Original Research

Revegetation in Arid Zones: Environmental Impact of Treated Wastewater Irrigation in Al-Karak Province, Jordan

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Received: 9 April 2012
Accepted: 23 August 2012

Abstract

This study was conducted in an arid area in southern Jordan to investigate the appropriateness of using treated wastewater for the cultivation of salt-tolerant fodder cover plants (i.e. *Tamarix sativa*, *Medicago sativa*, *Pennisetum glaucum*, and *Atriplex hallimus*) in Al-Lajoun Valley and its environmental impact in terms of heavy metal concentrations like copper, lead, chromium, and cadmium in soils and leaves in the context of arid land revegetation. Although the treated wastewater contains higher concentrations of Cu, Pb, Cr, and Cd than the Jordanian recommended maximum concentration of metals in irrigation water, the results showed no accumulation of heavy metals in irrigated soils and plants. Concentrations of metals in wastewater-irrigated soils were much lower than the critical soil total concentration. In addition, heavy metal concentrations in leaves of the grown cover plants were within the normal range in plants, which is advantageous if such plants are to be used as fodder for animals. Pollution load index and plant concentration factor varied with the grown cover plants. High transfer values of Cu, Pb, and Cr from soil to particularly *P. glaucum* were observed. An inverse relationship between transfer factor and total metal concentrations also was observed. In conclusion, treated wastewater can be used, at least in the short term, as a practical solution for irrigation water shortage to minimize soil degradation and for revegetation purposes.

Keywords: arid climate, cover plants, degraded soil, heavy metals, low-quality irrigation water

Introduction

Arid and semiarid areas are seriously affected by extreme human activities leading to soil degradation and, consequently, expansion of the desertification process, mainly due to the damage of plant cover. Revegetation of such areas is challenging due to both water shortage and the poor quality of their soils [1]. In such regions, treated wastewater is becoming an important addition to water supplies. Several studies have reported the benefits and limitations of using wastewater for irrigation of various crops [2-5]. The reuse of treated wastewater is a good alternative for increasing water supplies to agriculture. One of its benefits is the plant's uptake of water nutrients and therefore a reduction in the pollution load that wastewater contributes to the surface water supply [6] as well as reduction in the use of synthetic inorganic fertilizers. However, depending on its sources and treatment technologies, treated wastewater may contain heavy metals, pathogenic organisms, and polycyclic aromatic hydrocarbons and, consequently, the reuse of treated wastewater in irrigation may cause adverse effects on soils and plants with direct effects on soil

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revegetation. Therefore, sound management strategies of treated wastewater including wastewater treatment technology, crops grown, irrigation methods, and cultivation and harvesting practices, can reduce contamination of irrigated plants and soils [7].

Jordan suffers from a serious water shortage problem. Therefore, treated wastewater is indeed an indispensable non-conventional water resource that is increasingly used as an essential alternative for limited freshwater resources. Wastewater is currently treated in 23 Wastewater Treatment Plants distributed across the country with total influent and effluent flows of 93.9 and 75.5 million $m^3 \cdot yr^{-1}$, respectively. According to Al Nasir and Batarseh [8], about 60% of the treated wastewater is currently used for agricultural purposes and groundwater recharge. In Al-Lajoun Valley; where the current study was carried out, severe droughts occurred during recent years as the average rainfall was below its annual average for the last few years. Thus, wastewater generated from the wastewater treatment plant in Al-Karak Province is the only available potential water source for the revegetation of the valley. Although the heavy metal concentrations in such a non-conventional water source are higher than the Jordanian standards (Irrigation Water Quality Guidelines, [9]), serious water shortage and the calcareous nature of soils in the Al-Lajoun Valley encourage the reuse of this water in the irrigation of cover plants to revegetate such an extremely arid region. This study was conducted in order to investigate the appropriateness of using such treated wastewater for the cultivation of salt-tolerant fodder cover plants (i.e. *Tamarix sativa*, *Medicago sativa*, *Pennisetum glaucum*, and *Atriplex hallimus*) in Al-Lajoun Valley and the environmental impact of using this treated wastewater in terms of levels of different heavy metals like copper, lead, chromium, and cadmium in soils and leaves of these fodder cover plants in the context of the revegetation of arid lands in Jordan. The suitability of wastewater-irrigated cover plants for animal consumption was discussed.

