frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 11 October 2022
DOI 10.3389/fenvs.2022.1023356

Comprehensive recycling of fresh municipal sewage sludge to fertilize garden plants and achieve low carbon emission: A pilot study

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SPECIALTY SECTION
This article was submitted to Water and Wastewater Management, a section of the journal Frontiers in Environmental Science

RECEIVED 19 August 2022
ACCEPTED 26 September 2022
PUBLISHED 11 October 2022

CITATION
Lin X, Chen C, Li H, Hei L, Zeng L, Wei Z, Chen Y and Wu Q-T (2022), Comprehensive recycling of fresh municipal sewage sludge to fertilize garden plants and achieve low carbon emission: A pilot study.
Front. Environ. Sci. 10:1023356.
doi: 10.3389/fenvs.2022.1023356

Recycling nutrients in municipal sewage sludge (MSS) to soil would support sustainable development. In this study, a comprehensive recycling using specific plants able to grow in the fresh MSS and an indirect application technique was developed. Fresh MSS was placed in permeable containers next to *Handroanthus chrysanthus* plants to provide indirect fertilization. Sludge treatment plants (*Alocasia macrorrhiza* and *Pennisetum hybridum*) were grown directly on the Fresh MSS to produce plant biomass and treat MSS. The basal diameters of the *H. chrysanthus* plants were markedly increased by the treatment. Nutrients were extracted from MSS more readily and more biomass was produced by the *P. hybridum* than the *A. macrorrhiza* plants. The heavy metal contents of the soil did not increase significantly and not generate potential ecological risk, but the organic matter, nitrogen, and phosphorus contents increased markedly. The fresh MSS leachate met the relevant fecal coliform and heavy metal irrigation water standards. At the end of the treatment, the MSS mass had markedly decreased and the treated MSS was used as a seedling substrate for two garden plant seedlings. The net carbon emissions from the comprehensive recycling are estimated as -15.79 kg CO_2e (CO_2 equivalent) per ton fresh sludge, in contrast, the emissions from composting treatment are estimated as 8.15 kg CO_2e. The method allows nutrients in MSS to be recycled without causing heavy metal pollution and without net carbon emission, while gives gardening products with commercial value.

KEYWORDS

municipal sewage sludge, indirect application, garden plant, greenhouse gas emissions, sludge treatment plant

1 Introduction

Municipal sewage sludge (MSS) is a solid waste produced during sewage treatment processes and contains large amounts of nutrients that could be utilized. However, MSS also contains relatively large amounts of harmful substances, and appropriate disposal of MSS is challenging but must be achieved to protect human and environmental health. Researchers around the world have been developing methods for treating and disposing of MSS for many years (Parr et al., 1978). Such methods involve phosphorus recovery, co-incineration, building material production, and anaerobic fermentation (Chang et al., 2020; Liang S. et al., 2021; Liang Y. et al., 2021; Iglesias-Iglesias et al., 2021; Zat et al., 2021; Ottosen et al., 2022). There are many excellent techniques for treating and disposing of MSS, but many are too expensive to be used in developing areas. The focus has previously been on disposing of MSS in economically developed areas, but MSS disposal in developing areas should not be ignored.

It is expensive to use advanced MSS treatment methods. Installing a MSS dehydration and incineration plant in China costs US$ 578,000/ (t MSS) before operating costs (Hao et al., 2019). There are additional costs involved in using MSS ash. Yu et al. (2021) calculated the cost of recovering phosphorus from MSS ash and found that, excluding the cost of producing the MSS ash and building a phosphorus recovery system, the reagents required to produce 1 kg of hydroxyapatite ($Ca_5(PO_4)_3OH$) cost US$ 32.2 whereas producing 1 kg of hydroxyapatite from phosphate ore cost only US$ 1.0 ± 0.3. These methods may be able to be used in large developed cities but cannot be afforded in developing areas. Many areas in China and other developing countries are economically developing. Local economic conditions clearly need to be considered when selecting a MSS disposal technique (Lu et al., 2019).

Applying MSS to land is a cheap disposal technique that has been used for a long time (Guoqing et al., 2019). This returns soil-derived nutrients in MSS to the soil and creates a circular flow of nutrients (Gronman et al., 2016). Sludge applications in forests can be environmentally sound if application rates are matched to site characteristics (Zasoski et al., 1984). Badza et al. (2020) assessed the use of MSS in agricultural processes using the characteristics of MSS from 18 wastewater treatment plants in South Africa and found that applying MSS to land was the best option. However, hazardous substances in MSS pose risks to soil, plants, and humans. In particular, heavy metals in MSS tend to accumulate in soil (Zhang et al., 2021), can enter the food chain through surface water and groundwater, and can be absorbed by crops (Zeng et al., 2019), so direct application of MSS to land is controversial (Hei et al., 2016). Composting MSS does not decrease the total amount of heavy metals in the MSS (Wei Y. et al., 2020), so heavy metals can be released into the soil when MSS compost is applied to soil. Riaz et al. (2018) found Cd concentrations higher than the relevant limits in rice grown in soil to which MSS compost and MSS had been applied at an application rate of 1% of the soil mass.

The heavy metals contamination issue is being attracted much attention in China because the soils in south China are acid and the capacity for heavy metals is low. This was why the MSS compost is being banned since 2021 by the Chinese Ministry of Agriculture to be an “organic fertilizer” to apply to agricultural lands *via* the organic fertilizer standards (NY/T 525–2021). Accordingly, an indirect application technique (IAT) allowing MSS to be used to fertilize crops while preventing heavy metal contamination of the soil was proposed (Lin et al., 2021b). This technique uses permeable bags to contain the sludge and, after the release of nutrients such as N, *p*, K *via* leaching by rainfall or spread irrigation, the most part of heavy metals (less soluble than major nutrients) is recovered and taken away from agricultural lands with the solid residue of sludge. It has previously been found that nutrients leached more readily than heavy metals from MSS (Xu et al., 2015; Lin et al., 2021a). Considerably less heavy metal pollution therefore occurs when the IAT is used than when normal MSS application methods are used. It was found in a nine-year study that the IAT is a cheap and simple method for using MSS to fertilize crops that provides nutrients for plants such as bananas, papayas, and corn and does not cause the soil to become contaminated with heavy metals (Lin et al., 2021b). It has been found that specific plants (later called sludge treatment plants) can be grown on fresh MSS and that the plant products can safely be harvested and used. Samake et al. (2003) found that *Alocasia macrorrhiza* can be grown on MSS. It has been found that *A. macrorrhiza* stabilized MSS in ~5 months, during which time the number of *Escherichia coli* markedly decreased and the cress seed germination index reached 100%. Hei et al. (2016) found that *Pennisetum hybridum* seedlings transplanted with substrate into fresh MSS survived and that the harvested *P. hybridum* was economically valuable. Combining the IAT with sludge treatment plants could allow MSS to be used to cheaply generate economic benefit while disposing of the MSS.

In this study, we developed a comprehensive recycling method to recycle MSS using the IAT and sludge treatment plants. The aim was to develop a low-carbon, cheap, and safe MSS disposal technique that will allow MSS to be treated of in developing areas. The fertilization effect and safety of the IAT were assessed at a high MSS application rate (720 t/ha fresh MSS) using the garden tree species *Handroanthus chrysanthus*. Sludge treatment plants (*A. macrorrhiza* and *P. hybridum*) were concurrently grown in the MSS and the products were harvested to give additional value. The treated MSS was then recycled and used as a substrate in a plant nursery to ensure that the resource was completely utilized. Finally, the carbon emission or the greenhouse gas emissions

TABLE 1 Municipal sewage sludge (MSS) and soil characteristics.

