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Fertilization Value of Biosolids on Nutrient Accumulation and Environmental Risks to Agricultural Plants

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Abstract Amendment with treated biosolids can increase soil fertility and plant nutrition to the soil, but the fertilization value compared with other commercial soil amendments on the soil ecosystem is poorly understood. The effects of different proportions (0%, 5%, 10%, and 15%) of thermal and pH-treated biosolid applications on the growth performance, nutrient contents, and toxicity performance of carrots (*Daucus carota* L.) and choy sum (*Brassica chinensis* var. *parachinensis*) were studied. Different commercial organic soil amendments, such as biochar, chicken manure (CM), and food waste compost (FWC), were also used as a comparison in the experiment to determine the feasibility of biosolid application on agricultural use. All four soil amendments resulted in similar growth trends for the carrots and choy sum, and this information can be applied in selecting the appropriate species of plants. Through thermal and pH treatments, the treated biosolids decreased environmental risks and resulted in higher amounts of N and P in comparison to the other soil amendments. The results showed that 10% biosolid-amended soil performed best in terms of plant growth, biomass, and nutrient content for both carrots and choy sum. Nutrient analysis (N, P, and K) and heavy metal analysis (As, Cd, and Pb) on both soil and plants were conducted. It was proven that biosolid application was as functional as CM application and could be used as organic fertilizer to replace biochar and FWC for agricultural use. No heavy metals were found in the pure biosolids, which were safe to use as fertilizers. Utilizing biosolids as fertilizers could be an effective way to address the problem of waste disposal and landfill loading for the environment.

Keywords Agriculture · Biosolids · Nutrition · Organic fertilizer · Plant growth

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1 Introduction

Hong Kong produces over 1200 tons of sewage sludge per day from different sewage treatment works (STWs). Due to population growth and upgrades or improvements to STWs, it is expected that the sewage sludge amount will increase to 2000 tons in 2030 (TPARK 2018). The main treatment methods of sewage sludge in Hong Kong are incineration and landfill disposal. Incineration processes can produce a large amount of toxic gases, such as dioxin and xylene, which may cause serious air pollution. Incineration reduces the volume of sewage sludge while increases air pollutant emissions (TPARK 2018), indicating it may not be a sustainable sewage sludge treatment method. Most of the residues and ashes generated from incineration are sent to landfills (AFCD 2018b). On the other hand, landfill is the most common approach for the disposal of sewage sludge. The increasing population number increased the quantities of solid waste disposed at landfills from approximately 5×10^6 tons in 2011 to 6×10^6 tons in

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2018. However, Environment Bureau (ENB) in Hong Kong estimated that three landfills would be full in 2019–2020 if the plan for landfill expansion could not be implemented. It is believed that these three landfills will be successively full in the 2020s (HKEB 2013). The expansion of landfills may not be sustainable in the long term due to land shortage in Hong Kong; therefore, we need to determine a more suitable treatment for sewage sludge.

Raw application of sewage sludge can cause environmental risks such as soil contamination and water pollution. The application of untreated sewage sludge on agricultural land may be restricted as it consists of different types of heavy metals such as cadmium (Cd) and lead (Pb). The long-term use of untreated sewage sludge could result in the high accumulation of heavy metals in soils (Balkhair and Ashraf 2016; Lu et al. 2012). Even though untreated sewage sludge is applied in a short time period, the heavy metal contents in soils can substantially increase. In this case, Oliveira and Mattiazzo (2001) reported that the Zn, Cr, and Cu contents in the soils were increased after only 2-year application of untreated sewage sludge (Oliveira and Mattiazzo 2001). As a result, food chain and crop yields could be affected directly by high levels of heavy metals (Liu et al. 2009). Therefore, it is necessary to convert untreated sewage sludge to useful biosolids for further use in terrestrial environments. Currently, several approaches can be used to convert sewage sludge as biosolids (Lu et al. 2012) such as thermal, pH treatment, dewatering, and digestion. Thermal and pH treatments are often applied as disinfection processes to eliminate potential pathogens and remove the odor of sewage sludge. Dewatering process reduces the water content in sewage sludge, which can improve the suitability for land application. Digestion can help to reduce disease-causing organisms and organic matter. Therefore, biosolids which are generated from these treatment processes can lower the environmental impacts during land application. In the late twentieth century, humans started using biosolids from municipal treatment plants on agricultural lands as a nutrient subsidy (Brisolara and Qi 2015). In the USA, almost half of biosolid production is being applied to agricultural lands as fertilizer. In European countries, the use of biosolids occurs in over 30% of their agricultural lands (Lu et al. 2012). In Taiwan, biosolid applications for agricultural purposes increased from approximately 7500 tons in 2004 to 13,500 tons in 2010 (Kookana et al. 2011). Biosolid application in soils can help to regulate the pH value, organic matter, and nutrient contents (Brisolara and Qi 2015). Biosolids consist of different amounts of nutrients, which include high amounts of nitrogen and phosphorus (Lu et al. 2012), which are necessary for plant growth and development; e.g., N is important for photosynthesis and transpiration; P can help to improve flower formation and seed production. In this case, the application of biosolids during agriculture can effectively increase the dry matter yield of crops and soil physical-chemical properties (White et al. 2011).

