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Phytoremediation of cadmium-, lead- and nickel-contaminated water by *Phragmites australis* in hydroponic systems

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ABSTRACT

This study was carried out to investigate the phytoremediation ability of *Phragmites australis* to remove cadmium (Cd), lead (Pb) and nickel (Ni) from contaminated water, to study the effect of pH and salinity on the removal of cadmium, lead, and nickel, and to estimate the pattern of accumulation of these metals in the roots, shoots, and leaves of the plant. The experiments were carried out in a deep-water hydroponic system and 5 mg/L was used as a concentration of each of the heavy metals. The results of the study showed that *P. australis* had a residual of 7% (93% removal) of cadmium, 5% (95% removal) of lead and 16% (84% removal) of nickel over a 6-week period. In the control experiment, there was a residual of 96% (4% removal) for both cadmium and lead and 89% (11% removal) for nickel over a 6-week period. There was no major effect of pH on the removal of cadmium except at pH10, which led to a slightly reduced removal of cadmium (89% removal). Also, there was no major effect of pH on the removal of lead, however, there was the enhanced removal of nickel at pH10 (93% removal). The major mechanisms employed by the plant were probably phytostabilization on the basis of the calculated Biological Concentration Factor (BCF) – metal concentration ratio of plant root to soil; and Translocation Factor (TF) – metal concentration ratio of plants shoots to roots.

1. Introduction

Heavy metals are hazardous to humans and other life forms, and their presence in the environment can cause soil and water pollution, deterioration of soil structure, destruction of ecological landscapes and decrease in biodiversity. The main threats to human health from heavy metals are attributable to exposure to lead, cadmium, mercury, and arsenic (Jarup, 2003); however, a number of other heavy metals have been implicated for health effect. In order to protect water bodies from heavy metal pollution, there are regulatory standards which are enforceable (US Environmental Protection Agency, 2009; World Health Organization, 2011; Presidency of Meteorology and Environment, 2011). Heavy metal pollution can be treated by physicochemical processes such as precipitation and use of metal chelators, ion exchange, reverse osmosis, coagulation and flocculation; and biological processes such as microbial metal uptake (Sierra-Alvarez et al., 2006; Saleh, 2015a,b, 2016), biosorption, activated sludge process, biofilter, anaerobic digestion, stabilization ponds (Dhokpande and Kaware, 2013) and phytoremediation.

Though the choice of treatment option depends on the contaminated site, the extent of contamination, and other factors, the physicochemical processes are generally more costly than the biological processes. The use of phytoremediation as an alternative treatment method offers much more advantages when compared to other methods. The phytoremediation, the uptake of contaminants through the growth of plant biomass, is a natural and in situ remediation system driven by solar and green plants. It is faster than natural attenuation and can conserve the soil resources and does not induce the secondary contamination. Successful phytoremediation can reduce movement of pollutants towards groundwater, sustains the soil structure, and enhance the soil quality. The costs are very low in comparison to current other physical or chemical methods because most of the energy for phytoremediation is supplied by the sun, and phytoremediation does not need to remove the soil out of the place (Interstate Technology &

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Regulatory Council, 2009; US Environmental Protection Agency, 2010). Phytoremediation is an innovative and cost-effective technique of using plants to extract, degrade, contain, or immobilize pollutants in the environment. It can be used for the treatment of a wide range of both organic and inorganic pollutants in air, soil, sediments, sludge, surface water, storm water, groundwater, wastewater, freshwater, salt marshes, and brackish water (Zhu et al., 2004; Interstate Technology & Regulatory Council, 2009; Nwoko, 2010).

Asides from the removal of pollutants, plants can also clean the air by absorbing carbon dioxide. Different plants have been used for the phytoremediation of heavy metals and among them is *P. australis*. Numerous phytoremediation feasibility studies have focused on the treatment of spiked soils with organic or inorganic contaminants (Sun et al. 2011; Wang et al. 2012), while only a limited number of recent studies have used native plants to treat anthropogenically contaminated estuarine sediments (Almeida et al. 2011; Cicero et al. 2015; Cristaldi et al. 2017).

P. australis (Cav.) Trin. ex Steud (common reed) is a large perennial grass (family Poaceae) that can grow to a height of 5 m (15 feet) and has an extensive system of scaly rhizomes and stolons (Magee, 2005; Swearingen and Saltonstall, 2010; Tilley and St. John, 2012). It is extremely widespread and found abundantly almost throughout the world, with the ability to exploit man-made habitats. It has a wide range distribution, occurring from north-west Europe through central and southern Europe to North Africa and Southern Africa through Russia and the Middle East to the Far East and South-east Asia to Australia, and it is native to over 260 countries including Saudi Arabia (Lansdown, 2013). Common reed is adapted to a wide range of soil conditions and can thrive in marshes, tidal and non-tidal wetlands, and along lakes and rivers. It can tolerate anaerobic conditions in soil, a variety of nutrient conditions and can survive a pH range of 3.7–8.7 (Tilley and St. John, 2012).

