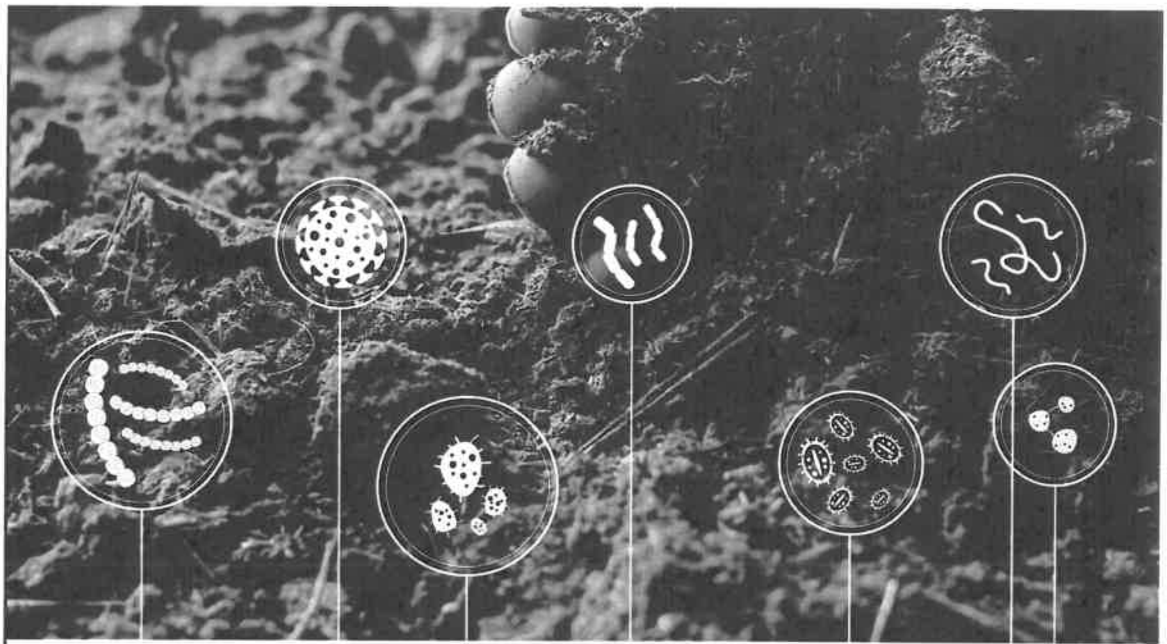

Fate of Biological Contaminants During Recycling of Organic Wastes

Edited by

Kui Huang, Sartaj Ahmad Bhat, and Guangyu Cui

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CHAPTER THREE

Potential of entomocomposting toward soil pathogen suppression

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1. Introduction

Soil degradation and waste accumulation are major challenges to food security and environmental health in most developing countries (Stewart et al., 2020; Wortmann et al., 2019; Jambeck et al., 2018; Somorin et al., 2017; FAO, 2017; Friedrich and Trois, 2016; Tully et al., 2015; Komakech, 2014; Okot-Okumu, 2012; Cobo et al., 2010; Muniafu and Otiato, 2010). Projections show increase in the volume of wastes generated in developing cities (von Blottnitz et al., 2010) yet, poor waste management continues to cause serious pollution problems (Nweke and Sanders, 2009; Kimani et al., 2010). Land filling is the commonest waste disposal method in Africa (Okot-Okumu, 2012), which might lock most of the nutrients that would have been recycled for improved soil fertility, crop production, and reduce environmental pollution (Aryampa et al., 2021a, b). Several studies have investigated the methods of treating organic wastes for agricultural use. Tumuhairwe et al. (2009) recommended the aboveground pile method for composting of market crop wastes, while recent studies have found insect-assisted composting (entomocomposting) a better strategy of waste valorization and compost hygienization (Lalander et al., 2016, 2015; Dortmans, 2015; Diener et al., 2011).

In addition to poor waste management, soils in most developing countries are affected by multiple degradation challenges. In sub-Saharan Africa (SSA), 40% of soils are deficient in nutrients required for optimum plant growth, with 25% affected by aluminum toxicity, 18% prone to leaching, and 8.5% characterized by phosphorus (P) fixation (Tully et al., 2015). This has led to deficiencies in nitrogen (N), P, and potassium (K), thus negatively affecting the nutrient balances in most farmlands (Stewart et al., 2020;

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Cobo et al., 2010; Ebanyat et al., 2010; Gachimbi et al., 2005). Despite the soil health challenges that smallholder farmers are grabbling with, they have been reported to use little ($\leq 10\,\text{kg}\,\text{ha}^{-1}\,\text{year}^{-1}$) or no mineral fertilizer due to the high-cost implications and limited access (Stewart et al., 2020; FAO, 2017), which has resulted into low crop productivity. Even in situations where mineral fertilizers are widely used, their efficiency has been limited by low soil organic matter, micronutrient deficiencies, and high acidity (Stewart et al., 2020; Wortmann et al., 2019; Liverpool-Tasie et al., 2017; Kihara et al., 2016; Vanlauwe et al., 2015), hence causing low profits.

