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The potential of black soldier fly to recycle nitrogen from biowaste

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Abstract

Nitrogen is an essential element for life on Earth. It is necessary for the production of food and feed, but excess nitrogen in nature leads to environmental problems such as eutrophication and climate change. To mitigate the negative impact of excess nitrogen, it is crucial to adopt sustainable and circular nitrogen management practices, such as nitrogen recycling from biowaste. Black soldier fly (BSF) biowaste treatment offers new possibilities for sustainable waste management and protein production, converting biowaste into protein-rich biomass and nutrient-rich residue. Understanding the nitrogen conversion efficiency (NCE) of BSF during biowaste treatment is essential for optimizing the process and minimizing nitrogen losses. Additionally, this review examines nitrogen emissions during BSF biowaste treatment, particularly NH_3 and N_2O, emphasizing the importance of adopting mitigation strategies for sustainable waste management practices. The potential of insects, especially BSF, in N recycling and waste management holds promise for addressing the challenges of sustainable agriculture and environmental conservation.

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Nitrogen, Nitrogen-recycling, Insect biowaste treatment, Black soldier fly.

Abbreviations
N, nitrogen; Nr, reactive N; NH_3, ammonia; NH_4^+, ammonium; NO, nitric oxide; NO_2, nitrogen dioxide; N_2O, nitrous oxide; NO_3^-, nitrate; NO2-, nitrite; BE, bioconversion efficiency; NCE, nitrogen conversion efficiency; BSFL, black soldier fly larvae.

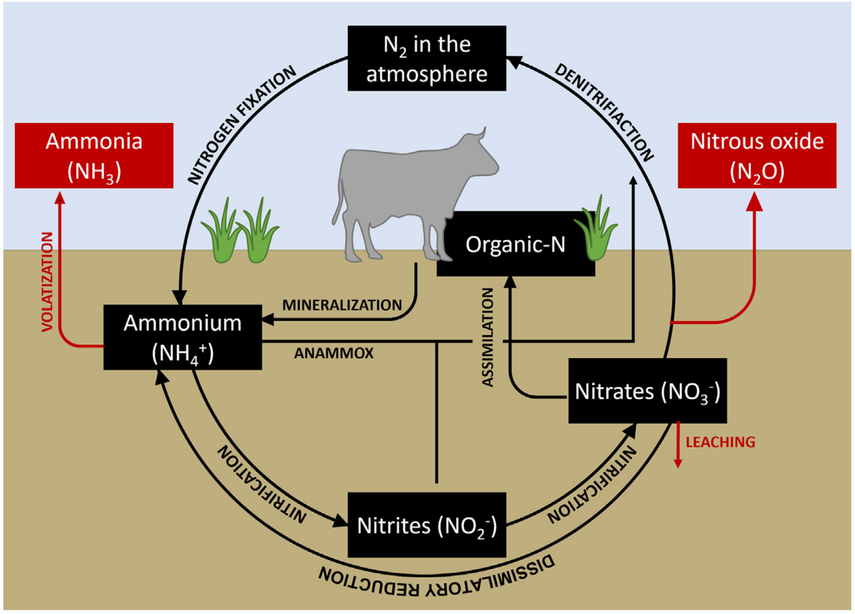
Introduction

Nitrogen (N) is one of the primary nutrients essential to life. It is a key element of many biomolecules, including proteins and nucleic acids. Although N makes up 78% of the Earth's atmosphere in the form of dinitrogen gas (N_2), it is largely inaccessible in this form to most organisms [1]. The series of processes by which N is transformed into its numerous chemical forms in nature is called the N cycle (Figure 1). The equilibrium of the N cycle plays a significant role in sustaining various aspects of life on Earth. Unfortunately, human activities have significantly altered the balance of the N cycle, leading to excess reactive N (Nr) in the environment [2]. Nr refers to the various forms of N that are highly reactive chemically and biologically, including nitrogen compounds such as ammonia (NH_3), nitric oxide (NO), nitrogen dioxide (NO_2), nitrous oxide (N_2O), and nitrate (NO_3^-). While Nr is essential for many biological processes and is a crucial component of fertilizers used in agriculture, excess Nr leads to environmental problems such as land and water pollution, and climate change [2,3].