Moreover, the scale of agricultural land use in Hong Kong is generally small due to the scarcity of land and geographic constraints. Existing agricultural land only occupies 7 km^2 in Hong Kong (AFCD 2018b). Therefore, only a small amount of local vegetables and ornamental plants can be produced. Local production of vegetables cannot fulfill the demand of 2427 tons of vegetables needed for daily consumption by Hong Kong's population (AFCD 2018a). According to the World Bank, fertilizer consumption in Hong Kong has increased continuously, from 598 kg per hectare of arable land in 2013 to 2704 kg per hectare of arable land in 2016. Therefore, plant growth performance is a qualitative aspect of plant species that is directly affected by mineral nutrition and external environmental factors. Organic fertilizers have been used on Hong Kong organic farmlands to preserve the natural environment while increasing field production. Organic fertilizers are made with a combination of different organic waste types, such as green waste and animal manure. Common types of organic fertilizer used are bone meal, peanut bran, chicken manure, horse manure, and food waste compost. They decompose slowly in the soil and release substantial nutrients for crop growth. The most common commercial organic fertilizers are biochar, chicken manure (CM), and food waste compost (FWC). Biochar is a carbonaceous recalcitrant product of biomass produced through the process of pyrolysis (Pessenda et al. 2001), which is a more stable form of carbon that is difficult to break into components (William and Qureshi 2015). CM is commonly used in agricultural applications since it consists of high concentrations of N and P (Schjegel 1992). The application of CM increases the organic C percentage and water-holding capacity by nearly 80% (Khaleel et al. 1980). FWC could increase the total organic matter and nutrients in the amended soils according to the rate of compost application (Stamatiadis et al. 1999).

However, there are limited studies that have been conducted to determine the nutritional value of biosolids by different treatments and to compare them with other commercial organic fertilizers, as well as to examine the effects of biosolid application on edible plants and soils. Therefore, this study measured the fertilization effects of biosolids on the growth performance of two common vegetable plants and examined the nutrient contents of different proportions of biosolids on the plants and soils for agricultural purposes. We hope to provide an alternative method of sludge disposal to address full landfills and incineration in different cities. Turning sewage sludge into useful biosolids is a concept of "waste-to-energy", which should be widely used to increase fertilization values for agricultural plants.

2 Materials and Methods

2.1 Treatment Method of Biosolid

In this study, sewage sludge was collected from the Shek Wu Hui STW, and the collected sewage sludge was placed for at least 3 months in a cold room, which was the residence time for the sewage sludge. Based on US Environmental Protection Agency (USEPA), pH amendment and heat drying methods were recommended to convert the sewage sludge to useful biosolid. The original pH values of the sewage sludge ranged from 8.3 to 8.7, which were slightly alkaline and not favorable for plant growth (Wong et al. 2002). It was recommended to control soil pH in the range of 5.5 to 7.5 to minimize metal leaching and maximize crop growing conditions (AFCD 2018b). Therefore, the pH of sewage sludge was adjusted to 6 for the pH amendment. The pH of well-mixed sewage sludge was measured by a pH meter, and sulfuric acid (1 M) and sodium hydroxide (1 M) were used to adjust the pH value. According to the US Environmental Protection Agency, sewage sludge needs to be dried until the moisture content reaches 10% or lower through indirect or direct contact without gases before application. A thermal treatment was conducted to remove moisture at temperatures over 80 °C to ensure that the soil is sterile (Ewing et al. 1978). Thus, the pH-adjusted sewage sludge was placed in aluminum containers for the 180 °C thermal treatment until the sewage sludge was completely dry and transformed to biosolids. The biosolids were ground to powder and passed through a 2-mm sieve for further analysis and planting.

2.2 Planting Materials

Soil in Hong Kong is mainly dominated by sandy loam soil (Chau and Chan 2000); therefore, sand, peat moss, and pond clay were mixed to simulate the sandy loam soil in this experiment. The pH of the original soil was 6.8 ± 0.3; the soil contained with 78.4% sand, 15.4% silt, and 6.2% clay; and the organic carbon was at 0.62%. Choy sum is native to mainland China and is believed to have been cultivated since the fifth century. Carrot and choy sum are one of the most popular vegetables found at local markets across Asia and Southeast Asia. Therefore, carrot (*Daucus carota* L.) and choy-sum (*Brassica chinensis* var. *parachinensis*) were selected for the plant experiment, and they were purchased from Brighten Floriculture, an urban farmland at Hong Kong.

2.3 Planting Experiment Setup

Three different organic fertilizers were selected for the fertilization value comparison with biosolids, which are biochar, CM, and FWC. The preparation of the biochar can be found in our previous publication (Pan 2020). FWC was obtained from Hong Kong Baptist University, and a schematic diagram of the compost reactor and operational details were presented in a previous publication (Wong et al. 2009). The CM was purchased from city farm, an urban farmland in Hong Kong. The planting medium mainly consisted of potting mixes with different proportions of biosolids, biochar, CM, and FWC. The application doses of biosolids, biochar, CM, and FWC were designed to be 0%, 5%, 10%, and 15% (dry weight, w/w) for each at the beginning. Each type of plant had 4 setups, and each set up consisted of four replicates for accuracy, and planting procedures can be found in our previous publication (Pan and Chu 2017; Pan and Chu 2018). Each pot has 3 kg potting mixes, and the irrigation volume was 200 mL for every 2 days; the planting experiment was conducted in a constant temperature (25 ± 2 °C) greenhouse. No additional fertilizers were added to ensure that the result was not affected. The growth performance, including height and leaf area, and soil moisture content and soil temperature were recorded every week. Soil physicochemical properties, plant nutrients, and heavy metal analysis tests were determinated when the target plants reached marketable size. Soil and plant analyses were conducted twice, before and after the planting experiment.