Combined application of organic and mineral fertilizers has been recommended as an integrated soil fertility and nutrient management strategy to reduce mineral fertilizer costs and improve fertilizer use efficiency, soil health, and crop yields (Stewart et al., 2020; Vanlauwe et al., 2015, 2014). However, use of organic fertilizers is still limited by poor quality, low availability, long production time, microbial contamination as well as inadequate sources of organic matter on the farm (Stewart et al., 2020; Ndambi et al., 2019; Rufino et al., 2011; Mugwe et al., 2009). Thus, there is need for alternative sources of organic fertilizers that are hygienic, affordable, readily available, and of good quality to support sustainable soil health management.

The use of insects to recycle organic waste into nutrient-rich insect biomass for feed has rapidly attracted attention globally (Makkar et al., 2014; van Huis, 2013) and presents an avenue for waste management that could also contribute to improved soil health and crop yields (Fig. 1) (Beesigamukama et al., 2021a, b; Moruzzo et al., 2021; Song et al., 2021; Bortolini et al., 2020; Houben et al., 2020; Poveda et al., 2019; Kagata and Ohgushi, 2012). Past research has demonstrated that black soldier fly larvae (*Hermertia illucens* L.) (BSF) and mealworms (*Tenebrio molitor* L.) take ≤ 5 weeks to produce mature, stable, nutrient-rich, and pathogen-free organic fertilizers (Table 1) compared with 8–24 weeks for conventional composting (Beesigamukama et al., 2021b; van Broekhoven et al., 2015), thus shortening the compost production time and improving compost hygiene (Klammsteiner et al., 2020a; Lalander et al., 2015).

On an annual basis, ex-ante macroeconomic estimates revealed that the BSF larvae can recycle between 2 and 18 million tonnes of waste into frass fertilizer worth approximately 9–85 million USD (Abro et al., 2020), thus cleaning up the environmental and increasing organic fertilizer availability. Field experiments have demonstrated that crops grown using BSF frass fertilizer yielded higher profits than those grown using other commercial

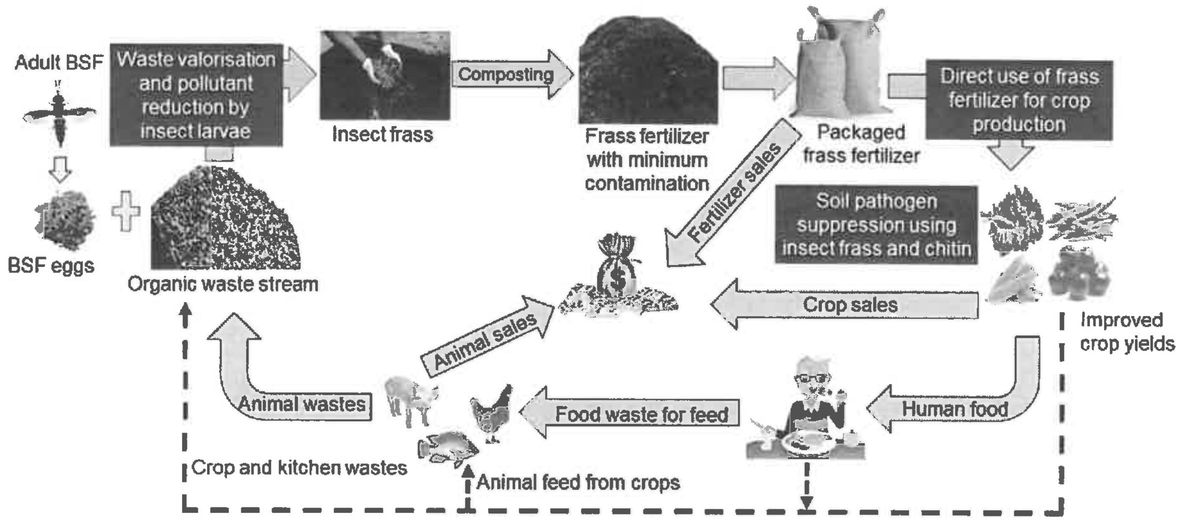

Fig. 1 Schematic representation of black soldier fly (BSF) as a recycler of organic wastes into hygienic organic fertilizer for crop production in a circular bioeconomy perspective.

Table 1 Physical–chemical properties of frass produced by different insect species.