P. australis is one of the most commonly used plant species for the treatment of wastewater in the constructed wetland (Vymazal and Krőpfelová, 2005). A constructed wetland is a planted artificial swamp area and a complex biological system that utilizes the interaction of vascular plants, saturated substrates, and microorganisms to treat wastewater (Todorovics et al., 2005; Mothes et al., 2010). Apart from its use in a constructed wetland, *P. australis* is among the plant species that are commonly found growing naturally in a contaminated environment such as industrial and mining areas. Globally, many researchers have assessed common reeds growing in such environments for the presence of contaminants (Bonanno, 2013). Some researchers have tried to assess the potential of common reed under greenhouse, pot, and hydroponic conditions and have suggested its use for phytoremediation in singly-contaminated media (Ali et al., 2004; Hechmi et al., 2014)

This study was therefore carried out to investigate the phytoremediation ability of *P. australis* to remove cadmium, lead and nickel under deep-water culture hydroponic system, to study the effect of pH and salinity on the removal cadmium, lead and nickel, and to estimate the pattern of accumulation of these metals in the roots, shoots and leaves of the plant.

2. Materials and methods

2.1. Sample location and plant establishment

P. australis used for this study was collected from Al-Asfar Lake (Fig. 1). The lake is located in Al-Hassa oasis and it is one of the most important wetlands in Saudi Arabia. It is a large man-made freshwater habitat that is formed by run-off from Al-Hassa oasis and sewage effluent from Al-Hofouf, Abqaiq and other neighboring small towns. The lake is characterized by many vegetation communities such as wetland vegetation, sabkha vegetation, and dune vegetation. Consequently, Birdlife International designates the lake as one of Saudi Arabia's 39 Important Bird Areas.

The plant samples, which served as the parent materials, were removed from Al-Asfar Lake by uprooting them using a stainless steel shovel and sickle to avoid contamination. Once removed, plant samples were put in clean plastic bags for transportation. The plant samples were first potted at their new location for a period of two weeks so as to grow new rhizomes, which served as the experimental plants. Three separate fresh and growing rhizomes were then transplanted into each of the prepared hydroponic media. Another set of hydroponic media were established for each of cadmium, lead and nickel solutions without the rhizomes of *P. australis* to serve as the control experiments. The location for this experiment was selected because it provided protection against heavy sandstorm that was prominent at the time of the experiment and at the same time, it also afforded the plants sufficient sunlight.

2.2. Hydroponic culture system

A deep-water hydroponic system shown in Fig. 2 was used for this study. Each hydroponic system was made up of a 2.25L container that held nutrient solution; a net pot that held the plants and allowed the plants' roots to go into the nutrient solution; an air pump for aeration to provide oxygen to the plants' roots; an air tube for connecting the air pump to the container; some gravels used as the growing medium for supporting the plants; and nutrient solution constituted using inorganic salts.

The nutrient composition of the hydroponic culture, as well as the volume of nutrients used, is shown in Table 1. The nutrient solution in each container labeled Cd, Pb and Ni were spiked with 5 mg/L of cadmium, lead, and nickel respectively. In order to prepare 5 mg/L of cadmium, lead, and nickel; 5 mg of each salt ($CdCl_2$ for cadmium, $PbCl_2$ for the lead, and $NiCl_2$ for nickel) was dissolved in one liter of water. The water used for all sample preparations was obtained from a Milli-Q Direct water purification system by Millipore Corporation. Four other sets of hydroponic systems were established using water solution at pH4; water solution at pH10; a 50% by 50% mixture of distilled water and groundwater; and 100% groundwater with total dissolved solids measured as 3645 mg/L. In each of these hydroponic setup, the nutrient solution was spiked with 5 mg/L of cadmium, lead, and nickel as explained above. Each experimental set up was replicated three times.

After the completion of the setup, triplicate samples were taken from each of the solutions in all the set up for cadmium, lead and nickel on that same day to represent time t_0. After this, the experiments were left to run for a period of 6 weeks with samples being taken from each of the solutions of cadmium, nickel and lead every two weeks to represent times t_1, t_2 and t_3. The solutions containing the nutrients and respective contaminants were replenished as at when due by adding already prepared stock solutions of nutrients plus respective contaminants. Samples were put in plastic vials and kept at 4 °C until analysis.

2.3. Digestion of plant samples and analysis of Cadmium, lead and nickel

The samples collected from the growing water media were analyzed for cadmium, lead and nickel. Since the types of water used were distilled water, a mixture of distilled water and groundwater, and groundwater, there was no need for sample digestion. However, in the case of harvested plants, there was the requirement of acid digestion.

Harvested plant samples were separated into leaves, shoots and roots before they were oven-dried at 75 °C for 48 h. After the thorough drying, the separate plant parts were ground using mortar and pestle and each part was put in a plain zipper bag. Plant digestion was done using aqua regia hot plate digestion method (Chen and Ma, 2001). Aqua regia is an acid mixture formed by adding concentrated HNO_3 to concentrated HCl in a ratio of 1:3 by volume. In this method, the digestion was performed in a 150 mL beaker covered with a watch glass for refluxing. 0.5 g of each ground sample was digested in 12 mL of aqua