2.4 Soil Physicochemical Properties and Nutrient Levels

Biosolids, biochar, CM, and FWC were ground into small particles and passed through a 2-mm sieve for soil extraction. Soil physicochemical properties and nutrient values, including the pH value; conductivity; total organic carbon (TOC); water-holding capacity; total N, P, and K content; and heavy metal concentrations, were measured at the beginning of and after the planting experiment. Soil physicochemical properties were determined according to methods of the American Society for Testing and Materials (ASTM 2006, 2007; ATSM 2009). The soil pH value was measured by a pH meter in distilled water (1:1). Organic carbon was analyzed using a TOC analyzer (Shimadzu, Japan). The maximum water-holding capacity was determined according to the guidelines of the International Organization for Standardization (ISO 2012). Total N content was extracted by the micro-Kjeldahl method (Jackson 1973) and determined by continuous flow analysis (CFA). Total P and K was extracted by the micro-Kjeldahl method (Jackson 1973) and determined by atom absorption spectrometry (AAS, Perkin Elmer 4100 ZL, USA). Heavy metal contents (As, Cd, and Pb) were extracted and acid digested according to DIN guideline 38414-S7 (DIN 384141-S7 1983) and analyzed by AAS.

2.5 Plant Growth Performance and Nutrient Levels

Leaf area, growth performance, and plant biomass were measured to determine the effects of biosolids, biochar, CM, and FWC application on plants. The growth performance of the plants was measured weekly. A plant nutrient test was also conducted to investigate the amount of nutrients and heavy metals within the plants. Briefly, all harvested plant samples were washed using distilled water and cut into small pieces with a disinfected knife. The vegetated parts of the plants were freeze dried at − 20 °C for a week, after which the dried plant samples were ground into a fine powder using a blender and stored in polyethylene bags for acid digestion. The extraction method was according to Allen et al. (1986). After the solution became transparent, the digested samples were filtered and diluted to 100 mL with deionized water for further nutrient and heavy metal analysis. Total N, P, and K contents and heavy metals were measured using the same methods as those for the soil nutrient analysis test.

2.6 Nutrient Balance Calculation

The nutrient balance was estimated for each biosolid, biochar, CM, and FWC treatment. Ten percent biosolid, 10% biochar, 5% CM, and 5% FWC were selected in the nutrient balance calculation, as they had the highest total N, P, and K values compared to the other proportions of the soil amendments.

The N balance can be written as:

$$N_{\text{initial}} + N_{\text{input}} + N_{\text{min}} - N_{\text{uptake}} - N_{\text{residual}} = N_{\text{surplus}} \quad (1)$$

where N_{initial} is the initial soil nutrient (total N, P, and K) contents; N_{input} is the nutrient (total N, P, and K) application rate for biosolids, biochar, CM, and FWC; N_{min} is the nutrient (total N, P, and K) mineralization; N_{uptake} is the nutrient (total N, P, and K) uptake by plants; N_{residual} is the residual nutrient (total N, P, and K) in the soil profiles; and N_{surplus} represents the nutrients (total N, P, and K) stored in various soil fractions (e.g., nutrient loss by leaching).

$N_{\text{mineralization}}$ (N_{min}) was estimated by the balance of the nutrient (total N, P, and K) inputs and outputs in the control as follows:

$$\mathrm{N_{min}} = \mathrm{N_{uptake,0}} + \mathrm{N_{residual,0}} - \mathrm{N_{initial,0}} \quad (2)$$

where $N_{\text{uptake, 0}}$, $N_{\text{residual, 0}}$, and $N_{\text{initial, 0}}$ are plant nutrient uptake and residual and initial soil nutrients in the soil profile of the control, respectively.

$$N_{\text{utilization}} = N_{\text{input}} - N_{\text{surplus}} \quad (3)$$

$$\text{NUE} = N_{\text{utilization}} / N_{\text{input}} \quad (4)$$

$N_{\text{utilization}}$ is the part of N_{uptake} offered by different soil amendments. NUE is the nutrient use efficiency of the biosolids, biochar, CM and FWC during the planting of carrot and choy sum.

2.7 Data Analysis

All data were analyzed by Statistical Product and Service Solutions (SPSS, IBM Statistics). One-way ANOVA was used to examine the effects of the application of different soil amendments and the growth performance of different plant species and their corresponding nutrient concentrations. All the data were checked by Levene's test for homogeneity of variances and Kolmogorov-Smirnov test for data normal distribution. The treatments were evaluated using Dunnett's test at the 5% level of significance. Data on growth performance and nutrient content were graphed using Sigma Plot (12.5 version).

3 Results and Discussion

3.1 Growth Performance of Plants under Different Treatments

In the first week, carrot growth under the treatments of biosolid, biochar, CM, and FWC is similar (Fig. 1). Carrots planted in biosolid- and CM-amended soil had similar trends starting from week 4, with heights ranging from 4.2–21 cm to 4.7–22 cm, respectively. However, carrots planted in biochar and FWC grew more slowly than those in the other two treatments did, with heights ranging from 4.0–17.6 cm to 4.2–18.6 cm, respectively. The growth performance of choy sum planted under different proportions of biosolids, biochar, CM, and FWC is similar to that of carrots (Fig. 1). The height of the choy sum increased from 3.7 to 20.1 cm and 3.8 to 20.7 cm under the treatments of 10% biosolids and 5% CM from week 1 to week 20, respectively. However, the height of the choy sum ranged from 3–17.2 cm to 3.6–18.9 cm under the treatment of 10% biochar and 5% FWC, respectively. The growth performance results showed that carrot and choy sum grew best under 10% biosolid, 10% biochar, 5% chicken manure, and 5% food waste compost. Both carrots and choy sum planted in 10% biosolid-amended soil and 5% CM-amended soil performed better in terms of height, which indicated that the biosolid and CM applications could promote plant growth. Both biosolid and CM could provide similar nutrients for carrot growth (Eskin 1989). CM application has been shown to promote plant growth in terms of height and number of leaves (Odedina et al. 2015), improve soil structure and water-holding capacity, as well as increase microbial populations (Dauda et al. 2008). Biosolids have been proven to have positive effects on the growth and yield of agricultural crops (Rouch et al. 2011). Leila et al. (2017) also found that the plants of *E. camaldulensis* fertilized with biosolids had 20% increased growth and 40% relatively higher leaf numbers and improved plant development, without negative effects on tree heath (Leila et al. 2017). Nevertheless, among these four soil amendments, the lowest height of the carrot and choy sum planted was measured in the biochar-amended soil, indicating that the promoting effect of biochar on plant growth was not as good as that of the other soil amendments.

