Compilation of Black Soldier Fly Frass Analyses

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Abstract

In the context of black soldier fly (BSF) rearing, often the residues from production — mainly faeces but also undigested substrate — are addressed as frass in a broader sense. As BSF production is expanding, the valorization of BSF frass as organic fertilizer is gaining importance. However, in contrast to established organic fertilizers, little is known on the properties and variation of this by-product, which is essential for assessing possible application purposes. To elaborate a first overview on this relatively new waste stream, BSF frass analyses from the literature and anonymized frass analyses enquired from BSF producers were compiled. For a possible agricultural use as a fertilizer, their nutrient patterns were assessed. With a balanced nitrogen:phosphorous pentoxide:potassium oxide (N:P₂O₅:K₂O) ratio of 1:0.9:1.1, BSF frass can be characterized as a slightly alkaline (pH 7.5), nutrient-rich compound fertilizer, with the nutrient and especially the micronutrient contents showing high variation. The comparably high carbon-to-nitrogen ratio and low shares of ammonium nitrogen indicate a limited immediate nutrient release and point to possible applications of frass as a long-term fertilizer. The use of frass as an organic fertilizer as one element in a fertilization strategy is promising. By improving nutrient cycling back to the field, BSF frass can represent an important element of sustainable circular agriculture. However, more information on BSF feed and production systems needs to be combined with the nutrient analyses to better understand the variation in frass nutrient contents.

Keywords *Hermetia illucens* · BSF · Fertilizer · Manure · Insect · Faeces

1 Introduction

With the intensification of livestock production in the last decades, the size of livestock farming units increased considerably (Steinfeld et al. 2006). Consequently, specialization of farms promoted a decoupling of livestock production and the areas for feed production and manure spreading, leading to adverse effects for the environment as a result of the unsustainable management of livestock manures (Zhang et al. 2019). On the way to sustainable agricultural systems, improved nutrient cycling through a thoughtful recoupling of livestock and cropland are crucial (Zhang et al. 2019).

In the context of shaping a circular economy, insect and especially black soldier fly (BSF) (*Hermetia illucens* L.) production is expected to play an important role: BSF can be reared on manifold organic waste substrates, even manures (Diener et al. 2011), and the processed larvae can be used as protein component in animal feeds such as for pets (Freel et al. 2021), poultry and pigs (Barragan-Fonseca et al. 2017) or in aquaculture (Belghit et al. 2019; Barragan-Fonseca et al. 2017; Cummins et al. 2017). Furthermore, it is possible to extract chitinous substances for the bioeconomy from BSF by-products (Soetemans et al. 2020) or use the oil from the extraction of the larvae for biodiesel (Surendra et al. 2016) or cosmetics (Rabani et al. 2019).

In the last years, the BSF industry has been expanding (Derrien and Boccuni 2018). BSF frass is considered to constitute a major output from these production systems (Schmitt and de Vries 2020), and with the upscaling of BSF production, the valuation of frass is getting more economic and ecological weight. The use of frass as a fertilizer is expected to be promising (Schmitt and de Vries 2020) and would increase the circularity of the production system (Cadinu et al. 2020). Marketable frass fertilizers with

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known application potentials would also avoid the change from a valuable by-product to a waste deposition challenge in upscaling processes of BSF production, possibly resulting in environmental implications, as this was observed for other manures in livestock farming (Steinfeld et al. 2006).

The data situation regarding the effects of frass fertilization on plant growth was recently assessed as small and unclear in its outcomes (Berggren et al. 2019). In the last years, there have been several studies investigating the fertilization effects of frass under greenhouse (e.g. Gärttling et al. 2020; Klammsteiner et al. 2020; Menino et al. 2021, Setti et al. 2019; Song et al. 2021) and field (e.g. Anyega et al. 2021; Beesigamukama et al. 2020a, b, Quilliam et al. 2020) conditions, so that knowledge on the applications of BSF frass fertilizers is building up. However, frass is not a uniform product: its quality and composition are strongly impacted by the feed substrates utilized in the rearing process (Klammsteiner et al. 2020), and also post-processing that may be recommendable for sanitation purposes (Lopes et al. 2020) can change its properties considerably (Anyega et al. 2021). Therefore, it is crucial for a further investigation of the application potentials of BSF frass fertilizers to put the nutrient values of one single study into greater contexts.

