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Phytoextraction of heavy metal from tailing waste using Napier grass

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ABSTRACT

Hybrid giant Napier (HGN) grass was used to examine its phytoextraction potential for removing heavy metal(oid)s from contaminated tailings. Following a two-year cultivation of HGN, the amount of heavy metal(oid)s Zn, Mn, Cu, Pb, Cd, Cr and As removed ranged from 12% to 26% in the tailings and 16% to 74% in the control soil. The root distribution profile and chemical analysis of the plant in the growth media suggest that heavy metal was phytoextracted by fibrous roots, then transported from roots to shoots and stored to all parts of the plant including fibrous roots, tap roots, stem and leaves. Most of the heavy metal was stored in the plant's stem due to its high biomass, although the highest concentration of the metal occurred in the fibrous roots. The plants grown in the contaminated tailings were generally stunted compared to those in the control soil, due to heavy metal phytotoxicity. Less biomass was produced in the HGN planted in the contaminated tailings, which was less than 1/2 amount of biomass yielded in the control soil. The biomass has the potential to be used in energy production. The phytoextraction of heavy metal by the HGN in this study was attributed to the well-developed root systems in the plant which is capable of phytoaccumulating nutrients and heavy metals. Results suggest that HGN has good phytoextraction potential in removing heavy metal(oid)s from contaminated tailing wastes and producing biomass.

1. Introduction

Human activity and natural events have resulted in the accumulation of heavy metal(oid)s in the terrestrial environment (Naidu et al., 1996) which is a global problem that poses a significant threat to sustainable development. As excess heavy metals enter the environment and disturb soil fauna, normal plant growth is interrupted, resulting in phytotoxicity with stunted growth and poor crop yields (Alloway, 2013). Furthermore, if the contaminated crop enters the food chain, it will pose a danger to human health and the ecosystem (Hapke, 1996; Streit, 1992). Heavy metal contamination in land and water has created major environmental problems in China. It is estimated that over 15% of total arable land in China has now been contaminated with heavy metals, leading to: firstly, huge losses in productivity that compromises the national food security; and secondly, enormous costs for remediation of the contaminated land (Li, 2013).

Many remediation technologies have been developed to combat heavy metal contamination in soil to protect the environment. Of these phytoremediation/phytoextraction is an attractive option for rehabilitation of heavy metal contamination in soil (Ali et al., 2013; Gramss et al., 2012). This method involves growing heavy metal tolerant plants with the ability to take up heavy metal into the plant tissue during their metabolic process to phytoremediate potentially toxic contaminants (Cuypers et al., 2013). Plants with high biomass and the ability to accumulate reasonable amounts of heavy metal serve this purpose (Garbisu and Alkorta, 2001). As biomass is harvested, along with excess heavy metal in the plant tissue, the soil's chemical and biological conditions in the rhizosphere of the removed plant improve substantially. The effects of remediation can be observed by monitoring changes in soil characteristics and growth conditions of the plant selected for phytoremediation. One promising candidate plant species for this purpose is the hybrid giant Napier (HGN, *Pennisetum sinese Roxb*). HGN is a fast-growing perennial *Gramineace* fodder crop that is widely adaptable with good tillering qualities (Ma et al., 2012). With its highly developed fibrous shallow root system and strong resistance to water stress, HGN grows well in poor quality soil and it improves soil structure and fertility after a period of cultivation (Angima et al., 2002). So far, research on HGN has mainly focused on mass production of the plant for livestock feed or for green energy. Published studies on HGN with reference to phytoremediation/phytoextraction for soil contamination are rare.

This study aims to determine the potential of HGN to phytoextract heavy metals in tailing waste collected from a mine site. The phytoextraction study involved plant growth experiment in a glasshouse over a two year period. The objective was to examine the effect

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of HGN on changes in soil properties, heavy meta(oid)s and nutrient contents in the tailing waste. In particular, soil chemical composition near the rhizosphere of the HGN was closely monitored to determine the extent of improvement in the root zone in relation to soil depth. The metabolic mechanism of heavy metal movement into the plant was also investigated by examining the distribution of heavy metal in different parts of the HGN plant during phytoextraction. The amount of harvested biomass produced in the tailing waste during the two year study was compared to that grown in the control soil for potential source of biomass energy.

2. Materials and methods

2.1. Tailing wastes

In this experiment, tailing waste, predominantly consisting of sand, was collected from a mine site in Dabaoshan, Shaoguan, China (24° 46′ N, 113° 39′ E). The control soil was a type of clay–loamy oxisols soil, which is common in Shaoguan in southern China. The collected samples were dried, sieved, evenly mixed and stored before the experiment.

2.2. Plant material and greenhouse study

HGN was propagated by cutting the middle stem of a two-year old healthy HGN plant. The cuttings from the mature plant were about 8 cm long with well-developed lateral buds. The cuttings were immersed in water immediately after cutout.

