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RESEARCH ARTICLE

Resistance of black soldier fly (Diptera: Stratiomyidae) larvae to combined heavy metals and potential application in municipal sewage sludge treatment

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Abstract Treating municipal sewage sludge (MSS) sustainably and economically in China remains a challenge because of risks associated with the heavy metals it contains. In this study, black solider fly larvae (BSFL) were used for MSS treatment. The resistance of larvae to combined heavy metals and their potential use in conversion of MSS were investigated. The results indicated that seven MSS samples contained large amounts of heavy metals, with the lead and nickel contents of several samples exceeding Chinese national discharge standards. BSFL were highly tolerant to an artificial diet spiked with combined heavy metals. Principal component analysis revealed that high concentrations of lead, nickel, boron, and mercury potentially interfered with larval weight gain, while zinc, copper, chromium, cadmium, and mercury slightly reduced larval survival. The addition of chicken manure and wheat bran as co-substrates improved the conversion process, which was influenced by the nature and amount of added co-substrate and especially the quantity of nitrogen added. With the amended substrate, the BSFL accumulated heavy metals into their bodies but not into extracted larval oil. The heavy metal content of the treatment residue was lower than that considered safe for organic-inorganic compound fertilizers standards in China and the harvested larvae could be used as a source of oil for industrial application.

Keywords Municipal sewage sludge · Black soldier fly · Combined heavy metals

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Introduction

The increase in the quantity of municipal sewage sludge (MSS) has posed significant environmental problems in China due to the widespread establishment of sewage treatment plants (Chen et al. 2008; Milinovic et al. 2014) and the complex chemical compounds and heavy metals present in the MSS. MSS management is important for the sustainable development of sewage disposal (Xiao et al. 2015). Until now, sanitary landfills have been the universal approach to the treatment of MSS in China. Many physical and biological technologies also have been developed that could produce biogas, provide energy, and prepare organic fertilizer through anaerobic digestion, co-pelletization, and composting (Ajeej et al. 2015; Liu et al. 2015; Tandukar and Pavlostathis 2015). However, these processes do not remove heavy metals (Hung et al. 2015; Shamuyarira and Gumbo 2014), thereby posing risks to underground water (via landfill), farmland (via fertilizer), and the atmosphere (via incineration) (Dede and Ozdemir 2016; Hsu et al. 2016; Peng et al. 2016).

Black soldier fly, *Hermetia illucens*, is an insect of potential value in waste disposal because of the low cost, short treatment time, and high efficiency of larval treatment (Diener et al. 2009; Lalander et al. 2014; Nakamura et al. 2016; Zhou et al. 2013). The black solider fly larvae (BSFL) feed voraciously on organic wastes and incorporate the nutrients into their bodies to produce extra insect protein and fat

(Čičková et al. 2015; Diener et al. 2011). Furthermore, the by-product of this process (i.e., biodiesel) can be obtained in high yield (Li et al. 2015; Zheng et al. 2012a, b), which is desirable for industrial applications.

Livestock manure, human feces, food waste, vegetable waste, compost leachate, and municipal organic waste can be converted by BSFL (Diener et al. 2011; Lalander et al. 2013; Parra Paz et al. 2015). Popa and Green (2012) used raw sewage effluent (obtained from the local water treatment plant) to feed BSFL and found that larvae had the potential to convert sewage, but little research has been conducted on the use of BSFL to convert MSS. Diener et al. (2015) examined the toxicity of cadmium, lead, and zinc to BSFL and found that none of the metals individually had a significant effect on the life cycle of BSFL, suggesting that they have considerable potential to treat heavy metal-containing waste. However, the effect of exposure to combined heavy metals on the growth of BSFL is unknown. In theory, compared with conventional microbiological and chemical treatments, the larval treatment has timesaving and low-cost advantages, and may reduce levels of heavy metals in treatment residues, lowering the risk of environmental contamination due to metal bioaccumulation in the larvae bodies (Diener et al. 2015). The metal-enriched larvae could then be incorporated into further industrial applications.

In view of the above, the objectives of this study were to (i) assess the growth of BSFL affected by heavy metals in MSS; (ii) analyze the effect of heavy metals and nutrient amendments on BSFL growth; and (iii) address the potential application of larval conversion to treat MSS.

Materials and methods

Source of BSFL and MSS

The BSFL were obtained from a colony maintained year-round in a greenhouse in Huazhong Agricultural University, Wuhan, China. The Wuhan colony was established from eggs collected at a poultry facility in November, 2008. The larvae were fed a standard colony diet (Li et al. 2011; Zheng et al. 2012b, 2013) for approximately 8 days and then used in the experiments (Sheppard et al. 2002; Zheng et al. 2012b).

MSS samples were collected from seven sewage treatment plants in Yucheng city in Shandong Province. Sludges A, B, E, F, and G were from plants serving soybean oil, saccharides, sugar alcohols, sweetened bean paste, and papermaking industries, respectively, while sludges C and D were from urban domestic sewage treatment plants.

Chemical analysis of MSS

Concentrations of zinc (Zn), copper (Cu), chromium (Cr), cadmium (Cd), lead (Pb), nickel (Ni), boron (B), and mercury (Hg) in MSS samples were determined by HNO_3–H_2O_2 digestion and inductively coupled plasma-optical emission spectroscopy (ICP-OES) analysis (Diener et al. 2015) using a microwave digester (MASXPRESS; CEM, USA) and an ICP-OES spectrometer (VISTA-MPX; Varian, USA).

