Colegio de Postgraduados

Impact of Treated Wastewater Use on Heavy Metal Accumulation in Soils and Sudan Grass Crops in the Mexicali Valley

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ABSTRACT

This study investigated the impact of using treated wastewater on the accumulation of heavy metals in soils and sudan grass crops. The transfer rate of heavy metals from soil to Sudan grass was determined. The Sudan crop was established in two plots: one irrigated with fresh water from the Colorado River and the other with treated wastewater from the Las Arenitas treatment plant. Metals Pb, Cr, Cd, Ni, and Cu were evaluated at two soil depths. Results showed that the concentration of metals in the treated wastewater is higher than in freshwater but within permissible limits. At a depth of 0-30 cm, the concentrations (mg/kg) of Pb, Cr, Cd, Ni, and Cu in soils irrigated with fresh and treated wastewater were 24.59, 19.25, 0.61, 25.33, 26.70, and 31.78, 20.10, 28.31, 28.33, respectively. These values show significant differences in the concentration of Pb and Cd. Analysis of metals in the Sudan grass showed similar results for soils irrigated with both types of water, with Pb and Cd not detected. The transfer rate was less than one for all metals. These results indicate no contamination or toxicity risks when using treated wastewater in Sudan grass crops. However, continuous monitoring is necessary to prevent contamination risks. These findings provide a scientific basis for developing policies and strategies for sustainable water resource management in arid and semi-arid regions.

Keywords: Heavy metals, wastewater, bioaccumulation factor, sudan grass cultivation, irrigation water.

INTRODUCTION

The rapid population growth has created the need to increase food production, intensifying agriculture and raising the demand for fresh water [1]. It has been reported that approximately 3 Mm^3 of water is allocated annually for agriculture, representing 70% of global freshwater use on the planet [2]. Additionally, the constant growth of the urban and industrial sectors exerts additional pressure on water resources. An alternative to alleviate the pressure on water resources is the use of treated wastewater for agricultural irrigation. This sustainable water supply practice is common in arid and semi-arid regions, where water deficits are more pronounced [3].

The agricultural use of treated wastewater promotes the conservation of water resources, reduces environmental impact on receiving bodies, and protects aquatic

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ecosystems [4]. Additionally, treated wastewater contains nutrients and organic matter that improve soil fertility, support crop growth, and reduce the need for fertilizers. However, its use raises significant concerns due to the potential accumulation of heavy metals in the soil and crops [5]. Heavy metals, such as lead (Pb), nickel (Ni), chromium (Cr), and cadmium (Cd), are toxic elements that can have harmful effects on human health and the environment. These metals can be absorbed by plants and enter the food chain, increasing the risk of chronic toxicity in humans and animals [6].

The Mexicali Valley is one of the most active agricultural regions in Mexico; however, it is located in the desert region of Baja California state. This area is characterized by low annual precipitation, with arid and semi-arid soils. Currently, the Mexicali Valley faces significant water scarcity, and its groundwater and surface freshwater sources are overexploited. It is estimated that the annual deficit amounts to 265.12 hm^3 [7]. To address water scarcity issues, the use of wastewater for irrigating certain forage crops, such as Sudan grass, has been adopted. In the Mexicali Valley, the wastewater used comes from the Las Arenitas treatment plant, located at latitude 32.42516 and longitude −115.32085. This plant processes approximately 27.4 Mm^3 annually, of which 40% is allocated to agriculture [8].

Currently, there is limited information on the presence of heavy metals in soils or crops irrigated with wastewater in the Mexicali Valley. Although there is significant global research on this topic, it cannot be generalized due to differences in soil conditions and wastewater quality. Therefore, this study investigated the effect of using treated wastewater on the accumulation of heavy metals in agricultural soils and Sudan grass crops. Two plots were compared: one irrigated with wastewater from the Las Arenitas plant and the other with fresh water from the Colorado River. The metals evaluated were Pb, Ni, Cr, and Cd. The results of this investigation provide fundamental information for developing policies and strategies for resource management.

