# Effects of black soldier fly frass on plant and soil characteristics – a literature overview

Auteurs | Hellen Elissen[1], Rommie van der Weide[1] & Luuk Gollenbeek[2]

[1]| Wageningen University & Research [2]| Wageningen Livestock Research, ACRRES

Report WPR-OT 996

WAGENINGEN
UNIVERSITY & RESEARCH

# Effects of black soldier fly frass on plant and soil characteristics – a literature overview

Hellen Elissen[1], Rommie van der Weide[1] & Luuk Gollenbeek[2]

[1] Wageningen Plant Research, ACRRES
[2] Wageningen Livestock Research, ACRRES

This study was carried out by the Wageningen Research Foundation (WR), Business Unit Field Crops and was commissioned and financed by the PPP Biobased valorisation of manure and digestate AF-17052b. This project is financially supported by the Dutch Topsector Agri & Food. Within the Topsector, private industry, knowledge institutes and the government are working together on innovations for safe and healthy food for 9 billion people in a resilient world. WR is part of Wageningen University & Research, the collaboration of Wageningen University and Wageningen Research Foundation.

Wageningen, February 2023

Elissen, H. J. H., R. van der Weide and L. Gollenbeek, 2023. *Effects of black soldier fly frass on plant and soil characteristics – a literature overview.* Wageningen Research, Report WPR- 996.

This report can be downloaded for free at https://doi.org/10.18174/587213

Summary Black soldier fly (BSF) frass, resulting after bioconversion of organic materials by *Hermetia illucens* larvae can be used as fertilizer. This overview provides a literature summary of the main (macronutrient) components in frass and its reported effects on plant growth/health and soil. Frass composition is highly dependent on the substrate. Based on average composition, BSF frasses show resemblances to cow manure (C/N ratio, N content), pig slurry (P content), poultry manure (DM, K content) and compost (DM). The frass has a higher organic matter content than compost and beforementioned manure types. Frass seems to be a fast acting fertilizer. Most of the nitrogen is organic, but ammonia content is highly variable. Reported effects on plant growth were often positive or neutral but also sometimes negative compared to organic and mineral control fertilizers and there seem to be maximum application rates above which positive effects diminish. Several authors mention that post-treatment of frass (for example by aerobic composting) is necessary to obtain a stable/mature product. Usually the frass is relatively high in P content, which may require extra N fertilizer addition. Several authors state that chitin in the BSF frass likely benefits resistance to plant pathogens. Finally, adding frass can induce changes in the microbial community of the soil/plant rhizosphere. BSF frass can be used as a circular fertilizer in agriculture.

Keywords: black soldier fly larvae, frass, fertilizer, plant growth, plant health, nutrients, soil, chitin



Chamber of Commerce no. 09098104 at Arnhem
VAT NL no. 8065.11.618.B01



Report WPR- 996

Photo cover: Klaas van Rozen

# Contents

# Preface

In the Netherlands, there are surpluses of manure and digestates/biogas slurries (digested manure and residual flows), which represent a negative value. At the same time, these residual flows contain valuable ingredients for the production of biomass (as raw material for food and feed products), for improving soil quality and for energy production. The number of feasible business cases in which the residual flow is upgraded has so far been limited. This is due both to the efficiency of the technologies used and the legislation and regulations related to the residual flows.

Recent information from research, scientific literature and companies provides new starting points for a biobased valorisation of manure/digestate streams and improving the efficiency of anaerobic digestion. The innovative aspect of our research is the cultivation of new types of biomass on the residual flows and the use of the conversion products to improve anaerobic digestion. This involves the use of separated manure and digestate products for the cultivation of mushrooms/fungi, worms, insects, specific bacteria and aquatic biomass. The resulting biomass can be further refined and marketed as food, feed and bio-based feedstock. There are also processed manure and digestate products that are valuable as fertilizer products for soil and plant growth, as substrate for improvement of anaerobic digestion or for export/use besides in agriculture. This gives a new interpretation to obligatory manure processing.

The aim of this project is to further explore and substantiate/test these ideas on lab and practical scale, leading to a proof of principles for new bio-based upgrading methods for manure and digestate that can be used in conjunction to better close cycles and/or sell outside regular agriculture. Bottlenecks in legislation and regulations are explored and put on the agenda. Key figures are also calculated that are necessary for assessing sustainability (e.g. costs, environmental effects) and for supporting legislation (e.g. minerals, food safety).

The livestock sector gains insight into the possibilities of biobased valorisation and better marketing of their most important residual flows. For the SMEs involved, this research provides proof of principle for their technology and input in their business cases. The combined effects of the technologies provide new knowledge, methods and research directions for science. In a social context, the use and upgrading of manure and digestates in other ways also contributes to the transition to a circular bio-economy with an efficient and sustainable agri-food sector.

More information:

- http://www.acrres.nl/en/projecten_acrres/biobased-valorization-of-manure-and-digestate/
- Rommie van der Weide: rommie.vanderweide@wur.nl, +31320291631
- Hellen Elissen: hellen.elissen@wur.nl, +31320291223

# Abstract

Black soldier fly (BSF) larvae (*Hermetia illucens*) are increasingly used worldwide for bioconversion of organic waste streams into protein-rich biomass and frass (insect faeces). The biomass can be used as animal feed, while the frass can be used as fertilizer. Multiple researches have been done in the past years on the effect of frass application on plant growth/health and soil health. This overview provides a summary of the main components of frass and its reported effects on plants and soil. Chitin, originating from the larval skins, is highlighted as a specific component of interest.
From the researches, it can be concluded that frass composition is highly dependent on the substrate. This makes comparisons to other fertilizers complicated. Based on average composition, BSF frasses show resemblances to cow manure (C/N ratio, N content), pig slurry (P content), poultry manure (DM, K content) and compost (DM). The frass has a much higher organic matter content than compost and also higher than beforementioned manure types. Frass seems to be a fast acting fertilizer. Most of the nitrogen is organic, but ammonia content is highly variable. Due to this ammonia content, but also anaerobiosis, salt content and VFAs (dependent on the specific substrate used) BSF frass can be toxic to plants and several authors mention that post-treatment of frass (for example by aerobic composting) is necessary to obtain a stable/mature product. Post treatment strategies (such as composting) may result in a more mature fertilizer even though C/N ratios of frass are already often indicative of a mature compost. Usually the frass is relatively high in P content, which may require extra N fertilizer addition.
Reported effects on plant growth were often positive or neutral but also sometimes negative compared to organic and mineral control fertilizers and there seem to be maximum application rates above which positive effects diminish. Several authors state that chitin in the BSF frass likely benefits resistance to plant pathogens. However, care should be taken not to ascribe certain effects to chitin only, as BSF frass contains many other nutrients that can affect plant and soil. Finally, adding frass can induce changes in the microbial community of the soil/plant rhizosphere.
Although it is clear from this overview that there is no universal frass composition, BSF frass has potential as an organic fertilizer for several agricultural applications and this application increases circularity in the agrifood sector.

# 1 Introduction

A large variety of organic waste streams (e.g. manure, food waste, biogas slurries) can be converted by black soldier fly (*Hermetia illucens*) larvae (BSFL) into new insect biomass and the residual fraction is called frass (Figure 1). According to Commission Regulation (EU) 2021/1925 frass is defined as *a mixture of excrements derived from farmed insects, the feeding substrate, parts of farmed insects, dead eggs and with a content of dead farmed insects of not more than 5 % in volume and not more than 3 % in weight* (EU, 2021).

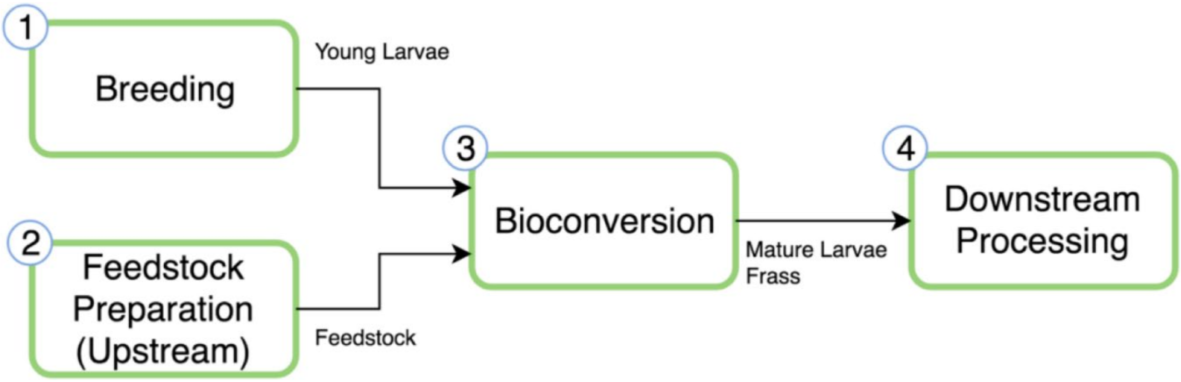


***Figure 1*** *Overview of waste bioconversion by black soldier fly (Hermetia illucens) larvae. (Figure from: Law and Wein, 2018).*

The produced biomass can be (either processed or unprocessed) applied as protein-rich animal feeds (e.g. (van Huis, 2022)). As an indication of the conversion efficiencies of organic wastes some mass balances for substrate conversion by BSF larvae are shown in Table 1.