Index	MSS I	MSS II	Soil
[a] WC (%)	[b] 87.98 ± 0.70	86.69 ± 0.50	-
[a] FC	0.0300 ± 0.0100	0.0005 ± 0.0003	-
[a] GI	0.08 ± 0.09	1.32 ± 0.16	-
pH	6.82 ± 0.11	5.84 ± 0.02	5.41 ± 0.15
[a] OM (g/kg)	435.6 ± 18.3	364.2 ± 9.8	17.9 ± 2.5
N (g/kg)	42.55 ± 0.76	34.25 ± 0.84	0.94 ± 0.08
p (g/kg)	30.09 ± 1.02	26.87 ± 0.59	0.61 ± 0.11
K (g/kg)	10.95 ± 0.06	5.37 ± 0.32	15.07 ± 2.83
Cd (mg/kg)	0.841 ± 0.075	1.466 ± 0.018	0.037 ± 0.008
Cu (mg/kg)	120.5 ± 2.2	3602.1 ± 99.8	14.1 ± 3.2
Pb (mg/kg)	44.72 ± 6.82	77.58 ± 2.49	57.15 ± 2.86
Zn (mg/kg)	389.9 ± 61.8	880.0 ± 19.5	75.6 ± 7.8

[a]WC, is water content in fresh weight (FW) basis; FC, is fecal coliform value (g^{-1}. FW); GI, is germination index of Chinese cabbage seeds; OM, is organic matter content; OM, and elements contents are all in dry weight (DW) basis.
[b]All data values represent the means ± standard error (n = 3).

(GHGE) of the comprehensive recycling of MSS were also estimated.

2 Materials and methods

2.1 Experiment one: comprehensive treatment of MSS on land in a garden

2.1.1 Experimental site and materials

The experimental site, which had mountainous lateritic red soil, was in a forest of one-year-old *H. chrysanthus*. The site was ~900 m2 and was far from any heavily populated areas (N 23°19′32.05″, E 113°46′5.79″). The MSS used in the experiment, later called MSS I, was collected at a sewage treatment plant in a residential area near the BYD Auto Co. Plant in Huizhou, Guangdong Province, China. The sewage treatment plant used the A^2/O method to treat domestic sewage, and the MSS was dehydrated through mechanical compression. The physicochemical properties of MSS I are shown in Table 1. In southern China, there are less Hg and As in MSS, the main heavy metals with high contamination risk are Cd, Cu, Pb, and Zn (Guo et al., 2014), so this study focuses on these four heavy metals.

The *P. hybridum* plants were obtained from the Ecological Experiment Base of the South China Agricultural University (Guangzhou, Guangdong Province, China). Old stems of *P. hybridum* with similar diameters and strengths were selected, and stem segments with two tillering nodes were cut. Seedlings were cultivated in small pots for 2 weeks and then transplanted with the nursery substrate into the MSS used in the experiment. The *A. macrorrhiza* plants were obtained from the green belt of the South China Agricultural University. Newly grown *A. macrorrhiza* seedlings were selected and grown in small pots. Two weeks later, the seedlings were transplanted with nursery substrate into fresh MSS.

The MSS utilization method that was used is called an indirect application technique (IAT; Lin et al., 2021b). Briefly, a permeable mesh was laid over the soil, then a cylindrical container was formed on the permeable mesh using a root controlling material that is commonly used in gardens (Peter, 2000). MSS was added to the container to allow the MSS to indirectly fertilize the *H. chrysanthus* plants. Sludge treatment plants (*A. macrorrhiza* and *P. hybridum*) were planted in the MSS to further utilize the nutrients in the MSS (Figure 1).

The experimental design is shown in Figure 1. The ~900 m^2 forested land containing *H. chrysanthus* was divided into nine rows. Treatments were randomly assigned to the rows. Three rows were used for each treatment, and there were three treatments (control (CK), AM (indirect fertilization of *H. chrysanthus* and planting with *A. macrorrhiza* on MSS), and PM [(indirect fertilization of *H. chrysanthus* and planting with *P. hybridum* on MSS)]. The CK rows received no treatment, meaning natural *H. chrysanthus* growth occurred. For the AM and PM treatments, a black fiber mesh was laid on the ground and four sludge containers, each with a diameter of 1 m, were placed around each tree. Fresh MSS (250 kg) was added to each container, and 4 *A. macrorrhiza* or *P. hybridum* seedlings were planted in the fresh MSS (about five plants per m^2 of sludge surface). The surface of the fresh MSS was covered with 1 kg of mature composted MSS after planting to prevent harmful organisms and gases being released to the air. MSS was applied to 48 trees, and 48 t of MSS was used to treat the trees. The basal diameter, diameter at breast height, height, and crown width of each *H. chrysanthus* tree were determined before and after the experiment to assess growth.

2.1.2 Sample collection and analysis

Surface soil (0–20 cm) and MSS samples were collected from the experimental area before and after the experiment. The N and *p* contents of the soil and MSS samples were determined using established methods (Lu, 2000). The Cd, Cu, Pb, and Zn contents of the soil and MSS were determined by atomic absorption spectrophotometry after digestion in a microwave according to a Chinese environmental standard method (HJ 832–2017, HJ means the method is certified by Ministry of Environmental Protection of China) and using the standard substance (GBW-07405: GSS-5) for analysis quality control. The germination index (GI) of MSS was determined using a method proposed by the Chinese sludge standards (GB/T 23,486–2009) using the Chinese cabbage seed germination test. This test is similar to the cress seed germination test, which is internationally recognized as a measure of the phytotoxicity of the sludge material (Zucconi et al., 1981), and calculates this parameter using the following equation:

GI = (seed germination rate (%) X root length) of treatment/(seed germination rate (%) X root length) of water control.

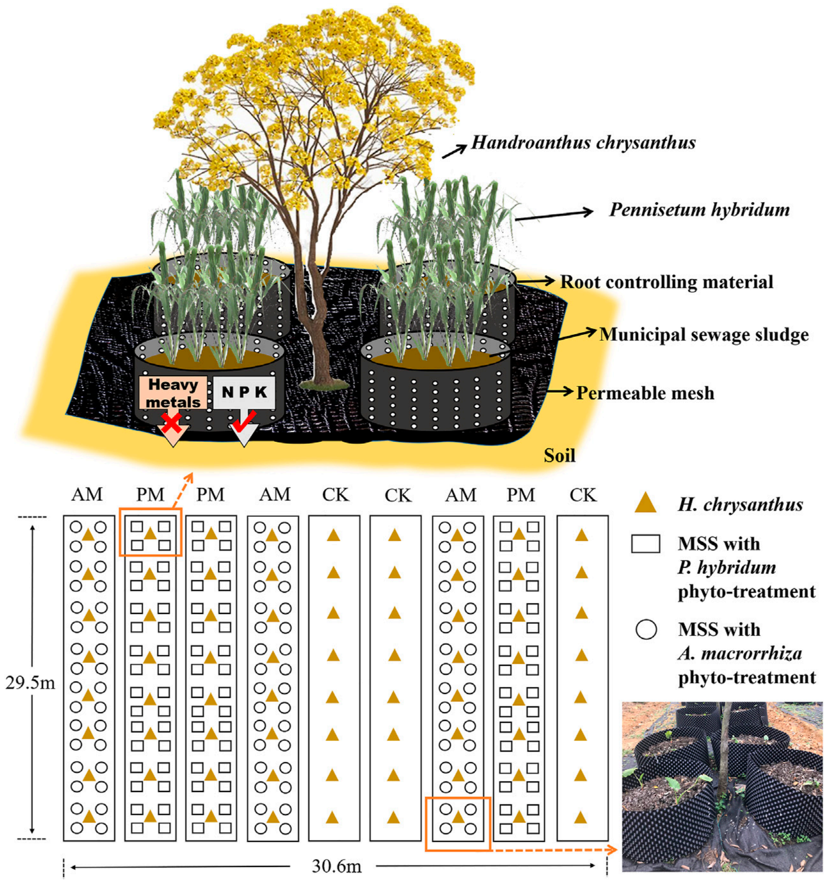

FIGURE 1
Layout of the experimental site and treatments (CK: control without MSS addition; AM: added MSS with *A. macrorrhiza* phyto-treatment; PM: added MSS with *P. hybridum* phyto-treatment).

