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Research Article

Characteristics and Fertilizer Effects of Soil-Like Materials from Landfill Mining

Landfills stock massive amounts of minerals and materials, where soil-like material is the primary component of stored waste in old landfills. A typical old landfill (Yingchun landfill) in China was taken as a study case. The stored wastes were sampled from different depths of the landfill, and then the soil-like materials were screened for further analysis. Physicochemical characteristics and the fertilizer quality of the soil-like materials were analyzed and the fertilizer effects were studied by cultivating *Impatiens balsamina* L. with different mixed ratios of soil-like materials and natural soils. According to the results, soil-like materials accounted for 75.02% of the total stored wastes and were in an advanced state of decomposition. Soil-like materials displayed a cation exchange capacity of $84.53 \text{ cmol}(+) \text{ kg}^{-1}$, pH 8.14, and an electrical conductivity of $1190.55 \mu\text{S cm}^{-1}$, and were also characterized by high levels of organic carbon and nutrient contents compared to natural soils. The total organic carbon, total nitrogen, total phosphorus, and total potassium of soil-like materials were 9.06, 0.16, 0.21, and 1.48%, respectively. Most of the heavy metal content was relatively lower than the law limits in China. However, As and Zn may have an environmental contamination risk. It could be shown that soil-like materials could significantly promote growing and flowering of *I. balsamina* L., and were proved to be a valuable bio-resource with utility as soil amendment, cultivating substrate, and raw materials for producing organic-inorganic compound fertilizers.

Keywords: Bio-fertilizer; Heavy metals; Landfill; Nutrients; Organic matter

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1 Introduction

Humans derive a massive amount of minerals and materials from nature for building infrastructures and producing consumer goods, but dispose their municipal solid waste to the landfills and formed urban stocks [1]. Statistics showed that about three billion tons of municipal solid wastes were disposed in landfills in the recent 30 years in China [2]. Many old landfills in China are now surrounded by urban built-up areas due to the rapid urbanization; some landfills are even at the center of the new developing urban areas [3]. Old landfills not only stocked amounts of waste materials, but also posed significant environmental impacts on the nearby human settlements, in the form of odor emission, groundwater contamination, and landscape fragment [4, 5]. Landfill mining, which focuses on both municipal waste management and material recycling, was put forward under the concept of sustainable material management and had been adopted as a feasible approach for remediating old landfills. Landfill mining has potentials for the recovery of

recyclable materials as bio-fertilizers, metals and glasses, and also for regaining the landfill spaces. [3]. Bockreis and Knapp summarized that there were about 60 reported landfill mining projects in the recent 30 years all over the world [6]. The Chinese National Twelfth Five-Year-Plan of Municipal Solid Waste Treatment and Management indicated a budget of 21.1 billion RMB (3.5 billion USD) for ecological remediating 1882 old landfills in China from 2011 to 2015 [7]. In Europe are more than 150 000 of old landfills, which need to be remediated [8].

Soil-like material excavated and screened from old landfills is the primary component and the main product obtained from landfill mining, and the possibility of recycling soil-like materials is one of the key issues for assessing the economic feasibility of landfill mining projects. According to previous researches, soil-like materials comprised decomposed garbage, soil, sand, and other fine fractions, and accounted for 50–60% of total stored wastes, while combustible fraction accounted for 20–30%. In addition, inorganic materials such as metal, concrete, stone, and glass accounted for 10% [9–13]. The composition of stored wastes in old landfills differed from dumped materials and storage years. The stored waste may contain more soil-like materials due to the longer time period of biodegradation, usually more than 6 years [14]. Soil-like material was ordinary recycled as a bio-fertilizer that could supply nutrients and minerals to plants, e.g., the first reported landfill mining project in Israel in 1953 was aiming at obtaining soil-like materials as fertilizers to orchards [15]. Although the

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Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; MSW, municipal solid waste; TK, total potassium; TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus

composition of stored waste and the characteristics of soil-like materials were discussed in some previous researches, the fertilizer effects of soil-like materials obtained from landfill mining was rarely reported.