***Table 1*** *Mass balances for substrate conversion by BSF larvae, DM = dry matter, WW = wet weight*

| Author, substrate | Substrate amount | | Larvae amount | | Frass amount | | Larvae yield | Substrate breakdown |
|---|---|---|---|---|---|---|---|---|
| | DM | WW | DM | WW | DM | WW | | |
| Ermolaev et al, 2019, food waste | 292 g | | 62 g | 181 g | 166 g | | 21 % (DM) | 43 % (DM) |
| Mason, 2016, food waste | 660 g | | 64 g | 161 g | 400 g | | 10 % (DM) | 40 % (DM) |
| Xiao et al, 2018, chicken manure | | 1,000 kg | | 80 kg | | 642 kg | 8 % (WW) | 36 % (WW) |
| Salomone et al, 2017, food waste | | 10,000 kg | 300 kg | 797 kg | | 3,346 kg | 8 % (WW) | 33 % (WW) |

Mason (2016) reported general DM yields of 7-24 % for BSF larvae from literature. They also report DM percentages of 28-37 % for larvae and of 29-38 % for frass. Parodi et al. (2020) found that of total C around 57 % ended up in frass, 20 % in larval biomass and the remainder was mainly converted to $CO_2$. Of the nitrogen 62 % was recovered in frass and 38 % in larvae, resulting in very small losses.
The composition of the produced frass is variable depending on the composition of the substrates. Frass can contain significant amounts of N, P, K, organic matter and other components such as chitin (from the larvae skins). To close the BSFL production cycle frass can be used for different applications: direct or composted as fertilizer or soil conditioner, or for biogas production (e.g. Bulak et al, 2020; Hol et al, 2022). This report provides an overview of literature found for frass as fertilizer or soil conditioner.

# 2 Frass as fertilizer and soil conditioner – reviews and general data

Similar to vermicompost (produced by earthworms digesting organic substrates) (e.g. Aira et al., 2007; Elissen & van der Weide, 2023), frass could impact soil fertility by influencing soil enzymes and bacterial growth. Several authors have written extensive reviews on the application of BSF frass for plant growth/health and soil quality.

Gärttling and Schulz (2019) compared BSF frass samples of 22 commercial ventures and analyzed their nutritional and fertilizer values. In a later publication Gärttling & Schulz (2022) also added literature data. Table 2 shows an overview of their main data. Their most important conclusion is that the composition of BSF frass is highly variable (especially regarding micronutrients, data not shown) and needs to be assessed on an individual basis for specific purposes. Palma et al. (2020) concluded that the feed substrate has a large effect on the nutrients in the frass. Gärttling and Schulz (2019) also concluded that frass composition is comparable to poultry manures but it has low nutrient contents compared to high-value commercial organic fertilizers. Frasses have a variable but usually low $NH_4$ content as percentage of $N_{total}$ and the C/N ratio is comparable to that of solid manures. The neutral to alkaline pH of the frass can lead to $NH_3$ emissions in case of higher $NH_4$ content, but high dry matter contents mitigate this effect. The authors see as most promising markets garden fertilizer or basic fertilizer in horti- and agriculture. In addition, the frass has a short-term nitrogen availability and a high dry matter content and therefore high amounts of macronutrients in comparison to other manures.

***Table 2*** *Nutritional values of frass samples both from producers and from literature; data represented as means and the coefficient of variation (CV) as percentage value (Producer data from: Gärttling and Schulz (2019); literature data from Gärttling & Schulz (2022)*

| Parameter | Unit | Producers | n | Literature | n |
|---|---|---|---|---|---|
| DM | % DM | 66.01 (0.27) | 14 | 78.03 (0.25) | 6 |
| OM | % DM | 86.6 (0.06) | 15 | 84.39 (0.03) | 3 |
| pH | % of $N_t$ | 7.75 (0.12) | 14 | 6.80 (0.18) | 9 |
| $N_t$ | % DM | 3.39 (0.24) | 18 | 3.35 (0.32) | 9 |
| $NH_4^+$-N | % DM | 0.61 (0.5) | 9 | 0.64 (0.57) | 5 |
| $NH_4^+$ | % of $N_t$ | 16.56 (0.45) | 9 | 16.21 (0.48) | 5 |
| C/N ratio | | 13.2 (0.24) | 14 | 15.73 (0.36) | 8 |
| P | % DM | 1.24 (0.16) | 18 | 1.16 (0.38) | 5 |
| K | % DM | 2.88 (0.28) | 16 | 2.91 (0.36) | 4 |

They concluded in 2019 that BSF frass can be classified as compound NPK fertilizer with 3.4 % N, 2.9 % $P_2O_5$, and 3.5 % $K_2O$ on average. Gärttling et al. (2020) mentioned that it can be difficult to discern between P and N fertilization effects. They gave an overview of fertilizer trials with BSF frass in this article on applying BSF frass in a pot trial with maize. Both positive, neutral and negative effects on growth and plant health have been found with different frass types and crops. It seems that frass cannot be applied at high concentrations, possibly due to ammonia toxicity. In contrast to results mentioned above pointing out low ammonia concentrations in frass, Green & Popa (2012) found that BSF larvae, while feeding on vegetable and food waste, produced high concentrations of $NH_4^+$ by N-mineralization and facilitated recovery of $NO_3^-$ via DNRA (dissimilatory nitrate reduction to ammonia). According to Basri et al. (2022) compost with a C/N ratio below 20 is beneficial to plants because the organic nitrogen has mineralized to inorganic nitrogen, which is then available for plant absorption. Compost with a C/N ratio higher than 30 is more likely to immobilize nitrogen for plant uptake. BSF frass has a relatively low C/N ratio (13-16 on average) and is easily available for plant uptake. They also mention that pH 6-8 is a good value for a mature compost for agronomic purposes. Most frasses comply with this range. Beesigamukama et al. (2021) amended brewery spent grains with sawdust as substrate for BSF larvae to increase the initial C/N ratio of 11 to 15, 20 and 25. At a C/N ratio of 15, more N and P were retained in the final BSF frass. Liu et al. (2019) found that the C/N ratios of frasses from cow, chicken and pig manure after 9 days were all lower than 20, which is indicative of a mature compost (i.e. lower than 25 according to the authors). In addition to frass being a more stable fertilizer than the three manure types, germination indexes and nutrient concentrations (e.g. $N_{Kjeldahl}$ and $P_{tot}$) of all frasses as compared to the original materials had increased.

Chavez & Uchanski (2021) give an overview of the frass composition of different insect species and application effects on different crops. They concluded that insect frass in combination with inorganic fertilizers produced the best results on crop and pathogen/disease resistance with a typical effective dosage of 10-40 percent of the total fertilizer volume administered. They also conclude that high conductivity values and sodium content can be drawbacks for application, depending on the insects' substrate.

Torgerson et al. (2021) explored knowledge of experts (on insect waste streams research, applications in agriculture or policy) on the characteristics and application of insect waste streams as a crop and soil health promoter by doing interviews. According to the expert opinions, insect waste streams could be produced as granulate-type compost, seed coating, or impregnated into a biodegradable seedling cup. Insect waste streams should be applied rather precisely around the root systems of the plants instead of being spread over all the field to prevent for example overdosing. However, there were contrasting opinions on dosage and expected effects on yield. Benefits are expected from the organic matter and nutrients (which could result in less use of chemicals and plant disease protection) and specifically the chitin content.