The fecal coliforms in MSS were detected using the fermentation method (GB 7959–2012, GB means the method is National Standard Method of China).

Once the experiment had started, samples of *A. macrorrhiza* and *P. hybridum* grown on MSS were collected from random four sludge container under two *H. chrysanthus* trees per treatment in months 1, 2, 3, and 6 to allow the optimal harvest times for *A. macrorrhiza* and *P. hybridum* to be determined. Plant samples collected in month 6, were deactivated at 105°C for 30 min, and then dried at 65°C for 48 h. The dry samples were ground and then the nutrient and heavy metal contents were determined. The plant samples were digested in H_2SO_4 and H_2O_2 and then the N and *p* contents were determined using the methods proposed by Chinese Society of Soil Science (Lin et al., 2021b). The K and heavy metal contents (Cd, Cu, Pb, and Zn) of the plant samples were determined by atomic absorption spectrophotometry (GB/T 5009.15–2014) and using a standard substance (GBW-10013: GSB-4) for quality control.

2.1.3 Evaluation of the potential ecological risk of soil heavy metals

Hakanson potential ecological risk assessment was used to assess the risk of heavy metal pollution in the soil (Hakanson, 1980). The potential ecological risk index for single heavy metal (E) and all heavy metals (RI) were calculated using the following equation:

$$E = T_i \times \frac{C_i}{C_s} \quad (1)$$

$$RI = \sum_{i=1}^{n} E_i \quad (2)$$

where Ci is the measured value of soil heavy metal i; Cs is the reference value (the natural background value of soil in Guangzhou city, they are 0.14, 13.6, 42.9, and 58.1 mg/kg for Cd, Cu, Pb, and Zn, respectively); and T_i is the toxicity coefficient of heavy metal i (Cd = 30, Cu = 5, Pb = 5, and Zn = 1).

The heavy metals evaluated in this study were different from the original method, so a correction was required (Li et al., 2015). Among the four heavy metals, Cd has the largest T (30),

TABLE 2 Potential ecological risk index grading criteria.

Category	Hakanson		Corrected	
	E	RI	E	RI
Low	<40	<150	<30	<50
Moderate	40–80	150–300	30–60	50–100
High	80–160	300–600	60–120	100–200
Very high	160–320	≥600	120–240	≥200
Extremely strong	≥320	-	≥240	-

according to which the limit value of the first grading standard (Low) of E in this study is 30, and the limit value of the grading standard of each grade of E is obtained by multiplying by two in turn. In the original method, the first level limit value of RI (150) is divided by the sum of all heavy metals E (133) to obtain the coefficient 1.13. The sum of four heavy metals E in this study is 41, multiplying 41 by 1.13 and taking tens place, the first level limit value of RI in this study can be obtained ($1.13 \times 41 = 46.33$~50), which is multiplied by two in turn to obtain each level of RI. The corrected grading criteria used to define ecological risk of this study are shown in Table 2.

2.2 Experiment 2: simulation of leaching from MSS

MSS I contained a relatively low number of fecal coliforms, so it did not represent the health risks posed by IAT of most MSS. A leaching experiment was therefore performed using a sample called MSS II that contained larger amounts of harmful microorganisms (with a fecal coliform bacteria value of <0.01; Table 1). Fecal coliforms and the heavy metal concentrations in the leachate samples were determined and compared with the Chinese national standard for irrigation water quality (GB 5084–2021) to indirectly determine whether fresh MSS that did not meet sanitary indicator standards could be used in the IAT.

MSS II was collected from the Heshan Sewage Treatment Plant in Jiangmen, Guangdong Province. The experimental site was at the Ecological Farm of the South China Agricultural University in Tianhe District, Guangzhou (N 23°09′57.21″, E 113°21′37.78″). The experimental system (shown in Supplementary Figure S1) consisted of a leachate collection vessel with an upper surface area of 0.12 m^2 on which 5 kg of fresh MSS II in a black fiber mesh bag was placed. Three control vessels without MSS bag were also set-up to collect rainwater. The experiment started on 13 April and rainwater was collected for the first time on 16 April. Leachate was collected three times in 30 days. The pH, chemical oxygen demand, fecal coliform concentration, and Cd, Cu, N, *p*, Pb, and Zn concentrations in the rainwater and leachate samples were determined. The pH was determined using a glass electrode. Fecal coliforms were detected using a rapid paper strip method (HJ 755–2015). The chemical oxygen demand was determined using the dichromate method (HJ 828–2017). The Cd, Cu, Pb, and Zn concentrations were determined by atomic absorption spectrophotometry (GB 7475–1987).

2.3 Experiment 3: investigation of follow-up utilization of MSS

At the end of Experiment one, *Jasminum sambac* and *H. chrysanthus* seedlings were planted in the MSS that had been treated by growing plants in it to investigate follow-up recycling uses of MSS. *J. sambac* seedlings 15 cm tall were purchased from Jianye Jasmine Base in Nanning, Guangxi, China. *H. chrysanthus* seedlings 50–60 cm tall were obtained from the Garden Company of the South China Agricultural University. The *J. sambac* plants were planted on Xinwei Road in Zengcheng District, Guangzhou (N23°19′32.05″, E113°46′5.79″), and the *H. chrysanthus* seedlings were planted at the Ecological Farm of the South China Agricultural University (N23°09′57.21″, E113°21′37.78″).

In the experiment using *J. sambac*, it was grown in two types of treated MSS (AM and PM) (10 kg/pot), one that had previously been used to grow *P. hybridum* (i.e., from the Experiment I PM group) and the other that had previously been used to grow *A. macrorrhiza* (i.e., from the Experiment I AM group). *J. sambac* was also grown in control soil (CK) (10 kg/pot), which was soil collected from a mountain near the experimental site. For each treatment, 10 replicates were performed. The *J. sambac* plants were grown for 3 months. At the end of the experiment, *J. sambac* plant survival and height were recorded.

In the experiment in which *H. chrysanthus* seedlings were planted, 20 kg of the treated MSS was mixed with 20 kg of soil to investigate whether a mixture of MSS and soil could be used as a seedling substrate. Three treatments were performed: 1) CK: Control, soil (40 kg) from local ordinary farmland without fertilizer or sludge. 2) CF: soil (40 kg) fertilized with chemical fertilizers (4 g N, 4 g P_2O_5, and 4 g K_2O added with a 15–15–15 compound fertilizer). 3) PM: mixture of soil and an equal mass of MSS on which *P. hybridum* plants had previously been grown (i.e., from the Experiment I PM group). Four replicates of each treatment were performed. The plants were grown for 6 months. The *H. chrysanthus* plant heights were recorded once each month.