MATERIALS AND METHODS

Study Area

This research was conducted in the Mexicali Valley, Baja California, Mexico. This region is situated at an altitude between 5-28 meters above sea level and is characterized by low precipitation, a dry and extreme climate, and arid to semi-arid soils. For this study, Sudan grass was planted in two plots of the Irrigation Module Number 12, part of the Irrigation District Number 014, Colorado River (DR-014). Plot No. 2 was irrigated with treated wastewater from the treatment plant, while Plot No. 50 was used as a control and irrigated with fresh water from the Colorado River. The studied plots are located relatively close to each other and have a similar surface area; their geographical location is shown in Figure 1.

Soil Sampling and Treatment

Soil sampling and treatment were conducted following current Mexican standards. A total of 10 sampling points were selected for each plot [9]. Soil samples were collected before planting and after harvesting Sudan grass, at two depths (0-30 and 30-60 cm) using

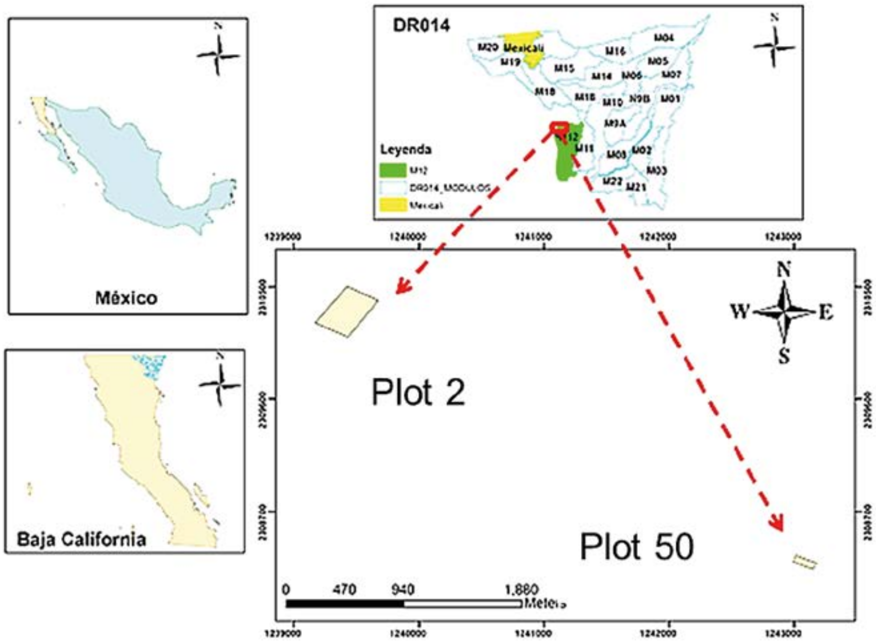

Figure 1. Plots used for the heavy metals study.

a soil auger. 1 kg of soil was extracted from each sampling point, which was then sieved to a particle size smaller than 0.25 mm. The ground and sieved samples were stored in airtight, sterile bags for subsequent analysis.

Water Sampling and Treatment

Fresh water and treated wastewater samples were collected from the irrigation channels of Module 12. Samples were collected from the gates allowing irrigation water to enter the plots, following the NOM-001-SEMARNAT-1996 standard [10]. Water samples were taken during each irrigation application, totaling five irrigations for each plot. Each sample contained 5 liters of water and was stored in polyethylene bottles that had been pre-washed with nitric acid (1%). The bottles containing the samples were then stored at 4 °C for subsequent analysis. For treated wastewater samples, a filtration process was applied to reduce turbidity [11].

Sampling and Treatment of Sudan Grass Plants

Plant samples were collected one day before the scheduled harvesting date for Sudan grass, following the NOM-021-SEMARNAT-200 standard [9]. The sampling points for plant collection coincided with the soil sampling points. Samples were collected by grouping 5 to 10 Sudan grass plants around the sampling site. Both aerial parts and roots were sampled, and the samples were washed with deionized water to remove soil or dust particles adhering to the surface. The samples were then dried at room temperature for 5 days. After drying, the samples were ground and sieved to reduce the particle size to 0.25 mm.

Physicochemical Analysis of Soil and Water

The physicochemical properties evaluated in soil and water were conducted according to the NOM-021-SEMARNAT-2000 and NOM-001-SEMARNAT-1997 standards, respectively [9,10]. The analyses performed included soil classification, pH determination, electrical conductivity (EC), organic carbon, and organic matter.