In our study, we collected nutrient analyses from producers as well as from the literature to create a first orientational data frame when assessing this comparably new fertilizer. We aim to give information on usual physical properties and nutritional values of BSF frass and their variation and put them into context with other organic fertilizers and manures.

2 Material and Methods

A qualitative literature review on already published nutrient analyses of frass was conducted that led to few comparable results. Based on the member list of the International Platform of Insects for Food and Feed (IPIFF), around 15 BSF producers in and around Europe were asked for existing nutrient analyses of frass. No further information on the production system was inquired; however, due to very different production size and project stage of the companies, a high diversity of production systems is probable. If multiple analyses from one producer were returned but were based on different diets or rearing systems, they were accounted as independent. Of the returned analyses, appropriate parameters were collected and anonymized through averaging; additional information on the dataset was given by adding the coefficients of variation and by displaying the standardized residuals (Table 1). Due to the scope of this work, different analysis procedures were not considered if the output units were comparable.

Nutrient analyses were classified by their source (literature and producer) and differences between those two

groups were analysed using a one-way analysis of variance (ANOVA). The statistical evaluation was conducted using SAS software, version 9.4 (SAS Institute Inc. 2013).

3 Results and Discussion

Nutrient analyses from the literature (Newton et al. 2005; Williams et al. 2006; Temple et al. 2013; Lalander et al. 2015; Elissen et al. 2019; Klammsteiner et al. 2020; Beesigamukama et al. 2020a; Menino et al. 2021) were supplemented with the high return of nutrient analyses of the contacted BSF producers, so that around 30 analyses could be evaluated. The averaged values are presented in Table 1.

The coefficient of variation (CV) varies strongly between parameters; especially, micronutrients and several macronutrients show high variation. Different frass qualities critically influence its effects on plant growth (Song et al. 2021). As the researchers used frass produced with different feeding substrates and post-processing methods, the variation in nutrients and their availability could partially explain why there have been reported high (e.g. Newton et al. 2005; Choi et al. 2009; Beesigamukama et al. 2020b) as well as low (Gärttling et al. 2020) fertilizing effects of BSF frass. This variation in plant nutritional and other properties of different marketable frass fertilizers was also addressed by Menino and Murta (2021).

High contents of dry matter (DM) (69.62%) and organic matter (OM) (86.22%) contents were observed. Generally, differences in the BSF production systems (rearing methods, feeding substrate, separation mechanisms, frass post-processing) can affect DM contents. As DM contents are evenly distributed between 40 and 90%, there seems to be a high variability within the considered production systems. Optimizing the DM contents of the residue is an important factor to successfully separate the BSF larvae by sieving: feed with moisture contents >75 % can lead to suboptimal sieving results due to clumping, whereas separation was best when BSF larvae were able to reduce the frass moisture content to around 50% (Cheng et al. 2017). Moreover, production systems leading to low DM contents in the residues will need additional post-processing to create a stable fertilizing product from it (Diener et al. 2011).