Sustainable N management involves optimizing the use of N-based fertilizers in agriculture, improving N use efficiency and recycling, reducing N losses to the environment, and promoting alternative sources of N [5]. This review focusses on the potential of insects for the recycling of N from biowaste. Insects have been shown to be effective at recycling N from biowaste materials, such as food waste, animal manure, and agricultural residues [6,7]. They can convert these materials into protein-rich biomass (i.e. insects) and nutrient-rich residue (i.e. frass) which can be used as animal feed and soil fertilizer respectively. As such insect biowaste treatment provides new opportunities for sustainable biowaste management and protein production, thereby reducing the amount of N-containing waste sent to landfills or composting facilities, reduce the need for synthetic fertilizers, and produce an alternative source for animal feed [8–10].

The most commonly used insect species for this purpose is the black soldier fly *Hermetia illucens* (BSF). The black soldier fly larvae hold great promise as a leading candidate in the fast-growing insect-farming sector. They have short life-cycles of 4–5 weeks and their larvae are remarkably voracious feeders, which are able to consume a wide variety of organic matter (varying from low-value side-streams, to manure and multiple types of decomposing materials) [6,7]. They can convert this wide range of organic wastes into insect biomass, which is rich in proteins (32–58% dry matter, DM) and lipids (15–39% DM) and have shown to be a good

Figure 1



Current Opinion in Green and Sustainable Chemistry

The nitrogen cycle. The nitrogen cycle comprises of several complex biological process that describes the transformation of nitrogen in various forms and its cycling through ecosystems. The major steps of the nitrogen cycle are as follows: **Nitrogen fixation**: dinitrogen gas (N_2) is fixed from the atmosphere into ammonium (NH_4^+) or ammonia (NH_3) by nitrogen fixing bacteria. **Nitrification**: nitrification is an aerobic process that occurs by nitrifying bacteria in two steps: nitritation, the oxidation of ammonia to nitrite (NO_2^-), and nitratation, oxidation of nitrite to nitrate (NO_3^-). **Dissimilatory reduction (DNRA):** Dissimilatory reduction of nitrite to ammonium. This process is carried out by certain bacteria and fungi under anaerobic conditions. **Anammox** (anaerobic ammonia oxidation): ammonium and nitrite are converted into nitrogen gas under anaerobic conditions. **Assimilation:** Plants and microorganisms take up the nitrate and ammonia from the soil to use as building blocks for proteins, nucleic acids and other organic compounds. **Mineralization**: decomposers such as fungi and bacteria break down organic matter into simpler compounds, releasing ammonia back into the soil. **Denitrifiaction**: in this anaerobic process nitrate and nitrite are reduced to gaseous forms of nitrogen, principally nitrous oxide (N_2O) and nitrogen [1,4].

source for animal feed [6–8,11]. The larvae show remarkable bioconversion efficiencies, however this efficiency, similar to other livestock, depends on many factors such as the nutritional and physical composition of the feed substrates, rearing conditions and etc. Understanding and further improvement of the bioconversion efficiency is essential for sustainable BSFL biowaste treatment. During BSFL biowaste treatment, nitrogen can be incorporated into larval biomass, remain in the residue or losses may occur through the emission of NH_3 and N_2O. This review provides an overview of the current knowledge on nitrogen conversion and emission of nitrogen that occur during BSFL biowaste treatment.

In this review paper, deeper focus will be laid onto the nitrogen conversion efficiency (NCE) of the black soldier fly (BSF) during biowaste treatment. Different factors that influence NCE, such as substrate composition and the carbon-to-nitrogen (C/N) ratio will be discussed. Additionally, the incorporation of different nitrogen sources into larval biomass and its potential benefits will be reviewed. Furthermore, the issue of nitrogen emissions will be addressed, particularly NH_3 and N_2O, during BSF biowaste treatment, emphasizing the significance of adopting mitigation strategies for sustainable waste management practices. Understanding the NCE of BSF and its environmental implications is crucial for optimizing biowaste treatment and minimizing nitrogen losses, contributing to more eco-friendly waste management solutions.