In addition, the height of carrots planted in all types of 15% soil amendments decreased; thus, the use of a higher amount fertilizer was not benefit for carrot growth. Overfertilization could increase soil acidity and then limit plant health. A similar tendency was reported by (Wilber and Williamson 2008). The bad effect on plant growth was found with higher fertilizer dosage which was attributed to the high incidence of stem blight. In addition, high concentrations of fertilizer application could also cause chemical burns to crops (Graham et al. 2002) and raise the water potential of the soil water, which leads to plant water loss (Molz 1981) and further affects plant growth.

3.2 Biomass of Plants Under Different Treatments

Generally, choy sum had higher biomass than carrot under different proportions of biosolids, biochar, CM, and FWC. Control treatment without solid amendment presented the lowest biomass concentration (Table 1). Similar to the results for the growth performance, the biomass of the carrots and choy sum was highest in 10% biosolids, 10% biochar, 5% chicken manure, and 5% food waste compost than the other proportions. Moreover, the 10% biosolid treatment resulted in the highest biomass for the carrots and choy sum compared to those with the other soil amendments, and the biomass was 2506 mg and 3480 mg for the carrots and choy sum, respectively. The 5% CM and 5% FWC treatments resulted in similar biomass values for carrots (2059 mg and 2092 mg, respectively) and choy sum (3080 mg and 2911 mg, respectively). Moreover, the biomass values of carrot and choy sum presented in the treatment of 10% biochar-amended soil were 1890 mg and 2786 mg, respectively. Therefore, among these four materials, biosolid can be identified as a proper carrier during soil bioamendment process, which helps to increase nutrient retention and utilization efficiency by plant biomass. At the same time, 10% biosolid application was recognized as the best amendment ratio for maximizing the use of fertilizer and facilitating plant growth of carrots and choy sum. Besides that, applying biosolids could promote the growth response to ornamental crops and urban tree, and plant quality exceeded horticultural standards (Hummel et al. 2014; Sax and Scharenbroch 2017).

