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RESEARCH ARTICLE

EFFECTS OF USING TREATED WASTEWATER FOR IRRIGATION ON HEAVY METAL BUILDUP IN PLANTS AND SOIL AND ITS INFLUENCE ON SOIL SALINITY

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ABSTRACT

Jordan is experiencing significant water scarcity, worsened by limited renewable resources, a growing population, and climate change. Reusing treated wastewater (TWW) for irrigation has become a promising solution to combat water shortages. This study examines the effects of TWW from three wastewater treatment plants (WWTPs)—Za'atri, Al-Salt, and As-Samra—on soil salinity, heavy metal accumulation, and plant uptake. Analysis of TWW samples revealed high levels of heavy metals such as cadmium (Cd), lead (Pb), and mercury (Hg), which exceed the permissible limits established by WHO. Soil irrigated with TWW showed increased salinity and heavy metal concentrations compared to soil irrigated with rainwater, especially at deeper layers. Some metals, including cadmium and selenium, were found to be bioavailable, raising concerns about environmental and health impacts. While TWW presents an alternative source for irrigation, it is crucial to implement careful monitoring and treatment adjustments to reduce the risks linked to heavy metal contamination and soil degradation.

KEYWORDS

Wastewater, Heavy metals, Soil, Irrigation, Salinity, Cadmium

1. INTRODUCTION

Jordan faces an acute water scarcity crisis, making water management one of the country's most pressing and strategic challenges. Per capita water availability has decreased from 3,600 cubic meters per year in 1946 to less than 60 cubic meters per year in 2024, far below the global water poverty threshold of 1,000 cubic meters per capita per year and representing less than 15% of the global average (Ministry of Water and Irrigation, 2015; MWI, 2024). This scarcity is compounded by the country's limited renewable and non-renewable water resources, with 94% of Jordan's land classified as desert or arid, receiving an average annual rainfall of only 100 mm and experiencing an evaporation rate of 93% (MWI, 2015). The water crisis in Jordan has been further exacerbated by climate change, declining rainfall, limited alternative water sources, and sudden population increase. As predicted that climate change could lead to a further reduction in rainfall, potentially dropping to 80 mm in central and eastern regions in the coming decades (Matouq et al., 2013). Additionally, population growth, improved living standards, and the depletion of water sources have intensified water scarcity. Projections suggest that Jordan's per capita water consumption could increase by 50–60% by 2025, placing immense strain on already limited resources (MWI, 2015). Consequently, Jordan is ranked as the second-most water-scarce country in the world, posing a significant challenge for policymakers and sustainable development efforts. Despite these challenges, Jordan has achieved notable progress in water infrastructure, with 97% of the population served by public drinking water networks and 67% by sewage systems. To address water scarcity, effective planning and resource management are essential to balance current and future demands. One promising solution is the reuse of treated domestic wastewater (TDWW), primarily for agriculture, which conserves freshwater for domestic use. Treated wastewater contributed 11% of Jordan's water budget in 2011, rising to 15% by 2021 (MWI, 2015). Treated wastewater consists of 99.9% water and 0.01% suspended and dissolved solids, and its use in irrigation has been extensively studied for its environmental impacts on soil and crops (Aljbour et al., 2021a, b).

AsI outline the health and environmental impacts of heavy metals in industrial wastewater, particularly in developing countries where regulatory enforcement is weak (Oladimeji et al., 2024). The highlighted the fact that traditional treatment methods are fractionally effective but are marred by limitations like low removal efficiency, sludge production, and pH dependency. New technologies like nanotechnology, photocatalysis, and electrochemical coagulation are offering greater performance and selectivity but are too costly to be applied on a mass scale. The article emphasizes the need for future research directed toward the creation of cost-effective, efficient, and sustainable heavy metal removal technology.