Nitrogen conversion by BSFL

The bioconversion efficiency (BE) in BSFL biowaste treatment is defined as the proportion of nutrients provided in the substrate which are incorporated into the larval biomass [12]. A lot of studies also calculate the nitrogen conversion efficiency (NCE) in BSFL waste treatment studies. The NCE reflects how much N is taken up from the substrate into larval biomass. The NCE is calculated using the following formula: $NCE = (Lend_{DM} \text{ x } \%N_{Lend} - Lstart_{DM} \text{ x } \%N_{Lstart})/(S_{DM} \text{ x } \%N_S)$. Where $Lend_{DM}$, $Lstart_{DM}$ and S_{DM} is the total dry matter of the larvae at the end (Lend), the larvae at the start (Lstart) and the substrate (S) and $\%N_{Lend}$, $\%N_{Lstart}$ and $\%N_S$ is the percentage N (% of DM) in the

Table 1

Bioconversion efficiency (%) and N conversion efficiency (%) of BSFL on different biowaste streams.

Substrate	Bioconversion efficiency (%)	N conversion efficiency (%)	Reference
Poultry feed	12.8 ± 0.7	80.4 ± 1.2	[6]
Dog food	13.4 ± 0.9	46.3 ± 2.8	[6]
Food waste	13.9 ± 0.3	58.7 ± 1.3	[6]
Fruit & veg.	4.1 ± 0.2	34.3 ± 1.1	[6]
Abattoir waste	15.2 ± 1.6	30.8 ± 2.8	[6]
Abattoir waste + fruit & veg.	14.2 ± 1.9	47.7 ± 6.6	[6]
poultry manure	7.1 ± 0.6	37.8 ± 3.4	[6]
Human faeces	11.3 ± 0.3	31.6 ± 0.6	[6]
Primary sludge	2.3 ± 0.1	15.0 ± 0.5	[6]
Undigested sludge	2.2 ± 0.2	7.8 ± 0.6	[6]
Digested sludge	0.2 ± 0.0	1.9 ± 0.3	[6]
47% yeast concentrate from wheat (ProtiWanze®), 47% starch-rich by-product from wheat and potatoindustry (DB-blend) and 6% binding agent	16	38	[13]
Chicken manure	3.4 ± 0.49	4.6 ± 0.59	[19]
Pig manure	4.5 ± 1.37	12.4 ± 40.4	[19]
Cow manure	2.9 ± 0.19	7.4 ± 0.48	[19]
Gainesville house fly diet	2.5–5.0	1.2–2.2	[20]
100% sorghum, 0% cowpeas	5.7–6.1	2.5–2.7	[20]
75% sorghum, 25% cowpeas	5.6–6.9	2.5–3.1	[20]
50% sorghum, 50% cowpeas	4.8–7.5	2.2–3.5	[20]
25% sorghum, 75% cowpeas	4.4–6.9	2.0–3.2	[20]
0% sorghum, 100% cowpeas	6.3–7.3	3.0–3.5	[20]
HPHF	24 ± 1.5	51 ± 3.2	[21]
60% spent grain, 20% beer yeast, 20% cookie remains			
HPLF	20 ± 1.3	51 ± 32.5	[21]
50% beer yeast, 30% potato steam peelings, 20% beet molasses			
LPHF	18 ± 4.8	55 ± 14.6	[21]
50% cookie remains, 50% bread			
LPLF	17 ± 5.0	43 ± 12.8	[21]
30% potato steam peelings, 20% beet molasses, 50% bread			
chicken feed	23 ± 5.3	52 ± 12.2	[21]
Vegetable waste	36	36	[22]
Butchery (25%) & vegetable waste (75%)	36	36	[22]
Butchery (50%) & vegetable waste (50%)	32	23	[22]
Pig manure + corncob C/N: 15/1	/	17.45	[14]
Pig manure + corncob C/N: 20/1	/	19.83	[14]
Pig manure + corncob C/N: 25/1	/	22.57	[14]
Pig manure + corncob C/N: 30/1	/	23.73	[14]
Pig manure + corncob C/N: 35/1	/	22.56	[14]
brewer's spent grain + sawdust C/N: 11/1	9–13.6	6.8 ± 0.7	[15]
brewer's spent grain + sawdust C/N: 15/1	9–13.6	9.0 ± 0.5	[15]
brewer's spent grain + sawdust C/N: 20/1	9–13.6	8.9 ± 0.6	[15]
brewer's spent grain + sawdust C/N: 25/1	9–13.6	7.4 ± 1.3	[15]
brewer's spent grain + sawdust C/N: 30/1	9–13.6	7.4 ± 0.4	[15]
Foodwaste + urea C/N: 21/1	30.6	73.5	[16]
Foodwaste + urea C/N: 18/1	29.7-34-6	83.0	[16]
Foodwaste + urea C/N: 16/1	29.7-34-6	81.3	[16]
Foodwaste + urea C/N: 14/1	29.7-34-6	68.1	[16]
Foodwaste + urea C/N: 12/1	29.7-34-6	39.9	[16]
Foodwaste + urea C/N: 10/1	29.7-34-6	35.2	[16]
Foodwaste + urea C/N: 21/1	26.5 ± 1.2	75.0 ± 7.0	[17]
Foodwaste + urea C/N: 18/1	27.8 ± 3.2	68.6 ± 7.5	[17]
Foodwaste + urea C/N: 16/1	30.6 ± 1.3	63.5 ± 3.2	[17]
Foodwaste + urea C/N: 14/1	25.1 ± 4.1	45.7 ± 6.1	[17]
Foodwaste + urea C/N: 12/1	25.7 ± 2.1	46.2 ± 18.1	[17]
Foodwaste + urea C/N: 10/1	24.1 ± 0.9	34.9 ± 0.9	[17]