Source of frass	pH	EC (mS cm^{-1})	TOC (%)	N	P	K	Ca	Mg	Fe (ppm)	Cu	Mn	Zn	S	C/N ratio	References
Black soldier fly	8.8	8.5	35.2	4.4	5.2	4.1	4.5	0.8	600	46.1	–	140	–	8.0	Setti et al. (2019)
	7.3	–	38.6	3.61	0.50	0.29	0.97	0.10	310	25	109	182	–	10.7	Anyega et al. (2021), Tanga et al. (2021b)
	9.0	–	–	3.3	3.4	2.4	0.4	1.0	–	–	–	–	5300	–	Gärttling et al. (2020)
	7.7	2.7	35.2	2.1	1.16	0.17	0.16	0.19	–	–	–	–	–	16.8	Beesigamukama et al. (2020a, b)
	–	–	30.7	3.19	0.08	0.054	0.079	1.9×10^{-3}	2.66×10^{-3}	7.0×10^{-5}	2.27×10^{-4}	1.4×10^{-5}	–	9.6	Song et al. (2021)
	–	–	42.0	6.0	0.13	0.081	0.13	1.9×10^{-3}	7.7×10^{-3}	1.700×10^{-5}	2.8×10^{-4}	3.9×10^{-5}	–	7.0	
Mealworm	–	–	38.9	2.92	1.53	1.86	0.10	0.54	140.68	–	171.89	–	0.18	13.3	Poveda et al. (2019)
	–	–	38.8	2.67	1.44	1.97	0.09	0.52	127.0	–	155.90	–	0.17	14.5	
	–	–	42.4	7.75	1.02	1.15	0.11	0.34	129.03	–	83.40	–	0.28	5.5	
	5.8	5.30	39.3	5.0	2.0	1.7	–	–	–	–	–	–	–	7.9	Houben et al. (2020, 2021)
Bees	5.7	–	53.2	5.2	0.72	1.2	0.35	0.19	7.9×10^{-2}	7.0×10^{-4}	–	6.1×10^{-3}	0.27	10.2	Mishra et al. (2013)

EC = electrical conductivity, TOC = total organic carbon, N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Fe = iron, Cu = copper, Zn = zinc, S = sulfur.

organic fertilizers (Beesigamukama et al., 2021c), hence improving farm productivity. The above advantages indicate that sustainable utilization of insect frass fertilizer will significantly reduce overreliance on the expensive mineral fertilizers, whose sole application also has overwhelming deleterious effects on soil and environmental health and is less effective in soils with multiple degradation challenges.

This chapter provides comprehensive information on organic waste pathogen reduction using insect larvae, mechanisms of pathogen suppression during entomocomposting, and the contribution of insect frass fertilizer to improving soil fertility and crop productivity in an environmentally sound, socially just, climate-resilient, and cost-effective manner. Finally, we provide concluding remarks and key recommendations on sustainable utilization of entomocomposting for waste management and fertilizer production. This knowledge will guide investors, entrepreneurs, and farmers who wish to use insects for waste recycling, environmental cleanup, and fertilizer generation to achieve sustainable development goals.

2. Persistent pathogens in compost

The common indictors of pathogen of contamination in compost are *Salmonella* spp., *E. coli, and Clostridium perfringens* (Liu et al., 2017). According to French composting standards, pathogen indicators of compost treatment efficiency are *Salmonella, Listeria monocytogenes,* helminths eggs, *E. coli, C. perfringens,* and *Enterococcus* (Brochier et al., 2012). For compost to be rendered as safe for crop production, there are required minimum detection limits for different microbes. The minimum detection limit for fecal coliforms, *E. coli,* fecal *streptococci,* and *Salmonella* is 0.18 MPN g^{-1}, 1.8 MPN g^{-1}, 0.065 MPN g^{-1}, and 1000 MPN g^{-1}, respectively (Brinton, 2000). Listeria should be $\leq$1.8 MPN g^{-1} while that of *E.coli* 0157:H7 is 3 MPN g^{-1} of total solids, and *C. perfringens* should be reduced to zero (Brinton, 2000).

Coliform bacteria and fungal contamination, especially *Aspergillus niger, Ammophilus fumigatus, A. sparsus, A. versicolor, Acremonium* spp., *A. flavus, A. restrictus, Cladosporium* spp., and *Penicillium* spp., have been reported in green waste composts (El-nagerabi et al., 2014; Elshafie and Alrawahi, 2012). Brinton et al. (2009) reported high presence of *Salmonella* spp., fecal coliforms, and fecal *streptococci* in composts and found that 55%, 23%, and 60% of the samples had pathogen levels that were above the US limit of