The moisture content, total nitrogen (TN), total phosphorus (TP), total potassium (TK), and organic matter (OM) of MSS were assayed according to the standard method coded as CJ/T 221-2005 Standardization Administration of the People's Republic of China. Briefly, they referred to gravimetric method, Kjeldahl method, molybdenum-antimony spectrophotometry, flame photometry, and potassium dichromate method, respectively.

Experimental design

Two different experiments were established to assess the tolerance of BSFL to combined heavy metals and to address the potential application of larval conversion to treat MSS, as follows:

1. Effect of combined heavy metals on BSFL growth

Seven different artificial diets, S1–S7 (60% final moisture level) were prepared from bran and wheat shorts (1:1, *w/w*) and included heavy metals corresponding to those present in sludges A–G. Each diet (500 g) in an open barrel was inoculated with four hundred 8-day-old BSFL and covered with damp cotton gauze in the greenhouse. The room temperature was controlled at 25–30 °C throughout the entire process. When approximately 50% of the larvae had become prepupa, the experiment was stopped. A control treatment (S8) was conducted with the artificial diet but no heavy metals. The experiment was conducted in triplicate.

2. Improvement of the BSF process by inclusion of additional substrate

Based on the heavy metal contents of all of the sludge samples, sample C was selected for this experiment because it had the greatest total heavy metal content. Two kinds of co-substrates, namely, chicken manure and wheat bran, were mixed into sludge sample C in an attempt to enhance the conversion process by increasing the transfer of metals into the bodies of the BSFL. The chicken manure and wheat bran were collected from the Chaotuo Ecological Agriculture Co. Ltd. in Wuhan City, China. The mean concentrations of OM, TN, TP, and TK were 61.4%, 25.1 mg/g, 11.7 mg/g, and 9.8 mg/g for bran and 40.2%, 35.4 mg/g, 22.8 mg/g, and 7.1 mg/g for chicken manure, respectively. The four hundred 8-day-old BSFL were introduced into different 500-g mixtures of the various materials (Table 1), and the conversion

Table 1 Components of different mixture material groups

Groups ID	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
MSS[a]										
Weight[b]/g	500	375	250	125	0	400	300	200	100	0
Percentage	100	75	50	25	0	84	63	42	21	0
Chicken manure										
Weight/g	0	125	250	375	500	0	100	200	300	400
Percentage	0	25	50	75	100	0	21	42	63	84
Bran										
Weight/g	0	0	0	0	0	100	100	100	100	100
Percentage	0	0	0	0	0	16	16	16	16	16
BSFL/larvea	400	400	400	400	400	400	400	400	400	400

[a] The moisture contents of MSS, chicken manure, and bran were 80.1 ± 0.1, 74.4 ± 0.2, and 3.02 ± 0.1%, respectively

[b] The weight of all was wet weight

process was controlled as described above. All experiments were carried out in triplicate.

Sampling and analysis

After the conversion process, the larvae and the residue were collected and dried separately at 105 °C for 10 min followed by 60 °C for 2 days, and then weighted. The parameters for BSFL conversion were calculated according to Eqs. (1) and (2) (Diener et al. 2009; Parra Paz et al. 2015):

$$\mathrm{WRR} = (S - R)/S \times 100\%, \quad (1)$$

$$\mathrm{CR} = (Wl_{\mathrm{f}} - Wl_0)/S \times 100\%. \quad (2)$$

where WRR and CR represent waste reduction rate and conversion rate, respectively; S is the total quantity of substrate provided throughout the experiment; R is the residue after conversion (non-digested substrate + excretion products); Wl_{f} is the larval weight at the end of the process; and Wl_0 is the larval weight at the start of the process. All weights were on a dry basis.

For evaluating the growth of BSFL, parameters were selected and calculated as shown in Eqs. (3), (4), and (5):

$$\mathrm{LWI} = (Wl_{\mathrm{f}} - Wl_0), \quad (3)$$

$$\mathrm{SR} = Nl_{\mathrm{f}}/Nl_0 \times 100\%, \quad (4)$$

$$\mathrm{ER} = N_{\mathrm{f}}/N_{\mathrm{p}} \times 100\%. \quad (5)$$

where LWI, SR, and ER represent the larval weight increase, survival rate of larvae, and eclosion rate of pupae, respectively; Wl_{f} and Wl_0 are the same as in Eq. (2); Nl_{f} and Nl_0 are the final and original numbers of live larvae in the conversion process, respectively; and N_{f} and N_{p} are the numbers of flies and pupa in the black soldier fly eclosion process.

Analyses of variance (ANOVA) were applied for all the data. Principal component analysis (PCA) was used to analyze the effect of the combined heavy metals on BSFL growth. The predictive analytic software SPSS (version 17.0) was employed for the analyses.

Results and discussion

Elements in MSS

The concentrations of heavy metals and nutrient elements in the various sludge samples varied widely (Table 2). The nutrient elements ranged from 50.2 to 69.9% for OM, 12.7 to 34.1 mg/g for TN, 15.8 to 65.0 mg/g for TP, and 1.07 to 15.4 mg/g for TK. Their contents were similar to those of the bran and chicken manure used in this research. The pH value of sludge varied from 5.8 to 8.2. The content of volatile phenols varied from 0.02 to 0.89 mg/kg (dry weight).

The distribution of heavy metals in these samples was similar to that reported by Weng et al. (Weng et al. 2014) and Ščančar et al. (Ščančar et al. 2000). The content of zinc was higher than that of other metals, while contents of copper, chromium, cadmium, boron, and mercury were at low levels. Most metal concentrations were below China's discharge standards for municipal wastewater treatment plant (GB 18918-2002), but those of lead and nickel in sludges A, D, and F were in excess of the standards.

