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Research article

Reducing greenhouse gas emissions and enhancing carbon and nitrogen conversion in food wastes by the black soldier fly

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ABSTRACT

Currently, sustainable utilisation, including recycling and valorisation, is becoming increasingly relevant in environmental management. The wastes bioconversion by the black soldier fly larva (BSFL) has two potential advantages: the larvae can convert the carbon and nitrogen in the biomass waste, and improve the properties of the substrate to reduce the loss of gaseous carbon and nitrogen. In the present study, the conversion rate of carbon, nitrogen and the emissions of greenhouse gases and NH_3 during BSFL bio-treatment of food waste were investigated under different pH conditions. The results showed that the pH of the raw materials is a pivotal parameter affecting the process. The average wet weight of harvested BSFL was 13.26–95.28 mg/larva, with about 1.95–13.41% and 5.40–18.93% of recycled carbon and nitrogen from substrate at a pH from 3.0 to 11.0, respectively. Furthermore, pH is adversely correlated with CO_2 emissions, but positively with NH_3 emissions. Cumulative CO_2, NH_3, CH_4 and N_2O emissions at pH ranging from 3.0 to 11.0 were 88.15–161.11 g kg^{-1}, 0.15–1.68 g kg^{-1}, 0.19–2.62 mg kg^{-1} and 0.02–1.65 mg kg^{-1}, respectively. Compared with the values in open composting, BSFL bio-treatment of food waste could lead greenhouse gas (especially CH_4 and N_2O) and NH_3 emissions to decrease. Therefore, a higher pH value of the substrate can increase the larval output and help the mitigation of greenhouse gas emissions.

1. Introduction

Globally, about 1.3 billion tons of food are wasted each year, equivalent to about $1 trillion in annual economic losses (FAO, 2014). Nowadays, the treatment of FW has become a serious issue worldwide due to the high costs related to its environmental management (Fersiz and Veli, 2015). The main approaches in FW management include disposal in landfills, incineration and composting for the production of fertilisers (Avagyan, 2017). Despite this, about one third of all the food produced today goes in landfills (Stuart, 2009). In Canada, for example, in the year 2017, 12.9 million tons of FW was produced, but only 4.4 million tons were recycled (Avagyan, 2017). In addition to the enormous financial costs, FW also result in many environmental problems, such as landfill consumption, odour nuisance and generation of leachate and landfill gas (Lee et al., 2007). On the other hand, the burning of FW reduces its economic value, and the dumped product can cause health and environmental problems (release of dioxins, etc.) (Avagyan, 2018). In order to alleviate this, it is necessary to develop economic and environmentally friendly alternatives (Avagyan, 2017, 2013).

Recently, composting has become an important way to manage FW, as it can reduce the volume and weight of FW, and produce innoxious, stable and rich in nutrients soil amendment materials even though it shows some limit (Avagyan, 2018; Yang et al., 2015). In particular, the biodegradation of organic matter can lead to the substantial loss of C and N during long processes, which both reduces the end-product quality and causes secondary environmental pollution. For example, some

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studies indicated that 16–74% of initial TN and 14–59% of initial TOC are lost during composting, mostly in the form of NH_3 and CO_2, respectively (Chen et al., 2019). About 0.2–9.9% of initial TN and 0.08–6% of initial TOC in organic wastes are lost in the form of N_2O and CH_4 (Yang et al., 2015), which are GHG of high concern (Chowdhury et al., 2014).

Currently, biowastes are treated by BSFL widely, and this new approach has attracted considerable interest by researchers worldwide. Previous studies were mostly focused on the bio-treatment of diverse organic wastes, and the residues can be utilised as fertiliser; Meanwhile, larvae provide protein- and fat-rich biomass, which can be further used for biodiesel production and animal feed (Salomone et al., 2017). In fact, the conversion of waste into protein for use as feed for aquaculture and poultry in USA (AAFCO, 2016), EU (Cutrignelli et al., 2018), and other parts of the world is allowed. *Hermetia. Illucens* L. is one of the authorised insect species. Practical approaches have been applied to ensure the retention of nutrients and control C and N loss in composting (Wang et al., 2018), including the use of different kinds of bulking agents which can increase the C/N ratio in raw materials, the modification of the aeration rate, and the addition of chemical agents or mineral additives. Compared with these methods, BSFL biowaste treatment can lead to end-products of higher economic value at lower costs.

The sustainable use of waste, including recycling and valorisation, is the current trend in waste management (Avagyan, 2013; Sánchez et al., 2015). However, there are few studies focused on the environmental benefit related to the treatment of wastes with BSFL in terms of sustainability. Mertenat et al. (2019) and Ermolaev et al. (2019) found that the BSFL FW treatment has potential to cut down GHG emissions compared with conventional composting. These researchers also suggest that there is still need of further exploration based on various raw materials and process parameters, to study the direct GHG emissions, C and N recycling during BSFL treatment, in order to correctly evaluate its environmental sustainability. Additionally, the FW biodegradation during composting has been reported to be mostly controlled by factors such as pH, moisture, C/N ratio and temperature (Cerda et al., 2018). Especially, the quick biodegradation of readily available organic matter can intensively acidify the substrate, resulting in low pH values in the initial phase of FW treatment and eventually inhibiting the larval growth and microbial activity (Chan et al., 2016; Ma et al., 2018). For this reason, to optimise the biowaste treatment by adjusting the initial pH of the substrate is of great significance. This may not only accelerate the decomposition of FW but also increase the yield and quality of BSFL. To date, the effects of pH on the bioconversion of C and N and on the emissions of GHG and NH_3 during BSFL bio-treatment of FW have not been reported, to the authors' knowledge. This study aims to investigate the GHG and NH_3 emissions during BSFL bio-treatment of FW under different pH conditions of the feeding substrate, as well as to improve the recycling of C and N from FW to larvae, and to mitigate the GHG emissions by adjusting the initial pH of FW. Besides, the amount of C and N was monitored alongwith parameters such as changes in larvae weight and physico-chemical properties of the substrate. The results of this study can provide important insights for the sustainable use of wastes by BSFL biowaste treatment.