Nurfikari (2022) wrote a PhD thesis on insect waste streams for crop management. She discusses the latest research on plant and soil effects and did several experiments with BSF frass, e.g. decomposition, N-mineralization, influence on the bacterial/fungal community composition. In general, rapid mineralization and release of plant available N were observed. Due to the chitin content of the frass and easily degradable components with high N content, increasing numbers of chitin-degrading bacteria (e.g. some Gammaproteobacteria) and somewhat increasing numbers of fast-growing high N-containing fungi (e.g. *Mortierellomycota*) were found in frass amended soils. She concludes that insect waste streams have potential as soil health-promoting amendments. Kawasaki et al. (2020) found that concentrations of *E. coli* were low in BSF frass produced from organic household waste but there was a relative high concentration of Xanthomonadaceae, some of which can cause plant diseases. Raimondi et al. (2020) analyzed microbial diversity in frass (and larvae) produced at different temperatures on a vegetable substrate. Bacteria species in the frass were quite similar to those in the larvae. Some changes in bacterial composition took place with increasing temperatures. They found also genera that could be dangerous to human health, such as *Bacillus*, *Myroides*, *Proteus*, *Providencia*, and *Morganella* and proposed a bacterial risk assessment for frass.

Basri et al. (2022) reviews frass produced on food waste and its applications. They write that BSF frass has the characteristics of immature compost. She also compares BSF frass on different food wastes to different types of fertilizers and discusses its pre- and posttreatment options.

Lopes et al. (2022) have compiled data on 17 BSF frass samples. They concluded that frass composition is highly variable and dependent on substrate, especially P, K and micronutrient concentrations. As a P dominated fertilizer N supplementation is necessary to make BSF frass a more balanced fertilizer product. The frass is a biologically unstable product, due to its rapid breakdown and the presence of substances with potential phytotoxic properties. Palma et al. (2020) also concluded that the frass needs stabilization before application as soil amendment. They mention that non-stable organic matter can make pest control more efficient through the production of ammonia and VFAs. The biological instability of frass could thus be useful in agricultural practices that depend on the biological activities of added organic matter. Basri et al. (2022) also mentioned that more research should be done on the varying composition of nutrients, microorganisms and bioactive compounds in the frass, its behaviour in soil and action in plant metabolism. Also post-processing measures to improve biological stability are important in future research. Klammsteiner et al. (2020) suggested that a high moisture content of frass can lead to anaerobic conditions and should be post-processed to be further degraded, for example by composting or anaerobic digestion.

Poveda (2021) wrote a general review on many other frass types apart from BSF frass and concluded that insect frass can add nutrients to the soil, mainly nitrogen, that are easily assimilated by plant tissues, add plant growth promoting biomolecules/microorganisms and increase abiotic stress

tolerance and resistance to pests/pathogens due to the presence of different compounds and microorganisms. Beesigamukama et al. (2022b) concluded that BSF frass has significantly higher N (20–130 %) and K (17–193 %) concentrations compared to frasses of other insects. Also, BSF frass application led to the highest seed germination rate/index.
Barragán-Fonseca et al. (2022) wrote a review on the potential effects of insect waste streams on beneficial soil microbes, plant growth, reproduction and resistance and microbial antagonisms against plant pathogens/insects. They also address important future research questions, which should focus on the effects of insect-derived products on insect–plant–microbe interactions.
Watson et al. (2022) critically reviewed literature on insect waste streams application in agriculture. As observed negative effects they mention nitrite build-up, emissions of substantial quantities of $CO_2$ and $N_2O$ and salinity and ammonia content of the frass. He also questions the mechanism of pathogen suppression by chitin as is claimed by many authors. More research is needed on different frass types (and related to the larval feedstock and possible thermal pre-treatment) and in long-term field experiments with a variety of crops with special emphasis on C and N mineralization.
Further details of frass composition and effects on plants/soil are given in Chapter 4 (Table 3).

# 3 Chitin in frass

Gärttling et al. (2020) mention that insect frass often contains chitin. Chitin is said to have fungicidal and nematocidal effects. Sharp (2013) review chitin and its derivatives, its effects on crop yield and its mode of action. Many researches point to chitin protecting crops from pests, pathogens and physiological disorders. Modes of action include antibiosis (one organism producing metabolites toxic to another organism) and induction of plant defences. A major effect is the stimulation of growth of beneficial (chitinolytic) bacteria. Korthals et al. (2014) found that, compared to chemical controls, additions of chitin are a good alternative for the control of plant-parasitic nematodes and soil fungus *V. dahlia*. It increased crop yield (> 60 %) without permanent negative changes in chemical/physical soil properties, probably due to changes in the soil biological community. Debode et al. (2016) found that chitin from crab shells in potting soil led to increased lettuce growth and decreased survival of human pathogens on the leaves. This was associated with changes in soil and rhizosphere microbiology. Hadwiger (2013) reviewed the effects of chitosan (from chitin) on plant systems. Chitosan exerts multiple effects on plant health, either on pathogens directly or indirectly by eliciting plant defence mechanisms, forming a chemical barrier etc. It is also a functional glue. Several mechanisms are summarized in this review how chitosan affects regulation of plant defence genes. The authors however warn that effects/claims should not be exaggerated and checked for each application, even though application of chitosan has major potential for plant health. Coudron et al (2019) mention a chitin content for BSF larvae of 14.5 % DM. According to the authors chitin from BSF larvae can induce plant defence mechanisms against insects. In a test where 5 % of the soil was replaced with BSF frass (weight based) they found that significantly less aphids were found in treated soils as compared to 100 % soil. Also the cabbage plants had a 22 % higher growth rate as compared to controls, but this was probably due to the frass fertilizer effect. Nurfikari (2022) found that BSF puparia (hardened shell from the pupal stage before fly emergence) contained 18 % chitin and stated that they are a good alternative for seafood waste streams. They can be easily separated from the frass. Quilliam et al. (2020) found that the loss of cowpea plants due to *Fusarium* was significantly lower with BSF frass, which the authors hypothesize is due to chitin in the frass. Postma et al. (2015) found that in sugar beet bioassays chitin stimulated *Rhizoctonia*-disease suppression.

# 4 Macro composition of different frass types with a short description of the effects on plants and soil

Table 3 shows nutrient concentrations, origins, other parameters and effects on crops/soil for different frass types from literature or obtained from Bestico BV (Berkel en Rodenrijs, the Netherlands). It was not always clear from experimental details in literature whether nutrient content was based on dry or fresh matter. In addition, the concentrations sometimes seem to be expressed in the wrong units, which is indicated with italics.