Soil-like material is a kind of loose material that comprised mineral particles, organic matters, moisture, air, and micro-organisms, and holds capacity of fertilizer effects for growing plants, which resembles natural black soils [11]. Nevertheless, soil-like material was highly disturbed and was artificial rebuilt, it was chemical and biological transformed from garbage, dirt, natural soil, cover soil, and other fine particles, and was mixed, co-transported, and co-disposed with other components of municipal solid waste and possibly contaminated by harmful substances [16, 17]. Researches on characteristics, distribution, and fertilizer effects of soil-like materials could bring new scientific evidence of human disturbed garbage–soil systems and could also give useful parameters for the practice of landfill mining and its ecological remediation. A representative old landfill of China was taken as a study case. Stored wastes and soil-like materials were sampled and the physicochemical properties, organics, nutrients, heavy metals, and the fertilizer effects of the soil-like materials were studied.

2 Materials and methods

2.1 Description of the site

The Yingchun landfill, which is located in Jingmen, Hubei Province, central China, was taken as a study case. The mean annual temperature is 16.1°C and the precipitation is 949.4 mm, with a maximum daily rainfall record of 233.7 mm. The Yingchun landfill was constructed in 1989 and closed in 2004. It covered an area of 28 acres and was used to dispose municipal solid waste from Jingmen City. Municipal solid waste disposed in this landfill was generated from urban communities and commercial places. Industrial waste and hazardous waste were not allowed to dump in this landfill. Jingmen City did not establish a household source separation system, but the Yingchun landfill was opened to rubbish collectors to pick up the recyclables during its operation. The annual amount of disposed municipal solid waste increased from 36 500 tons in 1989 to 154 800 tons in 2004. The total amount of disposed municipal solid waste was 1 470 000 tons, and the total stored solid waste has been estimated to be around 501 000 tons (551 000 m³). Yingchun landfill was built up on clay (without liner) and a drainage system was also built for leachate collecting. Currently, this site produces approximately 80 m³ leachate per day, accompanied by uncontrolled emissions of landfill gases, and the whole landfill was covered by 50 cm local soils after its closure.

2.2 Sampling methods

Nine sampling locations were determined following the grid sampling method (100 m × 100 m), and a drilling machine (with a Ø12 cm sampling head) was used for sampling stored wastes in the Yingchun landfill, and sampling was ongoing from June 18–22, 2012. Firstly, about 50 cm covering soils were removed which was used for landfill closure, and sampling was started when the stored wastes (black materials) were detected. The stored wastes were then sampled for every 6 m, and sampling was stopped when the bottom clay (yellow or grey) was detected (see Fig. 1). The number of samples in different layers and sampling locations in the Yingchun landfill is

shown in Table 1. The number of the samples in each sampling location differed (maximum four samples in one sampling location (#1, #3), minimum one sample in each sampling locations #8 and #9), because the Yingchun landfill was constructed in a small valley. The landform of the original site was low in the north and high in the south, and the thickness of landfill layers was different for each sampling location. In total, 22 samples were collected from different landfill layers: the first layer (0–6 m, nine samples), the second layer (6–12 m, seven samples), the third layer (12–18 m, four samples), and the fourth layer (18–24 m, two samples), and each sample weighed around 50 kg. According to the historical data of the landfill, the first to the fourth layer of the solid waste were generated from wastes disposed in the years of 2001–2004, 1997–2000, 1993–1996, and 1989–1992, respectively.

Each sample of stored wastes was firstly fully mixed, then divided into samples of about 5 kg on a plastic cloth to reduce the weight, and separated through a Ø10 mm screen. The upper-sized fractions were manually sorted according to the categories of plastic waste, stone, wood and bamboo, textile, glass, metal, paper, and other waste (not identifiable). The under-sized fraction, black biomass, was mentioned as the studied soil-like materials (impurities were manually sorted out). The average composition (*i.e.*, soil-like material, plastic waste, stones, wood and bamboo, textile, glass, metal, paper, and other wastes) of stored wastes was weighed and analyzed, and the soil-like materials (around 1–2 kg for each sample) were sent to the laboratory for further analysis.