2. Materials and methods

2.1. Raw materials

BSFL (*Hermetia illucens* L., Stratiomyidae: Diptera) used in this study were bred at Wuhan ChaoTuo Ecology Agricultural Ltd. Food waste was collected from the restaurants in Wuhan, China, Hubei Tianji Bioengineer Co. Ltd, China. The chopped rice straw (RS) was obtained from the experimental field of Huazhong Agricultural University, Wuhan China. The physical and chemical characteristics are shown in Table 1.

Table 1
Physico-chemical characteristics of food waste and rice straw offered to BSFL.

	TOC(g/kg)	TKN(g/kg)	Moisture content (%)	C/N ratio	pH
Food waste	401.6 ± 14.31	46.8 ± 4.41	69.3 ± 1.32	8.6	5.03 ± 0.15
Rice straw	484.3 ± 10.22	4.08 ± 0.45	9.2 ± 0.38	118.7	–

TOC: total organic carbon; TKN: total Kjeldahl nitrogen.

2.2. Experimental design

Before BSFL rearing, FW and RS were mixed at a fixed ratio (FW:RS, 9: 1 w/w) to adjust the moisture content. The substrate pH was set at 3.0, 5.0, 7.0, 9.0 and 11.0 (±0.1) by the addition of 2 M NaOH-H_3PO_4 buffer. The dry matter and moisture content (65 ± 2%) of each treatment were consistent. A total of 1.2 kg (wet weight) substrate was added in each cylindrical glass jar (20 cm diameter × 35 cm depth). Based on preliminary experiments (Chen et al., 2019), about 1800 3-day-old BSFL (about 5.5 mg/larva) were inoculated into the substrate mixture. The experiment was not stopped until the occurrence of the first prepupa in each replicate; the larval biomass was separated from the residue through manual sieving. The BSFL were deactivated at 105 °C for 5 min after being washed with distilled water. They were then dried at 55 °C for 3 days. All the treatments were subjected to incubation at 30.0 ± 1.0 °C. In the first three days, the substrate pH was maintained constant as much as possible by the addition of 50 mL NaOH-H_3PO_4 buffer.

2.3. Measurements of GHG and NH_3 emissions

The gaseous samples containing CO_2, CH_4 and N_2O were measured on a daily basis. According to a procedure defined in literature (Wu et al., 2018), gas samples (30 mL) were taken from the headspace of the bottles with a gastight syringe, at 0 and 20 min after the container closure. The gas concentrations were measured by a gas chromatograph (GC-7890A; Agilent Technologies, Santa Clara, CA, USA) equipped with a flame ionisation detector for CH_4 and CO_2 analyses and an electron-capture detector for N_2O analysis. NH_3 released during BSFL treatment was captured in H_2SO_4 solution and determined by 0.02 M NaOH titration (Koyama et al., 2018).

2.4. Sample collection and analysis

Representative FW samples were collected after gas sampling for determination of physical and chemical properties. Both initial and final samples were analysed for the determination of TOC and TN according to the method suggested by a previous study (Song et al., 2013). FW inorganic N (ammonium-N and nitrate-N) was measured (FW sample:2 M KCl, 1:5 w/v ratio and shaken for 1 h) using the indophenol blue spectrophotometric method and ultraviolet spectrophotometry at 220 nm and 275 nm, respectively (UV-1800, SHIMADZU, Japan) (Wu et al., 2018). DOC in the mixtures was measured using $K_2Cr_2O_3$ oxidation (FW sample:water, 1:10 w/v ratio and shaken for 1 h) (Zhu et al., 2015). The pH value was analysed according to standard test methods (PHS-3C, Leichi, Shanghai) (TMECC, 2002). At the same time, forceps were used to select 50 larvae from a given replicate of treatment randomly to measure the average larval wet weight. The larvae were washed with distilled water, dried with cotton gauze, weighed using an electronic analytical balance (BSM-120.4, Shanghai, China), and then returned to their respective containers.

2.5. Statistical analysis

All the experiments were repeated in triplicate. Statistical analyses were conducted using the SPSS 18 software. Effects of BSFL on the physico-chemical characteristics of FW mixtures and on gas emissions were analysed by one-way ANOVA. Significance for all the statistical analyses was accepted at $\alpha = 0.05$ level.