As studied the effect of reusing TWW from an industrial wastewater treatment plant and from a domestic wastewater treatment plant, the results show that there is no significant adverse effects on soil and plant properties (Al-Mubaidin et al., 2022). As investigated the reuse of treated grey water (TGW) for irrigating olive trees and vegetables revealed that while soil salinity, sodium adsorption ratio (SAR), and organic content increased over time, these changes could be managed by periodic leaching with freshwater (Al-Hamaiedeh and Bino, 2010). The chemical properties of olive trees and vegetable crops were unaffected, but the biological quality of some vegetables was negatively impacted. Moreover, the reuse of TGW in home gardens raised public health concerns due to fly breeding and unpleasant odors. As found that applying olive mill wastewater (OMW) at a rate of 60 m^3/ha under rain-fed conditions significantly

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improved wheat growth without negatively affecting soil properties (Mohawesh et al., 2019). Further research on controlled land application of OMW indicated no harmful effects on soil properties or barley growth parameters for all tested application rates (Mohawesh et al., 2020). Conversely, highlighted the risks associated with untreated wastewater (WW) reuse for irrigation (Baker, 2007). The study found that untreated WW exceeded permissible quality limits and adversely impacted topsoil texture, total carbon and nitrogen levels, and caused heavy metal accumulation (arsenic, cadmium, lead) in the soil profile. The findings concluded that using untreated WW for irrigation poses significant environmental and health hazards.

Treated wastewater remains Jordan's primary non-conventional water source. The Ministry of Water and Irrigation's strategy approved the reuse of 167 million cubic meters of TWW in 2021, with projections estimating an increase to 250 million cubic meters by 2050 to address rising demand and alleviate pressure on groundwater resources (MWI, 2021; MWI, 2004).

This aim of this study is to investigate the impact of using TWW from three wastewater treatment plants (WWTPs) in Jordan, namely As-samra, Za'atri, and Al-Salt WWTPs on the irrigated plants and soils in terms of heavy metal accumulation and salinity of the soil and the uptake of heavy metals by the plants.

2. Study Area Settings

2.1 Za'atari Wastewater Treatment Plant (ZWWTP):

The treatment plant is located in Mafraq Governorate and serves the Zaatari camp for Syrian refugees. The plant has a design capacity of 3520 m^3/day and consists of two treatment systems: (MBR) system with a design capacity of 1760 m^3/day per unit, and a Trickling Filter system with a design capacity of 1760 m^3/day per unit. According to 2023 statistics: The amount of water entering the plant is 2602 m^3/day. The amount of reclaimed water leaving the plant is 2448 m^3/day. The reclaimed water is utilized in the cultivation of fodder crops, which are restricted crops allowed to be irrigated with reclaimed water according to Jordanian standards (893/2021). Formal agreements are made between farmers and the Water Authority. The area of agricultural land using this water is approximately 300 dunums =30 hectares

2.2 Al-Salt Treatment Plant:

The treatment plant is located in the Balqa Governorate utilizing activated sludge treatment system with design capacity of 9,000 cubic meters per day. There is currently a project to expand the plant to a capacity of 11,000 cubic meters per day. The area of land irrigated with treated water is 150 dunums. According to 2023 statistics of (MWI), the influent to the plant is 9,084 cubic meters per day and the effluent from the plant is 9,063 cubic meters per day. Part of the reclaimed water is utilized the irrigation of olive trees and some types of fruit trees (citrus), which are restricted crops allowed to be irrigated with reclaimed water according to Jordanian standard (893/2021). The other part is discharged into nearby streams and valleys, eventually reaching the Wadi Shuaib Dam, where it is mixed with other water and used for irrigation in the Jordan Valley area.

2.3 As-Samra Treatment Plant:

The As-Samra treatment plant in Zarqa Governorate, it is the largest treatmen plant in Jordan. It utilizes activated sludge treatment process. According to 2023 statistics of (MWI), The amount of water entering the plant is 410,643 cubic meters per day and the amount of reclaimed water leaving the plant is 398,323 cubic meters per day. The reclaimed water is utilized for irrigating forage crops and olive trees around the plant, covering an area of approximately 2,300 dunums. The rest of treated water is discharged to Zarqa river to reach the King Talal Dam where it mixed with fresh water and used for irrigation in Jordan valey.