***Table 3*** *Macronutrients, origins and other parameters of different frass types*

| Reference | Substrate | $N_{total}$ g/kg DM | P g/kg DM | K g/kg DM | OM g/kg DM | C/N | $N_{org}$ | pH | DM % | Crop & effects |
|---|---|---|---|---|---|---|---|---|---|---|
| Agustiyani et al., 2021 | 'Garbage', not specified, nor is the composition of the frass | | | | | | | | | Pakchoi. BSF frass, compared to other fertilizers, improved plant growth and soil biochemical properties, comparable to compost effects |
| Alattar et al., 2016 | Food waste | | | | | | | | | Corn (*Zea mays*). Corn plants grown in soil amended with frass (2:1) resulted in stunted plants, growing 39 % shorter and 19 % fewer leaves. Phytotoxicity was ascribed to ammonia or anaerobic conditions due to low porosity of the frass |
| Anyega et al., 2021 | Brewer's spent grains | 36.1* | 5.0* | 2.9* | | 10.7* | | 7.26* | | French beans (*Phaseolus vulgaris* L.), tomato (*Solanum lycopersicum* L.), and kales (*Brassica oleracea* L. var. *acephala*). Vegetable yields achieved using a combination of composted frass and NPK were 5.4, 4.5, and 2.4-folds higher respectively than control yield. N was more effectively taken up with this combination. Yields were also higher than for NPK alone. Also the nutritional quality of the crops increased. **Composition is from frass composted with rice husks* |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Arabzadeh et al., 2022 | Fruit/vegetable/bakery waste-based diet with brewery waste, Gainesville (GV) reference diet | 20.1-27.0 | 12.7-19.4 | 29.7-36.5 | 875-887 | 19.1-25.4 | | 8.4 | 22.1-25.6 | Nutrients in both frasses are comparable to commercially available organic fertilizers. Frass microorganisms produce antifungal compounds and inhibit growth of some plant pathogens |
| Banavar et al., 2022 | Hemp waste | 20.2 | 7.1 | 14.8 | 822 | | | | 84.3 | |
| Basri et al., 2022 | Different food wastes | 6-48 | 0.4-10.9 | 0.8-17.4 | | 8-27 | | 5.6-8.0 | 30-72 | The frass is an immature compost, based on germination and microbial tests, and needs post-treatment. Frass from food waste for example often has a high moisture content (>45%) |
| Beesigamukama et al., 2020a | Brewery spent grains, biochar, gypsum | 19.4-24.5 | 10.6-11.0 | 0.82-4.56 | | | | | | N retention in BSF frass was improved by adding biochar and gypsum |
| Beesigamukama et al., 2020b | Brewery spent grains | 30.0 | 16.6 | 2.43 | | 16.8 | | 7.7 | 69.9 | Maize. Yield and N use efficiency improved with the application of pre-composted BSF frass. Frass performed better than commercial organic and inorganic fertilizers. A rate equivalent to 30 kg N/ha was recommended |
| Beesigamukama et al., 2022a | Brewery spent grains, sawdust, biochar, gypsum | | | | | | | | | Maize. Plants grown with composted frass yielded 29-44 % more net income than with commercial organic fertiliser |
| Beesigamukama et al., 2022b | Irish potato peels with brewery spent grains | 29 | 13 | 40 | | 13.2 | | 7.5 | 88.8 | The highest seed gemination rate (> 90 %) and germination index (267 %) were observed in seeds treated with BSF frass. Compared to frasses of nine other edible insects BSF frass had the highest fertilizing index |
| Bestico (2019/2020) | Food processing waste | 19.8-23.7 | 5.3-6.4 | 9.3-13.9 | 751 | 11-13.5 | | | 46-69 | |
| Bortolini et al., 2020 | Chicken manure, chabazite | 26.6 | 11.9 | 67.2 | | 11.7 | 19.0 | 8.5 | 53.4 | Baby leaf lettuce. BSF frass lead to improvements in soil quality. Germination improved with frass added to peat moss, compared to solely peat moss or solid fertilizer added to peat moss. Shoots had a lower fresh weight with frass compared to the other treatments |
| Bulak et al., 2020 | Carrot/beetroot waste | 22.1 | | | 852 | 15.5 | | 8.2 | 84 | |
| Cai et al., 2020 | Pig manure | 14.7 | 66.9 | 20.3 | | | | 8.62 | | Maize. BSF frass was spiked with cadmium. Plant growth and chlorophyl content seemed comparable to when applying regular fertilizers |
| Chiam et al., 2021 | Okara | 51.5 | 0.29 | 1.9 | | 7.2 | | | | Lettuce. 10 % frass in soil produced lettuce plants with a biomass similar to those of the controls with compost. At higher concentrations crop growth was stunted, likely caused by the rapid frass mineralization. Microbial diversity in frass treated soil decreased while new micronutrients were added. No foodborne pathogens were detected in frass |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Devic, 2016 | Processed food wastes or brewery spent grains | ~29.5-33.2 (calculated from protein content) | 103-149 | 31-193 | | | | | 87.5-92.3 | Spring onions (*Allium Cepa*, White Lisbon). Growth results with two frass types were the same as with commercial NPK fertilizer. Frasses led to higher OM in the soils and food waste frass led to a higher soil conductivity than brewery waste frass. Food waste frass performed better than brewery waste frass |
| Ermolaev et al., 2019 | Food waste | 24 | | | 904 | | | 5.4 | 22.2 | |
| Fischer et al., 2021 | Spent coffee grounds and donut dough | 42 | 3.1 | 6.3 | | | | | | The substrates produced BSF frass that was nutritionally comparable to soybean meal and many organic fertilizers |
| Fuhrmann et al., 2022 | Spent malted barley grain | 31.6 | 5.6 | 2.7 | | 12.7 | 26.7 | 6.9 | 87.4 | Grass clover. BSF frass altered the soil microbial community and tended to increase microbial activity (basal respiration) and crop yield when compared to compost-amended or unamended soils. There was a limited influence on soil physicochemical properties. BSF frass contains specific bacterial species |
| Gärttling et al., 2020 | Unknown | 33.0 | 14.9 | 24.0 | | | | 9.0 | 81.7 | Maize. BSF frass is more suitable as basic fertilizer or potting substrate amendment than as short-term fertilizer, due its low N availability resulting from volatilization losses caused by high pH and ammonium contents |
| Gebremikael et al., 2022 | Combinations of potato waste, brewing by-product, mushroom stalk, orange/mandarin/clementine waste, beetroot peelings, chicken feed waste, vegetable food wastes collected from supermarkets, commercially available frass made from general food waste | 20-34 | | | | 12-23 | | | | Maize. N availability and soil microbial quality varied depending on BSF substrate. Most frass treatments did not increase plant growth, but increased bacterial biomass and enzyme activities. About 56–70 % of applied C in frass is estimated to be stable in soil. Frass is valuable for improving soil quality but should be applied with readily available N sources, to prevent nutrient shortage during crop growth |
| Guo et al., 2021 | Chicken manure | *4.3 mg/kg* | *3.8 mg/kg* | *3.0 mg/kg* | *66.2* | | | 8.6 | | Moderate saline alkali soil. Frass and distiller's grains increased $N\text{-}NO_3$, $P_{available}$, $K_{available}$ and OM in soil and reduced pH |
| Hodge & Conway, 2022 | Brewery waste | 35 | 20 | 10 | 600 | | | | | Chicory (*Cichorium intybus* L.) and plantain (*Plantago lanceolata* L.). $N_{total}$ contains 77 % insoluble/slow-release N and 23 % soluble/fast-release. Frass increased shoot growth of both crops, but up till a maximum and not in nutrient-rich media. Frass also increased re-growth of shoots after cutting |
| Kawasaki et al., 2020 | Organic household waste | 21.6 | 0.5 | 0.7 | 874 | 16.6 | | 7.4 | 44.4 | Komatsuna (*Brassica rapa* var. *perviridis*). Frass can be an incomplete compost, containing ammonium nitrogen as an effective N source for plants. Care should be taken about plant pathogens (i.e. Xanthomonadaceae) in the BSF microbiota. Frass led to the highest |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | above ground dry matter production of the crop compared to cow, horse and poultry compost and household waste. BSF frass resulted in higher ammonium nitrogen and lower nitrate nitrogen |
| Klammsteiner et al., 2020 | Chicken feed, grass-cuttings, fruit/vegetables frass | 18.3-25.9 | | | | 18.2-26.6 | | 5.4-6.2 | 90-91 | Perennial ryegrass. Soil properties were not different between frass and mineral fertilizer, but there were some differences in nitrate and dissolved N contents. Growth of the crop was also not different between treatments, which indicates that frass is a fast acting fertilizer comparable to $NH_4NO_3$. Coliform bacteria from the frass were outcompeted by gram-negative soil bacteria |
| Kebli & Sinaj, 2017 | Vegetable waste | 35.4 | 11.5 | 32.7 | | | | 7.5 | | Grass (*Lolium perenne* L.) and lettuce (*Lollo rosso*). BSF frass performed equally well (and sometimes better) as a mineral fertilizer in three soil types. In some of their experiments BSF frass was enriched with KCl or ashes for K supplementation. BSF frass is especially suitable for low fertile soils (acidic, sandy) and to a lesser extent for soils containing high organic matter concentrations. Lettuce cultivation on acidic soil with BSF frass supplemented with wood ash is a good combination |
| Lanno et al., 2022 | Raw vegetable and fruit waste, hot-pressed rapeseed cake, rye/wheat bread, canola oil, catering waste | 79 | 2.4 | 0.1 | | 7.7 | | 8.1 | | Compared to other treatments, frass has a relatively high fulvic to humic acid ratio and relatively low humifcation rate of the organic material processed. Furthermore frass showed a high organic matter polymerization |