2.3 Analysis techniques

200 g soil-like materials of each sample were dried in an oven at a constant temperature of 75°C for 24 ± 1 h to test the moisture content. Other samples of soil-like materials were air dried on a shady site. Samples were grinded and passed through a Ø2 mm screen, and then mixed and stored for further analyzing of cation exchange capacity (CEC), electrical conductivity (EC), total organic carbon (TOC), nutrients and heavy metals, and each measured in triplicate. CEC was measured following the chloride-ammonium acetate exchange method. EC was measured with a conductivity analyzer (Model TP120, Shidaixinwei, China) following method ISO 11265–1994. For analyzing TOC, total carbon (TC) and inorganic carbon (IC) were tested separately by a total organic carbon analyzer (Shimadzu TOC-V_{CPH}, Shimadzu, Japan), and then TOC was calculated (TOC = TC – IC). The concentrations of total nitrogen (TN) in the soil-like material samples were determined using an element analyzer, Model Vario EL III. To measure the total phosphorus (TP) concentration, 0.2 g of litter samples were digested in 10 mL of triacid mixture (nitric, perchloric, and sulfuric acids; 5:1:1), and then cooled. The concentrations of phosphorus were determined colorimetrically in the digested samples using the ammonium molybdate method [18]. Potassium was extracted with ammonium lactate and hydrochloric acid according to the methods reported by [19]. Heavy metals such as Cu, Zn, Pb, Cd and Cr were measured using the hot plate digestion with nitric acid following method 3050B [20]. Samples with high metal concentrations were diluted to fit within the linear region of the calibration curve, and then measured with inductively coupled plasma MS (ICP-MS), NexION 300, PerkinElmer, U.S., following method 6010B [20]. The As concentrations were analyzed using a Perkin-Elmer 5100 (PerkinElmer, U.S.) graphite furnace atomic absorption spectrometer (GFAA), following method 7060 A [20]. The

Figure 1. Method for sampling stored solid wastes and soil-like materials in the old landfill.

Hg concentrations were measured using the cold-vapor atomic absorption technique, following method 7471 of SW-846 [20].

2.4 Experiment of testing fertilizer effects

Impatiens balsamina L. was selected as the experimental plant for testing fertilizer effects of soil-like materials because it is a normal species of ornamental plants in Asia, and is widely planted in gardens and green strips in China. Moreover, it is a typical therophyte herbaceous, and the growing and flowering processes can be possibly observed during the experimental period. *Impatiens balsamina* L. was transplanted into pots after seed cultivating and the experiments were started when the extension degree of *I. balsamina* L. was about 1.5 cm. *I. balsamina* L. was cultivated in soils under different mixing ratios of soil-like materials and natural soils (C_0 : 0%, C_1 : 25%, C_2 : 75%, C_3 : 100%). The chemical characters of natural soil (brown soil) were tested: 0.124% TN, 0.001%

TP, 0.015% TK, and pH 6.80. The experimental design was arranged with four treatments and three replications. *I. balsamina* L. was then grown in the greenhouse with a constant temperature of around 25°C and a humidity of 80%, and the experiment was conducted from April 19 to November 12, 2013 and lasted for 207 days (after withering). The dry weight biomass (roots, stems, leaves) and total flower numbers were measured to analyze the fertilizer effects of the soil-like materials.

2.5 Statistical analysis

Statistical analyses were performed using SPSS version 16.0 for Windows. One-way analysis of variance (ANOVA), followed by least significant difference and Duncan test, was used to analyze CEC, EC, TOC, TN, TP, TK, Cu, Zn, Pb, Cd, Cr, As, Hg, the dry weight biomass (roots, stems, leaves), and total flower numbers. The significant difference was considered at $p < 0.05$.

Table 1. Sample numbers of soil-like materials in different layers and sampling locations in the Yingchun landfill, China

Landfill layer	Depth (m)	Disposal year	Mean storage age	Number of sample	Sampling location
1	0–6	2001–2004	10	9	#1, #2, #3, #4, #5, #6, #7, #8, #9
2	6–12	1997–2000	14	7	#1, #2, #3, #4, #5, #6, #7
3	12–18	1993–1996	18	4	#1, #3, #5, #6
4	18–24	1989–1992	22	2	#1, #3

Figure 2. Composition of stored solid waste in different layers in the Yingchun landfill, China (wet weight).