3. Results and discussion

3.1. Dynamics of pH value, larval growth during black soldier fly larvae bioconversion process

As one of the crucial factors affecting the BSFL activity and GHG emissions, time-changes in pH are presented in Fig. 1a, with reference to treatments at different nominal pH (from 3.0 to 11.0). BSFL were able to adjust the pH of the substrate. However, this capability was not observed when the substrate was highly acidic (pH 3.0). The final pH value (after 10 days), for treatments at nominal pH from 5.0 to 11.0, ranged from about 8 to 9, indicating that the residues after BSFL conversion could be used to repair acidic soils (Huang et al., 2014). In contrast, the case of strongly acidic substrate (pH 3.0) resulted in final pH values below 5. These findings confirm the results of previous studies of Ma et al. (2018) and Meneguz et al. (2018), who indicated that BSFL might modify the environmental pH to 8.5–9.2, which could be attributed to the combination of the production of organic acids by environmental and BSFL gut microorganisms, and the release of NH+ 4 and NH_3 from mineralisation of organic matter.

The BSFL growth rates in all treatments are listed in Fig. 1b, where the larval weight is reported as a function of time. The larval weight curves show that BSFL could grow over a wide range of pH. There were only slight differences in BSFL wet weight among different treatments (pH from 5.0 to 11.0) during the first five days, and after that, the BSFL wet weight was generally higher at higher pH. In the present study, the average wet weights of harvested BSFL were 13.26, 60.18, 68.44, 80.16 and 95.28 mg per individual under pH 3.0, 5.0, 7.0, 9.0 and 11.0 treatments, respectively. This result indicates that higher pH value of the FW contributes to faster growth of BSFL, which is desirable because it can shorten the production time. Ma et al. (2018) reported that pH values of 4.0 and 10.0 contribute to higher insects gain. The departure of their results from those here presented could be due to the different properties of the substrates and experimental set-up. Moreover, it should be noted that the larval growth was inhibited in substrates with low pH (pH 3.0). The pH of the substrate can significantly affect the activity of acid-producing bacteria (Zheng et al., 2012). Based on this, the authors hypothesise that a strongly acidic environment may result in an unfavourable medium for the BSFL gut microbes. Under low pH conditions, the slow decomposition of FW causes that the larvae spend more time in gaining their nutritional requirements. Meneguz et al. (2018) indicated that the pH could influence the development of BSFL by affecting the performance of larval gut microbes secreted enzymes (e.g. amylases, lipases and proteases). Especially, the activity of proteases enhances at a pH of 8.0, compared to strongly acidic pH values. BSFL shift the pH to a more suitable pH condition, which could increase the protein availability, thus positively influencing the larval growth. The BSFL treatment of waste is a complex biological system affected by many elements. Further research is still needed concerning the relationship between BSFL and the community dynamic changes within a substrate, as these factors most likely play a vital role in the growth of BSFL and FW bioconversion.

3.2. Changes in the chemical properties of the substrate during black soldier fly larvae bioconversion process

The changes in NH+ 4-N content as a function of time for different nominal pH values are shown in Fig. 2a. Only small amounts of NH+ 4-N were detected in all treatments at the early stages during the acidification condition. As the experiment continued, organic N is biodegraded to inorganic N via ammonification, resulting into a continually increasing in NH+ 4-N content. At the end of BSFL treatments (10 days), the content of NH+ 4-N for pH 3.0, 5.0, 7.0, 9.0 and 11.0 treatments reached 2.14, 6.04, 5.60, 5.26, and 3.73 g kg^{-1}, respectively. The results showed that the initial pH values had a negative correlation with NH+ 4-N concentration (the higher the pH, the lower the concentration), except for the case of pH 3.0. It is clear that higher pH values led to the transformation of more NH+ 4-N to NH_3-N, while a low pH value led to the formation of NH+ 4 (Li et al., 2012). However, the NH+ 4-N concentration in treatments with pH 3.0 was much lower than for the other four cases, possibly because the microbes postponed the mineralisation and ammonification of organic N under highly acidic conditions.

Similar trends in the change of nitrate-N (NO- 3-N) concentration were observed for pH 5.0–11.0 treatments (Fig. 2b). The NO- 3-N concentration stayed relatively stable during the early stage (0–5 days) and then increased rapidly. The final NO- 3-N contents were 0.07, 0.34, 0.33, 0.37, 0.38 g kg^{-1} for nominal pH ranging from 3.0 to 11.0, respectively, showing a good nitrification effect in BSFL treatment process. Organic N was firstly converted into NH+ 4 and subsequently oxidised into NO- 3 via nitrification in the presence of O_2 (Sánchez et al., 2015). The initially low concentrations of NO- 3-N might be ascribed to the low concentrations of NH+ 4. FW normally has high moisture content and compact structure that tends to agglomerate the media, thus possible reducing the free air space and creating anaerobic regions (Cerda et al., 2018). Nevertheless, it must be taken into account the facilitated air diffusion into the substrate by larvae movement and digestion, which destroy the anaerobic regions and also improved the process of ammonification and nitrification. Previously studies also observed that the movement of earthworms had the similar effect in vermicomposting (Lv et al., 2018). As the NH+ 4 content increased, NH+ 4-N was transformed into NO- 3-N by nitrobacteria, but at the same time, the anaerobic regions were destroyed, preventing the production of N_2O from the anaerobic