Total Metals Analysis

The total metal content in soil, water, and plant samples was determined. For solid samples, an acid digestion process was necessary. The digestion was performed on a heating plate using oxidizing acids such as HF, HNO_3, and HCl for 35 minutes. The digested samples were treated with a saturated H_3BO_3 solution to neutralize excess HF. The samples were then filtered and transferred to 50 mL volumetric flasks. The flasks were filled up to the mark with MilliQ water, and the contents were transferred to polyethylene flasks. Total metals were quantified using an atomic absorption spectrophotometer (Perkin Elmer 3100) with a hollow cathode lamp and an air-acetylene flame. The metals analyzed were Pb, Cd, Cr, and Ni, following the NMX-AA-051-SCFI-2016 standard [11]. Calibration curves were created from stock solutions, and the analyses were performed in triplicate to ensure the accuracy of the experimental data. The instrument's response was constantly verified during the analyses using certified standards of known concentration.

Transfer Factor

The transfer factor or bioaccumulation factor was studied to determine the fraction of trace elements that are transferred from the soil to the edible fraction of the Sudan plant. The transfer rate is determined by dividing the total metal concentration in the plant by the total metal concentration in the soil, as shown in Equation 1 [1, 3].

$$Tr = C_p / C_s \qquad \text{Equation 1}$$

Where Tr is the transfer rate (dimensionless), C_p is the total metal concentration in the plant sample (mg/kg), and C_s is the total metal concentration in the soil (mg/kg).

Statistical analysis

The analyses were conducted in triplicate, and the results are expressed as mean and standard deviation. The experimental data were analyzed using Minitab 17 statistical software. A one-way analysis of variance (ANOVA) was applied, and pairwise comparisons were performed using Tukey's test with a 95% confidence interval [12].

RESULTS AND DISCUSSION

Physicochemical analysis of soil and water

The results of the physical and chemical analyses of water and soil samples used for the cultivation of Sudan grass are presented in Table 1. Regarding water analysis, significant differences were found between the electrical conductivity (EC) of fresh water and treated wastewater. Additionally, it was found that the average pH of treated wastewater exceeded

Table 1. Physicochemical analysis of soil and irrigation water.

Parameter	Soil FW		Soil TW		FW	TW
	0 – 30 cm	30 – 60 cm	0 – 30 cm	30 – 60 cm		
pH	8.2±0.2	8.3±0.1	8.5±0.1	8.3±0.1	7.90±0.10	8.10±0.20
E.C. (dS/cm)	1.730	1.704	2.213a	2.445a	1.24±0.17a	2.12±3.17a
% Moisture	23.1±5.7	27.7±7.1	17.9±1.3	19.8±3.2	-	-
% OM	5.6±0.7	2.2±1.9	2.6±1.3	4.6±1.2	-	-
Texture	Clayey	Fragic clayey	Clayey	Clayey	-	-

[a] Indicates that the pairs of FW and TW values are significantly different ($p<0.05$).

the standards established for irrigation water by the WHO (2007) [13]. Regarding soil analysis, it was found that the pH of soil irrigated with fresh water (FW soil) is slightly lower than the pH of soil irrigated with treated wastewater (TWW soil). However, Tukey's test indicates that there are no significant differences in soil pH at different depths. Regarding EC, significant differences were found between FW soil and TWW soil at different depths. However, TWW soil exhibited higher conductivity compared to FW soil. Another parameter studied was moisture content. It was found that FW soil contains a higher moisture percentage compared to TWW soil. Additionally, the highest organic matter percentages were observed at depths of 0-30 cm and 30-60 cm for FW soil and TWW soil, respectively. Finally, the soil texture was determined, classifying them within the category of clay loam soils [9].

Total Metal Analysis in Irrigation Water

Table 2 presents the concentration of total metals in agricultural irrigation water from the Mexicali Valley. These values are compared with the permissible ranges reported by different national and international standards or organizations. The results indicate that the concentration of the studied metals in fresh water from the Colorado River and treated wastewater are within the permissible limits according to Mexican regulations and WHO standards [10, 13]. Specifically, Pb and Cd are below the detection limit (<0.025 mg L^{-1}), indicating a low presence of these metals. However, the results highlight the need to continuously monitor Cd and Cu metals, as they approached the limit values proposed

Table 2. Concentration of heavy metals in treated wastewater and fresh water.