larvae (L) and the substrate (S) [12,13]. The NCE varies depending on the substrate used in de BSFL waste treatment as shown in Table 1. For example, Lalander et al. (2019) studied the NCE of BSFL on eight urban organic waste fractions [6]. They found a NCE varying between 80% and 1.9% and showed that the NCE does not necessarily correlate with the BE. Fruit and vegetables, abattoir waste, poultry manure and human faeces, had similar nitrogen conversion ratio's (respectively 34%, 31%, 38% and 32%), yet the bioconversion ratio varied significantly. For instance, abattoir waste, which had the highest nitrogen content (1.6% N), had the highest BE (15%), whereas fruit and vegetables (0.23% N) had a low BE (4%). Furthermore, they explored the effect of balancing the carbon to nitrogen (C/N) ratio (to C/N 9:1, 0.93% N) by mixing fruit and vegetable waste (C/N 24:1) with abattoir waste (C/N 6:1), which resulted in a high BE (14%) and a better NCE (48%) compared to the individual substrates. These results indicated that balancing the C/N ratio by using a mixture may enable the larvae to utilize the available nutrients, in particular N, to a higher degree [6]. Indeed, several studies have shown that the C/N ratio influences the N conversion efficiency of BSFL production. Pang et al. (2020) was the first to describe this phenomenon [14]. They used pig manure (2.43% N) to which they added corncob at different mass ratios to C/N ratios of 15:1, 20:1, 25:1, 30:1, and 35:1. The NCE ranged between 17.45% (C/N 15:1) to 22.56% (C/N 35:1). Overall, a C/N ratio of 25:1 proved to be the best for BSFL biomass generation among the mixtures of pig manure and corncob as it had the highest larval weight gain [14]. In a similar study brewer's spent grain with a C/N ratio of 11:1 (2.69% N) (control) was amended with sawdust to obtain substrates with C/N ratios of 15:1, 20:1, 25:1 and 30:1 [15]. Here, larval yield decreased as more sawdust was mixed into the substrate. The highest NCE (6.8%) was achieved at the C/N ratio of 15:1. In a study by Lu et al. (2021) local food waste (2.26% N) was supplied with urea from the initial 21:1 C/N ratio to 18:1, 16:1, 14:1, 12:1, and 10:1 [16]. The BE (between 29.7% and 34.6%) did not differ significantly between the different C/N ratios. High urea concentrations (lowering the C/N down to 12:1—10:1) did however have a negative impact on yield, survival and the NCE (C/N (12:1) (39.9%) and C/N (10:1) (35.2%)). However mild additions of urea (C/N range of 18:1 to 16:1) seemed to increase larval yield and the NCE (C/N (18:1) (83.0%), C/N (16:1) (81.3%), and C/N (14:1) (68.1%) groups were similar to the blank control (73.5%) [16]. Similar results were reported by Jin et al. (2022) who supplied food waste with urea to obtain a C/N ratio from 21:1 (2.26% N) to 10:1 (4.7% N) [17]. They also found that NCE depend on the C/N ratio, with C/N 21:1—16:1 (63.5—75.0%) being higher than C/N 14:1—10:1 (35.0—45.7%) [17]. Lu et al. (2021) and Jin et al. (2022) both used food waste with an initial N content of 2.26% as substrate to which they added urea to reduce the C/N ratio [16,17]. Pang et al. (2020) and Beesigamubama et al. (2021) used N-rich substrates (with an N content of 2.43% and 2.69% respectively) and added a carbon source to it to increase the C/N ratio. Both carbon sources had a high fiber content [14,15]. Because fibers are indigestible to BSFL, large amounts of fibers can reduce the process performance by reducing the overall nutrient density for BSFL development, which could explain the low NCE obtained in these studies [8]. On the other hand, the N digestibility may also depend on the specific substrate itself. The high NCE obtained in the studies by Lu et al. (2021) and Jin et al. (2022) may indicate that urea is a good N source in a BSFL waste treatment process and more specifically N conversion [16,17].