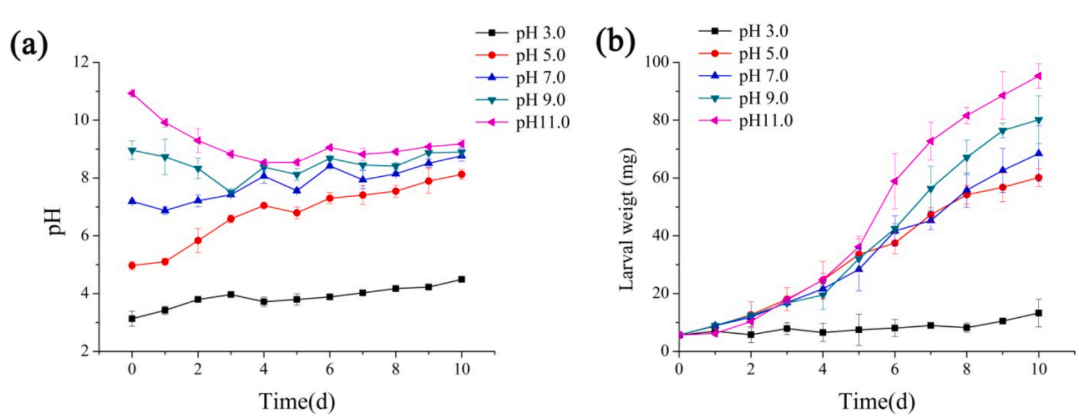

Fig. 1. Dynamics of pH (a) and daily average larval wet weight (b).

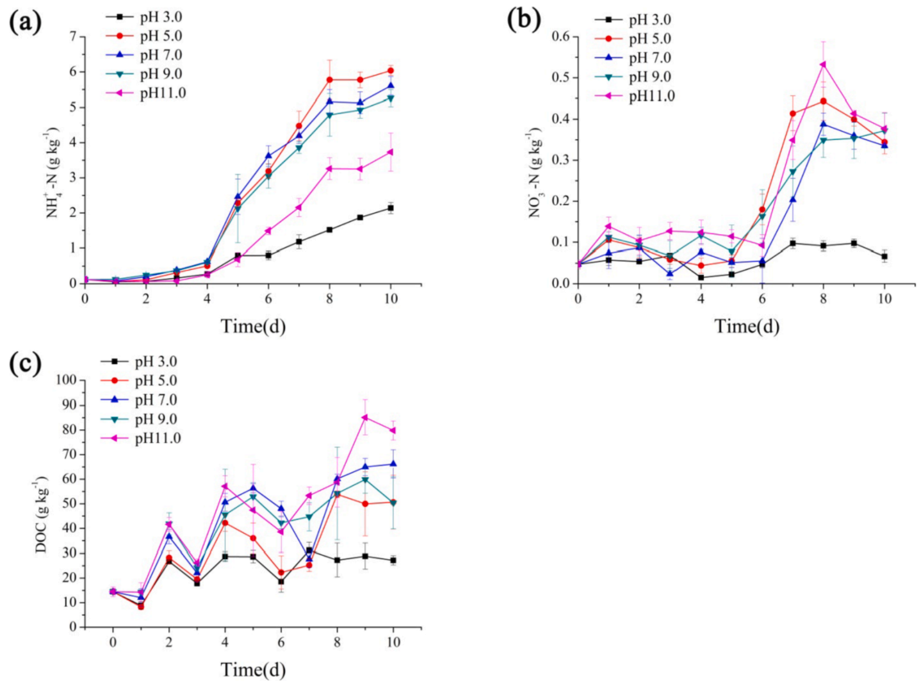

Fig. 2. Changes of NH+ 4-N (a), NO- 3-N (b) and DOC (c) during the bioconversion process of all treatments.

denitrification of NO- 3. Hence, high accumulation of NO- 3-N was observed in the late stage and the N_2O emission profile also supports this result (see below in this article).

During the whole experiment, a slow and fluctuating increasing trend of DOC concentration was observed (Fig. 2c), possibly because the organic C of raw material is decomposed into carbohydrates, organic acids and other DOC, then utilised by BSFL for conversion and reserve. The results indicated that the degradation rate of organic materials was higher than the utilisation rate by BSFL during the treatment, causing an overall increase in DOC content till the end of the bioconversion process in all runs, and suggesting that BSFL could accelerate the decomposition of organic matter.

3.3. Carbon dioxide emissions during black soldier fly larvae bioconversion process

CO_2 emissions from the biodegradation process of organic matter are usually not considered in the evaluation of global warming potential due to the biogenic origin of CO_2 (Sánchez et al., 2015). However, it is still important to quantify CO_2 emissions to better understand the C cycling in BSFL bio-treatment. CO_2 is the main gas produced during the treating process which could intuitively reflect the metabolic activities of BSFL and microorganisms (Wang et al., 2018). The CO_2 emission rate under all the treatments first increased, followed by a decreasing trend, and finally became relatively stable from the 6th day on (Fig. 3a), indicating the stabilisation of the substrate by BSFL treatment (Lv et al., 2018). The peaks of CO_2 emissions under pH 3.0, 5.0, 7.0, 9.0 and 11.0 treatments were 33.84 (1st day), 31.64 (1st day), 33.73 (2nd day), 26.56 (1st day) and 15.91 (2nd day) g kg^{-1} day^{-1}, respectively. Interestingly, the CO_2 emissions from the pH 11.0 treatment on the first day were very low, probably because most of the CO_2 formed carbonate under high pH.