| Liu et al., 2019 | Chicken, cow and pig manure | 17.9-18.7 | 9.6-27.0 | 13.9-21.2 | | 15.1-18.8 | | 8.2-8.4 | 26-41 | |
| Lopes et al., 2022 | Gainesville diet, distiller's grains, brewery spent grains, okara and wheat bran, household waste, wheat bran, chicken, pig and cow manure, chicken feed, grass, fruits and vegetables, fresh okara | 18-51 | 3-52 | 2-41 | | 7.3-26.6 | | 5.4-9.0 | | |
| Mason, 2016 | Mix of fruits, vegetables, seaweeds | 2.45 | 0.69 | 2.62 | | | | | 24.5 | Barley. Frass had positive effects on plant growth when used in potting medium |
| Menino et al., 2021 | Onion and potato by-products | 28.1 | 15 | 33 | 837 | | 25.7 | 8.6 | 85 | Ryegrass. Frass increased crop production as well as soil OM, P, K and dehydrogenase activity |
| Newton et al., 2005 | Swine manure | | | | | | | | | Basil (*Ocimum basilcum*), Sudan grass (*Sorgham sudanense*). BSF frass in sand or Cecil red clay soil led to lower growth rates compared to commercial potting soil |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nicksy et al., 2021 | Pre-consumer urban food waste | 32 | 8.7 | 8.7 | | 12.5 | | | 91 | Italian ryegrass (*Lolium multiflorum*). In N sufficient conditions, frass increased cumulative crop yield compared to the control and was similar to inorganic fertilizer. Frass supplied an equal amount of P compared to the inorganic fertilizer |
| Nurfikari, 2022 | Agro-industrial waste | 29 | | | | 13.3 | | | | Frass leads to a rapid and consistent stimulation of soil bacteria and fungi i.e. Bacilli, Actinobacteria, Gammaproteobacteria and Mortierellomycetes, as well as bacterial chitinase genes, that are known to suppress certain pathogens. Adding frass to soil is a promising alternative for managing *Fusarium* wilt in lettuce. Exuviae incorporation in soil had even more beneficial effects on disease control than frass, which is likely due to the higher chitin content of the exuviae |
| Oonincx et al., 2015 | Chicken, pig and cow manure | 13.5-30.3 | 9.9-39.4 | | | | | | 20.8-40.0 | Bioconversion of chicken manure by the larvae decreased its N content, while that in cow and pig manure remained the same. P concentrations decreased and N:P ratio as well, as 23-78 % of N was lost |
| Palma et al., 2020 | Almond by-product (hulls and shells), amended with urea | 12.3-22.3 | | 17.9-44.6 | | 20.5-38.3 | | 7.2-8.8 | | Radish (*Raphanus sativus* var. Sparkler). Frass requires more stabilization before applying it to soil |
| Papa et al., 2022 | Different types of organic fraction of municipal solid waste | 20-25 | | | 738-802 | 17.3-23.2 | | 7.7-8.2 | 45.7-50.3 | |
| Parodi et al., 2020 | Wheat yeast concentrate, by-product from wheat and potato, binding agent | 29.4 | 5.7 | 20.2 | | | | | 79.6 | |
| Postma et al, 2022 | | 30.8 | 8.0 | 19.9 | 920 | 14.9 | | 6.5 | 87.1 | Frass qualifies as an organic fertilizer and has positive effects on nitrate and *Pythium* compared to unfertilized soil. Frass has positive effects on PMN (potentially mineralizable N, an indicative soil parameter for disease suppression) and HWC (hot water extractable carbon) compared to mineral N fertilizer |
| Protix Flytilizer | Food industry byproducts | | 14.6 | 25 | | | 37.2 | | 90 | |
| Quilliam et al, 2020 | Poultry manure, brewery waste and organic market fruit waste | | | | | | | | | Chili pepper, shallot, maize, cowpea. BSF frass (stabilized for 1-3 weeks) in general performed equally well to chicken manure based local and commercial fertilizers. Some differences were found between the different types of frass and also the influence on the different crops. Frass from brewery waste was more effective for plant growth than frass from poultry manure. For some frass types extra NPK was added |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Romano, 2022 | Spoiled fish feeds with or without cardboard | 87-91 | 20-21 | 12 | | | | | 23 | The leftover frass had lower nitrogen (9.1 % vs. 8.7 % in control versus cardboard respectively) |
| Romano et al., 2022a | Combination of various grains, fruits, and vegetables | 62 | 14.4 | 17.6 | | | | | | Sweet potato (*Ipomoea batatas*) cuttings. No significant difference in length, number of nodes and stem diameter were found with frass versus control |
| Romano et al., 2022b | Spent coffee, dough, spoiled fish feeds, and a mixture of fruits/vegetables. | 62 | 14.4 | 17.6 | | | | | | Sweet banana chili plants (*Capsicum annuum*) and sweet potato (*Ipomea batatas*) slips. BSF frass tea did not increase production in an aquaponics system, but altered some mineral/nutrient contents |
| Rummel et al., 2021 | Pre-consumer vegetable wastes or brewer's spent grains/spent coffee grounds | 26.5-38.6 | 2.8-9.3 | 2.1-47.6 | | 13.3-16.8 | | 5.9 | | Arable soil. Depending on C, N, and nutrient content of frass, N will be immobilized or mineralized, and C will be used more or less efficiently by soil microorganisms leading to microbial, especially fungal growth. High nutrient availability after adding frass to soil can result in substantial rapid losses of C (as $CO_2$, partly $CH_4$) and N gases, especially $N_2O$. This reduces the fertilizer (N) and organic amendment (C) value of frass, and substantially increases the environmental footprint lowering the ecological benefit associated with insect based proteins |
| Salomone et al., 2017 | Organic municipal waste | 14.9 | 9.8 | 10.3 | | 20.9 | 13.5 | 7.0 | 74.3 | |
| Sarpong et al., 2019 | Municipal organic solid wastes from domestic, markets and restaurant | *3.6-4.8 mg/kg* | *0.8-0.9 mg/kg* | *0.54-0.62 mg/kg* | | 8-9 | | 7.3-7.4 | 63-65 | |
| Setti et al., 2019 | Wheat bran, alfalfa meal, corn meal | 44 | 22.7 | 34 | | 8.0 | 38 | 8.8 | 51.4 | Baby leaf lettuce, basil, tomato. Frass used in a proportion up to 20 % increased growth of all crops, comparable to when using peat with slow acting inorganic solid fertilizer, without leading to abiotic stress |
| Song et al., 2021 | Okara and wheat bran | 3.2-6.0 | 0.8-1.3 | 0.54-0.99 | | 7-9.6 | | | | Pakchoi. Plants cultivated in composted BSF frass treatments grew larger than those in fresh frass. A seed germination test suggested the presence of phytotoxins in fresh frass, possibly being phenols |
| Tan et al., 2021 | Restaurant waste or okara | 31.5 | 0.39 | 1.33 | | | | | | Pakchoi. Crop yields from treatments with surplus restaurant waste frass and biochar at a 1:9 (v/v) ratio and inorganic fertilizer were comparable to those of the control which consisted of soil, peat-based compost and inorganic fertilizer, but yields decreased with increasing frass input, due to high salinity and potentially low oxygen conditions in the growing media. Differences in fertilizer value were found for the two different substrates |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Tanga et al., 2021 values are raw vs. composted | Brewery spent grains | 50-36 | 9.3-5.0 | 2.2-2.9 | | 10.1-10.7 | | 6.8-7.1 | | Maize. Composted frass increased grain yield at higher rates: 2-25, 25-113 and 153-212 % than NPK, brewers' spent grain compost and Evergrow, respectively. Also frass led to higher growth and yield than the control. The agronomic N use efficiency of the crop with frass was 2 and 3 times higher compared to that of BSG and Evergrow, respectively. Maize grown using frass and NPK had higher crude protein and fibre content compared to other treatments |
| Ushakova et al., 2020 | 3 mixes containing various percentages of potatoes, apples, crushed corn, sunflower meal, coniferous flour, sawdust, skim milk, wheat bran, feeding yeast | 10.8-23 | 35-53 | 21-22.4 | | 17.9-39.3 | | | | Tomato. Frass was able to stimulate plant immunity to phytopathogenic nematodes and inhibit their development. Frass did not have a growth-stimulating effect on tomato plants |
| Visvini et al., 2022 | Decanter cake, palm kernel expeller from palm oil processing | 16.4 | | | 452 | 16 | | 7.4 | | Germination of white radish was the same with frass as with water (> 80 %), which indicates stability and maturity of the fertilizer and no plant toxicity. The salinity of the frass from these substrates was relatively low |
| Wantulla et al., 2022 | Bestico frass | | | | | | | | | Brussels sprouts, *Brassica oleracea* L. Soil amendment with BSF frass or exuviae reduced cabbage root fly survival and biomass. Amendment with either residual stream from BSF larvae resulted in lower plant shoot biomass compared with the synthetic fertilizer treatment |
| Watson et al., 2021 | Residual product from the wheat processing industry composed mainly of wheat bran | 28 | 14.4-19.8 | 22.4-24.0 | 770 | 16 | 19.5 | 6.8 | | Sandy loam soil. Different frass types stimulated C mineralisation, nitrification, bacterial and archaeal 16S rRNA gene copy numbers, and fungal biomass. BSF frass specifically could be used as ameliorant in metal-contaminated soils or organic fertiliser as its use did not cause soil nitrite build-up |
| Xiao et al., 2018 | Chicken manure | | | | 450-460 | 60 | | 8.4 | 47 | Chinese cabbage and rape seeds. Frass inoculated with extra bacteria had a higher maturity (germination index >92 %), compared with the control (germination index ~86 %) and thus was more suitable as organic fertilizer |
| Yildirim-Aksoy et al., 2022 | Enviroflight frass | 34 | 8 | 11 | | | | | | |
| Zahn, 2017 | Fruit waste | | | | | | | | | Spring onion. No clear differences were observed between compost and frass in affecting soil fertility or plant growth |