1000 MPN g^{-1} for *Salmonella* spp., fecal coliforms, and fecal *streptococci*, respectively.

The presence of pathogens in compost presents a high risk of disease transmission to humans, animals, and cultivated crops and high possibility of environmental pollution. For example, application of contaminated swine manure has been found to contaminate soil and water with *E. coli, Salmonella,* and *C. perfringens* (Samarajeewa et al., 2012). Therefore, strategies are needed to ensure elimination of pathogens before field application of compost. Maintenance of temperatures between 60°C and 70°C for at least 72h in all particles of compost has been recommended to cause significant reduction in the populations of persistent pathogens and improve compost hygiene (Wichuk and McCartney, 2007; Jouraiphy et al., 2005). However, the efficiency varies with the method of composting; for instance, windrow composting has been found more effective in suppressing *E. coli* and fecal coliforms than other methods (Brinton et al., 2009). The low pathogen inactivation efficiency associated with conventional composting methods warrants the pursuit for more efficient, faster, sustainable, and environmentally friendly methods of waste recycling.

3. Fate of pathogens in insect-composted wastes

Significant reductions in *Escherichia coli* O157:H7 and *Salmonella enterica* serovar enteritidis have been reported in BSF frass generated from chicken manure (Erickson et al., 2004), thus improving suitability for fertilizer use. Furthermore, composting a blend of pig manure, dog food, and human feces using BSF larvae suppressed *Salmonella* spp. to below detection limit, reduced thermotolerant coliforms to permissible levels for application of frass as fertilizer, but had minimal impact on *Enterococcus* spp. (Lalander et al., 2013, 2015). Previous studies have found that BSF larvae can effectively reduce adenovirus, enterovirus, and reovirus in organic waste to minimum levels (Lalander et al., 2015). Although the exact mechanisms are not well-understood yet, it is anticipated that the secretion of antimicrobial peptides (AMPs) into microbe-rich BSF substrates such as manure might help to reduce its pathogenic load (Vogel et al., 2018; Elhag et al., 2017; Yi et al., 2014). Mudalungu et al. (2021) underscored the role of edible insects as a source of novel AMPs that can be effective against multidrug-resistant pathogens. In particular, StomoxynZH1 and DLP4 were found as predominant AMPs in the BSF gut with potent antibacterial and antifungal activity (Mudalungu et al., 2021; Vogel et al., 2018). Pathogen waste reduction might also be achieved by microbe ingestion and/or lysis in the insect's gut (Tanga et al., 2021a). Putting the accent on this matter is of utmost importance for human health to prevent the spread and transmission of unwanted microorganisms into the environment.

On the other hand, edible insects can also act as reservoirs of foodborne pathogens with detrimental effects on humans and animals as recently reviewed by Vandeweyer et al. (2021). For instance, members of the genus *Providencia* were found as part of BSF gut microbiota, and they are known to cause gastroenteritis or urinary tract infections (De Smet et al., 2018). Of note is that *Providencia* can exert a positive effect on the insect physiology by enhancing BSF oviposition (Tanga et al., 2021a). Other bacteria associated with BSF gut and with important biosafety considerations include *Wohlfahrtiimonas* (Tanga et al., 2021a; Khamis et al., 2020), which has been found to cause sepsis upon myiasis infestation (Kõljalg et al., 2015). The genus *Campylobacter* that can cause diarrhea in humans has also been reported as member of the BSF larval gut microbiota (Tanga et al., 2021a; Klammsteiner et al., 2020b; Wynants et al., 2019). Other relevant foodborne pathogenic bacteria in edible insects comprise *Staphylococcus aureus* and spore-forming bacteria like *Clostridium* spp., with the species *C. perfringens* and *Clostridium botulinum* being the most relevant food pathogens within this genus and the *Bacillus cereus* group. Nonetheless, *Salmonella* spp., *Campylobacter* spp., and *L. monocytogenes* are considered of low health risk for edible insects. The same occurs for *Cronobacter* spp., *Vibrio* spp., and *Yersinia* spp. that are rarely reported (Vandeweyer et al., 2021, 2019). Microbiome analyses based on high-throughput sequencing revealed the existence of a core microbiota in the BSF gut (Tanga et al., 2021a; Klammsteiner et al., 2020b), but it is likely that most potential human pathogenic bacteria might be acquired during feeding and transit through the gut without particular selection or retention in the host. Supporting this, the type of diet appeared to be a determinant factor shaping the community composition of bacteria, and more strongly of fungi, in BSF gut (Tanga et al., 2021a).

With respect to other biological risks, bacteria linked to edible insects can be a reservoir of antibiotic resistance (AR) genes, which could be horizontally transferred to animals or humans through the food chain during insect mass rearing (Milanović et al., 2021). Previous studies have reported a high prevalence of genes primarily conferring resistance to tetracyclines and erythromycin in insect larvae and frass (Milanović et al., 2021, 2018, 2016; Osimani et al., 2017a, b). Furthermore, Bertola and Mutinelli (2021) found more than 70 species of viruses in edible insects, and they underscored that insect-specific viruses are of major concern in mass-rearing systems because of their ability to actively replicate and persist on the target species. Nonetheless, the fate of AR genes and viruses in the insect frass is still in its infancy and needs to be further explored.