2.4 Net greenhouse gas emissions estimation

Greenhouse gas emissions (GHGE), also called carbon emissions, are generally calculated in terms of carbon dioxide equivalents (CO_2e). Net GHGE consist of three main components: direct carbon emission, indirect carbon emission and carbon emission reduction. The comprehensive treatment proposed in this research use green plants and sunlight, might have less carbon emission, and the *P. hybridum* produced in the treatment process could be used as fuel biomass, which could replace fossil fuels to achieve carbon reduction. Similar to aerobic composting treatment, the comprehensive treated MSS could use as an organic fertilizer. Therefore, comparing the net GHGE of the comprehensive recycling with the aerobic composting treatment can measure the carbon emission level of the integrated method. This study assessed the net GHGE according to the accounting guidelines given in Intergovernmental Panel on Climate Change (IPCC, 2019).

2.4.1 Direct carbon emission

MSS may release CH_4 and N_2O during the treatment process. Therefore, the direct carbon emissions in the treatment process are calculated as follows:

$$E_{D,CO_2} = M \times \left(E_{CH_4} \times GWP_{CH_4} + E_{N_2O} \times GWP_{N_2O}\right) \quad (3)$$

Where: E_{D,CO_2} is the direct carbon emission, kg CO_2e; M is the mass of treated MSS, t; E_{CH_4} is the CH_4 emission of the treatment, kg/t; GWP_{CH_4} is the 100-year global warming potential (GWP) for CH_4, 25 (IPCC, 2007); E_{N_2O} is the N_2O emissions of the treatment, kg/t; GWP_{N_2O} is the 100-year GWP for N_2O, 298 (IPCC, 2007).

2.4.2 Indirect carbon emission

The treatment of MSS consumes fuel and electricity, which indirectly generates carbon emissions are calculated as follows:

$$E_{I,CO_2} = (M/M_L) \times S \times \varphi_t \times EF_D + W_E \times EF_E \quad (4)$$

Where: E_{I,CO_2} is the indirect carbon emission, kg CO_2e; M is the transport mass of MSS, t; M_L is the transport vehicle load, 10 t; S is the transport distance, km; φ_t is the vehicle fuel consumption, 0.17 kg/km (Wang et al., 2022); EF_D is the carbon emission factor for diesel, 3.0956 kg CO_2/kg (MEE, 2020); W_E is the power consumption of the treatment, kWh/t; EF_E is the carbon emission factor of electricity, 0.8042 kg/kWh (MEE, 2020).

2.4.3 Carbon Reduction

Both treatments are capable of producing fertilizer that can replace the carbon emissions from the production of chemical fertilizers, calculated as follows:

$$E_{N,CO_2} = -(M_{LU} \times w_N \times EF_N) \quad (5)$$

Where: E_{N,CO_2} is the carbon reduction from fertilizer substitution, kg CO_2e; M_{LU} is the mass of treated MSS, kg; w_N is the mass fraction of elemental nitrogen; EF_N is the nitrogen fertilizer carbon emission factor, 2.041 kg CO_2e/kg (Chen et al., 2015).

As an energy plant, the use of *P. hybridum* as a fuel can offset carbon emissions from fossil fuel combustion, calculated as follows:

$$E_{P,CO_2} = -\left(\frac{M_P \times Q_P}{Q_s} \times EF_s\right) \quad (6)$$

Where: E_{P,CO_2} is the carbon emission reduction from *P. hybridum* as a fuel, kg CO_2e; M_P is the dry mass of *P. hybridum*, kg; Q_P is the calorific value of *P. hybridum*, which is taken as the average of energy plants, 17,350 kJ/kg (Nazli et al., 2020); Q_s is the calorific value of standard coal, 29,300 kJ/kg (Wang et al., 2022); EF_s is the carbon emission factor of standard coal, which is 2.493 kgCO_2/kg (Wang et al., 2022).

2.5 Statistical analysis

SPSS 22 (SPSS Inc., Chicago, IL, United States) was used to conduct statistical analyses. The normality of distribution and homogeneity of variance were tested before performing ANOVA. Significant differences between the treatments were analyzed using ANOVA and Duncan's multiple range tests. Significance was accepted at $p < 0.05$. For the principal component analysis (PCA), Bray-Curtis dissimilarities were calculated using the vegan package (v.2.5.4) in R (v.3.6.3). Barplot was generated using the ggplot2 package (v.3.3.3).

3 Results

3.1 Growth of *H. chrysanthus*

We measured the basal diameters, diameters at breast height, heights, and crown widths of the *H. chrysanthus* trees before and after the experiment and then calculated the amounts by which the four measurements had increased. The results are shown in Table 3. After a year, the basal diameters and diameters at breast height had increased by only 2.13 and 1.43 cm, respectively, for the trees in the control (CK), but 3.06 and 2.61 cm for the trees in the AM treatment, 3.26 and 2.83 cm for the trees in the PM treatment. The basal diameters and diameters at breast height for the trees in the three treatments were significantly different ($n = 24$, $p = 0.05$). The crown widths and tree heights were also higher for the trees treated with MSS than for the CK trees but the differences were not significant ($n = 24$, $p = 0.05$). We concluded that the IAT and sewage plant treatment had a favorable effect on *H. chrysanthus* growth.

3.2 Effects on the sludge treatment plants

3.2.1 Optimal sludge treatment plants harvest times and yields

The sludge treatment plants needed to be harvested regularly to maximize MSS utilization. The planting times that gave the highest plant yields were identified by harvesting and weighing the sludge treatment plants at different times. The *A. macrorrhiza*

TABLE 3 Changes in growth indicators of *H. chrysanthus*.

Treatment	Basal diameter (cm)	Diameters at breast height (cm)	Crown width (m)	Height (m)
Before treatment				
[a] CK	[b] 9.80 ± 0.64	7.05 ± 0.50	2.86 ± 0.18	4.87 ± 0.02
AM	9.56 ± 0.75	6.81 ± 0.38	2.82 ± 0.16	4.81 ± 0.16
PM	9.44 ± 0.82	6.72 ± 0.51	2.90 ± 0.15	4.75 ± 0.16
After treatment				
CK	12.15 ± 0.84	8.41 ± 0.64	4.21 ± 0.43	6.26 ± 0.23
AM	12.53 ± 1.18	9.42 ± 0.59	4.25 ± 0.47	6.11 ± 0.40
PM	12.61 ± 1.24	9.47 ± 0.89	4.58 ± 0.12	5.97 ± 0.25
Increases in various indicators				
CK	2.13 ± 0.61a	1.43 ± 0.64a	0.69 ± 0.46a	0.76 ± 0.32a
AM	3.06 ± 0.90b	2.61 ± 0.74b	0.95 ± 0.74a	1.16 ± 1.17a
PM	3.26 ± 0.87b	2.83 ± 0.91b	0.76 ± 0.69a	0.88 ± 0.48a

[a]CK: Control without MSS, addition, AM: added MSS, with *A. macrorrhiza* planting, PM: added MSS, with *P. hybridum* planting.
[b]Data are mean ± standard deviation, different lowercase letters indicate that the difference was significant between the treatments according to Duncan's multiple range test (p = 0.05, n = 24).

and *P. hybridum* plants were harvested and weighed in months 1, 2, 3, and 6. The yields in months 1, 2, 3, and 6 were converted into annual yields by multiplying the yields by factors of 12, 6, 4, and 2, respectively, to allow the yields to be compared. *P. hybridum* harvested in month three gave the highest annual yield (100 ± 25 t/ha). *A. macrorrhiza* harvested in month 6 gave the highest annual yield (9.0 ± 1.4 t/ha). The annual yields at the same harvesting times were significantly higher for *P. hybridum* than *A. macrorrhiza* (n = 4, p = 0.05). For example, the annual yield was 18.5 times higher for *P. hybridum* than *A. macrorrhiza* when the plants were harvested in month 3 (Supplementary Figure.S2). This indicated that more biomass could be harvested if *P. hybridum* was planted than if *A. macrorrhiza* was planted in the MSS.