# 5 Comparison of BSF frass to other fertilizers

Table 4 shows the composition of different common livestock manures and composts. As is clear from Table 3, frass composition is highly variable dependent on the BSF substrate composition and it is sometimes not clear in what units the data are expressed. Therefore, for BSF frass the average values in Table 2 were taken from Gärttling and Schulz (2019) and Gärttling & Schulz (2022) for producers and literature.

***Table 4*** *Composition of different common livestock manures and composts*

| Parameter (g/kg DM unless stated otherwise) | Pig slurry | Cow slurry | Poultry manure | Green compost | BSF frass |
|---|---|---|---|---|---|
| Dry matter (g/kg product) | 107 | 92 | 562 | 599 | 660-780 |
| Organic matter | 738 | 772 | 740 | 299 | 844-866 |
| $N_{total}$ (N) | 65 | 43 | 51 | 8 | 34 |
| $N_{organic}$ (N) | 31 | 23 | 46 | 8 | - |
| Phosphate ($P_2O_5$) | 36 | 16 | 41 | 4 | 27-28 |
| Potassium ($K_2O$) | 44 | 59 | 34 | 7 | 35 |
| C/N ratio* (dimensionless) | 12 | 17 | 8 | 19 | 13-16 |

Source: Handboek Bodem en Bemesting, online, Gärttling & Schulz (2019), Gärttling & Schulz (2022). *C/N ratio calculated as (0.5*OM)/$N_{org}$

BSF frass has a very high dry matter content, which could be due to 1. High temperatures during the bioconversion process 2. Post-drying for hygienisation. According to Gärttling and Schulz (2019) there are two categories of frass: one containing around 50 % DM, the other around 80 %. They assume this is due to two different production methods. Organic matter content is also higher than all other manure and compost types. N content and C/N ratio are closest to the values of cow slurry, while P content is most comparable to that of pig slurry and K content is most comparable to that of poultry manure.

# 6 Conclusions and recommendations

From this literature overview on the composition of different types of BSF frass and its effect on plant growth/health and soil characteristics several things can be concluded:

1. Composition of the BSF frass is strongly dependent on the feed substrate and as such there is no universal BSF frass composition. In addition, the production process for the frasses is sometimes not clearly explained, e.g. was the frass hygienised.
2. Units for frass composition vary between different researches and it is often not clear whether they are based on dry or fresh matter, which makes comparison difficult
3. Based on average compositions BSF frass has resemblances to cow manure (C/N ratio, N content), pig slurry (P content), poultry manure (DM, K content), compost (DM). It has a much higher organic matter content than compost and also higher than beforementioned manure types. Frass seems to be a fast acting fertilizer.
4. Usually the frass is relatively high in P content, which may require extra N fertilizer addition.
5. Most of the nitrogen is organic, but ammonia content is highly variable.
6. Effects on plant growth can be positive, neutral or negative, compared to organic and mineral control fertilizers and there seems to be maximum application rates above which positive effects diminish.
7. Application of BSF frass can add different bacteria to the soil/plant rhizosphere
8. Several authors state that chitin in the BSF frass likely benefits resistance to plant pathogens. However, care should be taken not to ascribe certain effects to chitin only, as BSF frass contains many other nutrients that can affect plant and soil.
9. It is important to compare the efficiency of BSF frass to that of appropriate control fertilizers.
10. Due to ammonia content, anaerobiosis, salt content and VFAs BSF frass can be toxic to plants and several authors mention that post-treatment of frass (for example by aerobic composting) is necessary to obtain a stable/mature product

Concluding from the literature overview, BSF frass has potential as an organic fertilizer for several agricultural applications and this application increases circularity in the agrifood sector.
For future research, it is recommended that frass parameters are displayed on dry matter basis and that the efficiency of BSF frass is compared to that of appropriate control fertilizers. It should also be clear whether pre- or post-processing (e.g. composting, hygienisation) of the frass has taken place prior to tests to be able to interpret the data.

# References

Agustiyani, D., Agandi, R., Arinafril, Nugroho, A.A., Antonius, S. 2021. The effect of application of compost and frass from Black Soldier Fly Larvae (*Hermetia illucens* L.) on growth of Pakchoi (B*rassica rapa* L.). *IOP Conference Series. Earth and Environmental Science*, **762**(1).

Aira, M., Monroy, F., Domínguez, J. 2007. Microbial biomass governs enzyme activity decay during aging of worm-worked substrates through vermicomposting. *Journal of Environmental Quality*, **36**(2), 448-452.

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 Science Today*, **3**(1), 57-62.

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. *Frontiers in Plant Science*, **12**(999).

Arabzadeh, G., Delisle-Houde, M., Tweddell, R.J., Deschamps, M.-H., Dorais, M., Lebeuf, Y., Derome, N., Vandenberg, G. 2022. Diet Composition Influences Growth Performance, Bioconversion of Black Soldier Fly Larvae: Agronomic Value and In Vitro Biofungicidal Activity of Derived Frass. *Agronomy*, **12**(8), 1765.

Banavar, A., Amirkolaei, S.K., Duscher, L., Khairunisa, B.H., Mukhopadhyay, B., Schwarz, M., Urick, S., Ovissipour, R. 2022. Nutritional Evaluation of Black Soldier Fly Frass as an Ingredient in Florida Pompano (*Trachinotus carolinus* L.) Diets. *Animals*, **12**(18), 2407.

Barragán-Fonseca, K.Y., Nurfikari, A., van de Zande, E.M., Wantulla, M., van Loon, J.J.A., de Boer, W., Dicke, M. 2022. Insect frass and exuviae to promote plant growth and health. *Trends in Plant Science*, **27**(7), 646-654.

Basri, N.E.A., Azman, N.A., Ahmad, I.K., Suja, F., Jalil, N.A.A., Amrul, N.F. 2022. Potential Applications of Frass Derived from Black Soldier Fly Larvae Treatment of Food Waste: A Review. *Foods*, **11**(17), 2664.

Beesigamukama, D., Mochoge, B., Korir, N., Menale, K., Muriithi, B., Kidoido, M., Kirscht, H., Diiro, G., Ghemoh, C.J., Sevgan, S., Nakimbugwe, D., Musyoka, M.W., Ekesi, S., Tanga, C.M. 2022a. Economic and ecological values of frass fertiliser from black soldier fly agro-industrial waste processing. *Journal of Insects as Food and Feed*, **8**(3), 245-254.

Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K.M., Nakimbugwe, D., Khamis, F.M., Dubois, T., Subramanian, S., Wangu, M.M., Ekesi, S., Tanga, C.M. 2020a. Biochar and gypsum amendment of agro-industrial waste for enhanced black soldier fly larval biomass and quality frass fertilizer. *PLoS ONE*, **15**(8 August).

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. 2020b. Exploring Black Soldier Fly Frass as Novel Fertilizer for Improved Growth, Yield, and Nitrogen Use Efficiency of Maize Under Field Conditions. *Frontiers in Plant Science*, **11**.

Beesigamukama, D., Mochoge, B., Korir, N.K., K.M. Fiaboe, K., Nakimbugwe, D., Khamis, F.M., Subramanian, S., Wangu, M.M., Dubois, T., Ekesi, S., Tanga, C.M. 2021. Low-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly. *Waste Management*, **119**, 183-194.

Beesigamukama, D., Subramanian, S., Tanga, C.M. 2022b. Nutrient quality and maturity status of frass fertilizer from nine edible insects. *Scientific Reports*, **12**(1), 7182.

Bestico, 2019/2020. Jeroen van Schelt, personal communication

Coudron, C., T. Spranghers, D. Elliot, J. Halstead, 2019. Insect Breeding Lab scale and pilot scale experiments with mealworm and black soldier fly (WP4). Bioboost. 68 pp.