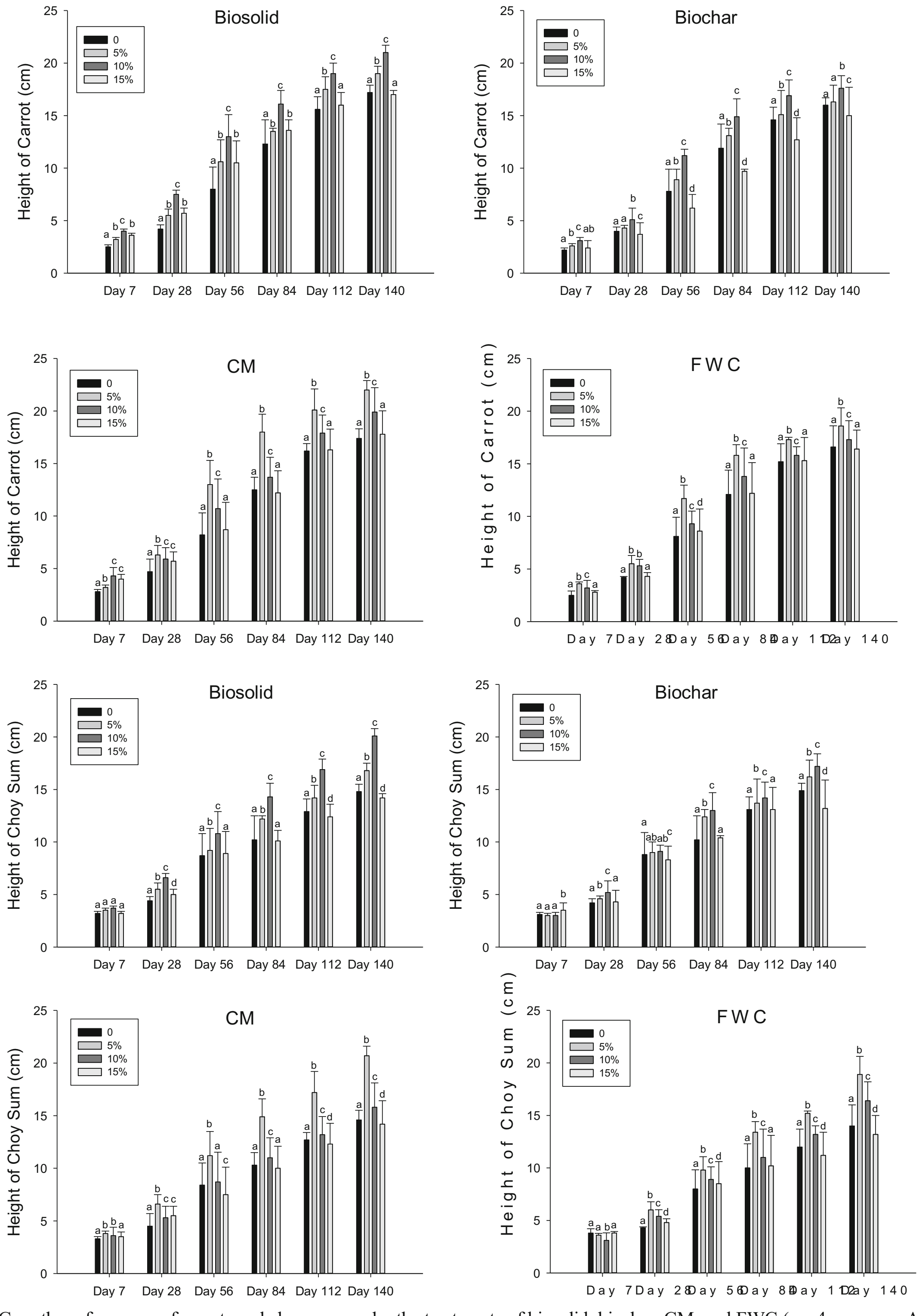

Fig. 1 Growth performance of carrots and choy sum under the treatments of biosolid, biochar, CM. and FWC ($n = 4$, one-way ANOVA)

Table 1 Biomass of carrots and choy sum under the different treatments (fresh weight, mean value ± SD, $n = 4$)

Biomass (mg)			
Soil amendment	Concentration	Carrot	Choy sum
Biosolid	0%	1270	2008
	5%	1853	2725
	10%	2506	3480
	15%	1214	2058
Biochar	0%	1270	2008
	5%	1450	2260
	10%	1890	2786
	15%	1240	2139
CM	0%	1270	2008
	5%	2059	3080
	10%	1872	2585
	15%	1308	2318
FWC	0%	1270	2008
	5%	2092	2911
	10%	1852	2743
	15%	1258	2232

3.3 Total Nutrients (Nitrogen, Phosphate, and Potassium) in Soil

In comparison to the other soil amendments, pure biosolids performed the best in terms of total N and P (Table S1). The biosolids contained 56,000 mg/kg of total N, 54,800 mg/kg of total P, and 42,137 mg/kg of total K. The concentration of total N in these four pure soil amendments followed the order: biosolids > CM > FWC > biochar. Biochar had the lowest total N with a concentration of 20,500 mg/kg. The concentration of total P in these four pure soil amendments followed a similar trend as that of total N, but the concentrations in biochar, CM, and FWC did not show significant differences ($p > 0.05$). Furthermore, pure biochar contained the highest total K with a concentration of 48,300 mg/kg. But there is no available information concerning how biochar affects the C and N stocks, microbial activity, and N mineralization in soil (Ippolito et al. 2012). The concentration of total K in these four pure soil amendments followed the order biochar > biosolids > CM > FWC. The control soil contained the lowest total nutrients after planting, which were 11,200 mg/kg (total N), 6700 mg/kg (total P), and 21,600 mg/kg (total K). As shown in Fig. 2, the highest concentrations of total N are presented in all of the 15% treatments with biosolid, biochar, CM, and FWC after the planting of the carrots and choy sum. However, in comparison to the control soil, the 5% treatments of biosolids, CM, and FWC had lower total N. For example, the total N for 5% biosolids was 10,897 and 10,579 mg/kg in the carrot and choy sum soils, respectively. The use efficiency of the applied fertilizer increased with the addition of biosolids, biochar, CM, and FWC to the soil and reduced the N_2O gas emissions and in turn increased the available nitrogen for plants (Case et al. 2015). The total P and total K concentrations in the soils increased gradually according to the added proportions of biosolids, biochar, CM, and FWC. For example, the total P increased from 6700 mg/kg in the control to 9920 mg/kg in 15% biosolid soil. Some studies also have shown that biosolids could supply large amounts of N and P to plants (Corrêa 2004), which would result in a 10 to 20% increase in nutrients in soil (Jacobs and McCreary 2001). In fact, the effects of biosolids on nutrient bioavailability depend on the nature of the organic matter, their microbial degradability, soil pH, and redox potential, as well as on the particular soil type and nutrients (Hooda et al. 1997). As revealed by Torri (2014), the application of biosolids could enhance the soil microbial activity due to the inputs of labile C and nutrients in biosolids. Therefore, in comparison to other organic fertilizers, soil fertilization with biosolids potentially provides more total N and P that could increase organic matter, improve nutrient retention, and improve soil structure (Arduni et al. 2018; Stehouwer et al. 2006).

3.4 Total Nutrients (Nitrogen, Phosphate, and Potassium) in the Plants

The nutrient levels in plant were corresponding to the total N, P, and K level retained in the soil. In the biosolid treatment, carrots planted in the 10% biosolid application perform the best in terms of total N, P, and K, with concentrations of 4450, 658, and 677 mg/kg, respectively (Table 2). Choy sum also showed a similar trend as that of carrots, and the highest amounts of total N (3,730 mg/kg), total P (547 mg/kg), and total K (595 mg/kg) were observed in the 10% biosolid application. These results showed that the application of 10% biosolid allowed carrots and choy sum to absorb and store more nutrients for growth. All nutrient concentrations decreased by 15% for the carrot and choy sum, indicating that the higher biosolid application did not