BSFL and microbial activities are the main reason for the production of CO_2. The maximum cumulative CO_2 emission in this study was observed under pH 5.0 treatment (161.11 g kg^{-1}) while lower CO_2 emissions were recorded from pH 3.0 (88.28 g kg^{-1}) and 11.0 (88.15 g kg^{-1}) treatment (Fig. 3b). The cumulative CO_2 emissions in pH 5.0, 7.0, 9.0 and 11.0 treatments were significantly different, showing a gradually decreasing trend with increasing pH, which may be attributed to the promoted transformation of CO_2 to carbonate at higher pH of the substrate. It is noteworthy that the cumulative CO_2 emissions in pH 3.0 treatment were not in conformity with the above trend, possibly because high acidity was unfavourable for the activities of BSFL and microbes.

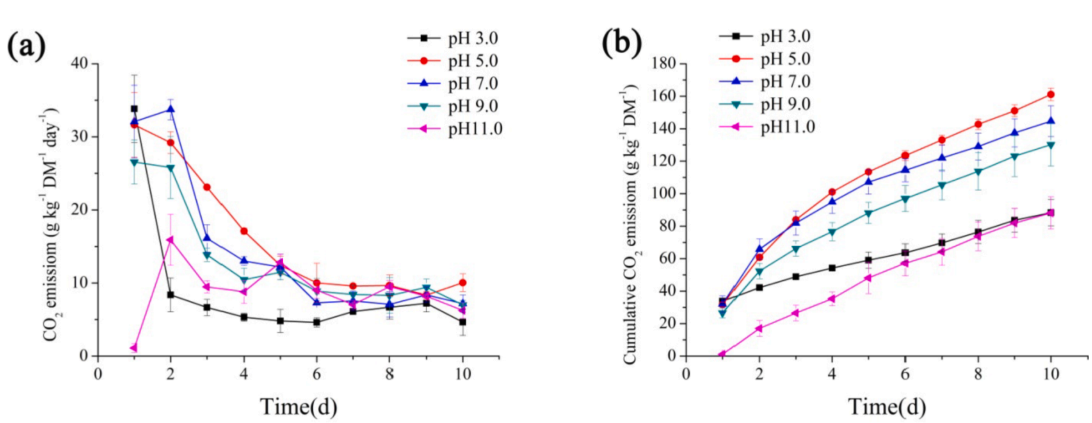

Fig. 3. Changes of emission (a) and cumulative emission (b) of CO_2 during BSFL bioconversion process.

3.4. Ammonia emissions during black soldier fly larvae bioconversion process

Although NH_3 is not considered as GHG, it is included in many environmental studies because it becomes essential in terms of agricultural value of the end-product and protection of ecosystems (Sánchez et al., 2015). Fig. 4a presents the results of the dynamic changes of NH_3 emissions under different treatments. Initially, NH_3 emissions were very low in all treatments, likely because of the low concentration of NH+ 4. After the 3rd day, NH_3 emissions in pH 7.0, 9.0 and 11.0 treatments sharply increased, in accordance with the changes in NH+ 4 concentrations (Fig. 2a). The maximum NH_3 emissions were 0.22, 0.34 and 0.45 g kg^{-1} day^{-1} for the pH 7.0, 9.0 and 11.0 treatments, respectively. The NH_3 emissions pattern obtained in this study was different from the case of the thermophilic composting process (Wang et al., 2018; Luo et al., 2014), where an initial emission peak is generally found in the biodegradation process, as the labile fraction of organic N source is transformed into inorganic N in a short period of time, such as NH+ 4. Furthermore, the NH_3 emission curve for pH 3.0 and 5.0 treatments was relatively stable, and the emissions remained at a relatively low level throughout the whole composting time. Interestingly, unlike in the pH 3.0 treatment, in the pH 5.0 treatment the NH+ 4 content was high (Fig. 2a), likely due to the presence of various organic acids that could react with NH+ 4 so preventing the free NH_3 production. A similar phenomenon was recently reported by Ermolaev et al. (2019), who found that almost no NH_3 emissions from BSF composting with a low pH (initial pH 4.42) were detected.

The cumulative emission trends of NH_3 were similar to the NH_3 emission rate (Fig. 4b). It is reported that relevant driving forces for NH_3 emissions were moisture, temperature, pH, NH+ 4 concentration and aeration (Nigussie et al., 2016). With the increase of pH, the cumulative emissions of NH_3 were 0.15, 0.29, 1.05, 1.68 and 1.55 g kg^{-1} for the treatments with pH from 3.0 to 11.0, respectively. Obviously, a high pH resulted in a shift of the NH+ 4↔NH_3 equilibrium to NH_3. On the other hand, low pH leads to slow degradation of organic N compounds by microorganisms, and the presence of BSFL could be another reason for the observed differences in NH_3 emissions. Compared with composting in other research (Table 2), the BSFL biowaste treatment showed more potential in mitigating NH_3 emissions. In the other researches listed in Table 2, it is reminded that composting is a thermophilic process at high temperature (>45 °C), which speeds up NH_3 volatilisation (Nigussie et al., 2016), while the BSFL biowaste treatment is a mesophilic process. Continuous turning of the substrate by BSFL and subsequent higher air circulation both keep the waste temperature relatively constant (about 30 °C), therefore partly reducing the NH_3 volatilisation. Chen et al. (2019) also indicate that the continuous movement of BSFL could lead to decreases in temperature in small-scale BSFL composting, and thus to the retention of N in the residues.