Differences in the production systems might as well explain a high CV especially of micronutrients, which play an important role in plant nutrition (Alloway 2008). The coefficient of variation for all listed micronutrients (Cu, B, Zn, Mn, Fe) was higher than most of other organic fertilizers (Möller and Schultheiß 2015), indicating a high variation of individual frass micronutrient values. As an example, iron contents of 1808.4 mg kg⁻¹ DM on average lie within the range given for ruminant manures in Moreno-Caselles et al. (2002), but with values from 130 to > 5000 mg kg⁻¹ DM,

the span of iron contents in frass is greater than of any other manure of this study. Other micronutrients (Cu, Mn, Zn) also show wide min/max spans with their average values being comparable to selected manures (Moreno-Caselles et al. 2002). When comparing them to commercial organic fertilizers (Möller and Schultheiß 2015), the average micronutrient values are within the common range; however, the maximum values of Cu (263 mg kg⁻¹ DM), Zn (386) and Fe (5032) were higher than in many commercial organic fertilizers. This indicates that it is important to pay attention to the individual nutrient analysis of frass when utilizing it for fine-tuned plant nutrition, especially when it comes to micronutrient contents.

The average pH of 7.46 is slightly alkaline and amongst the parameters with the least variation. However, the individual values range from 5.4 to 9.0. It is known from former studies that BSF larvae actively shift the substrate pH towards an alkaline environment (Green and Popa 2012; Ma et al. 2018; Meneguz et al. 2018). Whilst BSF larvae

can grow at a broad range of pH (Ma et al 2018; Meneguz et al. 2018), their performance seems to be best at higher pH of the feeding substrate (Meneguz et al. 2018; Pang et al. 2020). The pH values of frass are mainly influenced by feed source properties (Ma et al. 2018; Klammersteiner et al. 2020) or larval density (Parra Paz et al. 2015; Meneguz et al. 2018). When comparing the collected nutrient analyses with values from the literature, only the pH value was significantly lower in literature ($p < 0.05$) (Table 2), with the reason being unclear by now. In contrast to the investigative aspects of the literature, producers may focus on high larval growth and run optimized processes, possibly leading to the observed differences in frass pH between those two groups. However, as the economically viable substrates may limit the ways to optimize the feed, e.g. regarding moisture contents (Cheng et al. 2017), it is not self-evident that high pH values are met in large-scale facilities.

With 32.2 g kg⁻¹ DM, the total nitrogen (N_t) content is high and has the least coefficient of variation (0.26) amongst

Table 1 Summarization of the collected frass nutrient analyses, displayed as mean with the coefficient of variation (CV) as percentage value and supplemented with the number (*n*) of analyses used for calculating a mean. All macronutrients and micronutrients are displayed as dry matter (DM) contents. The boxplots show the distribution of

standardized residuals ($Z = \frac{x - \mu}{\sigma}$) with an exclusive median at uneven *n*. From the median to the right/left box margin, 25% of the values are contained each, and the whiskers contain Q1 and Q4, respectively. Values outside the 1.5-fold of the interquartile range were considered outliers

	Parameter	Unit	Mean (CV)	n	Distribution of standardized residuals						
					-3.0	-2.0	-1.0	0.0	1.0	2.0	3.0
Physical parameters	DM	%	69.62 (0.27)	20							
	OM	% DM	86.22 (0.06)	17							
	pH		7.46 (0.15)	20							
	EC	mS cm ⁻¹	4.03 (0.42)	16							
Macronutrients	N _t	g kg ⁻¹	32.2 (0.26)	24							
	NH ₄ ⁺ -N	g kg ⁻¹	5.6 (0.55)	12							
	NH ₄ ⁺ -N	% of N _t	15.78 (0.51)	12							
	C : N ratio		14.71 (0.31)	18							
	P	g kg ⁻¹	12.4 (0.35)	20							
	K	g kg ⁻¹	29.3 (0.35)	19							
	Mg	g kg ⁻¹	4.7 (0.45)	16							
	Na	g kg ⁻¹	5.7 (0.79)	16							
	Ca	g kg ⁻¹	8.8 (0.94)	13							
	S	g kg ⁻¹	6.3 (0.48)	16							
Micronutrients	Cu	mg kg ⁻¹	43.76 (1.47)	14							
	B	mg kg ⁻¹	34.54 (0.78)	13							
	Zn	mg kg ⁻¹	136.32 (0.72)	14							
	Mn	mg kg ⁻¹	79.54 (0.44)	13							
	Fe	mg kg ⁻¹	1808.4 (0.96)	14							

Table 2 Comparison of the values collected from the literature and from producers, displayed as mean with the coefficient of variation (CV) as percentage value and supplemented with the number (*n*) ofanalyses used for calculating a mean. The *p* value of the performed one-way ANOVA is marked (*) when significant (*p* < 0.05).