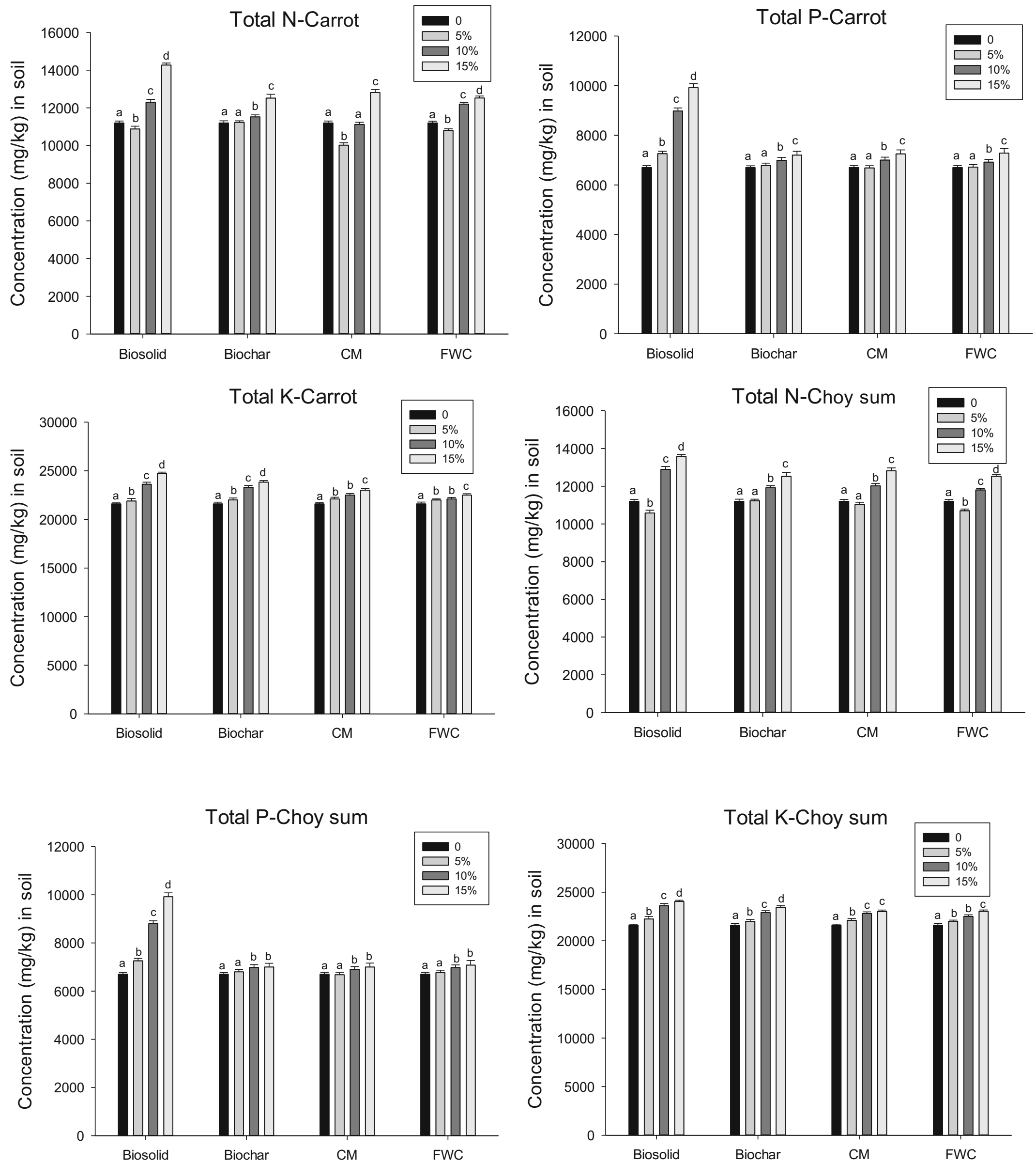

Fig. 2 Total nutrients (nitrogen, phosphate and potassium) in the soils of carrot and choy sum ($n = 4$, one-way ANOVA)

provide more nutrients during planting. A field study also showed multiyear effects of biosolid applications on the nutrient availability of agricultural soil and elemental sufficiency in plants (Dede et al. 2017; Mossa et al. 2020). Moreover, the nutrient content for the carrots and choy sum planted with biochar-amended soil was much lower than that planted with the other fertilizers (Table 2). The 10% biochar application had the highest nutrient concentration for carrot, resulting in 2790 mg/kg of total N, 412 mg/kg of total P, and 509 mg/kg of total K. Choy sum planted in the 10% biochar application also performed the best in terms of total N, P, and K, with concentrations of 1960, 347, and 487 mg/kg, respectively. Furthermore, the nutrient content of both the carrots and choy sum decreased with the 15% biochar application.

For the CM application treatments, the highest amount of nutrients appeared in carrots and choy sum planted in 5% CM-amended soil (Table 2). The amount of total N was 4260 mg/kg, total P was 592 mg/kg, and total K was 670 mg/kg in carrot. Choy sum planted in 5% CM-amended soil also had high levels of total N

Table 2 Total nutrient (nitrogen, phosphate, potassium) in carrot and choy sum under different treatments (mean value ± SD, *n* = 4)