4. Mechanisms of pathogen suppression by insect frass fertilizer

The activation of defensive responses in the plant when in contact with insect frass fertilizer may rely on the recognition of chitin and/or chitinase enzymes by cellular receptors present in the roots (Fig. 2), as reviewed by Poveda (2021). Chitin is a major structural constituent of the periotrophic gut membrane in insects and enzymes known as chitinases are necessary for the proper formation of this membrane. The signaling recognition of these eliciting biomolecules can confer systemic resistance to the plant through the activation of metabolic pathways involved in the synthesis of phytohormones such as salicylic acid or jasmonic acid, with a key role in plant defense against disease pathogens (Kemboi et al., 2022; Poveda, 2020; Quilliam et al., 2020). As shown in Fig. 2, other chemical-based mechanisms for pathogen suppression could be related to the presence of defense substances such as phenols and flavonoids (Ahmed et al., 2013) and/or the emission of

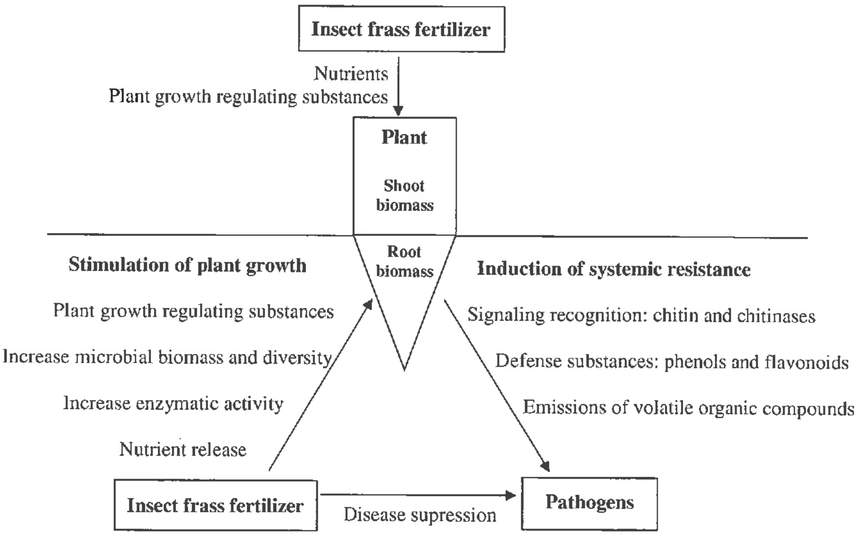

Fig. 2 Mechanisms of soil pathogen suppression and plant growth promotion using insect frass fertilizer.

volatile organic compounds by the insect frass fertilizer (Revadi et al., 2021; Zhang et al., 2019). Previous studies have found that treatment with 2%–5% chitosan from BSF pupal exuviae caused significant growth inhibition for resistant strains of bacteria, especially *E. coli, Bacillus subtilis, Pseudomonas aeruginosa, S. aureus,* and *Candida albicans* (Lagat et al., 2021).

Furthermore, the insects' gut microbiota harbors microorganisms that can help the plant to activate its response against pathogens, for instance, by promoting the expression of genes encoding proteins involved in plant defense mechanisms (Acevedo et al., 2017). Additionally, Sonawane et al. (2018) isolated siderophore-producing bacterial taxa from the gut of the grasshopper species *Sathrophyllia femorata.* Some of these bacteria have been used in plant growth promotion and as biocontrol agents against insect pests of plants. Altogether, this points toward plausible microbial-based functions that may explain the positive influence of frass fertilizer on soil and plants. Organic fertilizers contain an endogenous active microbiome that may exert a long-term effect on the productivity and sustainability of agroecosystems (Mas-Carrió et al., 2018). Focusing on this aspect is therefore of particular interest to broaden our understanding about the role of insect frass fertilizer as a plant biostimulant and unravel how its addition into soil may enhance nutrition efficiency and/or crop quality traits.