The N conversion in BSFL does not only reflect the uptake of protein from the substrate into larval biomass. Insects are, in fact, capable of ingesting other forms of N. Lu et al. (2021) studied the effect of the addition of different N sources (i.e., NH_4Cl, $NaNO_3$, urea, uric acid, Gly, L-Glu, L-Glu:L-Asp (1:1, *w/w*), soybean flour, and fish meal) to food waste [16]. Addition of the different N sources altered the N% in the food waste from 2.26% to 3.26% or the C/N ratio from 21:1 to 14—17:1. They found that addition of the inorganic N sources NH_4Cl and $NaNO_3$ led to poor larval growth, N conversion and survival, while the other 7 organic N sources exerted no harm to the larvae. Recently Parodi et al. (2022) investigated the incorporation of NH_3—N into the larval body mass and larval proteins after pig manure bioconversion with BSFL [18]. The study demonstrated that at least 13% of pig manure NH_3—N can be incorporated into BSFL body mass. The outcomes of this study showed the potential of manure bioconversion with BSFL for reducing manure NH_3 emissions and to upgrading NH_3 as a circular protein source for animal feed [18].

Jin and colleagues also showed that the N conversion can be enhanced by manipulating the C/N ratio [17]. In this study they calculated the N balance from the BSFL treatment and found that it differed among different C/N ratios, with more N remaining in the residue and less taken up by the larvae with a decreasing C/N ratio. However, the N balance also indicated a higher N loss with decreasing C/N ratio.

Nitrogen emissions during BSFL biowaste treatment

Besides increasing BE, avoiding nutrient losses via gaseous emissions is also key to sustainable BSFL biowaste treatment. N_2O and NH_3 are both nitrogen-containing gases that can have negative impact on our environment. N_2O is a potent greenhouse gas, while NH_3 is specifically associated with eutrophication [2]. Only a few studies investigated the emission of these gases during BSFL biowaste treatment [13,14,23—30].

