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Original article

Application rate and plant species affect the ecological safety of sewage sludge as a landscape soil amendment

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ABSTRACT

Recycling sludge as a soil amendment has become a viable option for sludge disposal. However, such application can lead to soil pollution because of its enrichment in contaminants, especially heavy metals. To identify an effective means to ensure the ecological safety of sewage sludge landscape utilization, a glasshouse experiment was conducted by mixing sewage sludge at 0%, 15%, 30%, 60%, and 100% (V/V) amendment ratios to landscape soils and planting five common landscape plants (*Aphelandra ruellia*, *Syngonium podophyllum*, *Schefflera odorata*, *Alocasia macrorrhiza*, and *Dianella ensifolia*). Sludge amendment significantly improved fertility and moisture retention capacity of soil, but dramatically increased the contents of Cd, Pb, Cu, and Zn. Compared with lateritic red soil (CK), sludge amended-soils increased the relative growth rate of landscape plants and enhanced their nutrient uptake and heavy metals accumulation. A rate of 30% or less of sludge application showed positive growth effects for all five landscape plants, and did not cause potential ecological risks of heavy metals to landscape soils. However, rates of 60% or higher posed very high potential ecological risk in multiple metals, particularly in Cd. Interestingly, *S. odorata*, *A. ruellia* and *A. macrorrhiza* could alleviate the ecological risks of Cd, Cu and Zn, respectively, and these results were confirmed by data of relative changes in heavy metal contents in post-experiment soil. Our results suggest that attention to reducing the environmental risks of heavy metals in sludge utilization as landscape soil-amendments should not only be paid to controlling the application dosage of sludge but also to planting suitable plant species.

1. Introduction

The handling of sewage sludge that is produced by wastewater treatment process is one of the most significant challenges in urban development and environment management. In China, more than 3.5×10^7 t sewage sludge (80% moisture) is produced by urban wastewater treatment plants per year (Ministry of Housing and Urban-Rural Development of P. R. China, 2015). It was estimated that sewage sludge production will be $3.2-4.5 \times 10^3$ t d^{-1} (80% moisture) in Guangzhou in 2020 (The People's Government of Guangzhou Municipality, 2016). In the European Union, annual sewage sludge production is expected to increase from 1.2×10^7 t (2010) to 1.3×10^7 t by 2020 (European Commission, 2010). Thus, sewage sludge treatment and utilization have become a matter of great concern.

Currently, the main disposal routes of sewage sludge are incineration, landfill, land application, and composting (Verlicchi and Zambello, 2015). In the European Union, 49% of sludge is being utilized in land application (37% is agricultural utilization and 12% is used in nonagricultural lands), 40% is landfill, and 11% is being incinerated (Fytili and Zabaniotou, 2008; European Commission, 2010). Land application has become one of the most widely available options for sludge disposal, because sludge contains significant amounts of organic matter and nutrients (Fytili and Zabaniotou, 2008). Moreover, sludge application not only produces favorable plant yield responses, but also improves soil physical, chemical, and biological properties (Carbonell et al., 2011; Koutroubas et al., 2014; Bai et al., 2017). However, sludge also contains potential contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) (Fytili and Zabaniotou, 2008; Liu et al., 2015).

Accumulation of contaminants, in particular heavy metals, has become a key factor limiting land application of sludge (Liu, 2016; Fang et al., 2016). The heavy metals in sludge can be taken up by and be

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toxic to plants, and moreover, they become great threats to human health after entering the human food chain (Verlicchi and Zambello, 2015; Li and Ma, 2016). Liu et al., (2015) found that Cu, Zn, Mn, Pb, Cd, Cr, and Ni concentrations in six kinds of sewage sludge from Guangzhou were high; moreover, Cu and Zn showed serious risks in agricultural use. Previous studies also showed that sewage sludge application could increase Ni, Cd, Cu, Cr, Pb, and Zn concentrations in palak (*Beta vulgaris*) (Singh and Agrawal, 2007), Cd, Cu, Zn, and Pb contents in maize (Carbonell et al., 2011), and Cd, Mn, Zn, and Cu contents in Spinach (*Spinacia oleracea* L.) (Kumar et al., 2016). Furthermore, heavy metals in sludge can be transferred to soils and groundwater, resulting in virtually permanent pollution to the environment. For example, Yeganeh et al. (2010) noted that compared to control, the Zn, Cu, and Pb concentrations in soils continually amended with sludge for four years run up to 1600, 7 and 4.5 times, respectively. Fang et al. (2016) found that when sewage sludge compost was applied to soil at the application rate of 48 t ha^{-1}, the characteristics of the amended soil and the speciation of heavy metals could be altered, further enhancing heavy metals leaching from the amended soil. Moreover, repeated additions of compost caused Cd, Cr, Cu, and Pb accumulation, and then could leach in soil under reducing conditions (Fang et al., 2017). Therefore, particular attention should be paid to the ecological safety of sewage sludge land utilization.