Species	Soil amendment	Concentration	Total N (mg/kg)	Total P (mg/kg)	Total K (mg/kg)
Carrot	Biosolid	0%	2060 ± 2	387 ± 1	393 ± 2
		5%	3670 ± 3	415 ± 2	542 ± 3
		10%	4450 ± 6	658 ± 2	677 ± 2
		15%	2500 ± 2	242 ± 1	483 ± 4
	Biochar	0%	2150 ± 3	373 ± 2	397 ± 3
		5%	2460 ± 4	381 ± 2	417 ± 2
		10%	2790 ± 3	412 ± 1	509 ± 3
		15%	1980 ± 1	173 ± 3	399 ± 5
	CM	0%	2080 ± 2	379 ± 1	365 ± 2
		5%	4260 ± 5	592 ± 2	670 ± 3
		10%	3820 ± 3	427 ± 1	622 ± 6
		15%	2370 ± 2	216 ± 5	354 ± 2
	FWC	0%	2040 ± 2	374 ± 2	378 ± 3
		5%	3080 ± 3	540 ± 3	619 ± 1
		10%	2140 ± 4	465 ± 5	582 ± 2
		15%	2010 ± 2	203 ± 3	350 ± 3
Choy Sum	Biosolid	0%	1840 ± 1	316 ± 2	332 ± 3
		5%	3130 ± 2	496 ± 4	412 ± 5
		10%	3730 ± 3	547 ± 6	595 ± 3
		15%	2940 ± 2	340 ± 1	312 ± 1
	Biochar	0%	1730 ± 3	290 ± 4	294 ± 1
		5%	1930 ± 2	303 ± 2	389 ± 6
		10%	1960 ± 2	347 ± 3	487 ± 3
		15%	1330 ± 1	273 ± 2	229 ± 4
	CM	0%	1810 ± 2	301 ± 2	315 ± 6
		5%	3040 ± 4	504 ± 4	581 ± 3
		10%	2800 ± 5	439 ± 1	434 ± 5
		15%	2220 ± 3	328 ± 1	317 ± 3
	FWC	0%	1780 ± 4	305 ± 3	330 ± 2
		5%	2910 ± 5	413 ± 2	506 ± 2
		10%	2140 ± 2	347 ± 3	439 ± 4
		15%	1840 ± 1	304 ± 2	316 ± 4

(3,040 mg/kg), total P (504 mg/kg), and K (581 mg/kg). For the FWC application treatment, the highest amount of nutrients appeared in 5% FWC-amended soil, which had 3080 mg/kg of total N, 540 mg/kg of total P, and 619 mg/kg of total K in carrot. Choy sum planted in 5% FWC-amended soil also had the highest amount of total N (2910 mg/kg), total P (413 mg/kg), and K (506 mg/kg). Then, the nutrient content gradually decreased with increasing CM and FWC concentration. Based on the comparison of different soil amendment applications, biosolids performed the best in terms of total N, P, and K in the carrots and choy sum. This result indicated that the 10% biosolid application could provide a large amount of essential nutrients for plant growth. Repeated applications of biosolids to soils would likely improve soil structure, water-holding capacity, physiochemical properties, and nutrient levels. Therefore, these results showed that biosolids are the best option for soil amendment in agricultural purposes. The results showed that using CM and FWC as fertilizers had similar effects on plant nutrients. However, both the carrots and choy sum planted in the biochar-amended soil had the least amount of nutrients. Some studies have also found that the application of biochar decreases the amount of N and P in soil (Laird et al. 2010). Biochar is a stable form of carbon that is difficult to break into components (William and Qureshi 2015), so that less nutrient could be released for plant utilization. Species selection also affected the nutrient content in the plants, as carrots had higher amounts of nutrients than choy sum under the same treatments.

3.5 Heavy Metal Concentrations in Soil and Plants

Cd, As, and Pb are the common components of heavy metal in organic fertilizer (Hooda et al. 1997), which were not detected in the biosolid- and biochar-treated soils. However, Cd, As, and Pb were detected at concentrations of 1.5, 1.2, and 3.5 μg/kg in the soil with 15% CM. In addition, 11 μg/kg Cd, 7.1 μg/kg As, and 33 μg/kg Pb were also found in the 15% FWC-treated soil. No heavy metals were detected in the carrots and choy sum under other proportions of biosolids, biochar, CM, and FWC. The detectable Cd, As, and Pb in the CM and FWC treatments indicated that their application may cause heavy metal pollution in terrestrial environments. According to USEPA, if one single heavy metal exceeds limits, the fertilizer cannot be applied in agricultural land. Meanwhile, the biosolid and biochar applications can be used as soil amendments since the amount of heavy metals was not detected compared to that in the CM and FWC treatments. The source of sewage sludge also affects the heavy metal content in biosolids, and the collected sewage sludge from Hong Kong mainly comes from household waste that has less heavy metal pollution than industrial waste. According to the City of Portland sewage sludge management reports, the concentration of heavy metals in sludge has continuously decreased since 2013 (Sullivan et al. 2015). Dede et al. (2017) also proved that the application of biosolids had little effect on the heavy metal contents of soil and fruit nutrient composition (Dad et al. 2018). Moreover, the treatments for biosolids in this study also reduced the presence of pathogens to below detectable levels and can be used without any pathogen-related restrictions for agricultural purpose. The results demonstrated that the biosolids can meet the regulatory safety restrictions and also be used as a commercial soil amendment for plant or crop production.

3.6 Nutrient Balance Calculation

Calculation of the nutrient (total N, P, and K) balance is a potentially useful method for predicting the risk of nutrient leaching from soil. The nutrient balances after the different treatments, e.g., 10% biosolids, 10% biochar, 5% CM, and 5% FWC, after the planting of the carrots and choy sum was calculated (Table 3). Nutrient use efficiency is a function of the capacity of a soil to supply sufficient levels of a nutrient and the ability of plants to uptake it (Baligar et al. 2001). Without the soil amendment, the amount of N_{min} ranged from 1730 to 2150 mg/kg, P_{min} ranged from 290 to 387 mg/kg, and K_{min} ranged from 294 to 397 mg/kg in the soil of the carrots and choy sum. The $N_{residual}$ level of the 10% biosolid and 10% biochar was higher than the $N_{initial}$ level for both carrots and choy sum, but the $N_{residual}$ level was lower than the $N_{initial}$ level for the 5% CM and 5% FWC applications. For the $P_{residual}$ of the treatments, only 5% CM showed lower values than the $P_{initial}$, and no $K_{residual}$ level of the treatments was lower than the $K_{initial}$. This indicated that the soil N and P were depleted to some degree. Compared to other treatments, the highest values of N_{uptake}, P_{uptake}, and K_{uptake} presented in the treatment of 10% biosolids; e.g., the N_{uptake} value was 4450 mg/kg for carrots and 3730 mg/kg for choy sum. This indicated the absorption of nutrients by roots could be promoted by 10% biosolid fertilization. After the application of different soil amendments to the soil, the residual N after plant harvest increased with the 10% biosolid and 10% biochar applications but decreased with 5% CM and 5% FWC applications. The residual P and K for all treatments increased after the harvest of the carrots and choy sum, resulting in less nitrogen accumulation in the soil profiles than that in the initial soil and therefore decreasing the environmental risk. These results suggested that of the treatments, the 10% biosolid application performed best and could be beneficial for crop uptake, balancing the nutrient level in the soil and alleviating soil nutrient leaching. The nitrogen utilization efficiency (NUE) in these fertilization treatments was 16.88–62.2% for carrots and 46.39–63.98% for choy sum. The PUE in these fertilization treatments was 37.49–46.57% for carrots and 38.4–46.6% for choy sum, and KUE ranged from 37.6 to 53.2% (carrots) and from 40.0 to 52.8% (choy sum). Among all the treatments, the 10% biosolid