3 Results and discussion

3.1 Composition of the stored waste

The average composition of the stored solid waste in the Yingchun landfill was mainly soil-like materials ($75.02 \pm 6.83\%$), followed by plastic ($10.62 \pm 5.12\%$), and then stone ($8.26 \pm 4.12\%$), the proportions of wood and bamboo, textile, glass, metal, and paper were 2.43 ± 1.50 , 1.49 ± 1.31 , 0.64 ± 0.40 , 0.41 ± 0.44 , and $0.15 \pm 0.35\%$, respectively. Other not identifiable waste accounted for $0.98 \pm 1.28\%$. Furthermore, compositions of the stored waste in the different landfill depths were studied in detail (Fig. 2). According to the results, the third layer of the disposed solid waste had the highest proportion of soil-like materials (82.77%). The proportion of plastic wastes in the first and second layers were 11.36 and 12.71% , and were higher than in the third and fourth layers, where they were 6.30 and 8.59% . It indicates that the consumption and disposal of plastics probably increased after 1997. The proportion of paper in the first and second layers was 0.18 and 0.22% , but was difficult to sort in the third and fourth layers, indicating that paper was completely biodegraded over time. As indicated in Fig. 2, the proportions of metals and glass, which can be easily recycled, were low during all years, given that 31.8 and 13.6% of the samples presented negligible levels of these components.

The composition of the stored waste may be different due to the municipal solid waste in the landfill [21]. For example, researches on European landfill mining projects showed different results compared to our work, where soil-like materials accounted for 50 – 60% and combustible fractions accounted for 20 – 30% [3, 21]. There are four reasons accounting for the composition variety of different landfills.

Firstly, the proportion of biodegradable waste in landfills is higher in China. Based on a study conducted by the Jingmen City council in 1990, biodegradable waste accounted for 78.55% , of which vegetable waste was 69.99% (w/w), animal waste was 1.35% (w/w), and paper waste was 4.63% (w/w). Secondly, the composition of disposed furnace coal slag was high because the natural gas coverage rate was low during 1980–1990. Thirdly, the Yingchun landfill was opened to scavengers for materials recycling in its early years of operation, and large amounts of recyclable waste were sorted out from the dumpsite before final disposal. Lastly, about 5 cm of the local soil was transferred to the landfill surface every day during its operational process to prevent odors and pests, therefore, these cover soils also partly accounted for the soil-like materials.

3.2 Physicochemical properties of the soil-like materials

The physicochemical properties of soil-like materials in the Yingchun landfill are shown in Table 2. The average density and water content of the soil-like materials were $0.69 \times 10^3 \text{ kg m}^{-3}$ and 22.62% (w/w). The pH ranged from 7.55 to 9.14 (mean of 8.14), and showed a neutral or slightly alkaline pH value. The EC, the index for soluble salt content, was $1190.55 \pm 454.59 \mu\text{S cm}^{-1}$, which is sufficiently low for it to be used as a fertilizer or soil amendment. CEC, the index for determining the potential for soil amelioration and fertility preservation, maintained an average value of $84.53 \pm 11.44 \text{ cmol}(+) \text{ kg}^{-1}$, higher than $20 \text{ cmol}(+) \text{ kg}^{-1}$, which was recommended for better preservation of soil fertility. CEC fluctuated from 66.5 to $109.0 \text{ cmol}(+) \text{ kg}^{-1}$, decreasing from the top layer ($86.36 \pm 11.87 \text{ cmol}(+) \text{ kg}^{-1}$) to the bottom layer ($72.80 \pm 7.78 \text{ cmol}(+) \text{ kg}^{-1}$). The value of CEC is contributed by both organic and inorganic groups in the soil-like materials, such as humic acids and clay minerals. The top layer of stored waste had a comparative higher pH, which may explain the higher CEC of the soil-like materials of this layer.

3.3 Organic carbon and nutrients in the soil-like materials

The TOC and nutrient contents of soil-like materials are shown in Fig. 3. The mean contents of TOC, TN, TP, and TK in soil-like materials were 9.06 ± 0.98 , 0.16 ± 0.05 , 0.21 ± 0.24 , and $1.48 \pm 0.48\%$, respectively. The contents of TOC in the first layer were significant lower than in the second layer ($p < 0.05$). There are two reasons for this trend: firstly, the construction waste and soil residue were disposed in the Yingchun landfill after 2001 due to rapid urbanization, which are relatively low in organic matter; and secondly, the waste in the second layer had some more years to decompose completely. TK decreased from the first and second layers to the third and fourth layers. This is because potassium salts are generally easily water-soluble and easily leached, and the layers experiencing longer landfill age may have discharged greater amounts of potassium salts.