5. Impact of insect frass fertilizer on soil pathogens

Soil treatment with frass fertilizer has been reported to increase freedom from pathogens, thus favoring plant growth. Soil amendment with frass has been found to increase microbial diversity, suppress pathogenic microorganisms, and reduce soil pollution. For example, soil treatment with BSF frass fertilizer increased the population of Gram-negative bacteria, which outcompeted the *coliforms,* thus improving soil hygiene (Klammsteiner et al., 2020a). Use of BSF or mealworm frass fertilizer has been found to increase protection of beans and tomatoes against fungal diseases, especially those caused by *Rhizoctonia solani, Fusarium oxysporum,* and *Pythium* (Kemboi et al., 2022; Gebremikael et al., 2020; Choi and Hassanzadeh, 2019). The exact mechanisms involved are not clearly understood, but it is anticipated that frass fertilizer stimulates chemical reactions that neutralize pathogens, increases soil enzyme and microbial activities, and supplies chitin that has pesticidal properties (Gebremikael et al., 2020; Quilliam et al., 2020; Poveda et al., 2019). For example, soil amendment with 10% BSF-chitin and chitosan reduced the incidence and severity of bacterial wilt disease of tomatoes by 30%–35% and 23%–24%, respectively, indicating high biocontrol potential of BSF frass fertilizer against soil-borne pathogens (Kemboi et al., 2022). Therefore, the use of insect frass fertilizers could reduce the use of synthetic pesticides for crop protection and contribute toward organic food production that is safer for human consumption. To minimize safety risks upon consumption of crops fertilized by the insect frass fertilizer, a new Regulation (EU) No. 2021/1925 implementing Regulation (EU) No. 142/2011 requires a heat treatment of 70 °C for at least 60 min to reduce the pathogenic load of the insect frass fertilizer to achieve the microbiological standards prescribed by legislation (European Commission, 2018).

6. Other benefits of insect frass

6.1. Impact of insect frass fertilizer on soil health

Several studies have demonstrated the positive impacts of frass fertilizer on soil health, especially nitrogen mineralization, nutrient availability, and addressing biotic and abiotic challenges to crop production (Table 2). Soil amendment with BSF frass fertilizer has been reported to cause significant increase in beneficial bacteria, fungi, and archaea, reduced soil acidity, and increased phosphorus and magnesium release compared with commercial and conventional fertilizers (Beesigamukama et al., 2021a; Rummel et al., 2021). Furthermore, soil amendment BSF frass fertilizer was found to increase mineral N in the topsoil and improve the synchrony of N mineralization for plant uptake (Beesigamukama et al., 2020a, b). Improvements in soil microbial activity, increase in soil N mineralization, and availability of soil P and K have also been noted in soils amended with mealworm frass (Houben et al., 2020). The improvements in soil fertility have been majorly attributed to the presence of P and K solubilizing bacteria and fungi, siderophores, and N-fixing bacteria in mealworm amended soils (Poveda et al., 2019).

Use of insect frass fertilizer has been associated with improvement in biological soil fertility and reduced environmental footprint. For example, soil amendment with BSF frass fertilizer was found to increase microbial biomass carbon, soil organic carbon sequestration and reduce greenhouse gas emissions (Rummel et al., 2021; Song et al., 2021; Gebremikael et al., 2020). Most of the N in frass fertilizer is in ammonium form (Beesigamukama et al., 2021a); thus insect frass fertilizer could act as a biological nitrification inhibitor and contribute to strategies for increasing soil N availability, reducing gaseous nitrogen loss, and supporting crop varieties bred to exploit

Table 2 Benefits of insect frass on soil health and crop productivity.

Nature of study	Key findings	Reference
BSF frass fertilizer		
Two-season field experiment involving maize crop	• 7%–27% increase in grain yield compared with commercial organic fertilizer and urea • 23%–76% and 29% increase in maize N uptake compared with commercial organic fertilizer and urea, respectively • 27%–166% higher agronomic N use efficiency compared with commercial organic fertilizer and urea • Higher mineral N content in top and sub soil layers compared with commercial organic and mineral fertilizers	Beesigamukama et al. (2020b)
	• 1.3–38 times higher N fertilizer equivalence values compared with commercial organic fertilizer. Soil N immobilization observed during the active growth stages of maize growth	Beesigamukama et al. (2020a)
In situ field incubation studies using BSF frass fertilizer	• BSF frass fertilizer amendment reduced N immobilization. Repeated application of BSF frass fertilizer increased total N release (threefold) and rates of mineralization (3–10 times) and nitrification (two- to fourfold) • Significant increase in concentrations of soil N, phosphorus, and magnesium achieved using BSF frass fertilizer. BSF frass fertilizer caused higher release of N (58%) and P (twofold) and Mg (82%–268%) release potential than commercial organic fertilizer • Increased populations of bacteria and fungi, reduced soil acidity, and increased phosphorus (twofold) and magnesium (two- to fourfold) release in soil treated with BSF frass fertilizer compared with commercial organic fertilizer	Beesigamukama et al. (2021a)