	Parameter	unit	Mean _{literature} (CV)	n _{literature}	Mean _{producer} (CV)	n _{producer}	<i>p</i> value
Physical parameters	DM	%	78.03 (0.25)	6	66.01 (0.28)	14	0.2014
	OM	% DM	84.93 (0.03)	3	86.50 (0.07)	14	0.6632
	pH		6.80 (0.18)	9	7.99 (0.10)	11	0.0162 *
	EC	mS cm ⁻¹	3.24 (0.42)	7	4.64 (0.37)	9	0.1008
Macronutrients	N _t	% DM	3.35 (0.32)	9	3.14 (0.22)	15	0.5622
	NH ₄ ⁺ -N	% DM	0.64 (0.57)	5	0.50 (0.56)	7	0.4790
	NH ₄ ⁺ -N	% of N _t	16.21 (0.48)	5	15.48 (0.56)	7	0.8842
	C:N ratio		15.73 (0.36)	8	13.90 (0.25)	10	0.4075
	P	% DM	1.50 (0.27)	5	1.16 (0.38)	15	0.1424
	K	% DM	2.99 (0.41)	4	2.91 (0.36)	15	0.9019
	Mg	% DM	0.42 (0.97)	2	0.48 (0.41)	14	0.6879
	Na	% DM	1.07 (0.79)	2	0.50 (0.74)	14	0.0942
	Ca	% DM	0.64 (---)	1	0.90 (0.95)	12	0.7769
	S	% DM	0.65 (0.34)	2	0.63 (0.49)	14	0.9596
	Cu	mg kg ⁻¹	16.33 (0.28)	3	51.25 (1.39)	11	0.4268
	B	mg kg ⁻¹	16.00 (0.80)	2	37.91 (0.73)	11	0.3085
Micronutrients	Zn	mg kg ⁻¹	85.33 (0.54)	3	150.23 (0.70)	11	0.3264
	Mn	mg kg ⁻¹	81.00 (1.19)	2	79.27 (0.30)	11	0.9524
	Fe	mg kg ⁻¹	855.67 (0.43)	3	2068.24 (0.91)	11	0.3005

the macronutrients. Total nitrogen contents in fresh matter (FM) are much higher than in most of the farm manures and composts, being largely below 1% N_t in FM (Gutser et al. 2005). The higher nitrogen contents in FM are mainly caused by generally high DM contents of the frass and make lower application rates for the same amount of nutrients possible.

Although the ammonium nitrogen (NH₄⁺-N) proportion of N_t (15.78 %) is on the level of solid manure and therefore low compared to other farm manures (Gutser et al. 2005), ammonia volatilization with the increasing humidity after application is assumed due to the high pH observed. In these terms, high DM contents are crucial for the conservation of NH₄⁺-N in frass (Ooninx 2017): increasing with the moisture content of the substrate, uric acid is converted to NH₄⁺ and further to ammonia (NH₃), as was shown for poultry litter by Liu et al. (2007). As uric acid and its degradation product allantoin are the main forms of nitrogen in frass (Green and Popa 2012), this mechanism probably is also relevant for BSF frass.

With phosphorus (P) contents of 12.4 g kg⁻¹ DM and potassium (K) contents of 29.3 g kg⁻¹ DM, the averaged ratio of their oxide forms (N:P₂O₅:K₂O) ratio is around 1:0.9:1.1. This balanced nutrient profile is not only a result of averaging but can roughly be confirmed for most nutrient analyses. A nearly even N:P₂O₅:K₂O ratio is not common amongst farm manures (Gutser et al. 2005). In most

manures, N exceeds P₂O₅, as is the case for the nitrogen removal of most agricultural crops (Gutser et al. 2005).