Among the seven kinds of sludge, the highest concentrations of copper, chromium, and mercury were from sludge C, cadmium from sludge B, and lead, nickel, and boron from sludge D. Thus, the heavy metal contamination of sludges C and D were more serious than those of the others. This contamination resulted from the fact that sewage treatment plants for sludges C and D served the whole city and their source of wastewater was more complex and harder to control than those of the others (Wang et al. 2005).

The hierarchical cluster analysis results for these seven samples, based on the data for heavy metal and nutrient content, are shown in Fig. 1. The shorter rescaled distances correlate to a closer relationship, and the short rescaled distances (less than 5) among sludges B, E, and F indicate that their chemical compositions were similar, as expected considering their similar sources (saccharides factory, sugar alcohols factory, and sweetened bean paste factory). Thus, five different clusters were obtained at a rescaled distance of 5, where sludges B, E, and F belong to one cluster and the other four to four additional clusters. With an increase in rescaled distance, the number of clusters decreased and sludges A, G, and C were successively combined with the cluster containing sludges B, E,

Table 2 Heavy metals and nutrient element in seven kinds of MSS

MSS	A S1[d]	B S2	C S3	D S4	E S5	F S6	G S7	China[f] (soil pH < 6.5)	China (soil pH ≥ 6.5)	Organic-inorganic compound fertilizer
Zn[a]	919.8 ± 7.6[e]	901.9 ± 10.2	1052.4 ± 9.3	609.6 ± 5.7	711.6 ± 5.2	743.3 ± 8.1	110.8 ± 3.3	2000	3000	NA
Cu	46.1 ± 1.7	139.7 ± 3.5	623.6 ± 12.2	57.6 ± 1.9	304.7 ± 6.8	53.2 ± 2.4	99.5 ± 8.0	800	1500	NA
Cr	53.4 ± 4.8	102.5 ± 4.9	396.1 ± 7.2	81.2 ± 2.5	67.7 ± 2.6	46.7 ± 2.5	10.1 ± 0.9	600	1000	500
Cd	ND	2.2 ± 0.1	1.76 ± 0.2	ND	ND	1.02 ± 0.1	ND	5	20	10
Pb	164.8 ± 7.8	15 ± 0.9	105.5 ± 4.5	416.6 ± 7.9	24.9 ± 1.1	132.2 ± 5.1	124.8 ± 6.1	300	1000	150
Ni	209.0 ± 9.8	26.3 ± 1.2	30.1 ± 1.9	260.7 ± 8.3	93.0 ± 3.2	146.8 ± 5.7	ND	100	200	NA
B	14.1 ± 1.1	ND	22.2 ± 1.4	54.0 ± 2.1	ND	10.3 ± 1.5	33.2 ± 1.8	150	150	NA
Hg	0.42 ± 0.05	1.26 ± 0.1	2.6 ± 0.2	2.58 ± 0.15	0.35 ± 0.03	0.19 ± 0.02	0.05 ± 0.01	5	15	5
OM[b]	69.9 ± 2.9	67.7 ± 2.4	50.2 ± 3.2	64.0 ± 3.1	64.4 ± 2.7	67.4 ± 3.9	63.2 ± 2.8	NA	NA	≥ 25
TN[c]	26.2 ± 1.1	27.1 ± 1.2	21.4 ± 1.1	34.1 ± 1.6	22.6 ± 1.2	28.4 ± 1.3	12.7 ± 0.8	NA	NA	$(N + P_2O_5 + K_2O) \geq 15.0$
TP	15.8 ± 1.2	45.9 ± 2.3	45.7 ± 2.4	65.0 ± 3.2	38.7 ± 1.9	46.1 ± 2.1	20.2 ± 1.7	NA	NA	

ND, not detected; NA, not applicable

[a] The unit of heavy metal concentration is milligrams per dry kilogram

[b] The unit of OM is percent dry weight

[c] The unit of TN, TP, and TK is milligrams per dry gram

[d] The seven different artificial diets, S1, S2 … S7, contain the corresponding heavy metals with seven kinds of MSS, A, B … G, respectively

[e] Results are expressed as the mean ± SD ($n = 3$)

[f] From "Discharge standards of pollutants for municipal wastewater treatment plant (GB 18918-2002)"

[g] From "Organic-inorganic compound fertilizers standards (GB 18877-2002)"

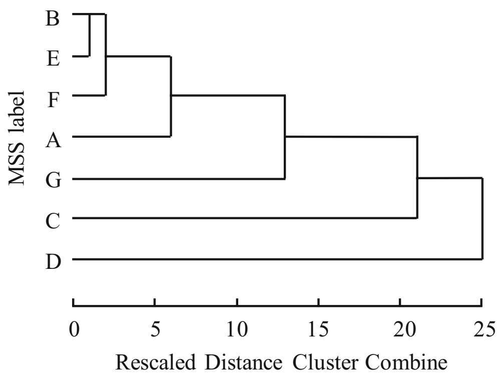

Fig. 1 Dendrogram of hierarchical cluster analysis for the seven kinds of MSS (Sludge A, B, C, D, E, F and G), using average linkage (between groups)

and F. At a rescaled distance of 20, three clusters were formed comprised of sludges B, E, F, A, and G; sludge C; and sludge D. That sludges C and D were from the city's domestic sewage while the others were from industrial sewage indicates that the heavy metal distribution in sludge was associated with the sewage source. In addition, sludges C and D were not combined into one cluster. This may be because of their complex sources. The sewage treatment plants of sludges C and D collected industrial effluents, domestic wastewater, and rainfall runoff from different areas of the city.