The Chinese National Standard for Urban Wastes for Agricultural Use (GB 8172–87) [22] requires the contents of TOC, TN, TP, and TK to be

Table 2. Physicochemical properties of soil-like materials in different layers in the Yingchun landfill, China

Depth (m)	Density (10^3 kg m^{-3})	Moisture content (%)	pH	EC ($\mu\text{S cm}^{-1}$)	CEC ($\text{cmol}(+) \text{ kg}^{-1}$)
0–6	0.70 ± 0.09	22.48 ± 2.45	8.26 ± 0.36	1105.11 ± 619.67	86.36 ± 11.87
6–12	0.64 ± 0.03	23.23 ± 1.74	8.20 ± 0.22	1401.71 ± 347.41	86.19 ± 12.68
12–18	0.72 ± 0.06	22.17 ± 1.69	8.04 ± 0.33	1117.50 ± 122.85	83.38 ± 9.46
18–24	0.72 ± 0.04	21.99 ± 3.13	8.18 ± 0.07	982.00 ± 110.31	72.80 ± 7.78

Figure 3. TOC and nutrient contents of soil-like materials in different landfill layers. Symbols (a–b) indicate statistically significant difference ($p < 0.05$). (a) TOC contents of soil-like materials; (b) TN contents of soil-like materials; (c) TP contents of soil-like materials; (d) TK of soil-like materials.

no < 10 , 0.5, 0.06, and 0.4%, respectively, in compost or other humic products processed from municipal solid waste. Compared with this standard, TP and TK contents of the soil-like materials were coincided but TOC and TN were not. The Waste and Resource Action Programme (WRAP) summarized the quality standard of composting products from different feedstock, and the average TN content in the MSW compost was 1.27% [23], higher than in the soil-like materials obtained from landfill mining. The soil-like materials were ordinary intermixed with small inorganic particles from construction waste, glass, plastics and paper, which account for lower organic carbon and nutrient contents when compared to composts derived solely from bio-waste. However, based on the results of local farmland soil quality monitoring conducted by the Department of Agriculture of Jingmen (analysis of 18 000 samples, completed in 2006), the contents of TOC, TN and TP were 2.23, 0.13, and 0.001%, respectively. Soil-like materials excavated from the Yingchun landfill presented a higher level of organic matter and nutrients compared to the local farmland soil, so it still had potential to be reused as a cultivating substrate or as raw material for producing organic-inorganic compound fertilizers.

3.4 Heavy metals in the soil-like materials

The heavy metal contents of the soil-like materials are shown in Table 3. The maximum contents of Zn (328 mg kg^{-1}), Pb (29.44 mg kg^{-1}), Cd (0.19 mg kg^{-1}), Cr (12.93 mg kg^{-1}), and As

(32.00 mg kg^{-1}) were in the second layer (6–12 m, years 1997–2000), while the maximum contents of Cu (59.02 mg kg^{-1}) and Hg (0.27 mg kg^{-1}) were in the third layer (12–18 m, years 1993–1996). The heavy metal contents of the soil-like materials may be different due to the dumped wastes and the storage years. The research by Masi et al. [21] showed higher heavy metal contents for a study case in Italy (particle size is also $< 10 \text{ mm}$). The pH of stored wastes was the most important factor affecting the vertical migration of heavy metals. In the primary stage of anaerobic digestion in landfill, the pH is extremely low (minimum pH can reach 1.5), which is beneficial to the migration of heavy metals. If the pH is > 8 after the biological digestion phase, the partition coefficient inhibits vertical migration [24, 25]. Therefore, heavy metals in the first layer may migrate downward through the flow of leachate, which is produced from rainfall and organic waste and had a lower pH value due to the anaerobic digestion phase. The accumulation of heavy metals may increase in the second and third layer of the landfill [26, 27]. As shown in Table 3, the Hg content in the third layer is significantly higher than in the first layer ($p < 0.05$). However, the statistical significance analysis of other heavy metals contents could not support the above hypothesis. Previous researches had analyzed the heavy metal contents of soil-like materials in different landfill layers, in different drilling locations or under different particle diameters [12, 14, 21, 28], and they did not find statistical significance either. It may be due to the fact that the compositions of stored wastes and the inner structure of landfill layers