3.2.2 Nutrient extraction by the sludge treatment plants

The measured K, N, and p contents (dry weight) of the *P. hybridum* biomass were 27.12 ± 7.15, 15.11 ± 3.67, and 5.56 ± 1.42 g/kg, respectively, and the K, N, and p contents of the *A. macrorrhiza* biomass were 45.40 ± 10.37, 27.84 ± 1.77, and 5.31 ± 0.07 g/kg, respectively. Under the optimal harvest time as previously mentioned (annual yield 100 and 9.0 t/ha respectively for *P. hybridum* and *A. macrorrhiza*), the *P. hybridum* plants extracted annually 2712, 1511, and 556 kg/ha of K, N, and p, respectively, from the MSS. The *A. macrorrhiza* plants extracted 408.6, 250.6, and 47.8 kg/ha of K, N, and p, respectively. More than 6.6, 6.0 and 11.6 times of K, N, and p were extracted when *P. hybridum* was planted than when *A. macrorrhiza* was planted in the MSS, meaning *P. hybridum* is more suitable than *A. macrorrhiza* for use as a sludge treatment plant to recycle the MSS nutrients into animal feed or organic fertilizer.

3.2.3 Heavy metal contents of the sludge treatment plants

Both *A. macrorrhiza* and P. hybridum are inedible by humans, so the risks posed to humans by directly planting *A. macrorrhiza* and P. hybridum in MSS are relatively low. However, we determined the heavy metal contents (dry weight) of the *A. macrorrhiza* and P. hybridum plants to evaluate possible subsequent uses of the sludge treatment plant biomass. The Cd, Cu, Pb, and Zn contents of the P. hybridum dry biomass were 0.082 ± 0.015, 5.88 ± 0.11, 0.50 ± 0.02, and 38.21 ± 2.22 mg/kg, respectively. The Cd, Cu, Pb, and Zn contents of the *A. macrorrhiza* dry biomass were 0.568 ± 0.121, 9.26 ± 0.90, 2.32 ± 0.97, and 196.53 ± 4.76 mg/kg, respectively. The Cd, Cu, Pb, and Zn contents were lower for *A. macrorrhiza* than P. hybridum. The Cd and Pb contents of the P. hybridum and *A. macrorrhiza* biomass were below the relevant limits for organic fertilizers (Cd ≤ 3 mg/kg, Pb ≤ 50 mg/kg; standard NY 525–2021, Chinese Ministry of Agriculture) and feed (Cd ≤ 1 mg/kg, Pb ≤ 10 mg/kg; standard GB 13078–2017). This indicated that the sludge treatment plant biomass produced on the MSS was safe, in terms of the Cd and Pb contents, for use as animal feed or as raw material for producing organic fertilizer.

3.3 Effects on the soil

3.3.1 Effects on the soil pH and heavy metal contents

After 1 year of the comprehensive treatment, there were no significant differences in the soil pH and the Cd, Cu, Pb, and Zn contents of the soil for the three treatments (n = 3, p = 0.05, Table 4). The Cd, Cu, Pb, and Zn contents of the soil in the AM

TABLE 4 Characteristics of soils and municipal sewage sludge (MSS) after planting.

Soil	pH	[c] OM g/kg	Cd g/kg	Cu g/kg	Pb g/kg	Zn g/kg	N g/kg	P g/kg	K g/kg
[a] CK	[b] 6.13 ± 0.10a	20.63 ± 2.33a	0.053 ± 0.001a	11.46 ± 1.88a	56.00 ± 1.48 a	75.13 ± 1.76a	1.00 ± 0.06a	0.94 ± 0.05a	15.41 ± 1.77a
AM	6.21 ± 0.53a	25.25 ± 4.47a	0.066 ± 0.007a	12.75 ± 1.06a	48.89 ± 5.60 a	73.75 ± 7.47a	1.30 ± 0.21 ab	1.00 ± 0.05b	12.40 ± 3.42a
PM	5.91 ± 0.33a	29.03 ± 5.11a	0.077 ± 0.021a	14.30 ± 1.18a	51.51 ± 3.46 a	79.56 ± 1.08a	1.56 ± 0.28b	1.61 ± 0.13b	15.25 ± 0.24a
[d] Standards	-	-	≤0.3	≤50	≤90	≤200	-	-	-
MSS							$N + P_2O_5 + K_2O$	[c] FC	[c] GI
Raw sludge	6.82 ± 0.11a	438.83 ± 18.29a	0.841 ± 0.075a	120.5 ± 2.2a	44.72 ± 6.82a	389.9 ± 61.8a	114.25 ± 2.51a	0.03 ± 0.01a	0.08 ± 0.09a
AM	5.40 ± 1.29 ab	415.34 ± 32.55a	0.854 ± 0.056a	140.6 ± 15.1a	67.20 ± 11.29b	570.0 ± 95.3a	94.24 ± 12.01b	0.03 ± 0.00a	0.87 ± 0.16b
PM	4.77 ± 0.39b	395.22 ± 20.97a	0.794 ± 0.050a	136.3 ± 20.6a	65.84 ± 5.90b	549.0 ± 184.1a	94.16 ± 4.28b	0.11 ± 0.05b	0.77 ± 0.24b
[d] Standards	6.5–8.5	≥250	≤5	≤800	≤300	≤2000	≥30	≥0.01	≥0.70

[a]CK: control without sludge addition, AM: added sludge with *Alocasia macrorrhiza* planting, PM: added sludge with *Pennisetum hybridum* planting.
[b]Data are mean ± standard deviation, different letters indicate that the difference was significant between the treatments according to Duncan's multiple range test (p = 0.05).
[c]OM, is organic matter content; FC, is fecal coliform value (g/MPN, in fresh weight basis); GI, is germination index of Chinese cabbage seeds.
[d]The soil standard is Soil Environmental Quality Standard of China (GB, 15618–2018); the MSS, standard is Quality of Sludge Used in Gardens or Parks of China (GB/T 2348–2009).