Continued

Table 2 Benefits of insect frass on soil health and crop productivity—cont'd

Nature of study	Key findings	Reference
Greenhouse and field experiments involving three vegetables	• 22%–135%, 20%–27%, and 38%–50% higher yields than NPK for tomatoes, kales, and French beans, respectively, under both greenhouse and open-field conditions. 52%–75% higher tomato yield than other organic fertilizers • Significant increase in N uptake in kales, 54%–59% and 70%–75% higher N uptake in tomatoes and French beans than other organic fertilizers assessed • 96%–106% and 26%–89% higher agronomic N use efficiency of tomatoes and kales, respectively, compared with other fertilizers. Higher crude protein and ash contents	Anyega et al. (2021)
Laboratory incubation experiments involving bean crop	• 8%–16% net mineral N release, 50%–66% C mineralization and increase in microbial biomass carbon • Increased concentration of gram-positive and gram-negative bacteria, actinomycetes, dehydrogenase enzyme activity and disease suppressiveness (*Rhizoctonia solani*) than conventional composts and control. Up to 91 days of N immobilization	Gebremikael et al. (2020)
Mealworm frass fertilizer		
Pot experiment involving rye grass	• Higher ryegrass biomass associated with mealworm frass. Increase in N uptake and similar P and K supply efficiencies to mineral NPK. Higher soil C and N mineralization achieved at higher rates of $10\,t\,ha^{-1}$	Houben et al. (2021)

Table 2 Benefits of insect frass on soil health and crop productivity—cont'd

Nature of study	Key findings	Reference
Pot experiment involving barley crop	• Improved biomass and N, P and K uptake by barley crop. Stimulated soil microbial activity, higher N mineralization rates (57% of total N released) and increased soil nutrient availability, especially P and K	Houben et al. (2020)
Pot experiment involving chard plants (*Beta vulgaris* Var. *cicla*) and beans (*Phaseolus vulgaris*)	• Increased plant resistance to salinity, drought, and water logging. Significant increase in bean shoot biomass, chlorophyll content, root growth, microbes with plant growth promoting traits and growth hormones • Increased nutrient availability due to presence of P and K solubilizing bacteria and fungi, siderophores, N fixing bacteria (major Phyla: *Firmicutes* and *Proteobacteria*) and beneficial fungi (major Phyla: *Ascomycota* and *Basidiomycota*)	Poveda et al. (2019)

environments with higher concentrations of ammonium (Subbarao and Searchinger, 2021; Subbarao et al., 2012, 2009).

It is important to note that with climate change, the rising atmospheric carbon dioxide levels are likely to inhibit plant assimilation of nitrates but not ammonium, thus ammonium could become even more advantageous in the future as an adaptation strategy (Subbarao and Searchinger, 2021). In the long term, it is anticipated that use of frass fertilizer will increase soil organic carbon stocks in highly degraded soils, reduce greenhouse gas emissions, and enhance crop productivity amidst climate change.

The impact of frass fertilizer on soil fertility largely depends on the nutrient concentrations, amendment rate, and mineralization rate (Beesigamukama et al., 2020b; Poveda et al., 2019; Kagata and Ohgushi, 2012). Frass fertilizer with low nutrition levels could affect soil nutrient availability by inducing longer periods of N immobilization (Kagata and Ohgushi, 2012). Previous studies have reported up to 3 months of N immobilization using insect frass fertilizer (Beesigamukama et al., 2021b; Gebremikael et al., 2020) and recommended mineral N supplementation to increase the synchrony of N release for plant uptake (Beesigamukama et al., 2020b).

6.2. Effect of insect frass fertilizer on crop productivity

Studies involving BSF frass fertilizer have reported significant increases in the yields of maize (27%) (Beesigamukama et al., 2020a) and vegetables such as tomatoes (135%), kales (27%), and French beans (50%) compared with existing commercial fertilizers (Anyega et al., 2021) (Table 2). Higher N, P, and K uptake and N use efficiencies have been reported in maize and vegetable crops grown using frass fertilizer, leading to improved nutritional quality in terms of crude protein, crude fiber, and ash content compared with commercial fertilizers (Anyega et al., 2021; Tanga et al., 2021b; Beesigamukama et al., 2020a). Use of BSF frass fertilizer was found to improve the yield of horticultural crops such as chili pepper and shallots better than poultry manure (Quilliam et al., 2020). Furthermore, combined application of frass fertilizer and mineral fertilizer has been found to enhance the agronomic nitrogen use efficiency of different crops, thus improving fertilizer use efficiency through a synergistic effect (Anyega et al., 2021; Tanga et al., 2021b; Houben et al., 2020).