3. Methodology

3.1 Sampling

3.1.1 Treated wastewater (TWW)

TWW samples were taken from the middle depth of the TWW receiving channel from the studied WWTP. The volume of the samples collected was 10 liter from each plant, the samples were kept in a polyethylene container, transported to the laboratory, and stored at 4°C as outlined to be tested for heavy metal content and salinity as suggested by the Standard Methods of Chemical Analysis and the standard conservation methods for the examination of water and wastewater (APHA, 1998; Tatsi et al., 2003; Kulikowska and Klimiuk, 2008). TWW samples have been tested for heavy metals: (Thorium (Th), Titanium (Ti), Aluminium (Al), Antimony (Sb), Arsenic (As), Barium (Ba), Berylium (Be), Bismuth (Bi), Boron (Br), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Lead (pb), Lithium (Li), Mercury (Hg), Molybdenum (Mo), Nickel (Ni), Palladium (Pd), Platinum (Pt), Scandium (Sc), Selenium (Se), Silver (Ag), strontium (Sr)). Water sample analyses were conducted according to the Standard Methods for the Examination of Water and Wastewater, (Barid and Bridgewater, 2017). The average concentration of three tested samples and the standard deviation were recorded for each metal and compared with the WHO and Jordanian standard for reclaimed wastewater reuse. The total dissolved solids (TDS) for each sample was determined as the mass of the dissolved solid normalized to the volume of water filtered. The value of TDS was measured according to the standard method 2540C (Barid and Bridgewater, 2017).

3.1.2 Soil

Soil samples were collected from fields that were irrigated with treated wastewater as well as from control fields that irrigated with rain water. Soil samples have been taken from two depths: 30 cm and 40 cm to assess the vertical distribution of heavy metals content and soil salinity. The samples were stored in clean, labeled polyethylene bags and transported to the laboratory. The average concentration of three samples from each depth has recorded as well as the standard deviation.

3.1.3 Plants

Plant Samples: Representative samples of olive and lemon leaves, fruits as well as fodder were collected from fields irrigated with TWW. Olive leaves and fruits from fields irrigated with rainwater were also collected and analyzed to serve as control samples. The plant samples were rinsed with deionized water to eliminate any soil and dust, air-dried, and stored in labeled paper bags for transport to the laboratory.

3.2 Sample Preparation Soil Samples:

Air-dried soil samples at room temperature were grinded to pass through a 2 mm sieve. About 1 g of soil was weighed and digested using a mixture of nitric acid (HNO3) and hydrochloric acid (HCl) in a 3:1 ratio, using either a microwave digestion system. The digested sample was filtered and diluted to a final volume with deionized water.

Plant Samples: The plant samples were dried in an oven at 70°C until they reached a constant weight. The dried samples were grinded into a fine powder using a stainless steel grinder. Approximately 0.5 g of the plant material was digested with nitric acid (HNO3) and perchloric acid (HClO4) in a 4:1 ratio. The digested sample was filtered and diluted with deionized water. Analysis Using an Atomic Absorption Spectrophotometer (AA-7000, Shimadzu), the AAS instrument was Calibrated with standard solutions of the target heavy metals (such as Cd, Pb, Cr, Ni). The digested soil and plant samples were analyzed for their heavy metal concentrations. The appropriate wavelengths and lamp settings were used for each metal to ensure accurate readings. Quality control by running blanks, duplicates, and certified reference materials with each batch of samples have been conducted. Data Analysis Compare the heavy metal concentrations in samples irrigated with treated wastewater against those from control fields. The EC values of all soil samples were measured according to the standard method SM 2510. The soil EC was determined by shaking a 1:2.5 (w/w) ratio of soil and deionized water. The mixture was homogenized for 30 min at 15 rpm using a horizontal shaker and then left at room temperature until the soil settled down before EC measurement. The conductivity of the supernatant liquid was determined using the conductivity meter without disturbing the settled soil (Conductivity meter 4310, JENWAY, UK) (El-Hasan and Al-Tarawneh, 2020).

4. Results And Discussions

The data presented in Table 1 allow comparing the concentration of various heavy metals in TWW generated from three wastewater treatment plants (WWTPs) in Jordan: Za'atri, As-Samra, and Al-Salte, with the allowable limits of concentration set up by the World Health Organization. The results indicate that the concentrations of Arsenic (As) in As-Samra - 16.64 µg/L and in Al-Salte - 15.27 µg/L exceed the WHO standard limit of 10 µg/L. The concentration of Cadmium (Cd) in TWW of all WWTPs (As-Samra, Al-Salte, and Za'atri) was reported to exceed the set value of 3 µg/L with As-Samra having the highest at 24.97 µg/L. Lead (Pb) concentration across the three plants exceeded the WHO in all of the WWTPs with Al-Salte stating the highest concentration of 32.51 µg/L compared to the WHO's limit.