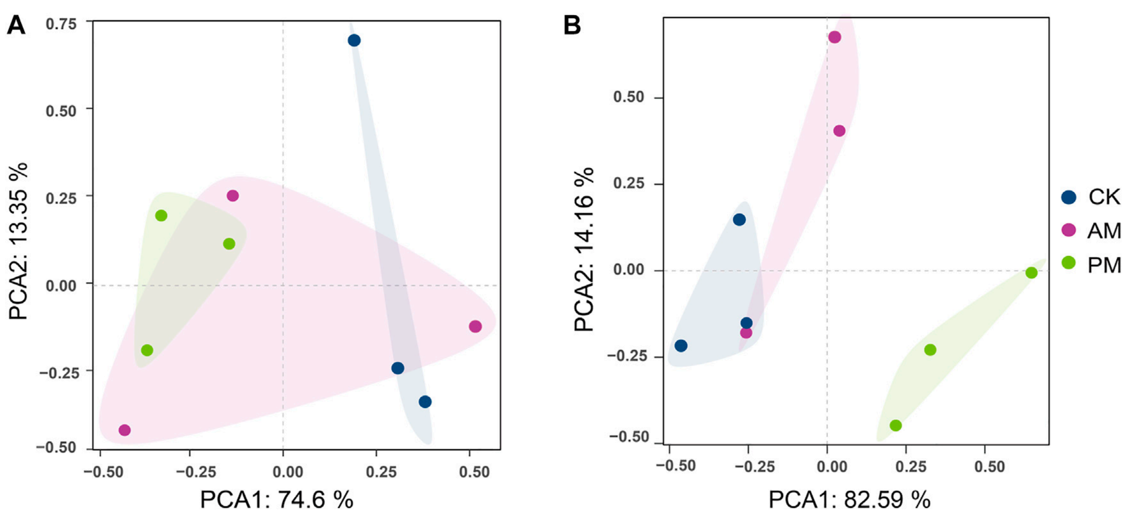

FIGURE 2
The effect of comprehensive treatment on soil, where: **(A)** shows the principal component analysis of heavy metals (Cd, Cu, Pb, Zn) in soil after the experiment; **(B)** shows the principal component analysis of soil nutrients (N, P, OM, K) after the experiment.

and PM treatment areas were all below the relevant Chinese soil environmental quality standard limits (GB 15618–2018). As shown in Figure 2A, principal component analysis indicated that there were no differences between the results for the CK, AM, and PM treatments after 1 year, indicating that the IAT and sludge treatment by plants posed little risk of soil pollution.

The assessment of the potential ecological risk of the soil also indicated that the comprehensive treatment poses little risk of soil contamination. According to Eqs 1, 2, E_{Cd}, E_{Cu}, E_{Pb}, and E_{Zn} for the AM treatment were 14.14, 4.69, 5.70, and 1.27, respectively, and the RI was 25.80; E_{Cd}, E_{Cu}, E_{Pb}, and E_{Zn} for the PM treatment were 16.50, 5.26, 6.00, and 1.37, respectively, and the RI was 29.13. Comparing the corrected grading criteria (Table 2), it can be found that the potential ecological risk to the soil for both treatments is the lowest grade.

3.3.2 Effects on soil nutrients

In the year in which the comprehensive treatment was applied, *H. chrysanthus* grew well while the N and *p* contents of the soil also increased significantly in the PM treatment areas than in the CK area, as shown in Table 4. However, the K content did not follow the same trend because the K content was lower for the MSS than the soil (Table 1). The principal component analysis indicated that, in general, the K, N, OM, and *p* contents of the soil after the experiment were different for the three treatments (Figure 2B) indicating that different amounts of nutrients were leached from the MSS into the soils of the different treatments.

3.4 Changes in MSS properties

3.4.1 Decreases in MSS mass

Each *H. chrysanthus* plant was treated with 1000 kg of MSS. After 1 year, the total remaining MSS masses for the AM and PM treatments were determined and the decreases in the MSS masses were calculated. The MSS masses in the AM and PM treatments had decreased by 84.42% and 85.37%, respectively, at the end of the year. The IAT and sludge treatment plants treatment transformed the fresh MSS into a soil-like substrate (Supplementary Figure.S3) that still had nutrient value, as shown in Table 4, and could be conveniently transported for further use.

3.4.2 Changes in the MSS pH and heavy metal contents

The pH of the MSS I decreased markedly after it had been applied, as shown in Table 4. The change in pH would have been affected by various factors, including precipitation and OM mineralization and nitrification. Plant root exudates could also have changed the MSS pH (Xu and Coventry, 2003). The heavy metal contents of the MSS increased during the experiment, as shown in Table 4. There were no marked differences between the heavy metal contents of the MSS in the AM and PM treatments. *A. macrorrhiza* and *P. hybridum* could have absorbed heavy metals and decreased the heavy metal contents of the MSS. However, *A. macrorrhiza* and *P. hybridum* are not hyperaccumulators, so they would not have absorbed very large amounts of heavy metals. Decomposition of OM and leaching of nutrients would have decreased the MSS mass and would have increased the heavy metal contents of the MSS. However, the Cd, Cu, Pb, and Zn contents of the MSS after the plant treatments were lower than the legal limits for MSS to be used in gardens or parks in China (GB/T 2348–2009).

3.4.3 Nutrient and hygiene indicators

Using the recovered MSS as a substrate for growing seedlings required the nutrient and sanitary indicators of the MSS to be assessed. The OM content of the MSS in the AM and PM treatments after 1 year of indirect MSS utilization and plant treatment was ~400 g/kg (i.e., >250 g/kg; Table 4). The total nutrient (N + P_2O_5+K_2O) content of the treated MSS was ~94 g/kg (i.e., >30 g/kg). There were no significant differences between the OM and total nutrient contents of the AM- and PM-treated MSS. The nutrient contents of the AM- and PM-treated MSS met the requirements for using the treated MSS in landscaping applications.

The seed germination index (GI) was used to indicate the toxicity of the MSS to plants. The AM and PM treatments strongly improved the GI. The GIs for the AM and PM treatments were 0.87 ± 0.16 and 0.77 ± 0.24, respectively, whereas the GI of the raw MSS was 0.08 ± 0.09, as shown in Table 4. The GIs for the AM- and PM-treated MSS met the requirements for the MSS to be used in gardens or parks in China (GB/T 2348–2009).

The fecal coliform bacteria value (FC) is the minimum sample size required to allow coliforms to be detected. The larger the FC the cleaner the MSS. The Chinese "Quality of Sludge Used in Gardens or Parks" standard (GB/T 2348–2009) stipulates that the FC for MSS must be ≥ 0.01 (equivalent to <100 MPN/g). The FCs for the AM- and PM-treated MSS after 1 year were 0.03 ± 0.00 and 0.11 ± 0.05, respectively. The FC for the PM-treated MSS was significantly different from the FCs for the AM-treated and untreated MSS (n = 3, p = 0.05). This indicated that the PM treatment markedly improved the sanitary level of the MSS.

3.5 Harmful substances in the MSS leachate

It can be seen from Table 1 that the FC for MSS II was above the relevant limit of 0.01 in standard GB/T 2348–2009 and reached 0.0005 ± 0.0003 (equivalent to 2.0×10^3 MPN/g). However, as shown in Table 5, the fecal coliform concentration in the first leachate was only 160 MPN/L. The fecal coliform concentration limit specified in the Chinese standard for irrigation water (GB 5084–2021) is 4.0×10^4 MPN/L. This indicated that microorganisms were retained well by the MSS in the mesh package because the fecal coliform concentration was expected to be higher for the first MSS leachate than for later MSS leachates.

The Cu content of the MSS II, 3602 ± 100 mg/kg (Table 1), was higher than the limit specified in Chinese standard GB/T 2348–2009. The Cu concentration in the leachate caused by rainfall was only 0.584 ± 0.285 mg/L (Table 5), which was lower than the Chinese limit of 1 mg/L for irrigation water (standard GB 5084–2021). The Cd, Pb, and Zn concentrations in the leachates were very low. Similar results were found in a previous study. Xu et al. (2015) performed multiple leaching tests lasting up to 9 months (n = 30) using polluted MSS with a Cd content of 4.92 ± 0.09 mg/kg. They found low Cd concentrations of between 0 and 0.00156 mg/L in the leachate.