The carbon-to-nitrogen (C:N) ratio of 14.71 is comparable to solid manure or biowaste compost (Gutser et al. 2005). In manures, mainly NH₄⁺-N is directly plant-available, which makes up 15.78% of the N_t in frass, being again on the level of solid manures (Gutser et al. 2005). Low shares of NH₄⁺-N and a high C:N ratio in fertilizers typically lead to a slow nutrient release and an enhanced long-term fertilization effect (Gutser et al. 2005). Additionally, those fertilizers help building up soil organic matter, can immobilize soil mineral nitrogen (Gutser et al. 2005) and, thereby, prevent nitrate leaching. However, this also means that BSF frass, when applied in economically and ecologically viable amounts in arable farming, is not predestined to be the sole nutrient source for the plant (Gärtling et al. 2020, Beesigamukama et al. 2020a). Consequently, Anyega et al. (2021) found the combined application of NPK fertilizer and BSF frass to result in the highest yields when comparing it against sole applications of these fertilizers at the same N level. When applying BSF frass fertilizers over a longer period of time, the long-term mineralization effects from former applications could also contribute to plant nutrition (Beesigamukama et al. 2020a). To assess the whole potential of BSF frass fertilizers, it is therefore recommendable to conduct cropping trials over several years.

When high doses of fresh frass were applied, yield reductions due to phytotoxicity were reported (Setti et al. 2019). To increase the fertilization effect of BSF frass and avoid adverse effects, composting BSF frass can be an option (Song et al. 2021). Apart from decreasing moisture contents of the substrate (Finstein et al. 1986), composting reduces the C:N ratio but at the same time the NH_4^+ -N shares of the substrate, so that stable compost typically has a low short-term N availability (Gutser et al. 2005). Similarly, Song et al. (2021) reported decreased NO_3^- contents and a lower C:N ratio when composting BSF frass. However, the direct fertilizing effect may also increase due to the reduction of phytotoxic compounds in the frass and an unusually low C:N ratio (Song et al. 2021). When producers are willing to implement composting to enhance the legal and practical applicability of frass as a soil amendment, they must be aware of higher greenhouse gas emissions compared to fresh frass (Song et al. 2021) and additional costs and labour for this post-processing step.

In the European Union, the labelling of frass as organic fertilizer is covered by Regulation (EU) 2019/1009 and usually is considered as solid organic fertilizer (PFC 1 (A) (I)). The minimum thresholds for compound, solid organic fertilizers are met: those are 1% of N_t , P_2O_5 or K_2O , whilst the sum of those primary nutrients must make up at least 4% by mass. To fulfil legal standards, frass must be heated to 70 °C for 60 min (Houben et al. 2020; IPIFF 2021). This makes post-processing necessary, e.g. composting (Barrena et al. 2009) or thermal drying, implying nutrient losses (Liu et al. 2019) as well as additional labour and costs for the commercialization of BSF frass as a fertilizer, as mentioned before. However, the final development of a European standard is still part of the current work (IPIFF 2021).

4 Conclusions

For the first time, a greater number of black soldier fly frass analyses was compiled and made accessible publicly. Public nutrient tables can be helpful as means of orientation for farmers and producers, preferably supplemented by a product-specific fertilizer analysis. BSF frass is a promising organic compound fertilizer with a trend to alkaline pH values, a limited short-term nitrogen availability and high dry matter contents leading to high macronutrient contents compared to common manures. Data anonymization through aggregation increased the acceptance and willingness of producers to share information. With additional, basic information on the production system, the variation of the parameters is expected to be reduced.

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Availability of Data and Material The authors elect not to share data. For further data insights, please contact the author as the data was part of a confidential communication to insect producers, and therefore anonymized data will only be disclosed for justified reasons.

Code Availability Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

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