Metal (mg L^{-1})	freshwater (Rio Colorado)	treated wastewater	Maximum permissible limits (mg L^{-1})	
			NOM-001-SEMARNAT-1996	WHO
Pb	<0.025	<0.025	5.00	0.50
Cr	0.004±0.001	0.007±0.002	0.50	0.10
Cd	<0.025	<0.025	0.05	0.01
Ni	0.035±0.006	0.039±0.010	2.00	0.20
Cu	0.010±0.001	0.020±0.001 [a]	4.00	0.20

[a] Indicates that the pairs of FW and TW values are significantly different ($p<0.05$).

by the WHO. Moreover, the statistical analysis showed significant differences between the concentration of copper in fresh water and treated wastewater.

Analysis of total metals in soil

The average concentration of metals present in FW soil and TWW soil at different depths was determined, as shown in Table 3. It was found that the average concentration of heavy metals in FW and TWW soil at different depths is below the limits established by the EPA (2012) [14], WHO (2007) [13], and the European Union (EU, 2001) [15]. However, it was observed that the concentration of heavy metals in TWW soil was higher compared to FW soil, except for copper at the 30-60 cm depth. Therefore, it is recommended to continuously monitor the concentration of heavy metals in soils irrigated with treated wastewater to prevent metal accumulation in agricultural soils and mitigate health risks.

A statistical analysis of the data obtained on the concentration of metals at different depths for each soil type was performed. It was found that there are no significant differences in the average metal concentration with respect to depth in FW and TWW soil, except for Cu in TWW soil. A second statistical analysis was carried out to compare the heavy metal concentration in FW soil with TWW soil. Significant differences were found in the average concentration of Pb and Cd between both soils at the two studied depths. Figure 2 shows the average total metal concentrations in FW Soil and TWW Soil for the depths of 0-30 cm and 30-60 cm, respectively.

Total metals in Sudan grass plants

The results of the total metal concentration in Sudan grass irrigated with fresh water (Sudan FW) and Sudan irrigated with treated wastewater (Sudan TWW) are presented in Table 4. The findings indicated that there is no risk of heavy metal contamination (Ni, Cr, Pb, Cu, and Cd) in Sudan grass when irrigated with fresh water or treated wastewater. Sudan TWW crops do not exceed the permissible limits reported by Lepp (1985) and MacLean *et al.* (1987) [13,16,17]. Previous studies have reported the use of wastewater in

Table 3. Concentration of heavy metals in agricultural soil according to depth and irrigation water.

Metals ($mg\ kg^{-1}$)	Soil irrigated with freshwater (Soil FA)		Soil irrigated with treated wastewater (Soil TW)		Maximum permissible limits		
	Depth of sampling (cm)				EPA [14]	WHO [13]	EU [15]
	0-30	30-60	0-30	30-60			

[redacted]

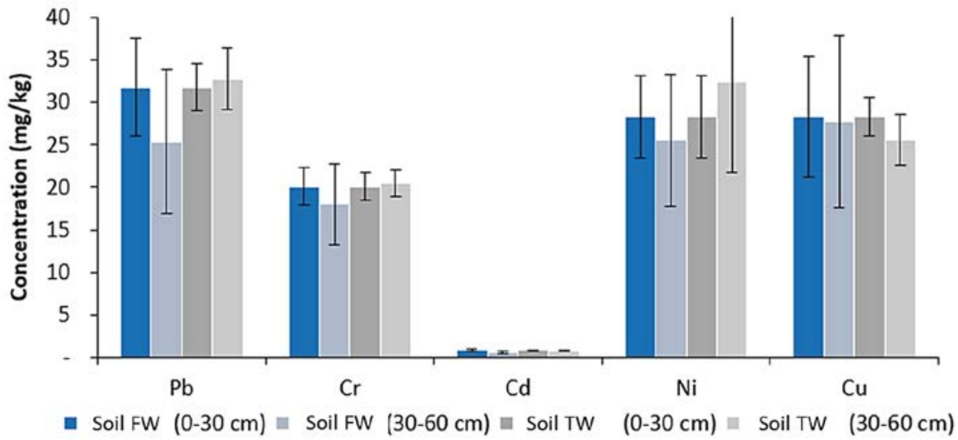

Figure 2. Total metal concentration in agricultural soil at different depths.