Materials and Methods

Study Area

The experimental area is located at Al-Lajoun Valley (31.08.36.77 N; 35.52.52.48 E); 30 km to the east of Al-Karak city in southern Jordan (Fig. 1). The area is characterized by an arid climate; the average daily evaporation is about 8.2 mm while rainfall is less than 80 $mm \cdot year^{-1}$, and very poor soil fertility due to low organic matter content, causing a general absence of natural vegetation cover. The vegetation of surrounding areas includes only scattered wild plant species at very low density. Soils of the study area are Aridosols/Xerosols. They are calcareous silty sand with more than 220, 0.7, 0.012, 0.301, and 5 $g \cdot kg^{-1}$ $CaCO_3$, N, P, K, and OM, respectively. The background concentrations of soil heavy metals in the study area were 0.19, 0.86, 0.26, and 0.58 $mg \cdot kg^{-1}$ dry soil, respectively, for Cu, Pb, Cr, and Cd.

Experimental Design

Four salt-tolerant fodder cover plants adapted to arid conditions; i.e. *Tamarix sativa*, *Medicago sativa*, *Pennisetum glaucum*, and *Atriplex hallimus*, were planted at Al-Lajoun Wastewater Treatment Plant in plots of 50 m^2 each, which was replicated three times. *T. sativa* and *A. hallimus* were planted at one $plant \cdot m^{-2}$, while *M. sativa* and *P. glaucum* were intensively seeded. Plants were irrigated with treated wastewater originating from the Al-Lajoun Wastewater Treatment Plant for six continuous months. The irrigation method used was flooding (i.e. basin irrigation), and the quantity of water established took into account the climate, the soil, and the water requirements of the cover crops and the precipitation registered during the period of the study.

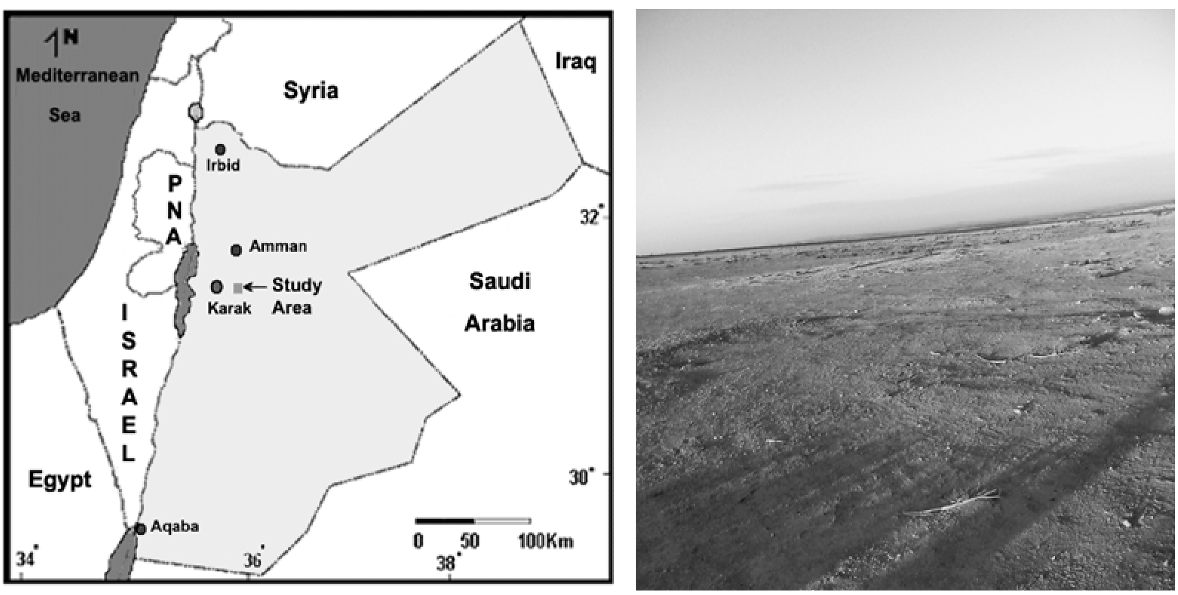

Fig. 1. Location of the study area (left) where no plant cover exists (right).