A preliminary study on HGN growth in the control soil during the two year period indicates that over 80% plant roots, including tap roots (primary roots), and fibrous roots (lateral roots), were located in the top 25 cm layer from the surface (Ma et al., 2012). Therefore, 25 cm high pots served to conduct this growth study in a greenhouse from March 2008 to March 2010. The pots were made from plastic with no holes in the bottom to prevent nutrients and heavy metals in the growth medium leaching out. The tailings used for HGN cultivation were evenly mixed before plant growth so that it was uniform in depth when the experiment began. Each pot was filled with 2250 g tailings or control soil near to the top. The HGN cutting with lateral buds was laid horizontally over the top of the partly filled pots and then covered with 250 g of control soil without added fertiliser. Triplicates of the samples were taken for all measurements. In total 9 pots in each growth medium were prepared. After planting, the moisture content of the soil with HGN was maintained at 60% of field capacity in the first week and a required amount of water was added weekly to retain similar moisture content.

The HGN was harvested in March 2010. Three pots of the HGN in each experiment were randomly selected and the above-ground portion of the HGN from the soil horizon was cut. The height, diameter of the stem, number of tillers and fresh weight of the HGN were recorded. The fresh plants were dried at 105 °C for 8 min followed by 80 °C for a period of time to achieve a constant weight for further analysis. The spatial distribution with depth of heavy metals and nutrients in the pots of soil were investigated after harvesting HGN by removing soil and all roots from the pot, separating them from depths of 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, and 20–25 cm and storing them in separate plastic bags. Tap water was used to remove the remaining soil attached to the fibrous root system and this was followed by rinsing the roots with Milli-Q water. They were then dried following the above procedure to a constant weight and the dried weight of the roots distributed in each layer was recorded. The nutrient contents at each depth in the control soil or the tailings were also determined.

2.3. Soil characterisation

Soil pH was measured in 1:5 soil:water suspensions using a pH electrode. Total N was determined using the micro-Kjeldahl method with 2.0 g soil being digested in H_2SO_4 and H_2O_2 solution before measurement (Stuart, 1936). Since the tailings and the control soil are acidic, the Olsen procedure was used to extract P with 0.5 M $NaHCO_3$ before being determined spectrometrically (Olsen et al., 1954). K was extracted using 1.0 M NH_4OAC and determined spectrometrically (Shainberg et al., 1987). Ionisation suppressant, $CeCl_2$, was added to both standards and the sample solution to minimise ionisation interference. Soil organic matter in both samples was determined using $K_2Cr_2O_7$–H_2SO_4 digestion (Nelson and Sommers, 1996; Walkely and Black, 1934).

For total heavy metal(oid)s analysis the air-dried soil, tailing and plant (0.5 g, <2 mm) sample was weighed directly into a Teflon digestion vessel and 5 ml of aqua regia was added. The soil suspension was digested in a micro-wave digestion oven (MARS5, CEM, USA) in accordance with Method 3051H (USEPA, 1997). Each microwave digestion batch included a standard reference material (Montana Soil SRM2711, certified by the National Institute of Standards and Technology, USA) and a blank to validate the digestion operation. Contents of heavy metal(oid)s were determined using an atomic absorption spectrometer (Pansu and Gautheyrou, 2006).

2.4. Analysis of data

Three replicated samples were used for all soil characterisation, plant growth study and biomass production. The effect of phytoextractible heavy metals and heavy metal transportation inside the HGN plant in both control soils and field contaminated soils was examined by calculating the bioaccumulation coefficients (B_c) and translocation coefficient (T_c), respectively (Bolan et al., 2013).

$$\text{Bioaccumulation coefficient } (B_c) = \text{Plant tissues concentration} / \text{Growing medium concentration}$$

$$\text{Translocation coefficient } (T_c) = \text{Mass of heavy metal in shoots (stem and leaves)} / \text{Mass of heavy metal in roots (tap roots and fibrous roots)}$$

where both growing medium concentration and plant tissue concentrations are expressed in mg kg^{-1}. Mass of heavy metals in both shoots and roots in mg.

Statistical comparisons among various samples in both tailings and control soils were made using SPSS statistics software, release version

Table 1
Characteristics of control soil and tailing waste for growth study.

Sample		pH	Specific gravity g/cm^3	Porosity %	C g/kg	Total N g/kg	Extractable		
							N mg/kg	P mg/kg	K mg/kg
Control soil	As sampled	4.93 ± 0.09a	2.38 ± 0.09b	35.3 ± 1.89c	30.2 ± 1.28a	1.4 ± 0.1a	245 ± 8.84a	53.9 ± 2.22a	75.9 ± 3.88a
	After HGN growth	5.02 ± 0.08a	2.19 ± 0.09b	38.9 ± 2.05c	29.7 ± 1.23a	1.0 ± 0.0a	155 ± 6.23b	45.5 ± 3.16b	56.0 ± 2.41b
Tailings	As sampled	2.75 ± 0.06c	2.73 ± 0.08a	58.8 ± 2.33a	3.64 ± 0.12c	0.2 ± 0.0b	37.0 ± 1.32c	11.8 ± 0.78d	36.3 ± 1.46c
	After HGN growth	3.43 ± 0.04b	2.52 ± 0.08a	42.6 ± 2.78b	11.7 ± 0.53b	1.0 ± 0.1a	24.1 ± 0.91d	17.2 ± 1.03c	35.8 ± 1.35c

Different letters represent significant difference ($p < 0.05$).