Table 4. Metal concentration in Sudan grass crops.

Metal (mg kg^{-1})	sudan FW	sudan TW	Maximum permissible limits (mg kg^{-1}) [13, 16, 17]
Pb	ND	ND	2.5
Cr	0.390±0.02	0.529±0.01	-
Cd	ND	ND	1.5
Ni	0.820±0.16	0.900±0.2	1.5
Cu	3.120±0.75	3.050±0.6	30

% recovery: Pb=98.5, Cr=97.1, Cd=96.9, Ni=99.0, Zn=89.1, Cu=93.3
[a] indicates that the pairs of values for Sudan FW and TW are significantly different ($p<0.05$).

forage crops for over 17 years without observing significant accumulation of heavy metals that pose toxicity risks [1]. The Tukey test indicated no significant differences in metal concentrations between Sudan FW and Sudan TWW plants.

Transfer Rate for the Agricultural Cycle of Sudan Grass

The transfer rate (Tr) of heavy metals (Pb, Cr, Cd, Ni, and Cu) from the soil to the Sudan grass plant was determined, considering different soil depths. The results are shown in Figure 3. It can be observed that Pb and Cd did not show any transfer rate (Tr) for either FW or TWW soils. In the case of Cr, low Tr values were observed, with no significant differences based on depth or water type. Meanwhile, Ni showed a consistent Tr under all studied conditions.

For Cu, lower Tr values than Ni were observed. However, when irrigated with treated wastewater and at a depth of 30-60 cm, the Tr increased significantly. This could be concerning from a toxicity and contamination perspective. In general, the Tr for most of the studied metals is less than one, indicating a low risk of metal accumulation in the sudangrass plant. The metals that showed the highest transfer for both water types, in ascending order, were Cu > Ni > Cr. The transfer values obtained are lower than those reported for other forage crops [1,4].

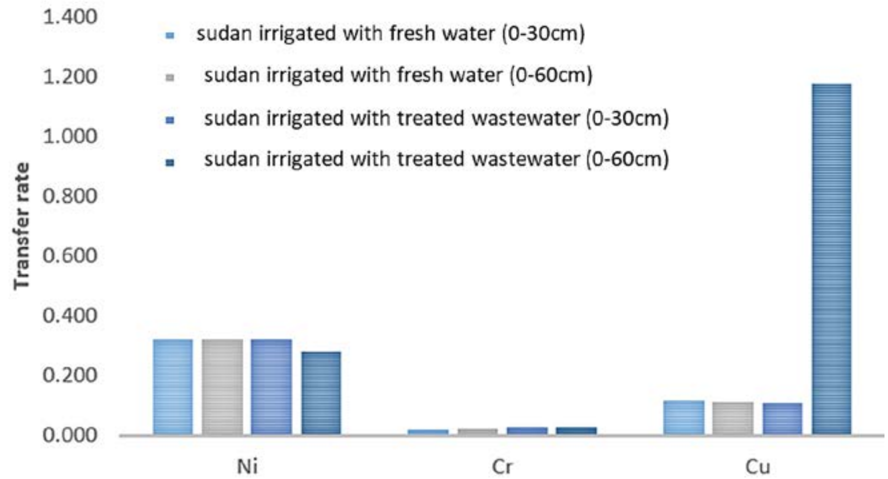

Figure 3. Heavy metal transfer rate from soil to plant.

CONCLUSIONS

This study investigated the accumulation of heavy metals in soils and Sudan grass crops irrigated with treated wastewater and fresh water in the Mexicali Valley. The results indicated that the use of treated wastewater could be a viable solution for agriculture in water-scarce areas like the Mexicali Valley. However, it is crucial to continuously monitor the concentration of heavy metals in both soil and crops to prevent toxicity risks. It was observed that the concentration of heavy metals in soil irrigated with treated wastewater was higher compared to soil irrigated with fresh water. Nonetheless, the values in both soils remained below the permissible limits established by the EPA, WHO, and the European Union. On the other hand, metal analyses in the Sudan grass tissue indicated no significant risk of contamination with heavy metals when irrigated with treated wastewater, as concentrations remained below permissible limits. Additionally, the transfer factors showed low risks of metal accumulation in plants, with values less than one.

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