The use of sewage sludge in urban landscaping soils is an economically attractive management strategy. Also, it has been considered as a feasible practice to avoid toxic elements entering the food chain (Ma et al., 2015). However, the heavy metal toxicity issue still occurs in sewage sludge-amended landscape soil, harming plant growth (Ma et al., 2015). Controlling the total amount of heavy metals from sewage sludge or using sewage sludge in compliance with environmental standards may be an effective method to reduce the environmental risks of heavy metals (Bai et al., 2017). Ntzala et al. (2013) reported that there was no pollution to soils and plants in sludge land application when sludge dosage did not exceed 30 t ha^{-1}. Additionally, it is generally accepted that one of the most ecological and effective methods to manage metal-polluted soils is phytoextraction which requires plant has high bioaccumulation and translocation potentials, and large biomass accumulation (Van der Ent et al., 2013; Fernández et al., 2017). Samake et al. (2003) found that 30 plant species could successfully grow on sludge in the greenhouse, with *Alternanthera philoxeroide* and *Alocasia macrorrhiza* as predominant species. Particularly, *Alocasia macrorrhiza* could accumulate more Zn than others. According to these studies, we hypothesize that both controlling the application dosage of sludge and planting suitable plant species may be effective ways to ensure the ecological safety of sewage sludge land utilization. However, there is a lack of information concerning the capacity of varying species of landscape plants to reduce pollutant exposure in sewage sludge landscape utilization.

To test the hypothesis mentioned above, we aimed to identify a safe application rate of sewage sludge landscape utilization by characterizing the properties of landscape soils amended with sewage sludge and investigating the growth of different landscape plant species as affected by different sewage sludge application rates. Further, we assessed and compared the potential environmental risk of heavy metals in sewage sludge-amended soils after planting different landscape plant species, and screened suitable landscape plants for reducing the ecological risk of heavy metals caused by the recycling of sewage sludge to landscape soil.

2. Materials and methods

2.1. Plants, soil and sewage sludge

Five plant species including *Aphelandra ruellia* (*A. ruellia*), *Syngonium podophyllum* (*S. podophyllum*), *Schefflera odorata* (*S. odorata*), *Alocasia macrorrhiza* (*A. macrorrhiza*), and *Dianella ensifolia* (*D. ensifolia*), which are widely used for landscaping in South China were used in this study. Healthy and consistent seedlings of each species were obtained from Bureau of Urban Utilities and Landscaping of Guangzhou Municipality. Natural landscape soil, classified as a lateritic red soil, was collected from 0 to 20 cm depth from a suburban area of Guangzhou. Sewage sludge (digested sludge) was collected from the Xintang Sewage Treatment Plant in Guangzhou. Soil and sewage sludge were air-dried and passed through a 2-mm sieve.

2.2. Pot experiment

A glasshouse pot experiment was designed to test growth and metal accumulation of *A. ruellia*, *S. podophyllum*, *S. odorata*, *A. macrorrhiza*, and *D. ensifolia* in growing mediums as follows: Control (CK), lateritic red soil only; Treatment 1 (T1), 85% lateritic red soil + 15% sewage sludge (v/v); Treatment 2 (T2), 70% lateritic red soil + 30% sewage sludge; Treatment 3 (T3), 40% lateritic red soil + 60% sewage sludge; Treatment 4 (T4), sewage sludge only. Growing mediums were thoroughly mixed and subsequently placed in plastic pots (30 cm in diameter and 35 cm in height, total volume 25 L). The growing mediums in the pots was watered to 80% of field capacity and left for two weeks' equilibration.

After equilibration, 100 cm^3 ring samples were collected for measuring soil bulk density and capillary capacity, and then porosity was calculated (Carter and Gregorich, 2008). Other samples of soil and sludge compost were collected, air dried and ground to pass through 0.25 mm or 1 mm sieve for chemical analysis by conventional methods (Bao, 2000). Soil pH was measured in deionized water (1:2.5 W/V) using a glass-electrode pH meter. Soil organic carbon (SOC) was determined by dichromate oxidation. Total nitrogen (N) was determined by the modified Kjeldahl method. Available N was determined with alkaline hydrolysis diffusion method. Both total and available phosphorus (P) were determined at a wavelength of 700 nm by the molybdenum-blue method after digestion with H_2SO_4-$HClO_4$ and extraction with double-acid solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4), respectively. Total potassium (K) was determined by NaOH melting flame photometry, and available K was measured using 1 mol L^{-1} NH_4OAc extraction flame photometry. Total cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) were digested by HCl-HNO_3-HF-$HClO_4$. K, Cd, Pb, Cu and Zn were further quantified via atomic absorption spectrometry (AAS, HITACHI JACO6-25, Hitachi Ltd., Japan).

2.3. Plant growth and metal contents measurement

After two weeks of equilibration in the growing media, seedlings of five landscape plants were transplanted to the pots (one seedling in each pot). They were then left to grow in glasshouse for three months with regular watering. For watering, an equal volume of deionized water was added to each pot. Leachate was collected and poured into the same pot. The plants were harvested after three months. The aboveground part which was separated into shoot was cut at the stem base. Roots were extracted carefully and the adhered soils were removed in running water. Plant growth was determined as dry biomass and nutrients uptake. Dry biomass was determined after oven drying at 70 °C to a constant weight. Dry plant sample (0.1 g) was digested with 5 mL H_2O_2-H_2SO_4 digestion mixture for 2–3 h at 360 °C. The digestion solution was dissolved with deionized water to volume of 100 mL 5 mL digests dilution was collected to analyze N concentration by the modified Kjeldahl method, 25 mL for determining P at a wavelength of 700 nm by the molybdenum-blue method, and 5 mL for K determination by AAS (Bao, 2000). The contents of heavy metals, including Cd, Pb, Cu and Zn in plants were digested by HNO_3 after dry ashing, and then were quantified via AAS (Bao, 2000).

To quantify the growth efficiency of the seedlings in different growth mediums, we defined the 'relative growth rate in dry weight'