Conversion and BSFL growth affected by combined heavy metals

The effectiveness of conversion and BSFL weight increase reflect the degree of resistance of BSFL to combined heavy metals (Fig. 2). The conversion rate (9.27 ± 0.46%) of S4 was the lowest, while that of S5 (11.14 ± 0.08%) was the highest. The conversion rate (mean range from 9.92 to 11.14%) of S1, S2, S5, S6, and S7 did not differ significantly from that of control sample 8 (10.81 ± 0.36%), which contained no heavy metal amendment. Because the quantity of initial substrate in all of the samples did not differ, the low conversion rate was related to the low weight gain of the BSFL and the results indicate that the combined heavy metals of S3 and S4 hindered weight gain by the BSFL, while those of the others did not.

The waste reduction rate (58.43 ± 1.03%) of S3 was significantly lower than that of others (mean ranges from 63.27 to 64.13%). The heavy metals in S3 were the same as in sludge C, which was rich in zinc, copper, and mercury, suggesting that the low waste reduction rate was due to the presence of the heavy metals.

The mean survival rate of BSFL ranged from 90.0% to 99.7% and the mean eclosion rate ranged from 85.6 to 94.5% in all groups. The analysis of variance showed that

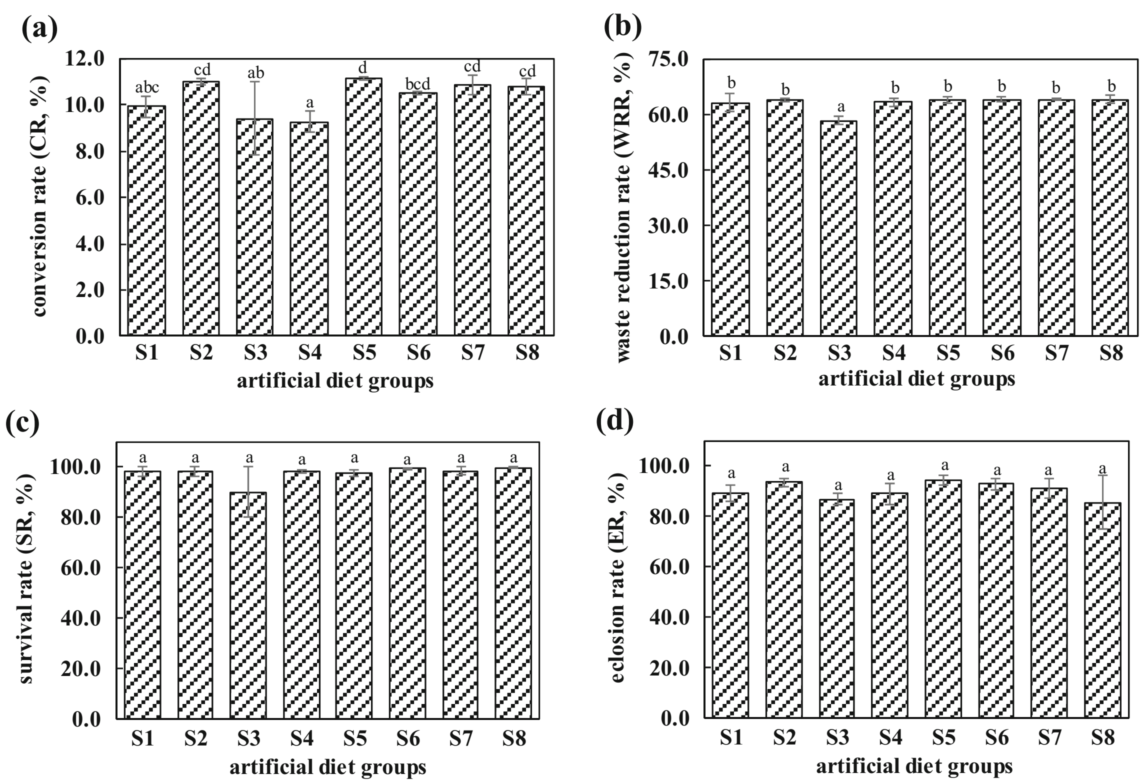

Fig. 2 The conversion effects (**a** conversion rate; **b** waste reduction rate) and growth of BSFL (**c** survival rate; **d** eclosion rate) in artificial diet groups that contained the different combined heavy metals (S1 to S7) or no heavy metals (S8, control). Different small letters (a) indicate significant difference ($n = 3$, $p < 0.05$)