Table 3. Heavy metal contents of soil-like materials in different landfill layers of the Yingchun landfill, China and the heavy metal limitations in compost quality standards

Comparison with standards	Depth (m)	Cu (mg kg ⁻¹)	Zn (mg kg ⁻¹)	Pb (mg kg ⁻¹)	Cd (mg kg ⁻¹)	Cr (mg kg ⁻¹)	As (mg kg ⁻¹)	Hg (mg kg ⁻¹)
Yingchun landfill	0–6	29.53 ± 26.76	122.54 ± 99.55	17.61 ± 16.72	0.13 ± 0.08	8.73 ± 8.32	31.02 ± 8.72	0.13 ± 0.08 ^{b)}
	6–12	44.16 ± 45.19	328.76 ± 419.89	29.44 ± 35.37	0.19 ± 0.14	12.93 ± 16.41	32.00 ± 9.78	0.16 ± 0.13 ^{a),b)}
	12–18	59.02 ± 68.65	262.25 ± 158.01	16.38 ± 12.77	0.11 ± 0.08	8.24 ± 8.23	26.45 ± 8.64	0.27 ± 0.12 ^{a)}
	18–24	26.90 ± 15.70	186.00 ± 74.95	21.75 ± 9.55	0.06 ± 0.08	8.85 ± 5.16	21.20 ± 16.69	0.14 ± 0.07 ^{a),b)}
	Average	39.31 ± 40.97	219.33 ± 257.77	21.53 ± 22.89	0.14 ± 0.11	9.99 ± 10.89	29.61 ± 9.57	0.17 ± 0.11
Compost quality standards	China ^{a)}	N/A	N/A	100	3	300	30	5
	Belgium ^{b)}	90	300	120	1.5	70	N/A	1
	Germany ^{c)}	100	400	150	1.5	100	N/A	1
	Australia ^{d)}	200	250	200	3	400	20	1

Symbols a) and b) indicate statistically significant difference ($p < 0.05$). a), b), and c) are cited from [22].

^{a)} China national standard for urban wastes for agricultural use (GB 8172–87) [21].

^{b)} Belgium Ministry of Agriculture.

^{c)} Quality assurance RAL GZ—compost/digestion.

^{d)} ARMCANZ limits for biosoils.

were very complex, heavy metal contents of soil-like materials did not show a significant difference of each landfill layers (storage years).

The heavy metal contents of soil-like materials were compared to the compost quality standards of China, Belgium, Germany, and Australia (see Table 3). The Chinese National Standard for Urban Wastes for Agricultural Use (GB 8172–87) specifies the following upper limits for these heavy metals: As (30 mg kg⁻¹), Pb (100 mg kg⁻¹), Cd (3 mg kg⁻¹), Cr (300 mg kg⁻¹), Hg (5 mg kg⁻¹), while no limits is specified for Cu and Zn. It indicated that soil-like materials were allowed to be applied to agricultural land according to the current law limits in China. But when comparing the results to the compost standards of Belgium, Germany, and Australia, we found that every heavy metal contents except As and Zn contents in soil-like materials were below the specified limits. The average As content was 29.61 ± 9.57 mg kg⁻¹ and the average Zn content was 219.33 ± 257.77 mg kg⁻¹, where some samples may exceeded the standards of Belgium and Australia. According to previous researches, among all categories of municipal solid waste, coal slag had high content of As, while dust, metal, and electronic waste had high content of Zn [29, 30], which maybe the source of the comparatively higher contents of As and Zn in soil-like materials. Masi et al. [21] revealed that As and Cd present the highest leaching potentials among the other heavy metals in the soil-like materials (sieved at 4 and 10 mm), whereas Mn, Pb, and Zn present the lowest [22]. Both As and Zn concentrations were close to the law limits of China in this research, but they may present different levels of environmental risks because of the leaching potentials. Although previous research showed that >80% of the heavy metals tend to be in an insoluble form and that most plants fertilized with compost do not accumulate heavy metals [31, 32], the environmental risks of heavy metals in soil-like material still need further discussion based on the information of concentration, form, leaching potential and plant accumulation. However, soil-like materials cannot be applied to edible plants according to the current results, but the relatively low content of heavy metals and high CEC makes them available for applying to inedible plants or for ecological restoration materials of heavy metal contaminated soils [14, 33].