Table 2
NH_3 emissions from BSF treatment and composting.

Treatment	NH_3 (g/kg)	References
BSFL	0.15–1.68	Current study
Composting	~3.16[a]	Komilis and Ham, 2006
Composting	~2.37[a]	Yang et al. (2013)
Composting	~2.61[a]	Zhang et al. (2016)

[a] Cumulative emissions during the first 10 days of composting, dry weight basis. ~: approximately.

3.5. Methane and nitrous oxide emissions during black soldier fly larvae bioconversion process

Data illustrated by Fig. 5a and b presents the daily and cumulative CH_4 emissions during the whole treatment period. Overall, the CH_4 emission rate peaked within days 4–7 and then decreased for all treatments. Moreover, the CH_4 cumulative emission is 0.20, 0.78, 1.19, 2.62 and 1.34 mg kg^{-1} in pH 3.0, 5.0, 7.0, 9.0 and 11.0 treatments, respectively. Compared with the results from previous studies (Table 3), the CH_4 emissions in the BSFL treatment were much lower than those from conventional composting. The N_2O emission profiles are shown in Fig. 5c. They were mostly found on the first day except for pH 3.0 treatment, which might be attributed to feeding effects (Nigussie et al., 2016). The N_2O cumulative emissions are in trace amounts in all the treatments during the whole process (Fig. 5d). Furthermore, no statistically significant differences in CH_4 and N_2O cumulative emissions were observed among all the treatments ($P > 0.05$).

The CH_4 and N_2O emission patterns observed in this study were consistent with the recent findings of Mertenat et al. (2019). CH_4 and N_2O emissions are directly related to the presence of anaerobic conditions during composting. Denitrification, which is traditionally considered as the main source of N_2O, is an anoxic process carried out by denitrifiers (Sánchez et al., 2015), while the CH_4 production is attributed to methanogens that deoxidise CO_2/H_2 and acetic acid under anaerobic conditions (Wang et al., 2018). Hence, according to the above analysis, the low emissions of CH_4 and N_2O might be ascribed to two reasons. Firstly, BSFL improve air circulation in the FW through continuous turning of substrate, and reduce the abundance of methanogens and denitrifiers, therefore preventing the generation of CH_4 and N_2O (Lv et al., 2018). Secondly, Jeon et al. (2011) reported that the bacterial communities in the gut of BSFL have not been found to be associated with produced CH_4 and N_2O. In this study, it can be inferred that BSFL themselves hardly produce any CH_4 and N_2O.

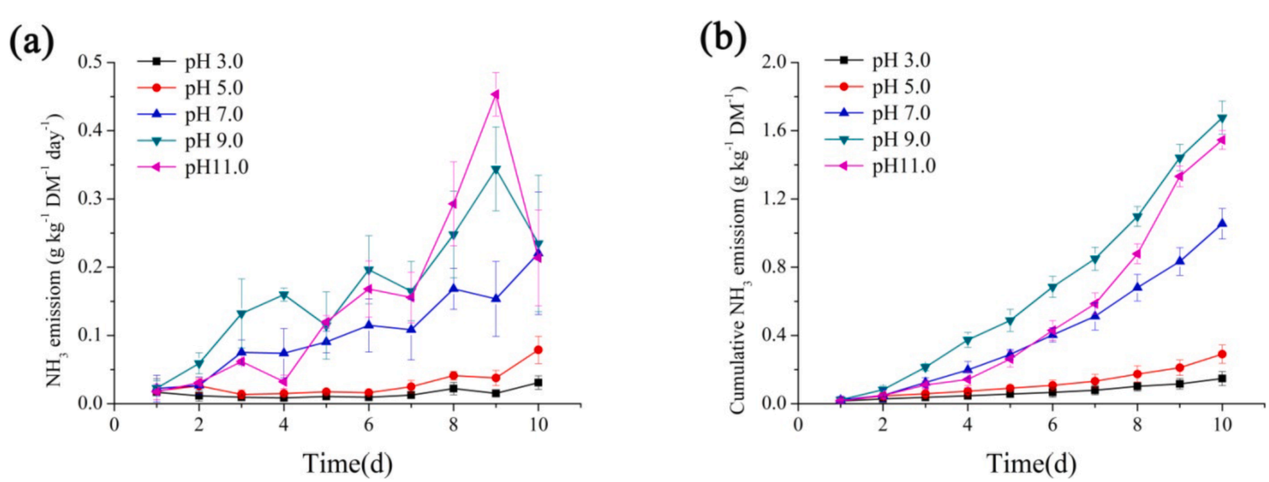

Fig. 4. Changes of emission (a) and cumulative emission (b) of NH_3 during BSFL bioconversion process.