Bortolini, S., Macavei, L.I., Hadj Saadoun, J., Foca, G., Ulrici, A., Bernini, F., Malferrari, D., Setti, L., Ronga, D., Maistrello, L. 2020. *Hermetia illucens* (L.) larvae as chicken manure management tool for circular economy. *Journal of Cleaner Production*, **262**.

Bulak, P., Proc, K., Pawłowska, M., Kasprzycka, A., Berus, W., Bieganowski, A. 2020. Biogas generation from insects breeding post production wastes. *Journal of Cleaner Production*, **244**.

Cai, R., Wu, X., Wang, X., Xu, X. 2020. Effects of insect frass with different cadmium content on maize plant growth and cadmium accumulation. *IOP Conference Series: Earth and Environmental Science*.

Chavez, M., Uchanski, M. 2021. Insect left-over substrate as plant fertiliser. *Journal of Insects as Food and Feed*, **7**(5), 683-694.

Chiam, Z., Lee, J.T.E., Tan, J.K.N., Song, S., Arora, S., Tong, Y.W., Tan, H.T.W. 2021. Evaluating the potential of okara-derived black soldier fly larval frass as a soil amendment. *Journal of Environmental Management*, **286**, 112163.

Debode, J., De Tender, C., Soltaninejad, S., Van Malderghem, C., Haegeman, A., Van der Linden, I., Cottyn, B., Heyndrickx, M., Maes, M. 2016. Chitin Mixed in Potting Soil Alters Lettuce Growth, the Survival of Zoonotic Bacteria on the Leaves and Associated Rhizosphere Microbiology. *Frontiers in Microbiology*, **7**.

Devic, E. 2016. Assessing insect-based product as feed ingredients for aquaculture.

Ermolaev, E., Lalander, C., Vinnerås, B. 2019. Greenhouse gas emissions from small-scale fly larvae composting with *Hermetia illucens*. *Waste Management*, **96**, 65-74.

EU, 2021. Commission Regulation (EU) 2021/1925. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1925

Fischer, H., Romano, N., Sinha, A.K. 2021. Conversion of Spent Coffee and Donuts by Black Soldier Fly (*Hermetia illucens*) Larvae into Potential Resources for Animal and Plant Farming. *Insects*, **12**(4), 332.

Fuhrmann, A., Wilde, B., Conz, R.F., Kantengwa, S., Konlambigue, M., Masengesho, B., Kintche, K., Kassa, K., Musazura, W., Späth, L., Gold, M., Mathys, A., Six, J., Hartmann, M. 2022. Residues from black soldier fly (*Hermetia illucens*) larvae rearing influence the plant-associated soil microbiome in the short term. *Frontiers in Microbiology*, **13**.

Gärttling and Schulz (2019). Compilation of Black Soldier Fly frass analyses. Poster Kassel University.

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. *Journal of Insect Science*, **20**(5), 1-11.

Gärttling, D., Schulz, H. 2022. Compilation of Black Soldier Fly Frass Analyses. *Journal of Soil Science and Plant Nutrition*, **22**(1), 937-943.

Gebremikael, M.T., Wickeren, N.v., Hosseini, P.S., De Neve, S. 2022. The Impacts of Black Soldier Fly Frass on Nitrogen Availability, Microbial Activities, C Sequestration, and Plant Growth. *Frontiers in Sustainable Food Systems*, **6**.

Green, T.R., Popa, R. 2012. Enhanced Ammonia Content in Compost Leachate Processed by Black Soldier Fly Larvae. *Applied Biochemistry and Biotechnology*, **166**(6), 1381-1387.

Guo, X., Zhao, B., Mao, Z., Wang, X., Xu, X. 2021. Effects of insect frass and distiller's grains on physicochemical properties of saline alkali soil. *IOP Conference Series. Earth and Environmental Science*, **781**(5).

Hadwiger, L.A. 2013. Multiple effects of chitosan on plant systems: solid science or hype. *Plant Sci*, **208**, 42-9.

Handboek Bodem en Bemesting, 2023. Online edition. https://www.handboekbodemenbemesting.nl/nl/handboekbodemenbemesting/Handeling/Organische-stofbeheer/Samenstelling-en-werking-organische-meststoffen/Samenstelling-organische-meststoffen.htm

Hodge, S., Conway, J. 2022. The Effects of Insect Frass Fertilizer and Biochar on the Shoot Growth of Chicory and Plantain, Two Forage Herbs Commonly Used in Multispecies Swards. *Agronomy*, **12**(10), 2459.

Hol, S., Elissen, H., & van der Weide, R. 2022. Combined digestion of insect frass and cow manure for biogas production. (Rapport / Stichting Wageningen Research, Wageningen Plant Research, Business unit Open Teelten; No. WPR-OT-944). Stichting Wageningen Research, Wageningen Plant Research, Business unit Open Teelten. https://doi.org/10.18174/584607

IPIFF, 2019. Contribution Paper on the application of insect frass as fertilising product in agriculture

Nicksy, J., B. Amiro and M. Entz. 2021. Recycled nutrients supply phosphorus and improve ryegrass yields on phosphorus-depleted soil. *Canadian Journal of Soil Science*, **101**(3), 565-569.

Kawasaki, K., Kawasaki, T., Hirayasu, H., Matsumoto, Y., Fujitani, Y. 2020. Evaluation of fertilizer value of residues obtained after processing household organic waste with black soldier fly larvae (*Hermetia illucens*). *Sustainability (Switzerland)*, **12**(12).

Kebli, H., Sinaj, S. 2017. Agronomic potential of a natural fertiliser based on fly larvae frass. *Agrarforschung Schweiz*, **8**(3), 88-95.

Klammsteiner, T., Turan, V., Juárez, M.F.D., Oberegger, S., Insam, H. 2020. Suitability of black soldier fly frass as soil amendment and implication for organic waste hygienization. *Agronomy*, **10**(10 October).

Korthals, G.W., Thoden, T.C., van den Berg, W., Visser, J.H.M. 2014. Long-term effects of eight soil health treatments to control plant-parasitic nematodes *and Verticillium dahliae* in agro-ecosystems. *Applied Soil Ecology*, **76**, 112-123.

Lanno, M., Klavins, M., Purmalis, O., Shanskiy, M., Kisand, A., Kriipsalu, M. 2022. Properties of Humic Substances in Composts Comprised of Different Organic Source Material. *Agriculture*, **12**(11), 1797.

Law, Y. Leo Wein. Reversing the nutrient drain through urban insect farming—opportunities and challenges. AIMS Bioengineering, 2018, 5(4): 226-237. doi: 10.3934/bioeng.2018.4.226

Liu, T., Awasthi, M.K., Chen, H., Duan, Y., Awasthi, S.K., Zhang, Z. 2019. Performance of black soldier fly larvae (Diptera: Stratiomyidae) for manure composting and production of cleaner compost. *Journal of Environmental Management*, **251**.

Lopes, I.G., Yong, J.W.H., Lalander, C. 2022. Frass derived from black soldier fly larvae treatment of biodegradable wastes. A critical review and future perspectives. *Waste Management*, **142**, 65-76.

Mason, B. Production of high value protein feeds and fertilizer from pre-consumer vegetable waste utilizing a novel black soldier fly larvae conversion process. https://divertns.ca/sites/default/files/researchreportsfiles/2021-09/Production-of-High-Value-Protein-Feeds-and-Fertilizer-from-Pre-Consumer-Vegetable-Waste-Utilizing-a-Novel-Black-Soldier-Fly-Larvae-Conversion-Process-%E2%80%93-Dr.-Beth-Mason-2016.pdf

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*, **7**(1), e05855-e05855.

Newton, L., Sheppard, C., Watson, D., Burtle, G., Dove, R. 2005. Using the Black Soldier Fly, *Hermetia Illucens*, as a Value-Added Tool for the Management of Swine Manure. *North Carolina State University*.

Nurfikari, A. 2022. Prospects of residual streams from insect cultivation for sustainable crop management. [internal PhD, WU, Wageningen University]. Wageningen University. https://doi.org/10.18174/578680

Oonincx, D. G. A. B., A. van Huis and J.J.A. van Loon, 2015. Nutrient utilisation by black soldier flies fed with chicken, pig, or cow manure. Journal of Insects as Food and Feed 1 (2): 131 - 139

Palma, L., Fernández-Bayo, J., Putri, F., VanderGheynst, J.S. 2020. Almond by-product composition impacts the rearing of black soldier fly larvae and quality of the spent substrate as a soil amendment. *Journal of the Science of Food and Agriculture*, **100**(12), 4618-4626.