Treated Wastewater Characteristics

Five treated wastewater samples were collected in polyethylene bottles during the experiment from the Al-Lajoun Wastewater Treatment Plant. Samples were analyzed for: pH, EC, Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, and HCO_3^- according to standard methods (APHA, [10]). A Wilcox diagram was used to determine the suitability of treated wastewater for irrigation based on sodium adsorption ratio (SAR) and water salinity. For heavy metals, subsamples were acidified with a few drops of concentrated nitric acid after the removal of suspended solid particles. Subsamples were stored at 4ºC until analysis. The concentrations of heavy metals (Cd, Cr, Cu, and Pb) were determined by atomic absorption spectrophotometer (AAS). The main characteristics of treated wastewater used for irrigation are shown in Table 1 and Figs. 2 and 3.

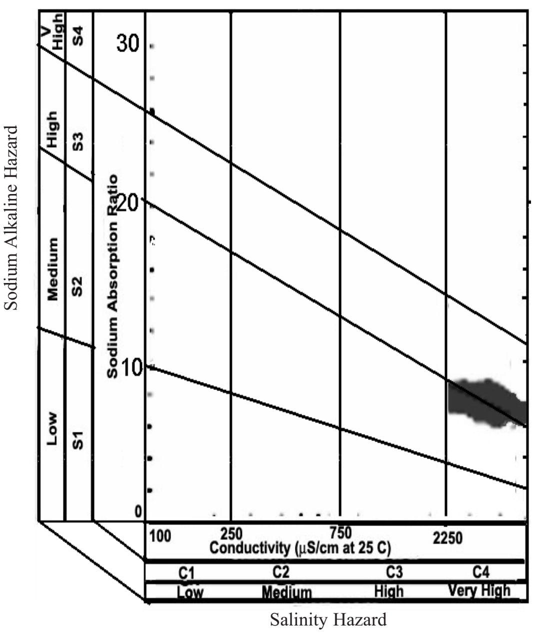

Fig. 2. Wilcox diagram for classification of treated wastewater.

Table 1. Chemical characteristics of treated wastewater used for irrigation.

Parameter	Mean±Standard deviation	Irrigation Water Quality Guidelines
pH	7.9±1.7	-
EC (µS·cm^{-1})	3,789±300.0	-
Na^+ (mg·l^{-1})	729±424.0	-
K^+ (mg·l^{-1})	92±21.0	-
Ca^{2+} (mg·l^{-1})	82±24.0	-
Mg^{2+} (mg·l^{-1})	71±15.0	-
NH_4^+ (mg·l^{-1})	321±148.0	-
Cl^- (mg·l^{-1})	1,011±255.0	-
NO_3^- (mg·l^{-1})	73±179.0	-
SO_4^{-2} (mg·l^{-1})	153±54.0	-
PO_4^{-3} (mg·l^{-1})	133±52.0	-
HCO_3^- (mg·l^{-1})	1,165±65.0	-
Cu (mg·l^{-1})	23.3±5.0	0.20
Pb (mg·l^{-1})	21.2±3.0	5.00
Cr (mg·l^{-1})	2 ±0.2	0.10
Cd (mg·l^{-1})	2.2±0.4	0.01

Soil and Leaf Sample Preparation and Analysis

Three soil samples were collected from 0 to 20 cm depth of the control (i.e., uncultivated soil) and treated wastewater-irrigated soils of each treatment. Samples were air-dried and sieved through a 2 mm mesh. Samples were prepared for the analysis of heavy metals (Cd, Cr, Cu, and Pb) according to Ziadat et al. [11]. The concentrations of