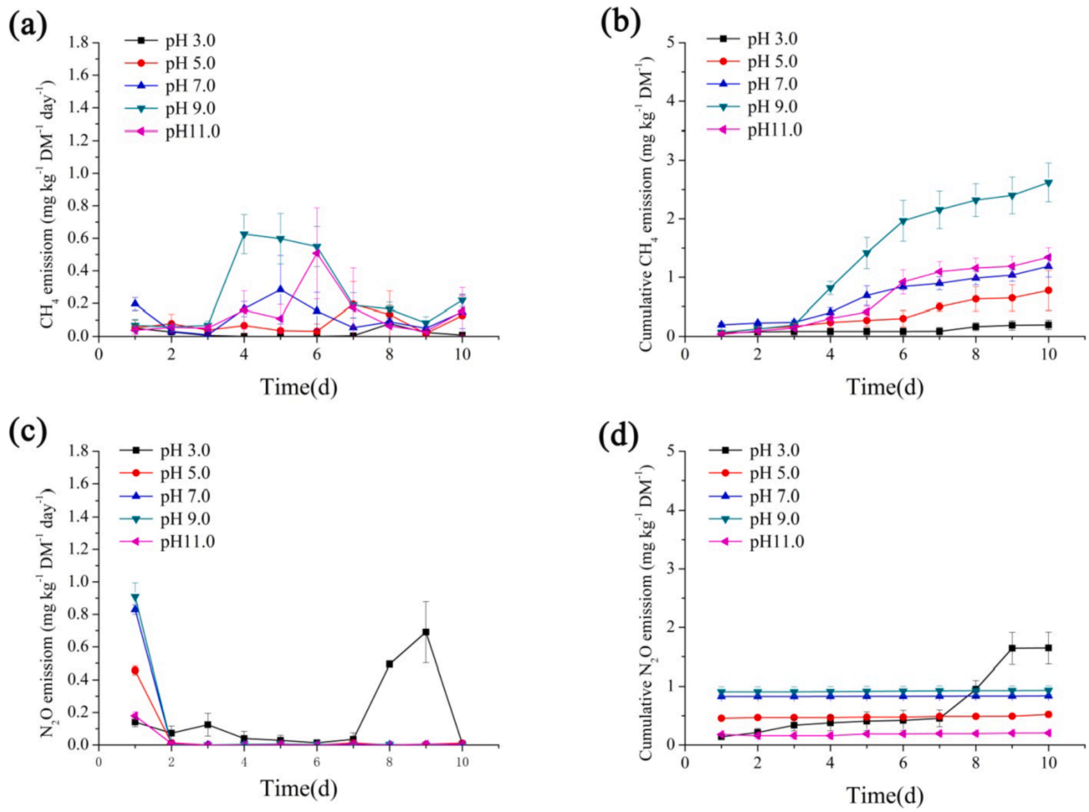

Fig. 5. Changes of CH_4 (a), cumulative CH_4 (b), N_2O (c) and cumulative N_2O (d) emissions during BSFL bioconversion process.

Table 3
Total GHG emissions from BSFL treatment and composting.

Treatment	CO_2 (g/kg)	CH_4 (mg/kg)	N_2O (mg/kg)	GHGs emissions (kg CO_2-eq t^{-1} DM)	References
BSFL, pH 3	88.28 ± 8.09	0.20 ± 0.08	1.65 ± 0.27	0.50 ± 0.07	Current study
BSFL, pH 5	161.11 ± 3.87	0.78 ± 0.34	0.52 ± 0.05	0.17 ± 0.04	Current study
BSFL, pH 7	144.61 ± 9.51	1.19 ± 0.18	0.84 ± 0.02	0.28 ± 0.11	Current study
BSFL, pH 9	130.18 ± 13.21	2.62 ± 0.33	0.93 ± 0.08	0.34 ± 0.14	Current study
BSFL, pH 11	88.15 ± 9.90	1.34 ± 0.16	0.20 ± 0.02	0.09 ± 0.03	Current study
Composting	–	~1500[a]	~1200[a]	~395.10[a]	Yang et al. (2019)
Composting	–	~790[a]	~124[a]	~56.70[a]	Yang et al. (2015)

GHG: greenhouse gas; DM: dry matter.
−: not reported; ~: approximately.
[a] Cumulative emissions during the first 10 days of composting, dry weight basis.

3.6. Greenhouse gas emissions and carbon and nitrogen balance

The present study evaluated the effectiveness of BSFL biowaste treatment in reducing GHG emissions using as variable the pH value. Data of GHG emissions are presented in Table 3. CO_2 is a significant GHG in BSFL biowaste treatment processes, but its contribution to the greenhouse effect should be excluded since this C has a biogenic origin (IPCC, 2007). Hence, only CH_4 and N_2O were taken into consideration when calculating the total GHG emissions. Taking the global warming potential of CO_2 as 1, that of CH_4 and N_2O was 25 and 298, respectively. The results were compared with GHG emissions in the first 10 days from open composting reported in published studies (Table 3). During the whole process, the total GHG emissions from the five treatments here scrutinised ranged from 0.09 to 0.50 kg CO_2-eq t^{-1} DM, i.e. much lower than those from aerobic composting. This should be of great concern since CH_4 and N_2O have great global warming potentials. Therefore, in these terms, the BSFL biowaste treatment should be strongly suggested as a preferred method to dispose FW.

Table 4 shows the data of C and N balances. The pH value plays a crucial role in the C and N bioconversion. The cumulative C loss through CO_2 emissions accounted for 8.01–12.98% of the initial TOC, respectively; while CH_4 for all treatments accounted for only <0.01% in TOC loss. For all treatments, the loss of total C ranged from 10.12 to 24.38% of the initial TOC. Perednia et al. (2017) observed a higher level (28.54%) of CO_2-C and CH_4-C loss when BSFL were used to treat rabbit manure. As a major pathway of the total loss of gaseous N, NH_3 emissions accounted for 0.51–4.31% of the initial TN. Although the NH_3 loss was enhanced at higher pH values, the degree of enhancement was relatively lower compared with the TN in the raw materials. Similarly to the CH_4 emissions, only <0.01% of the initial TN was emitted in the form of N_2O in all treatments. The TN loss for all treatments ranged from 2.12% to 29.91% of the initial TN in raw materials.

