growth make it essential to develop new strategies for sustainable food production. The mass breeding of insects could be a good strategy, due to the advantages that it has over conventional livestock in the production of animal protein. The development of industries specializing in the mass breeding of insects entails the production of a large amount of waste that must be managed for its elimination or used for some purpose.

Due to its high nutritional content, and the presence of compounds and microorganisms of interest in agriculture, the use of insect frass as fertilizer could help limit the use of agrochemicals and contribute to the development of sustainable agriculture. Several studies have suggested its efficient use (Tables 1 and 2), although the vast majority have been performed in the last 5 years, indicative of the great novelty that this agricultural resource represents. These studies focus on the contribution of nutrients to the soil and the plant, especially nitrogen, with very few studies on compounds or microorganisms capable of promoting plant growth or activating tolerance and defense responses in plants against biotic and abiotic stresses, which are powerful lines to develop in the future. Despite all this, currently more studies are needed on agricultural systems to understand whether insect frass can be used as a complete substitute for mineral fertilizer or not. To date, there have been no studies that can make a resounding statement in this regard.

Therefore, with a forecasted dramatic growth of insect rearing in the near future, insect frass should be considered as a sustainable resource for managing plant nutrition and health in sustainable crop systems and as a promising alternative to conventional fertilizer and pesticides. The use of insect frass as organic fertilizer responds to the need to seek a circular economy without residues in the scenario of mass production of insects for food and feed. Like the excreta of animals from conventional livestock, the use of

insect frass as organic fertilizer in sustainable agriculture supposes the contribution of nutrients, beneficial microorganisms, and biomolecules of interest to the soil. Being uricotelic animals, insect frass has an important N content, as it is the route of elimination of the residue. This aspect happens in the same way as bird excreta, but unlike that, the microbial diversity present can be much greater, as well as its stability in storage and ease of use, due to its reduced humidity.

Regarding its introduction to the market, the use of animal excreta in agriculture requires some type of sanitizing treatment, in order to eliminate possible microorganisms that are harmful to health. So far, there are no regulations specifically developed for the use of insect frass as fertilizer in agriculture, so it must be integrated into the same regulations as other animal excreta. Sanitizing treatments, such as high temperatures, could completely eliminate many of the benefits that insect frass provides as fertilizers, by eliminating the beneficial microorganisms and/or biomolecules that it is capable of contributing to soils.

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Compliance with ethical standards

Conflicts of interest The author declares that he has no conflict of interest.

Author contribution J.P. conceived and designed the manuscript. J.P. performed the bibliographic search and analyzed the information. J.P. wrote the manuscript and made the corresponding revisions.

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