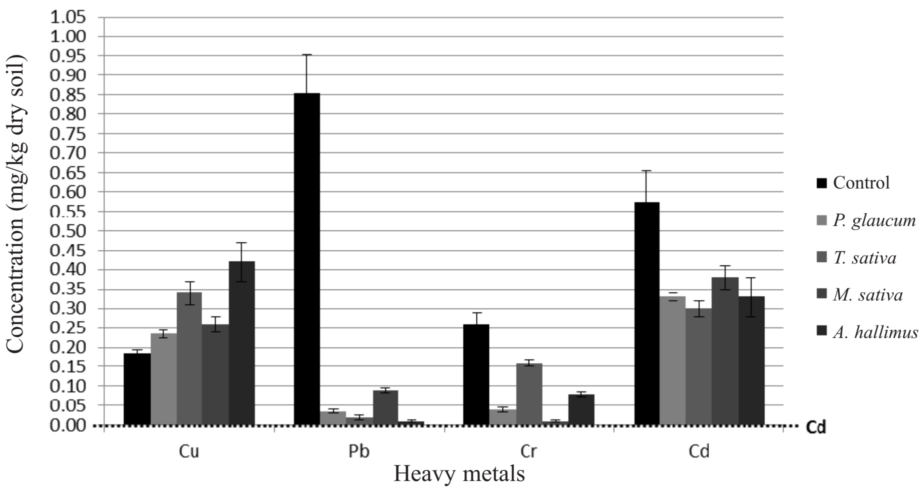

Fig. 3. Concentration of heavy metals in treated wastewater-irrigated soils cultivated with different cover plants. The dashed line represents the lower limit of the normal range of Cd in soils. The lower limits of the normal range of Cu, Pb, and Cr in soil are 2, 2, 5 mg·kg^{-1}, respectively.

Table 2. Plant concentration factor (PCF) and pollution load index (PLI) of plants and soil irrigated with treated wastewater.

Data analysis	Heavy metal	*P. glaucum*	*T. sativa*	*M. sativa*	*A. hallimus*
PCF	Cu	2.89	2.29	2.82	1.90
	Pb	8.16	7.41	5.56	0.00
	Cr	8.04	3.70	0.00	5.42
	Cd	2.27	2.47	2.11	2.22
PLI	Cu	1.27	1.84	1.41	2.27
	Pb	0.04	0.02	0.11	0.01
	Cr	0.15	0.62	0.04	0.31
	Cd	0.57	0.52	0.66	0.57

heavy metals were determined by AAS after nitric-perchloric acid (2:1) digestion. The physico-chemical properties (i.e., soil texture, $CaCO_3$, N, P, K, and OM) were also determined according to Ryan et al. [12]. Plant leaves from each plot were collected at the end of the study. A random mixture of leaves from each plot was collected for analysis at the end of the experiment. Leaves were washed with a special detergent (Alconox 0.1%) and rinsed in tap water followed by a dilute solution of 0.005% HCl and finally distilled water. Leaves were oven dried for at least 2 days at 65ºC. Following wet digestion in a HNO_3-$HClO_4$ acid mixture, the concentrations of heavy metals were determined by AAS.

Data and Statistical Analysis

Transfer Factor

Metal concentrations in the extracts of soils and leaves were calculated on the basis of dry weight. The plant concentration factor (PCF) was calculated as follows [13]:

$$PCF=C_{leaf}/C_{soil}$$

...where C_{leaf} and C_{soil} represent heavy metal concentrations in extracts of wet digested leaves and soils expressed on dry weight basis, respectively.

Pollution Load Index

The degree of heavy metal-polluted soils was determined using the pollution load index (PLI) technique. The following equation was used to assess the PLI level in wastewater-irrigated soils [3]:

$$PLI=C_{soil}/C_{reference}$$

...where C_{soil} and $C_{reference}$ represent the heavy metal concentrations in the treated wastewater-irrigated and control soils, respectively.

In tables, data was presented as means followed by standard deviations. In figures, the error bars indicate standard deviations as well.

Results

Analysis of treated wastewater samples revealed that it was saline as the electrical conductivity ranged from 3,546 to 3,970 µS·cm^{-1} with an average value of 3,789 µS·cm^{-1} (Table 1). In addition, the major ions were Na^+, Cl^-, and HCO_3^- (Table 1). The high concentration of HCO_3^- reflects the chemical characteristics of water at sources where most of the aquifers are of carbonate lithology. The PO_4^{-3} was found to be relatively high, ranging from 96 to 170 mg·l^{-1} with an average value of 133 mg·l^{-1}, which mainly originates from detergents. Since water used for irrigation was recently discharged into the collection pool, the NH_4^+ concentration also was high (Table 1). To determine the appropriateness of water for irrigation purposes a Wilcox diagram was used, which takes into consideration both sodium adsorption ratio (SAR) and water salinity as shown in Fig. 2. SAR values of the treated wastewater ranged from 10.5 to 19.6 and the EC from 3,546 µS·cm^{-1} to 3,970 µS·cm^{-1}, making treated wastewater unsuitable for sensitive plant species. However, it can be suitable under specific conditions (e.g. revegetation of degraded soils) using some salt-tolerant cover plants as those used in the current study.