Papa, G., Scaglia, B., D'Imporzano, G., Savoldelli, S., Jucker, C., Colombini, S., Toschi, I., Adani, F. 2022. Valorizing the organic fraction of municipal solid waste by producing black soldier fly larvae and biomethane in a biorefinery approach. *Journal of Cleaner Production*, **379**, 134422.

Parodi, A., De Boer, I.J.M., Gerrits, W.J.J., Van Loon, J.J.A., Heetkamp, M.J.W., Van Schelt, J., Bolhuis, J.E., Van Zanten, H.H.E. 2020. Bioconversion efficiencies, greenhouse gas and ammonia emissions during black soldier fly rearing – A mass balance approach. *Journal of Cleaner Production*, **271**, 122488.

Postma, J. and M. T. Schilder, 2015. Enhancement of soil suppressiveness against *Rhizoctonia solani* in sugar beet by organic amendments. Applied Soil Ecology 94: 72-79

Postma, J., Jansen, S., Franssen, M., Schilder, M., Visser, J., Bloem, J., & Korthals, G., 2022. Kringloop voor organische stof én bodemweerbaarheid bevorderen. (Rapport / Wageningen Plant Research; No. WPR-1183). Wageningen Plant Research. https://doi.org/10.18174/579469

Poveda, J. 2021. Insect frass in the development of sustainable agriculture. A review. *Agronomy for Sustainable Development*, **41**(1), 5.

Protix Flytilizer, 2023. https://www.brimexbv.nl/protix-bodemverbeteraar-meststof.html

Quilliam, R., Nuku-Adeku, C., Maquart, P., Little, D., Newton, R., Murray, F. 2020. Integrating insect frass biofertilisers into sustainable peri-urban agro-food systems.

Raimondi, S., Spampinato, G., Macavei, L.I., Lugli, L., Candeliere, F., Rossi, M., Maistrello, L., Amaretti, A. 2020. Effect of rearing temperature on growth and microbiota composition of *hermetia illucens*. *Microorganisms*, **8**(6), 1-13.

Romano, N. 2022. Cardboard supplementation on the growth and nutritional content of black solider fly (*Hermetia illucens*) larvae and resulting frass. *International Journal of Tropical Insect Science*, **42**(5), 3357-3362.

Romano, N., Fischer, H., Powell, A., Sinha, A.K., Islam, S., Deb, U., Francis, S. 2022a. Applications of Black Solider Fly (*Hermetia illucens*) Larvae Frass on Sweetpotato Slip Production, Mineral Content and Benefit-Cost Analysis. *Agronomy*, **12**(4), 928.

Romano, N., Powell, A., Islam, S., Fischer, H., Renukdas, N., Sinha, A.K., Francis, S. 2022b. Supplementing aquaponics with black soldier fly (*Hermetia illucens*) larvae frass tea: Effects on the production and composition of sweetpotato slips and sweet banana peppers. *Aquaculture*, **555**, 738160.

Rummel, P.S., Beule, L., Hemkemeyer, M., Schwalb, S.A., Wichern, F. 2021. Black Soldier Fly Diet Impacts Soil Greenhouse Gas Emissions From Frass Applied as Fertilizer. *Frontiers in Sustainable Food Systems*, **5**(278).

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., Savastano, D. 2017. Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using *Hermetia illucens*. *Journal of Cleaner Production*, **140**, 890-905.

Sarpong, D., Oduro-Kwarteng, S., Gyasi, S.F., Buamah, R., Donkor, E., Awuah, E., Baah, M.K. 2019. Biodegradation by composting of municipal organic solid waste into organic fertilizer using the black soldier fly (*Hermetia illucens*) (Diptera: Stratiomyidae) larvae. *International Journal of Recycling of Organic Waste in Agriculture*, **8**, 45-54.

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 Management*, **95**, 278-288.

Sharp, R.G. 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.

Song, S., Ee, A.W.L., Tan, J.K.N., Cheong, J.C., Chiam, Z., Arora, S., Lam, W.N., Tan, H.T.W. 2021. Upcycling food waste using black soldier fly larvae: Effects of further composting on frass quality, fertilising effect and its global warming potential. *Journal of Cleaner Production*, **288**, 125664.

Tan, J.K.N., Lee, J.T.E., Chiam, Z., Song, S., Arora, S., Tong, Y.W., Tan, H.T.W. 2021. Applications of food waste-derived black soldier fly larval frass as incorporated compost, side-dress fertilizer and frass-tea drench for soilless cultivation of leafy vegetables in biochar-based growing media. *Waste Management*, **130**, 155-166.

Tanga, C., Beesigamukama, D., Berresaw, M., Egonyu, J., Ghemoh, C., Nkoba, K., Subramanian, S., Onyoni, A., Ekesi, S. 2021. Tanga et al. (2021) Performance of black soldier fly frass fertilizer on maize growth yield nutritional quality and economic returns. *Journal of Insects as Food and Feed*, **8**.

Torgerson, K.L., Meijering, J.V., Sok, J., Dicke, M., Lansink, A.G.J.M.O. 2021. Towards circular agriculture – exploring insect waste streams as a crop and soil health promoter. *Journal of Insects as Food and Feed*, **7**(3), 357-368.

Ushakova, N.A., Udalova, Z.V., Zinovieva, S.V., Garmash, N.Y. 2020. Development of effective substrates for growing *Hermetia illucens* larvae with a high protein content and assessment of the effect of the obtained zoocompost on phytonematode. *IOP Conference Series: Earth and Environmental Science*.

van Huis, A. 2022. Edible insects: Challenges and prospects. *Entomological Research*, **52**(4), 161-177.

Visvini, L., Latifah, O., Ahmed, O.H., Kurk, W.J. 2022. Frass Production From Black Soldier Fly Larvae Reared On Palm Oil Wastes. *IOP Conference Series. Earth and Environmental Science*, **995**(1), 012012.

Wantulla, M., van Zadelhoff, K., van Loon, J.J.A., Dicke, M. 2022. The potential of soil amendment with insect exuviae and frass to control the cabbage root fly. *Journal of Applied Entomology*, **00**, 1– 11.

Watson, C., Houben, D., Wichern, F. 2022. Editorial: Frass: The Legacy of Larvae – Benefits and Risks of Residues From Insect Production. *Frontiers in Sustainable Food Systems*, **6**.

Watson, C., Schlösser, C., Vögerl, J., Wichern, F. 2021. Excellent excrement? Frass impacts on a soil's microbial community, processes and metal bioavailability. *Applied Soil Ecology*, **168**, 104110.

Xiao, X., Mazza, L., Yu, Y., Cai, M., Zheng, L., Tomberlin, J.K., Yu, J., van Huis, A., Yu, Z., Fasulo, S., Zhang, J. 2018. Efficient co-conversion process of chicken manure into protein feed and organic fertilizer by *Hermetia illucens* L. (Diptera: Stratiomyidae) larvae and functional bacteria. *Journal of Environmental Management*, **217**, 668-676.

Yildirim-Aksoy, M., Eljack, R., Beck, B.H., Peatman, E. 2022. Nutritional evaluation of frass from black soldier fly larvae as potential feed ingredient for Pacific white shrimp, *Litopenaeus vannamei*. *Aquaculture Reports*, **27**, 101353.

Zahn, N.H. The Effects of Insect Frass Created by *Hermetia Illucens* on Spring Onion Growth and Soil Fertility. Univ. Stirling 2017, 1, 1–65. Available online: https://www.researchgate.net/publication/321831639_The_effects_of_insect_frass_created_by_Hermetia_illucens_on_spring_onion_growth_and_soil_fertility

To explore the potential of nature to improve the quality of life

Wageningen University & Research
**Open Teelten**
Edelhertweg 1
Postbus 430
8200 AK Lelystad
T (+31)320 29 11 11

***www.wur.nl/openteelten***
Report WPR-OT 996

De missie van Wageningen University & Research is 'To explore the potential of nature to improve the quality of life'. Binnen Wageningen University & Research bundelen Wageningen University en gespecialiseerde onderzoeksinstituten van Stichting Wageningen Research hun krachten om bij te dragen aan de oplossing van belangrijke vragen in het domein van gezonde voeding en leefomgeving. Met ongeveer 30 vestigingen, 7.200 medewerkers (6.400 fte) en 13.200 studenten en ruim 150.000 Leven Lang Leren-deelnemers behoort Wageningen University & Research wereldwijd tot de aansprekende kennisinstellingen binnen haar domein. De integrale benadering van de vraagstukken en de samenwerking tussen verschillende disciplines vormen het hart van de unieke Wageningen aanpak.