Table 3 Nutrient balance and Nutrient translocation (total N, P, and K) from soil amendment to plant ($n = 4$)

Species	Treatment	$N_{initial}$ (mg/kg)	N_{input} (mg/kg)	N_{min} (mg/kg)	N_{uptake} (mg/kg)	$N_{residual}$ (mg/kg)	$N_{surplus}$ (mg/kg)	$N_{utilization}$ (mg/kg)	NUE
Carrot	Biosolid 10%	11,200	5600	2060	4450	12,293	2117	3483	62.20%
	Biochar 10%		2050	2150	2790	11,521	1089	961	46.88%
	CM 5%		1865	2080	4260	10,021	864	1001	53.67%
	FWC 5%		1260	2040	3080	10,801	618.6	641	50.89%
Choy sum	Biosolid 10%		5600	1840	3730	12,893	2017	3583	63.98%
	Biochar 10%		2050	1730	1960	11,921	1099	951	46.39%
	CM 5%		1865	1810	3040	11,021	814	1051	56.35%
	FWC 5%		1260	1780	2910	10,701	628.6	631	50.10%
Species	Treatment	$P_{initial}$ (mg/kg)	P_{input} (mg/kg)	P_{min} (mg/kg)	P_{uptake} (mg/kg)	$P_{residual}$ (mg/kg)	$P_{surplus}$ (mg/kg)	$P_{utilization}$ (mg/kg)	PUE
Carrot	Biosolid 10%	6700	5480	387	658	8981	2928	2552	46.57%
	Biochar 10%		883	373	412	6992	552	331	37.49%
	CM 5%		446	379	592	6689	244	202	45.29%
	FWC 5%		445	374	540	6720	259	186	41.80%
Choy sum	Biosolid 10%		5480	316	547	8801	3148	2332	42.55%
	Biochar 10%		883	290	347	6982	544	339	38.39%
	CM 5%		446	301	504	6681	262	184	41.26%
	FWC 5%		445	305	413	6771	266	179	40.22%
Species	Treatment	$K_{initial}$ (mg/kg)	K_{input} (mg/kg)	K_{min} (mg/kg)	K_{uptake} (mg/kg)	$K_{residual}$ (mg/kg)	$K_{surplus}$ (mg/kg)	$K_{utilization}$ (mg/kg)	KUE
Carrot	Biosolid 10%	21,600	4330	393	677	23,621	2025	2305	53.23%
	Biochar 10%		4830	397	509	23,303	3015	1815	37.58%
	CM 5%		1525	365	670	22,102	718	807	52.92%
	FWC 5%		1450	378	619	21,992	817	633	43.66%
Choy sum	Biosolid 10%		4330	332	595	23,621	2046	2284	52.75%
	Biochar 10%		4830	294	487	22,903	3334	1496	30.97%
	CM 5%		1525	315	581	22,102	757	768	50.36%
	FWC 5%		1450	330	506	22,012	862	588	40.55%

treatment resulted in the highest NUE, phosphate utilization efficiency (PUE), and potassium utilization efficiency (KUE) due to the highest uptake by plants, implying this is the optimum fertilization method. Increasing the uptake and utilization of nutrients by plants improved the use efficiency of the 10% biosolid application, reduced the cost of inputs, and prevented nutrient loss to ecosystems (Brisolara and Qi 2015; Li et al. 2020). Therefore, this treatment could increase the soil cation exchange capacity, thus protecting nutrients against leaching and making N, P, and K more available for plants utilization. Hence, the 10% biosolid application can be used as a substitute for organic fertilizers when reclaiming agricultural soils because of its high usage of nutrients; however, its use will depend on the type of plant residues.

4 Conclusion and Recommendation

The results showed that the 10% biosolid-amended soil performed the best in terms of plant growth and nutrient content for both carrots and choy sum. No heavy metals were detected in the soils and plants in the biosolid treatment. However, CM and FWC applications may result in a small amount of heavy metal residue in soil that may cause risks to plants. This proved that biosolid application is functional as an organic fertilizer application and can be used as fertilizer to replace biochar, CM, and FWC for agricultural use. The thermal and pH treatment of sewage sludge could decrease the environmental risks of soil pollution. The 10% biosolid application plays an important role in environmental management, as it could improve soil properties, waste management, climate change mitigation, and nutrient pollution, as well as energy production. This could be an effective way to address the problem of waste disposal and relieve the filling of landfills. Promoting the use of biosolids through education can reduce the expense of purchasing fertilizers and minimize the use of chemical fertilizers to protect the environment.

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