3.6 Subsequent MSS utilization

3.6.1 Growth of *J. sambac* planted in treated MSS

The MSS that had been used to grow *A. macrorrhiza* and *P. hybridum* in experiment one (see section 2.1) was used to grow *J. sambac* plants. The *J. sambac* plants grown in the AM- and PM-treated MSS survived well, the survival rates all being 100% (n = 10). The *J. sambac* seedlings were ~15 cm tall at the beginning of the experiment. Three months after being planted, the *J. sambac* plants grown in the AM- and PM-treated MSS were >70 cm tall (70.11 ±

TABLE 5 Main properties of municipal sewage sludge leachate of the first collections.

Index	pH	[a] FC	[a] COD (mg/L)	N (mg/L)	*p* (mg/L)	Cd (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)
Rainwater	5.26 ± 0.09	0 ± 0	0 ± 0	0.11 ± 0.19	0.20 ± 0.05	0.0001 ± 0	0.0168 ± 0.001	0.0029 ± 0.0009	0.028 ± 0.018
Leachate	6.59 ± 0.17	160 ± 157	19.3 ± 4.7	16.86 ± 6.12	7.73 ± 1.98	0.0002 ± 0	0.5840 ± 0.285	0.0023 ± 0.0005	0.060 ± 0.017
[b] Standard	5.5–8.5	≤40,000	≤200	-	-	≤0.01	≤1	≤0.2	≤2

[a]FC, is fecal coliform number (MPN/L); COD, is chemical oxygen demand; Data values represent the mean ± standard deviation (n = 3).
[b]The standard is Agricultural Irrigation Water Standard of China (GB, 5084–2021).

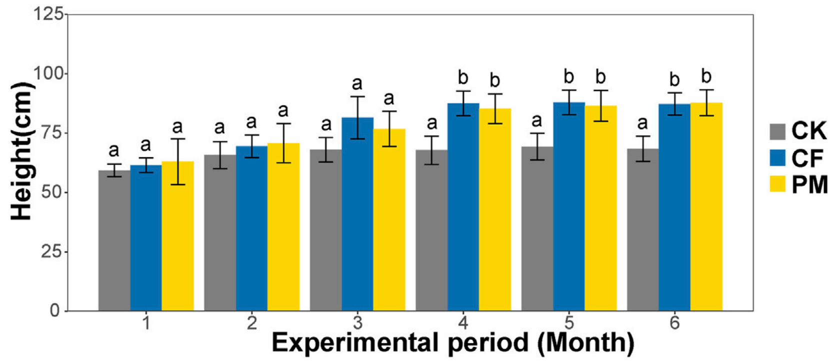

FIGURE 3
Plant heights of *H. chrysanthus* seedlings grown in soil with or without sludge addition (CK: the seedlings were grown in soil; CF: the seedlings were grown in soil with chemical fertilizers; PM: the seedlings were grown in soil amended by an equal mass of *P. hybridum* phyto-treated sludge. Different letters indicate that the difference was significant in the height between the treatments according to Duncan's multiple range test (n = 4, p = 0.05)).

4.58 and 75.35 ± 13.11 cm, respectively) and the plants grown in soil were only ~50 cm tall (49.33 ± 6.66 cm). The *J. sambac* plants grown in the AM- and PM-treated MSS were significantly taller than the *J. sambac* plants grown in soil (n = 10, p = 0.05).

3.6.2 Growth of *H. chrysanthus* seedlings fertilized with treated MSS

The heights of the *H. chrysanthus* plants from the three treatments are shown in Figure 3. The seedling heights were significantly different for the different treatments in month 4 (n = 4, p = 0.05). The plants from the chemical fertilizer treatment and PM (i.e., *P. hybridum* treated MSS) treatment were significantly taller than the plants from the CK treatment, but the plants from the chemical fertilizer and PM treatments were not significantly different (n = 4, p = 0.05). The PM-treated MSS performed as well as or better than the chemical fertilizer treatment, indicating that *P. hybridum* treated MSS provided a good degree of fertilization.

3.7 Carbon emission

The net GHGE is estimated for 1 t fresh MSS. The properties of MSS were referred to MSS I (87.98% water content, 43.56% organic matter, and 4.26% total nitrogen), and the MSS reduction was 85% for the comprehensive recycling and 63% was taken for the composting treatment (Liu et al., 2014). Only the carbon emissions in the treatment processing are considered, excluding the carbon emissions generated during the sludge concentration and dewatering in sewage treatment plant and the subsequent utilization/ application of sludge products.

The emissions of CH_4 from aerobic composting treatment can be taken as 0.2 kg/t (Wang et al., 2022), and are negligible in the comprehensive treatment due to the small volume of MSS in each planting unit. The emission of N_2O during aerobic composting was taken as 0.043 kg/t (Liu et al., 2014). The denitrification of the comprehensive treatment is weak, and the production of N_2O should not exceed that of the composting treatment. The value taken is consistent with that of composting, 0.043 kg/t. Therefore, according to the calculation of Eq. (3), the direct carbon emission from composting treatment is 17.81 kg CO_2e, and the comprehensive treatment is 12.81 kg CO_2e.

The garden forestry site of the comprehensive treatment is usually farer than that of composting site, so the transport distance for the comprehensive treatment is taken as 50 km, while the composting treatment is taken as 30 km. The composting process consumes electrical energy with a

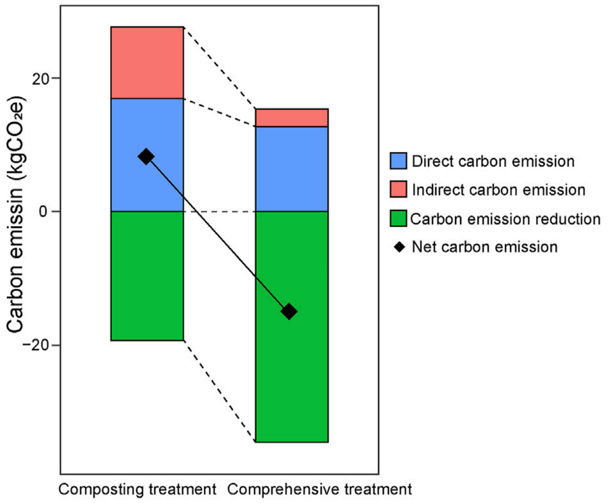

FIGURE 4
Comparison of the carbon emissions of a composting treatment and the comprehensive treatment.

consumption of about 10.06 kWh/t (Liu et al., 2014), while the comprehensive treatment has no electrical energy consumption. Therefore, the indirect carbon emission of composting treatment is 9.67 kg CO_2e and the comprehensive treatment is 2.63 kg CO_2e, calculated according to Eq. (4).

According to the reduction rate of MSS after treatment, the sludge mass after composting is 370 kg, and the comprehensive recycling is 150 kg. The loss rate of N in composting treatment is about 40% (Wang et al., 2019), then the N content of composting treatment is calculated as 2.56%, and the comprehensively treated MSS is measured as 2.60%. In addition, the comprehensive recycling is capable of producing plant products, for example, 1 t fresh MSS can produce about 16 kg of dry matter in the case of *P. hybridum*. Therefore, according to the calculation of Eqs 5, 6, the carbon reduction of composting treatment is -19.33 kg CO_2e and the comprehensive recycling is -31.22 kg CO_2e.