Results also showed that the residual concentrations of heavy metals, particularly of Pb, Cr, and Cd, in treated wastewater-irrigated soils, were generally lower than those in the control treatment, while the concentration of Cu in treated wastewater-irrigated soil was higher than that in the control treatment after six months of continuous irrigation (Fig. 3). In addition, the residual concentrations of heavy metals in treated wastewater-irrigated soils generally varied with different grown cover plants (Fig. 3). Pollution load index and plant concentration factor varied with heavy metals as well as the grown cover plants (Table 2). The degree of Cu-polluted soils as reflected by the PLI was much higher than that of the other heavy metals. Moreover, high transfer values of Cu, Pb, and Cr from soil to particularly *P. glaucum* was observed as reflected by PCF (Table 2). An inverse relationship between transfer factor and total metal concentrations also was observed.

Discussion

Elevated salinity of the treated wastewater and high concentrations of sodium and chloride would deteriorate the water quality for irrigation purposes. However, the cover plants used in the current study are salt-tolerant and soils of the study area are characterized by low cation exchange capacity and high infiltration rate and hydraulic conductivity, which would alleviate the possible adverse effects of water salinity, Na, and Cl. On the other hand, the relatively high concentrations of phosphorus and nitrogen would provide growing plants with their N and P requirements. Concerning the concentrations of heavy metals in the treated wastewater used for irrigation, their concentrations were much higher than the recommended maximum concentrations in irrigation water according to the Irrigation Water Quality Guidelines [9] as shown in Table 1. However, serious water shortage and high calcium carbonate content in soils of the study area encourage the reuse of this water in irrigation of cover plants to revegetate such an extremely arid region. Across the study area, a wide range of soil heavy metal concentrations was observed (Fig. 3).

The application of treated wastewater has influenced both soil heavy metal concentrations and their uptake by cover plants. Soils irrigated with treated wastewater had lower metal concentrations than those of the control soil; particularly for Pb, Cr, and Cd, as shown in Fig. 3. According to Alloway [14], low-molecular-weight organic ligands, not necessarily humic in origin, can form soluble complexes with metals. Such ligands could be added to irrigated soils via the treated wastewater, resulting in mobilizing these metals and enhancing their translocation. In addition, Holm et al. [15] concluded that dissolved organic carbon (DOC) acts as a precipitation inhibitor and was the reason for the apparent lack of $CdCO_3$ precipitation in Cd-amended soils. Only the concentration of Cd was within the normal range in soils (0.01-2.0 mg·kg^{-1}; [16]), but it was much lower than the critical soil total conctentration; i.e. the range of values above which toxicity is considered to be possible (3-8 mg·kg^{-1}; [17]). The concentrations of the other heavy metals were much lower than the critial soil total concentration of these metals in soils (60-125, 100-400, and 75-100 mg·kg^{-1}, respectively for Cu, Pb, and Cr [17]). Although there was slight build-up of Cu in the treated wastewater-irrigated soils compared to the control soil as also indicated by PLI index for Cu (which was higher than 1), the results indicated that all the metal concentrations were below the critical soil total concentration. Consequently, it is evident that toxcicity of heavy metals is not possible under the conditions of the current study. Concerning the concentrations of heavy metals in leaves of the cover plants, the concentration of Cu was even much lower than the normal range in plants (5-20 mg·kg^{-1}) (Fig. 4), while those of Cr, Pb, and Cd of most cover plants were within the normal range in plants according to Bowen [16] (0.03-14, 0.2-20, and 0.1-2.4 mg·kg^{-1}, respectively) (Fig. 4). It is also evident that plant tissues have heavy metal concentrations that are far below the critical concentrations, above which toxicity effects are likely [17].

Although the concentrations of heavy metals in treated wastewater were higher than the recommended maximum concentration in irrigation water, the PLI indices for Pb, Cr, and Cd were below 1 (Table 2), which can be attributed to the calcareous nature of the soil in the study area. Our results are in agreement with those reported by Al-Lahham et al. [18], Soumare et al. [19], Dère et al. [20], Abbas et al. [21], Madrid et al. [22], and Kiziloglu et al. [23]. In addition, the PLI indices slightly varied with the grown cover plants.