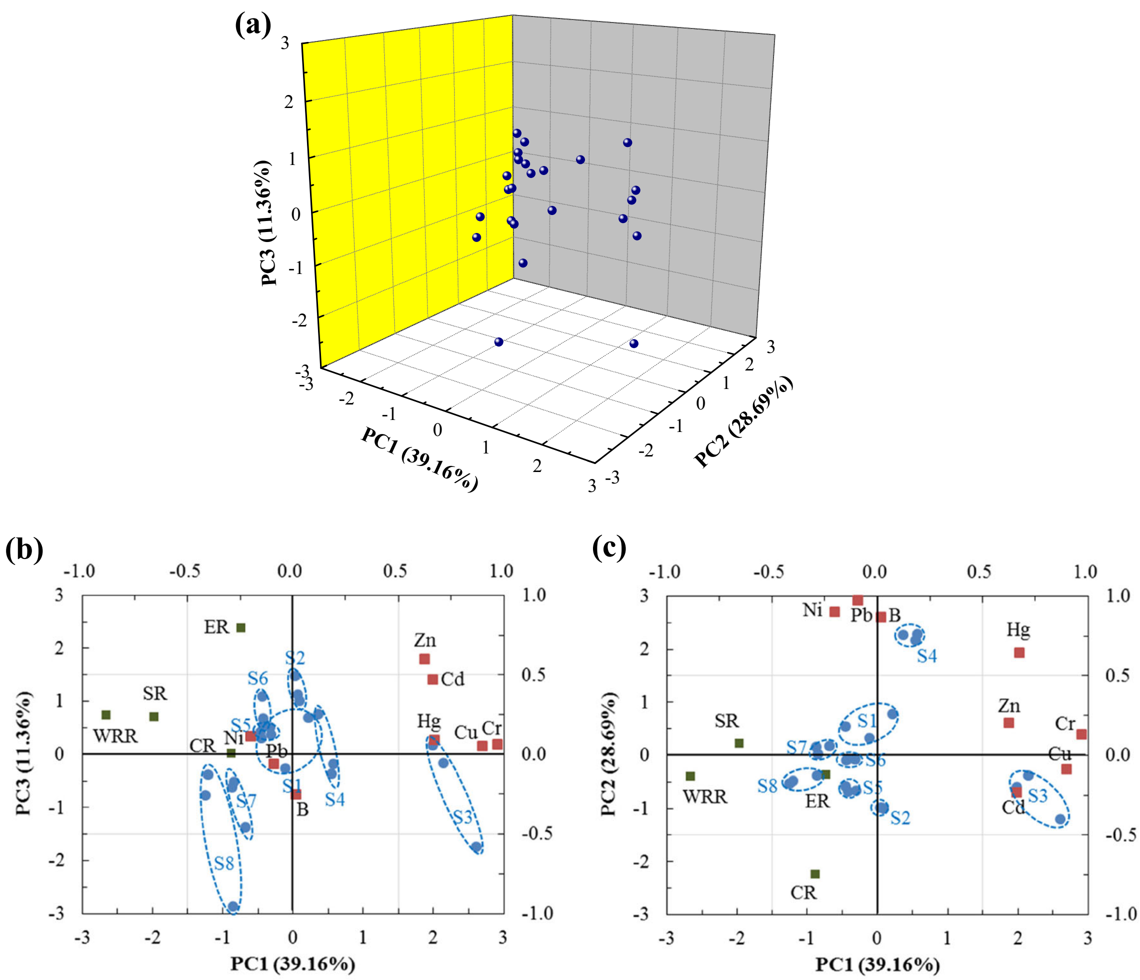

Fig. 3 PCA results based on 12 parameters (eight heavy metal concentration and four conversion parameters) of 24 samples. **a** 3D score plot of the eight different artificial diets that contained the different combined heavy metals ($n = 3$); **b**, **c** 2D biplots on PC1–PC2 and PC1–PC3 plane overlapping scores and loadings

the survival and eclosion rates of the heavy metal groups (S1 to S7) and the control group (S8) did not differ significantly, indicating that the combined heavy metals did not significantly affect the BSFL life cycle.

Three principal components, namely PC1, PC2, and PC3, were obtained totaling 79.21% (PC1, 39.16%; PC2, 28.69; and PC3, 11.36) in all parameters (Fig. 3a). PC1 mainly represented the parameters zinc, copper, chromium, cadmium, and mercury, survival rate and waste reduction rate (Fig. 3b); PC2 was comprised of the parameters lead, nickel, boron, mercury, and conversion rate (Fig. 3c); and PC3 represented the parameters zinc and eclosion rate (Fig. 3b). With sufficient nutrition (artificial diets) and a controlled environment, the survival rate of BSFL could be negatively affected mainly by zinc, copper, chromium, cadmium, and mercury, while weight gain could be hindered by elevated concentrations of lead, nickel, boron, and mercury. Borowska et al. (2004) reported that zinc in food offered to house fly larvae led to a 60% mortality in larvae and 70% in pupae. However, pupal eclosion was positively correlated with zinc as represented by PC3. The statistical results indicated that heavy metals could potentially have a slight negative effect on the growth of BSFL. The data indicate that the effect of combined heavy metals on the BSFL is clearly complex. Each metal could potentially affect the growth of BSFL either negatively or positively, but the combined heavy metals apparently did not affect them significantly.

Improved conversion by inclusion of additional substrate

The effectiveness of the conversion process was very poor in the MSS group (G1), and the conversion rate and larval weight increment were negative (Fig. 4). However, adding the bran and chicken manure obviously improved the conversion. Rates of conversion, waste reduction, and larvae weight increased with the increasing proportion of co-substrates, providing a readily available approach to converting MSS with BSFL.

Compared with the two positive controls G5 of chicken manure and G10 of chicken manure mixed with bran, mixture groups G4, G7, G8, and G9 yielded feasible and effective