Mealworm frass fertilizer has also been found to enhance growth, yield, biomass accumulation, and uptake of N, P, and K by crops such as barley and ryegrass (Houben et al., 2021, 2020). The same studies noted that mealworm frass fertilizer also enhanced the P and K use efficiencies as good as the mineral NPK fertilizer. Furthermore, use of insect frass fertilizer has been reported to boost crop production by increasing tolerance and resistance against multiple abiotic and biotic stresses. For example, soil amendment with mealworm frass fertilizer has been found to increase tolerance and resistance against soil salinity, water logging, and drought (Guo et al., 2021; Poveda et al., 2019). Soil treatment with BSF frass fertilizer caused suppression of *Fusarium* disease in cowpeas, thus improving plant health (Quilliam et al., 2020). Bean crops grown using mealworm frass fertilizer had higher root growth and extension, due to high presence of plant growth promoting bacteria and growth hormones such as auxin, aminocyclopropane-1-carboxylic acid deaminase (Poveda et al., 2019). These attributes confirm that insect frass fertilizer is a quality organic fertilizer product worth integrating into farming systems of most developing countries, where mineral fertilizers are less effective due to multiple soil degradation challenges.

Economic assessment has found that maize grown using frass fertilizer would yield 29%–44% higher net income compared with commercial organic fertilizer, the profits were higher for smallholder insect farmers who could directly use frass fertilizer crop production compared with those farmers that purchase similar frass fertilizer (Beesigamukama et al., 2021c). These findings demonstrate the role of insect farming in circular economy and justify the opportunities for future investments that would lead to enhanced sustainability for agricultural and food systems, especially for smallholder farmers in low- and middle-income countries.

7. Research prospects

Although entomocomposting and the utilization of insect frass as fertilizer have attracted a flurry of interest, harnessing the full potential of this emerging technology still requires key research and policy interventions. Studies have shown that benchtop and industrial-scale results on BSF larval performance usually differ, making it difficult to transfer laboratory results to industrial scale (Kooienga et al., 2020). Therefore, future research should involve industrial-scale experiments or semi-natural environments to generate credible findings and recommendations that can be adopted at industrial scale.

Most studies on agronomic effectiveness of insect frass fertilizer have been conducted under controlled conditions (laboratory, pots, or greenhouse), and little is known about the performance of insect frass fertilizer under open field conditions/natural environment. Future studies should include field experiments and farmer-managed trials to generate accurate information on fertilizer potential of insect frass fertilizer for scaling-up and adoption.

Existing knowledge on frass fertilizer is limited to annual crops, yet perennial crops require large quantities of fertilizer. The impacts of frass fertilizer on perennial crops' productivity should be adequately investigated to generate the information necessary for integrating frass fertilizer into perennial cropping systems.

The influence of insect frass fertilizer on soil health has been investigated using short-term studies; future research should assess short-long term impacts of frass fertilizer on soil fertility, especially physical soil fertility, which has not received any research attention. Although soil amendment with frass fertilizer has been found to suppress soil-borne plant pathogens and pests, the scientific mechanisms involved have not been clearly elucidated. The biochemical mechanisms involved in frass fertilizer-mediated inactivation of below- and above-ground pests and pathogenic microorganisms should be explored to fine-tune research aimed at utilizing insect frass fertilizer as a biopesticide.

Different insects and organic wastes produce frass fertilizer with different physical–chemical properties and varying degrees of compost maturity and stability. However, to date, there are no established standards for assessing the quality of frass fertilizers produced by insects reared on various organic wastes. Consequently, frass fertilizer quality is assessed using standards established for conventionally composted organic fertilizers (Bernal et al., 2017, 2009, 1998), yet entomocomposting is different from conventional composting. Therefore, future research should establish the standards for assessing the quality of insect frass fertilizers to ensure quality control, approval by standard regulatory bodies, and integration of frass fertilizer into existing fertilizer markets at both national and international levels. This could be achieved through development of policy and legal framework by major stakeholders, especially researchers/research institutions, agro-input dealers, standard regulatory bodies, and governments at national and international levels.

8. Conclusion

This chapter provides the first review of the influence of insect larvae on pathogen reduction during organic waste composting and discusses the key mechanisms involved in pathogen suppression during entomocomposting. The additional benefits of insect frass fertilizer on soil fertility, crop growth, yield, nutritional quality, pathogen and disease suppression, and plant protection are also presented. Analysis of existing literature shows the high efficiency of insect larvae in suppressing pathogens contained in organic wastes to produce an organic fertilizer with little or no biological contamination and potential for soil remediation using insect frass fertilizer. Existing research has demonstrated additional benefits of entomocomposting, especially the positive impacts of insect frass fertilizers on soil health and crop productivity with a lower environmental footprint compared with conventional fertilizers. Consequently, entomocomposting will immensely contribute toward sustainable bioremediation, soil health management, close biogeochemical cycles, and meet plant nutrient requirements using smart fertilizers and innovative organic amendments. However, exploring the full potential of these technologies requires more research to: optimize pathogen suppression during entomocomposting and soil remediation using insect frass fertilizer, develop quality standards for insect frass fertilizer, assess the mid-long-term impacts of frass fertilizer on soil and plant health, and develop policy and legal framework for scaling up the use of insect frass fertilizer in existing fertilizer markets and farming practices.

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