These studies indicate that during BSFL biowaste treatment emissions of N_2O and NH_3 occur, but that the amount greatly depends on the biowaste composition and rearing conditions.

Similar to conventional composting the initial moisture content of the substrate also has an impact on NH_3 and N_2O emissions during BSFL biowaste treatment. In composting, high moisture contents reduce the porosity of the compost mixture, thereby limiting oxygen transfer and enhancing the formation of anoxic zones. In a study by Chen et al. (2019) this was investigated by rearing BSFL on pig manure mixed with corncob with varying moisture content from 45 to 85% [24]. Higher NH_3 emission was detected for the drier substrates (45—55%) compared to the moister substrates (65—85%). NH_3 emission mainly occurred at the start of the experiment, which could be due to fast organic degradation and the conversion of NH4+-N to NH3. Emission of N_2O was low and did not seem to vary with moisture content. The study also compared NH_3 and N_2O emissions to traditional composting of pig manure and showed that this was reduced by 82.30%—89.92% and 99.61%—99.90% respectively [24]. Other studies also compared BSFL biowaste treatment and show similar results [13,25—27,29].

In conventional composting the C/N ratio also influences the emissions of N_2O and NH_3 as this ratio strongly determines microbial metabolism [4]. Pang et al. (2020) also investigated how this ratio influences N_2O and NH_3 emissions during BSFL biowaste treatment [14]. The emission of N_2O was relatively low and did not differ significantly between the different C/N ratios. For NH_3 emission, there was however a clear link to the C/N ratio. The lower the C/N ratio (the less corncob), the higher the NH_3 volatilization. This trend is also visible in composting, where it is suggested that a high C/N ratio of substrates improves microbial assimilation and thus reduces NH_3 emissions [4,31]. Although NH_3 loss was enhanced at lower C/N ratios, the degree of enhancement was relatively low compared to the total nitrogen in the raw materials. For all the treatments, the loss of nitrogen ranged from 8.93 to 18.68% of the initial total nitrogen [14]. Besides the C/N ratio, the moisture content of the substrates must also be taken into account when interpreting these results. The higher the C/N ratio (the more carbohydrates/corncob), the higher the final moisture content in this study (from 54.23% to 67.96%), which could also partly explain the reduced NH_3 volatilization [32]. However, NH_3 volatilization mainly occurred at the start of the experiment, when moisture content was equal for all substrates. The changes in NH_4^+ and NO_3^- were also measured during the experiment. The initial concentration of both NH_4^+ and NO_3^- were positively correlated to the N concentration in the substrates. NH_4^+ concentration consistently dropped throughout the experiment whereas the NO_3^- initially dropped and then increased until relatively stable. This phenomenon could be explained as the transformation of NH_4^+ by nitrifying bacteria to NO_3^- or by the transformation of NH_4^+ tot NH_3 [4].

Another study by Pang et al. (2020) examined the influence of pH on NH_3 and N_2O emissions and other greenhouse gases [23]. Here, food waste (46.8% N, C/N 9:1) and rice straw (4.08% N, C/N 119:1) were mixed and pH was varied from 3 to 11 by adding 2M $NaOH-H_3PO_4$ buffer. The final pH varied between 8 and 9, except for the acidic substrate (starting pH 3), where the final pH remained below 5. During the experiment, both NH_4^+ in the substrate and NH_3 emissions were measured. Throughout the experiment, NH_4^+ levels increased. However, there was a clear negative correlation between the final NH_4^+ concentration in the substrate and the initial pH (the higher the pH, the lower the NH_4^+ concentration). In accordance with the changes in NH_4^+, NH_3 emissions in pH 7.0, 9.0 and 11.0 treatments sharply increased throughout the experiment and NH_3 emission was positively correlated with pH [23]. The correlation of NH_3 emissions with pH is generally recognized and caused by the pH dependent shift of the NH_4^+- NH_3 equilibrium [33]. Only small amounts of N_2O emissions were detected, which mainly occurred at the start of the experiment. In line with the NH_4^+ concentration, NO_3^- concentration in the substrate was relatively stable at the start of the experiment and then increased rapidly, showing a good nitrification effect in the BSFL treatment process. No correlation was detected between the NO_3^- concentration and pH. The low concentrations of N_2O emissions indicate that anaerobic denitrification of NO_3^- is inhibited during BSFL treatment. Rising concentrations of NH_4^+ and NO_3^- indicate the improved processes of ammonification and nitrification, which mainly take place in oxygen-rich conditions. This is most likely a consequence of facilitated air diffusion into the substrate by BSFL movement, which creates aerobic conditions while eliminating anaerobic conditions.