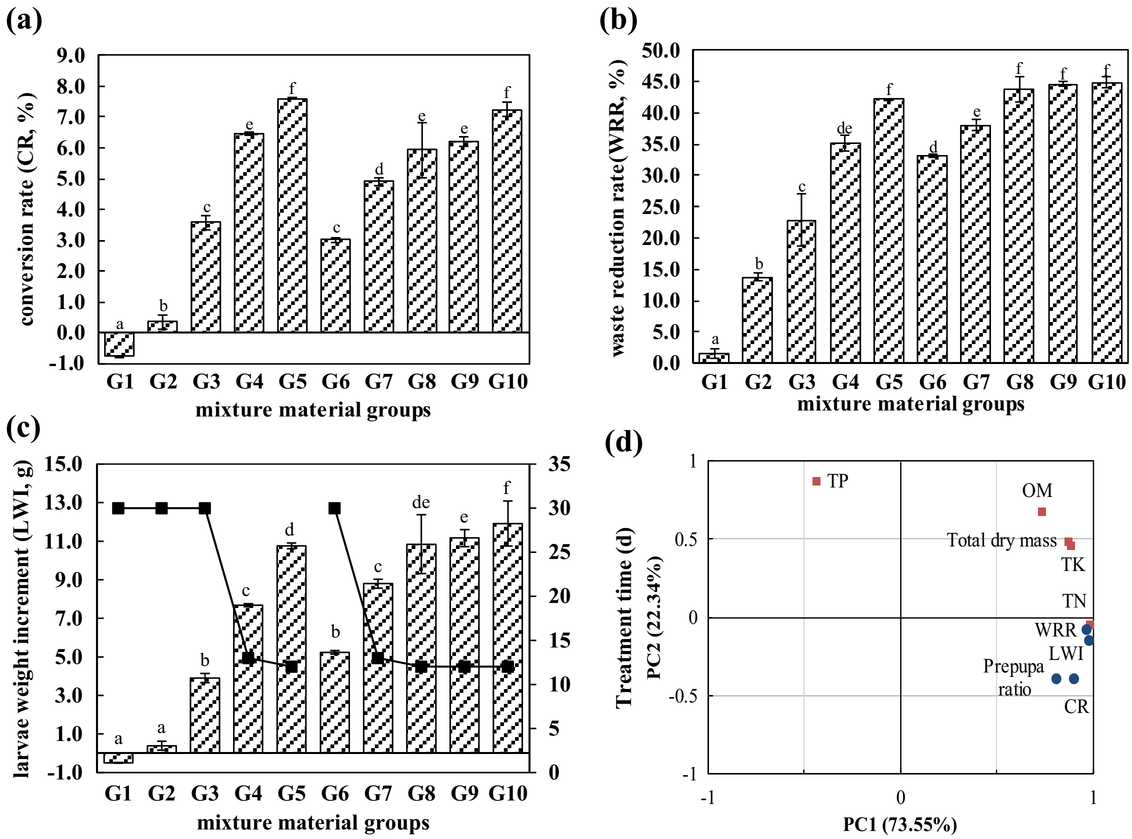

Fig. 4 Conversion parameters (**a** conversion rate; **b** waste reduction rate; **c** larvae weight increment and treatment time) in mixture material groups mixed with MSS, chicken manure, and bran of various ratios and PCA results based on five kinds of nutritive and four conversion parameters (**d**). Different small letters (a) indicate significant difference (n = 3, $p < 0.05$)

conversion. Conversion rates of G4, G7, G8, and G9 ranged from 5.0 to 7.6%, and waste reduction rates ranged from 38.0 to 44.9%. Diener et al. (2009) fed BSFL with chicken feed (UFA 625) in a series of feeding rates and obtained conversion rate values of 6.0 to 16.1% and waste reduction rates from 23.1 to 42.2%. Zhou et al. (Zhou et al. 2013) investigated the conversion of three black soldier fly strains on three livestock manures and found conversion rates of 5.37–6.55, 6.92–7.67, and 2.24–3.13% and waste reduction rates of 28.8–53.4, 31.8–61.7, and 34.6–57.8% for swine manure, chicken manure, and dairy manure, respectively. Diener et al. (Diener et al. 2011) used municipal organic waste (kitchen waste) for BSFL conversion, obtaining a conversion rate of 11.8% and a waste reduction rate of 68%. The conversion effectiveness rate of G7 was similar to that of swine manure, and those of G4, G8, and G9 were similar to those of chicken manure and chicken feed (UFA 625).

Larval weight increases corresponded to the growth of BSFL in these groups. Larvae weight increases of G4, G7, G8, and G9 ranged from 7.8 to 11.1 dry grams, and those of G8 and G9 were equal to or greater than that of the chicken manure control (G5). The mixture of MSS, bran, and chicken manure was better suited to the appetite of BSFL than that of MSS and chicken manure.

The treatment time of G1, G2, G3, and G6 was 30 days, while that of G4, G7, G8, and G9 was 12 or 13 days. Co-conversion of MSS with inclusion of chicken manure and bran shortened the larval treatment time of MSS. Compared with the process time of aerobic composting (45 days, Dzulkurnain et al. (2017) and 34 days, Budych-Gorzna et al. (2016)), the

Table 3 Pearson correlation analysis of five kinds of nutritive and four conversion parameters (n = 20)

	Total dry mass	OM	TN	TP	TK
WRR	*0.7832***	0.6461**	*0.9406***	− 0.4231	*0.7685***
CR	0.5648**	0.3857	*0.8446***	− 0.6658**	0.5444*
LWI	0.6996**	0.5377*	*0.9220***	− 0.5553*	0.6816**
Prepupa ratio	0.5715**	0.4219	*0.7891***	− 0.5315*	0.5547*

*$p < 0.05$; **$p < 0.01$; italic, |Pearson's correlation coefficient values| > 0.75

larval treatment time of G4, G7, G8, and G9 was much lower, a clear advantage over other biotechnology.

Principal component analysis (Fig. 4d) and Pearson's correlation analysis (Table 3) of the five kinds of nutritive and four conversion parameters was conducted to understand the nutrient requirements of BSFL. Two principal components, namely PC1 and PC2, represented 95.89% of all parameters (PC1, 73.55% and PC2, 22.34%). PC1 mainly represented the nutrient parameters of total dry mass, OM, TN, and TK of substrate, conversion parameters of waste reduction rate and conversion rate, and prepupa ratios. PC2 represented the nutrient parameters of TP and OM. TN concentration was highly significantly correlated with all four conversion parameters, indicating that the *N* content of the substrate was an important indicator for forecasting the effectiveness of larval conversion. In addition, it appeared that nitrogen source was also very important for BSFL growth and development, which was consistent with the effect of *N* on composting effectiveness (Gao et al. 2009; Ogunwande et al. 2008). Thus, the addition of appropriate co-substrates and sufficient nitrogen could be key factors for BSFL conversion.