Moreover, the trends of PCF for heavy metals in different cover plants were, generally, on the order of Pb (8.16; *P. glaucum*) > Cr (8.04; *P. glaucum*) > Cu (2.89; *P. glaucum*) > Cd (2.47; *T. sativa*) (Table 2). The PCF for Pb and Cr are much higher than those reported by Kloke et al., [24]; 0.01-0.1 for both Pb and Cr; whereas those of Cu and Cd were within the reported range (0.1-10 and 1-10, respectively [24]. The very high transfer values for heavy metals (particularly for Pb and Cr) from soil to plants indicate a strong accumulation of the respective metals by the grown cover

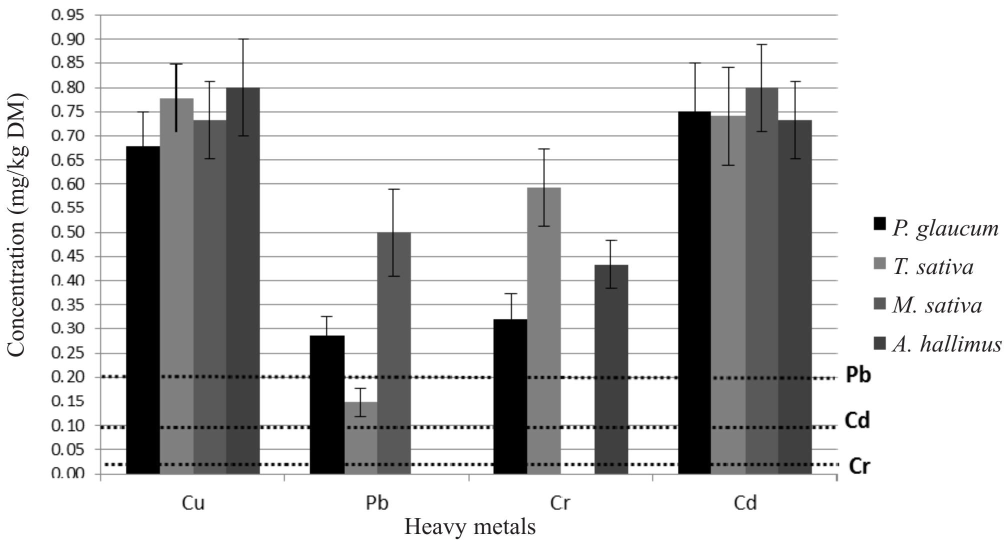

Fig. 4. Concentrations of heavy metals in tissues of different cover plants irrigated with treated wastewater. The dashed lines represent the lower limits of the normal range of Pb, Cd, and Cr in plants. The lower limit of the normal range of Cu in plants is 5 mg·kg^{-1}.

plants; especially by *P. glaucum*. This indicates that choosing the proper type of plants for revegetation purposes is essential, particularly when such plants can be also used as fodder for animals. However, no phytotoxicity of heavy metals in the grown cover plants could be found from the concentrations of these metals in the leaves. The current results (PCF values) were much higher than for food crops as reported by Khan et al. [25], which may be due to the differences in soil properties and plant types. The factors affecting the amounts of metal absorbed by a plant are those controlling:

i the concentrations and speciation of the metal in the soil solution
ii the movement of the metal from the bulk soil to the root surface
iii the transport of the metal from the root surface into the root
iv its translocation from the root to the shoot [26, 27].

Moreover, an inverse relationship between transfer factor and total metal concentrations was observed. Such inverse relationships also were reported by Wang et al. [28] and Khan et al. [25] for food crops. Concentrations of heavy metals in leaves of cover plants were far below the toxic level for animals, according to Underwood and Suttle [29].

Conclusions

The characteristics of treated wastewater and soil and type of cover plant should be considered in managing wastewater irrigation during revegetation of arid areas. The harvested aboveground biomass (i.e. leaves) can be safely used to feed animals. *P. glaucum* tends to accumulate more Pb and Cr compared to other cover plants, but their concentrations were within the normal range in plants. All the grown cover plants can be safely used as fodder to feed livestock. Such results indicate that the reuse of treated wastewater is indeed a technical solution for irrigation water shortage to revegetate arid regions with no adverse environmental impacts. However, long-term reuse of treated wastewater might bring some questions about environmental quality. Contamination with heavy metals should be further investigated in order to determine the long-term residual effects of treated wastewater.

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