Ermolaev and colleagues evaluated the effect of pretreatment of food waste with BSFL-associated bacteria on BSFL (N-)conversion efficiency and N_2O and NH_3 emissions [25]. The results indicated negligible emissions of N_2O and NH_3 from the system. This was also indicated by the total N recovery in the N balance. The pretreatment of the substrate did not seem to influence N conversion or emission as it gave similar results as the non-pretreated samples. In a recent study by Lindberg et al. (2022) the effect of substrate pretreatment on bioconversion and N_2O and NH_3 emissions was also investigated [26]. Orange peels and a mix of broccoli and cauliflower trimmings were pretreated with fungi or ammonia to improve bioconversion. Fungal pretreatment could assist BSFL in the degradation of fibers and ammonia pretreatment could help microorganisms break down complex molecules and stimulate microorganisms to convert non-protein nitrogen (NH_3) into proteins through nitrogen assimilation to generate amino acids. Pretreatment with fungi or ammonia did not significantly improve BE during BSFL composting. However, both pretreatments significantly increased the material reduction for the peels. Ammonia pretreatment reduced emissions N_2O but significantly increased NH_3 emissions [26].

The above studies used periodic measurements of the gases, consequently they may have missed changes in emissions between measurements and prevented a completion of a complete mass balance. Parodi et al. (2020) was the first to perform continuous measurements [13]. When using a compound feed used in industrial BSFL rearing, low N_2O and NH_3 emissions were observed. By tracking metabolic heat, CO_2 and NH_3 emissions through time, it could be observed that NH_3 emission occurred only after the metabolic heat and CO_2 peak. This however was not true for NH_3 emissions during BSFL treatment of pig manure, which was measured by the same group. Similar to other studies on manure, NH_3 emissions occurred at the start of the experiment [24].

While most studies have found low N losses via gaseous emissions, it should be mentioned that some studies have reported losses up to 40% [34]. Large-scale BSFL producers have also reported high levels of NH3 emissions during the rearing process. This indicates the importance to gain more knowledge on the causes of N emission during BSFL biowaste treatment and on the mitigation strategies that could be taken.

Conclusion

Insects, such as the black soldier fly (BSF), present a promising solution for sustainable nitrogen management and biowaste recycling. BSF biowaste treatment offers an innovative approach to recycling nitrogen-rich biowaste, such as food waste and animal manure, by converting it into protein-rich biomass and nutrient-rich residue. This novel process may not only reduce waste in landfills but also can provide valuable resources for animal feed and soil fertilization. However, understanding and enhancing the nitrogen conversion efficiency (NCE) of BSF during biowaste treatment are essential for maximizing its potential and minimizing nitrogen losses.

Nitrogen emissions during BSF biowaste treatment, specifically NH_3 and N_2O, need to be addressed to ensure eco-friendly waste management. Studies show that emissions vary depending on biowaste composition, rearing conditions, and substrate properties. By adopting mitigation strategies, such as balancing the carbon-to-nitrogen (C/N) ratio and optimizing moisture content, nitrogen losses can be further reduced. Incorporating insects like BSF into nitrogen recycling and waste management practices can lead to a more sustainable and efficient system for addressing nitrogen-related environmental issues. However, continued research and development are required to fully optimize insect bioconversion systems and unlock their potential for mitigating environmental impacts.

Author contributions

LF prepared the original draft. LB and SB reviewed and edited the manuscript. SVM supervised the process and acquired funding.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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