As a result, the carbon emissions of the two treatments are shown in Figure 4. The net GHGE from the composting treatment was 8.15 kg CO_2e and the comprehensive recycling was -15.79 kg CO_2e. This means that the comprehensive recycling of MSS is carbon-negative and contributes to the reduction of carbon emission.

4 Discussion

Comparison between the comprehensive recycling and the conventional land application in environmental benefits.

The comprehensive recycling could fully utilize the nutrients in fresh MSS. A water-permeable material was used to separate the MSS from the soil. Nutrients could be leached from the MSS for use by the *H. chrysanthus* trees but heavy metals were mainly retained by the MSS. The method effectively decreased the amounts of heavy metals that were released from the MSS into the soil (Lin et al., 2021b). In addition, both *A. macrorrhiza* and *P. hybridum* could strongly grow on the MSS, so these species could be used to treat the MSS and therefore offer economic benefits. The conventional method for utilizing MSS on land is the application of composted MSS. Organic pollutants in MSS can be decomposed during the composting process (Zhang et al., 2019) and the bio-availabilities of heavy metals can decrease (Chen et al., 2019). However, composting cannot fundamentally solve the problems caused by heavy metals in MSS. Applying MSS compost can still cause heavy metals to accumulate in soil and plants (Papafilippaki et al., 2015). Repeated applications of MSS compost to soil can markedly increase the amounts of heavy metals leached from the MSS-treated soil and pose the risk of underground water becoming polluted (Fang et al., 2017). The comprehensive treatment could decrease the amounts of heavy metals released into the soil. Our results indicated that the heavy metal contents of the soil did not increase markedly when large amounts of MSS were utilized by comprehensive treatment, as shown in Figure 2A and Table 4.

China has currently proposed two goals of carbon peaking and carbon neutrality, which set a higher standard for how MSS should be treated. The carbon emissions of composting treatment and the comprehensive recycling were also calculated. The emission of N_2O of the comprehensive treatment was set to equal to aerobic composting and the emissions of CH_4 was omitted, due to the lack of available data. Wang et al. (2022) calculated net carbon emissions from different treatment processes for MSS (40–50% OM) and found that composting treatment had lower net carbon emissions than landfills, incineration, pyrolysis, and anaerobic digestion. This study shows that the net carbon emissions of the comprehensive recycling are even lower than those of composting (Figure 4). The comprehensive recycling achieves carbon reduction and is conducive to achieving the dual carbon goals.

In addition, the comprehensive treatment also facilitated the fixation of CO_2 by *H. chrysanthus.* The carbon stock was estimated to be 50% of the total biomass (IPCC 2005) which consist of above ground biomass (AGB) and below ground biomass (BGB). The BGB was estimated from AGB using a root-shoot ratio of 0.26 and the AGB of the trees can be estimated as Khadanga and Jayakumar (2020) proposed. The formula is as follows:

$$AGB\,(kg) = \rho \times \exp\left(-0.667 + 1.784 \times lnD + 0.207 \times (lnD)^2 - 0.0281 \times (lnD)^3\right) \quad (7)$$

where ρ is the wood specific gravity, 1.096 g/cm^3 (Castellanos and Ramón, 2018), ln is the natural logarithm, and D is the diameter at breast height, cm.

According to Table 3, the diameter at breast height was from 7.05 ± 0.50 cm to 8.41 ± 0.64 cm for the CK treatment, and was from

6.72 ± 0.51 cm to 9.47 ± 0.89 cm for the PM treatment. Therefore, according to Eq. (7), the increased biomass of one *H. chrysanthus* tree in the CK treatment can be estimated as 20.41 kg and the PM treatment can be estimated as 43.89 kg. The biomass of each *H. chrysanthus* tree in the PM treatment increased by 23.48 kg over the CK treatment. The planting density of the PM treatment is 800 plants/ha, which means an additional 18.78 t of biomass and 9.39 t of carbon sequestration per hectare of land can be obtained. The comprehensive recycling achieves more carbon fixation, which likewise contributes to the dual carbon goal.

Comparison between the comprehensive recycling and the conventional land application in economic benefits.

The proposed comprehensive recycling does not require a large investment but does require a large area of garden forestry lands (including fruit forestry). However, the garden forestry lands do not affect its productivity by additional sludge phyto-treatment, the garden trees even grow better than the control as shown in this study. In addition, the comprehensive recycling can produce economic benefits in a number of ways: 1) Nutrients for garden plants are provided, meaning smaller amounts of mineral fertilizers need to be purchased; 2) The system markedly improves the nutrient contents of the soil under the indirect application device and improves the soil; 3) Sludge treatment plants growing in the MSS can be used as organic fertilizer or animal feed or plant fuel even for papermaking; 4) After the utilization process is complete, the MSS is fully mature and can be used as organic fertilizer or substrate for garden plants; 5) Carbon emission reductions from MSS treatment can be traded in the carbon trading market.

The main methods to dispose MSS are land application, incineration, disposal in sanitary landfills and making building materials, which accounted for 29.3%, 26.7%, 20.1%, and 15.9%, respectively, of the total amount of MSS disposed of in China in 2019 (Wei L. et al., 2020). The comprehensive recycling used in this study is in the 'land application' category. The ultimate goal of any land application system is to make use of the nutrients in MSS, it means less expenditure on chemical fertilizers and more economic value generation. Gouin (1985) reported that composted sewage sludge could replace a complete fertilizer to get comparable growing of Chrysanthemums. The comprehensive recycling reuses directly and comprehensively the nutrients in fresh MSS, and is suitable in gardening developed areas such as Guangdong Province of China.

5 Conclusion

The main conclusions are drawn as follows:

(1) The comprehensive recycling increased the growth of *H. chrysanthus*. Good levels of biomass production and nutrient extraction were achieved when *P. hybridum* was planted in fresh sludge and harvested in month 3.
(2) The heavy metal contents of the soil did not markedly increase during the experiments but the N, OM, and P contents increased markedly, the comprehensive recycling has little impact on potential ecological risk to the soil.
(3) The MSS became mature by the end of the process and was suitable for use as a substrate for cultivating flower seedlings.
(4) Even fresh MSS that exceeded the relevant standards gave leachate with fecal coliform and Cu concentrations that met the standards for irrigation water.
(5) The comprehensive recycling, which has lower carbon emissions than composting, is carbon-negative and suitable in gardening developed areas.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

XL: Investigation, Writing – original draft, Formal analysis. CC: Investigation. HL: Methodology. LH: Resources. LZ: Visualization. ZW: Formal analysis. YC: Supervision. Q-TW: Conceptualization, Writing – review and; editing, Funding acquisition.

Funding

This study was supported by the R & D program of Guangdong Provincial Department of Science and Technology (Grant No. 2018B030324003, 2021B1212040008, 20220307); Local Innovation and Entrepreneurship Team Project of Guangdong Special Support Program, China (Grant No. 2019BT02L218); the Water Resources Innovation Project of Guangdong Province, China (Grant No. 2017-29); the National Natural Science Foundation of China (Grant No. 21606092).

Acknowledgments

We thank Gareth Thomas, PhD, from Liwen Bianji, Edanz Group China, for editing the English text of a draft of this manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1023356/full#supplementary-material

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