Potential application of BSFL for conversion of MSS

Based on the results above, group G7 was selected to analyze the fate of heavy metals in the conversion process. Following larval conversion in group G7, the BSFL biologically enriched the heavy metal content in their bodies (Table S1), suggesting that at least part of heavy metals could be recovered by harvesting the larvae. It also is notable that the heavy metal concentration of extracted larval oil is very low (Table S1), less than 1% of that in their bodies. Thus, the harvested larvae could potentially be used to extract oil for industrial application. The residual oil-free larvae should not be used for agriculture, and especially not for feed, however, due to retention of most of the heavy metals in their bodies. After removal of the metal-enriched larvae, the residual heavy metal concentration in the treatment residue were lower than the safe level indicated by the organic-inorganic compound fertilizers standards in China, so the it could be used to produce organic-inorganic fertilizer, for example.

Conclusions

The MSS samples contained abundant nutrient elements for agricultural application, but the lead and nickel contents were higher than those acceptable to the Chinese national standard, thereby posing risks for utilization. The heavy metal distribution in sludge was associated with the sludge source, and the MSS from city sewage treatment plants was more complex and harder to convert than others. BSFL displayed strong tolerance to the combined heavy metals present in MSS samples. Their life and metamorphosis processes were not significantly affected by the combined heavy metals. However, the ability of BSFL to increase in weight was slightly hindered by heavy metals in MSS from city sewage treatment plants, which probably was due to the presence of lead, nickel, boron, and mercury. In addition, zinc was found to be potentially beneficial to eclosion of pupae, while zinc, copper, chromium, cadmium, and mercury were harmful to the survival of BSFL. However, BSFL showed significant potential for the conversion of organic solid waste containing heavy metals.

Adding co-substrates effectively improved the conversion of MSS by BSFL. Conversion rates, waste reduction rates, and larvae weight gain increased in proportion the increase in amounts of co-substrates. Furthermore, the nutrients influenced the conversion process, with carbohydrate, potassium, and nitrogen in particular promoting BSFL weight gain. The nitrogen source was very important for BSFL growth and waste conversion.

BSFL enriched the content of heavy metals in their bodies during the conversion process, but the heavy metal content of extracted larval oil was very low, suggesting that larval treatment could provide for recovery of a significant fraction of the heavy metals by harvesting larvae. After conversion, the heavy metal concentration in the treatment residue was much lower than that considered safe according to the organic-inorganic compound fertilizers standards in China, and the harvested larvae could potentially be used to extract oil for industrial use. This conversion process is therefore applicable to the use of BSFL to treat MMS for a variety of applications.

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Compliance with ethical standards

Ethical statement The work has not been published previously and is not under consideration for publication elsewhere.

Competing interests The authors declare that they have no competing interest.

References

Ajeej A, Thanikal JV, Narayanan CM, Senthil Kumar R (2015) An overview of bio augmentation of methane by anaerobic co-digestion of municipal sludge along with microalgae and waste paper. Renew Sust Energ Rev 50:270–276

Borowska J, Sulima B, Nilińska M, Pyza E (2004) Heavy metal accumulation and its effects on development, survival and immunocompetent cells of the housefly Musca domestica from closed laboratory populations as model organism. Fresenius Environ Bull 13:1402–1409

Budych-Gorzna M, Smoczynski M, Oleskowicz-Popiel P (2016) Enhancement of biogas production at the municipal wastewater treatment plant by co-digestion with poultry industry waste. Appl Energ 161:387–394

Chen M, Li X-m, Yang Q, Zeng G-m, Zhang Y, Liao D-x, Liu J-j, Hu J-m, Guo L (2008) Total concentrations and speciation of heavy metals in municipal sludge from Changsha, Zhuzhou and Xiangtan in middle-south region of China. J Hazard Mater 160:324–329

Čičková H, Newton GL, Lacy RC, Kozánek M (2015) The use of fly larvae for organic waste treatment. Waste Manag 35:68–80

Dede G, Ozdemir S (2016) Effects of elemental sulphur on heavy metal uptake by plants growing on municipal sewage sludge. J Environ Manag 166:103–108

Diener S, Zurbrügg C, Tocknera K (2009) Conversion of organic material by black soldier fly larvae—establishing optimal feeding rates. Waste Manag Res 27:603–610

Diener S, Studt Solano NM, Roa Gutiérrez F, Zurbrügg C, Tockner K (2011) Biological treatment of municipal organic waste using black soldier fly larvae. Waste Biomass Valori 2:357–363

Diener S, Zurbrügg C, Tockner K (2015) Bioaccumulation of heavy metals in the black soldier fly, Hermetia illucens and effects on its life cycle. J Insects Food Feed 1:261–270

Dzulkurnain Z, Hassan MA, Zakaria MR, Wahab PEM, Hasan MY, Shirai Y (2017) Co-composting of municipal sewage sludge and landscaping waste: a pilot scale study. Waste Biomass Valori 8:695–705

Gao M, Liang F, Yu A, Li B, Yang L (2009) Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios. Chemosphere 78:614–619