3.5 Fertilizer effects of the soil-like materials

The dry weight biomass and total flower numbers of *I. balsamina* L. cultivated by the substrates with different mixed ratios of soil-like

materials and natural soil are shown in Figs. 4 and 5. The dry weight biomass of *I. balsamina* L. cultivated with 25% (C₁), 75% (C₂), and 100% (C₃) soil-like materials were 3.23 ± 0.26 , 6.73 ± 0.31 , 5.15 ± 0.17 , which were significantly higher than the group without adding soil-like materials (2.47 ± 0.11 g, $p < 0.05$), and the highest group of biomass weight was C₂. The flower numbers cultivated with 25% (C₁), 75% (C₂), and 100% (C₃) soil-like materials were 122 ± 13 , 153 ± 6 , 201 ± 5 , which were significantly higher than the group C₀ (41 ± 2 , $p < 0.05$), and the highest group of flower number was C₃. The soil-like materials showed a capacity of promoting growing and flowering of *I. balsamina* L., average dry weight biomass of *I. balsamina* L. cultivated by 25, 75, and 100% soil-like materials were 1.3, 2.7, 2.1 times higher than C₀ (0%) after 207 days of cultivating, and average flower numbers were 1.0, 3.0, 3.7, 4.9 times higher than C₀ (0%).

Organic carbon and nutrients in soil-like materials could affect growing and accumulating biomass of *I. balsamina* L. TN, TP, and TK in soil-like materials were 0.16, 0.21, and 1.48%, higher than in natural soil (0.124% TN, 0.001% TP, 0.015% TK). The group cultivated with 75% soil-like materials achieved higher dry weight biomass of *I. balsamina* L. than the group cultivated with 100% soil-like materials, the reason may be that the soil-like materials were slightly alkaline (pH 8.14) compared to natural soil (pH 6.80), but

Figure 4. Dry weight biomass of *I. balsamina* L. with different mixed ratio of landfill soil and natural soil. Symbols (a–d) indicate statistically significant difference ($p < 0.05$).

Figure 5. Total flower numbers of *I. balsamina* L. with different mixed ratio of landfill soil and natural soil. Symbols (a–d) indicate statistically significant difference ($p < 0.05$).

usually *I. balsamina* L. grows better in slight acidic soil. TP and TK contents in soil could affect *I. balsamina* L. flowering. The soil-like materials had average TP and TK contents of 0.21 and 1.48%, higher than in natural soil (0.001% TP, 0.015% TK). This could explain the differences of flower numbers of the different groups. Moreover, CEC and EC of the soil present the capacity of holding and exchanging irons in the soil. They also may contribute to the growing of *I. balsamina* L., while the mineral particles and hormones in soil-like materials may contribute to promoting flowers of *I. balsamina* L.

4 Conclusions

Old landfills result in land occupation and environmental pollution, and landfill mining is a feasible approach for recycling the stored materials and remediating the occupied land. The conducted research focuses on the physicochemical characteristics and fertilizer quality of soil-like material, which is the primary fraction of stored wastes of old landfills and also the main product of landfill mining projects. A field study on a representative old landfill in China was conducted to figure out the contents and vertical distributions of organics, nutrients and heavy metals and the fertilizer effects of soil-like materials. It can be concluded that the soil-like material has a high level of organic matter and nutrients compared to local natural soils, and can significantly promote the growing and flowering of ornamental plants (*I. balsamina* L.). The heavy metal contents of the soil-like material are lower than the law limits in China. Further studies will be concentrated on the form, leaching potential and plant accumulation of heavy metals to reveal the environmental risks. However, the soil-like material represents a valuable bio-resource with utility as soil amendment, cultivating substrate and raw material for producing organic-inorganic compound fertilizers, and will be an important source of bio-resource in China due to the huge amounts of old landfills.

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