Furthermore, in absence of treatment, the C and N in the substrate would be emitted into the atmosphere by microbial decomposition so causing environmental pollution, while BSFL can recycle 1.95–13.41% and 5.40–18.93% of the C and N in the substrate into stable and readily harvestable biomass such as fat and protein. These data demonstrates that high pH value of the substrate effectively enhanced BSFL in recycling C and N. A potential explanation might be that increasing the initial pH of the substrate leads to a faster organic matter degradation, so that the available organic C and N in the materials can be quickly released and then converted into biomass of larvae at a higher degree. A previous study demonstrated that better buffering capacity (pH) of substrate promotes the utilisation by larvae of material difficult to be

Table 4
Carbon and nitrogen balance in BSFL bio-treatments.

Treatments	Carbon balance[a] (%)						Nitrogen balance[b] (%)					
	CO_2-C	CH_4-C	Other C loss	Total C loss	Larva-C	Residue-C	NH_3-N	N_2O-N	Other N loss	Total N loss	Larva-N	Residue-N
pH 3.0	8.02± 1.62	<0.01	2.10± 0.88	10.12± 2.15	1.95± 0.14	87.93 ± 4 .23	0.51± 0.21	<0.01	1.61± 0.24	2.12± 0.18	5.40± 1.23	92.48± 5.37
pH 5.0	12.98± 2.37	<0.01	10.31± 2.31	23.29± 4.38	7.89± 1.83	69.82± 3.22	0.85± 0.19	<0.01	2.63± 0.96	3.48± 0.64	15.72± 3.15	80.80± 5.26
pH 7.0	11.86± 0.78	<0.01	12.52± 1.39	24.38± 4.02	9.51± 2.22	66.11± 4.14	3.02± 0.89	<0.01	16.23± 3.28	19.25± 3.24	16.00± 2.01	64.75± 4.85
pH 9.0	10.87± 1.12	<0.01	8.64± 2.03	19.51± 3.87	9.28± 1.15	71.21± 2.36	4.31± 1.09	<0.01	25.60± 2.79	29.91± 3.56	15.90± 2.59	54.19± 4.16
pH 11.0	8.01± 0.89	<0.01	7.03± 0.76	15.04± 3.54	13.41± 2.77	71.55± 3.69	4.27± 1.30	<0.01	24.68± 3.85	28.95± 2.55	18.93± 1.87	52.12± 4.28

a, b Percentages of initial total organic carbon and total nitrogen of raw materials, respectively, dry weight basis.

decomposed (Rehman et al., 2017). Therefore, the BSFL bioconversion to some extent can reduce C and N loss, although this may not necessarily be a definite conclusion. In addition, the residue still contains 66.11–87.93% of C and 52.12–92.48% of N. These valuable nutrients can further generate bioenergy (Win et al., 2018) or used as bio-fertilisers (Rehman et al., 2017). Based on C and N mass balance, there might be some unaccounted C (2.10–12.52%) and N (1.61–25.60%) loss during the treatment process, possibly because the sampling frequency and testing items were inadequate for capturing all C and N, particularly from BSFL treatment where intensive decomposition occurs. However, the overall C and N recovery rates appear to be acceptable according to the reports of Chowdhury et al. (2014) and Nigussie et al. (2016).

Thus, based on the conversion efficiency of C and N from waste into BSFL biomass and on the GHG emission mitigation potential, increasing the initial pH of the substrate is recommended for the bio-conversion of FW by BSFL.

4. Conclusions

This study demonstrates that increasing the pH of the initial substrate effectively accelerates the BSFL growth and decreases CO_2 emissions, but simultaneously increases NH_3 emissions. The BSFL biotreatment of FW could reduce CH_4, N_2O and NH_3 emissions, when compared with traditional composting methods. BSFL can be harvested and preserved, providing a short-term means of C and N sequestration, rather than allowing them to be directly decomposed by microbes and released in the form of gases. Moreover, BSFL may affect the physicochemical characteristics of the substrate that control the gas-producing processes, and thus indirectly reduce NH_3 and GHG emissions. Various analyses indicate that pH 3.0 treatment has no application value in real practice, although it resulted in very low C and N loss. Overall, increasing the pH of the FW could be beneficial to the recycling of C and N from FW to BSFL, and keeps the environmental footprint low. Future research is needed to explore the influences of pH on microbial flora in BSFL bioconversion system.

Credit author statement

Wangcheng Pang: Designed experiments, Carried out experiments, Writing- Original draft preparation. Dejia Hou: Designed experiments, Carried out experiments, Writing-Reviewing and Editing. Jiangshan Chen: Carried out experiments, Analysed data. Elhosseny E. Nowar: Commentary and revision. Zongtian Li: Commentary and revision. Jeffery K. Tomberlin: Commentary and revision. Ziniu Yu: Financial support for the project leading to this study. Ronggui Hu: Financial support for the project leading to this study. Qing Li: Designed experiments, Management and coordination responsibility for the research activity planning and execution. Shucai Wang: Management and coordination responsibility for the research activity planning and execution.

Declaration of competing interest

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

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