Hsu L-C, Huang C-Y, Chuang Y-H, Chen H-W, Chan Y-T, Teah HY, Chen T-Y, Chang C-F, Liu Y-T, Tzou Y-M (2016) Accumulation of heavy metals and trace elements in fluvial sediments received effluents from traditional and semiconductor industries. Sci Rep-UK 6:34250

Hung CV, Cam BD, Mai PTN, Dzung BQ (2015) Heavy metals and polycyclic aromatic hydrocarbons in municipal sewage sludge from a river in highly urbanized metropolitan area in Hanoi, Vietnam: levels, accumulation pattern and assessment of land application. Environ Geochem Health 37:133–146

Lalander C, Diener S, Magri ME, Zurbrügg C, Lindström A, Vinnerås B (2013) Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens)—from a hygiene aspect. Sci Total Environ 458–460:312–318

Lalander CH, Fidjeland J, Diener S, Eriksson S, Vinnerås B (2014) High waste-to-biomass conversion and efficient salmonella spp. reduction using black soldier fly for waste recycling. Agron Sustain Dev 35:261–271

Li Q, Zheng L, Qiu N, Cai H, Tomberlin JK, Yu Z (2011) Bioconversion of dairy manure by black soldier fly (Diptera: Stratiomyidae) for biodiesel and sugar production. Waste Manag 31:1316–1320

Li W, Li Q, Zheng L, Wang Y, Zhang J, Yu Z, Zhang Y (2015) Potential biodiesel and biogas production from corncob by anaerobic fermentation and black soldier fly. Bioresour Technol 194:276–282

Liu J, Chen J, Huang L (2015) Heavy metal removal from MSS fly ash by thermal and chlorination treatments. Sci Rep-UK 5:17270

Milinovic J, Vidal M, Lacorte S, Rigol A (2014) Leaching of heavy metals and alkylphenolic compounds from fresh and dried sewage sludge. Environ Sci Pollut R 21:2009–2017

Nakamura S, Ichiki TR, Shimoda M, Morioka S (2016) Small-scale rearing of the black soldier fly, Hermetia illucens (Diptera: Stratiomyidae), in the laboratory: low-cost and year-round rearing. Appl Entomol Zool 51:161–166

Ogunwande GA, Osunade JA, Adekalu KO, Ogunjimi LA (2008) Nitrogen loss in chicken litter compost as affected by carbon to nitrogen ratio and turning frequency. Bioresour Technol 99:7495–7503

Parra Paz AS, Carrejo NS, Gómez Rodríguez CH (2015) Effects of larval density and feeding rates on the bioconversion of vegetable waste using black soldier fly larvae Hermetia illucens (L.), (Diptera: Stratiomyidae). Waste Biomass Valori 6:1059–1065

Peng C, Cai Y, Wang T, Xiao R, Chen W (2016) Regional probabilistic risk assessment of heavy metals in different environmental media and land uses: an urbanization-affected drinking water supply area. Sci Rep-UK 6:37084

Popa R, Green TR (2012) Using black soldier fly larvae for processing organic leachates. J Econ Entomol 105:374–378

Ščančar J, Milačič R, Stražar M, Burica O (2000) Total metal concentrations and partitioning of Cd, Cr, Cu, Fe, Ni and Zn in sewage sludge. Sci Total Environ 250:9–19

Shamuyarira KK, Gumbo JR (2014) Assessment of heavy metals in municipal sewage sludge: a case study of Limpopo province, South Africa. Int J Environ Res Public Health 11:2569–2579

Sheppard DC, Tomberlin JK, Joyce JA, Kiser BC, Sumner SM (2002) Rearing methods for the black soldier fly (Diptera: Stratiomyidae). J Med Entomol 39:695–698

Tandukar M, Pavlostathis SG (2015) Co-digestion of municipal sludge and external organic wastes for enhanced biogas production under realistic plant constraints. Water Res 87:432–445

Wang C, Hu X, Chen M-L, Y-H W (2005) Total concentrations and fractions of Cd, Cr, Pb, Cu, Ni and Zn in sewage sludge from municipal and industrial wastewater treatment plants. J Hazard Mater 119:245–249

Weng H-X, Ma X-W, F-X F, Zhang J-J, Liu Z, Tian L-X, Liu C (2014) Transformation of heavy metal speciation during sludge drying: mechanistic insights. J Hazard Mater 265:96–103

Xiao Z, Yuan X, Jiang L, Chen X, Li H, Zeng G, Leng L, Wang H, Huang H (2015) Energy recovery and secondary pollutant emission from the combustion of co-pelletized fuel from municipal sewage sludge and wood sawdust. Energy 91:441–450

Zheng L, Hou Y, Li W, Yang S, Li Q, Yu Z (2012a) Biodiesel production from rice straw and restaurant waste employing black soldier fly assisted by microbes. Energy 47:225–229

Zheng L, Li Q, Zhang J, Yu Z (2012b) Double the biodiesel yield: rearing black soldier fly larvae, Hermetia illucens, on solid residual fraction of restaurant waste after grease extraction for biodiesel production. Renew Energ 41:75–79

Zheng L, Crippen TL, Holmes L, Singh B, Pimsler ML, Benbow ME, Tarone AM, Dowd S, Yu Z, Vanlaerhoven SL, Wood TK, Tomberlin JK (2013) Bacteria mediate oviposition by the black soldier fly, *Hermetia illucens* (L.), (Diptera: Stratiomyidae). Sci Rep-UK 3:2563

Zhou F, Tomberlin JK, Zheng L, Yu Z, Zhang J (2013) Developmental and waste reduction plasticity of three black soldier fly strains (Diptera: Stratiomyidae) raised on different livestock manures. J Med Entomol 50:1224–1230