The allowable limits of these metals according WHO

Table 1: The concentration of Heavy Metals in Treated Wastewater from Different Wastewater Treatment plants (WWTPs)

Elements	Za'atri WWTP		As-Samra WWTP		Al-Salt WWTP		WHO standard
	Concentration (µg/L)		Concentration (µg/L)		Concentration (µg/L)		
	Average	SD	Average	SD	Average	SD	
Thorium (Th)	0	0	2.37	1.06	0	0	1
Titanium (Ti)	0	0	16.27	3.18	0	0	100
Aluminium (Al)	12.87	2.02	35.35	3.95	12.57	2.2	200
Antimony (Sb)	3.27	1.72	4.87	2.08	3.6	1.93	6
Arsenic (As)	10.17	1.67	16.64	3.27	15.27	4.13	10
Barium (Ba)	3	1.34	1.67	1.25	5.87	2.02	100
Berylium (Be)	3.93	2.07	N.D	N.D	2.54	1.36	4
Bismuth (Bi)	2.23	0.9	4.49	1.8	3.74	2.29	10
Boron (Br)	9.83	2.1	13.08	2.17	15.24	1.58	300
Cadmium (Cd)	17.67	3.12	24.97	2	20.29	1.72	3
Chromium (Cr)	13.27	1.76	9.37	1.6	26.51	3.24	50
Cobalt (Co)	13.03	3.03	11.29	1.68	26.39	3.65	50
Lead (pb)	22.97	1.97	20.71	2.06	32.51	1.3	10
Lithium (Li)	18.03	2.04	7.8	2.14	11.93	2.48	40
Mercury (Hg)	35.9	2.41	37.98	2.14	24.93	2.02	6
Molybdenum (Mo)	N.D	N.D	5.27	1.71	7.91	2.09	10
Nickel (Ni)	7.7	1.93	7.99	2.03	1.57	1.11	70
Palladium (Pd)	3.77	2.15	3.39	1.85	1.23	0.69	10
Platinum (Pt)	8.53	1.97	4.51	1.84	0.53	0.29	2
Scandium (Sc)	6.2	2.49	3.44	1.8	2.57	1.06	7
Selenium (Se)	4.13	2.13	5.83	1.77	8.17	1.59	10
Silver (Ag)	8.27	1.67	10.54	0.59	12.27	1.55	100
Strontium (Sr)	5.87	2.44	35.38	2.41	0	0	1000

The concentration of Mercury (Hg) in all plants exceeded the WHO limit of 6 µg/L with figures rising to 37.98 µg/L in As-Samra.

Estimates for the concentration of Platinum (Pt) in the Za'atri first appeared to be less than 6 µg/L at 8.53 µg/L, which also happened to be the case for As-Samra who was also higher than the 2 µg/L limit set by the WHO. The WHO hasn't included limits for specific elements such as Chromium (Cr), Cobalt (Co), Nickel (Ni), Selenium (Se), Silver (Ag), and Strontium (Sr): which means that these elements were present in all WWTPs in concentrations not higher than permissible levels. Beryllium (Be) and Molybdenum (Mo): Not detected in As-Samra WWTP which could either mean that the elements have been effectively removed or were not present in the influent. The discharge of industrial WW with domestic WW is the main source of heavy metals in WW. Therefore, separation and pretreatment of the industrial WW before discharge to the sewer system is highly important to reduce the concentration of heavy metals in TWW. Moreover, adding more advanced selective treatment methods for the removal of heavy metals can eliminate their adverse effects on public health. As the public health concerns arise due to Arsenic, Cadmium, Lead, and Mercury as they are all raised above the limit which can cause health issues if exposed to such high amounts. Also, It can cause many adverse effects to the food, soil, and water by pumping heavily nitrogenized, cadmium, and lead-filled water that exceeds the set levels.

Table 2 presents the concentrations of heavy metals found in soils irrigated with treated wastewater from three different treatment plants (Za'atri, As-Samra, and Al-Salt) as well as rainwater, measured at depths of 30 cm and 40 cm. The concentrations of heavy metals show considerable variation depending on the water source used for irrigation. For instance, arsenic (As) levels are notably higher in soils irrigated by the Assamra WWTP (42.74 μg/L at 30 cm depth) compared to those irrigated with rainwater (4.27 μg/L at 40 cm depth). Depth-wise Distribution: In many instances, the concentration of heavy metals varies between the two depths of 30 cm and 40 cm. For example, lead (Pb) is found in higher concentrations in soils irrigated by the As-Samra WWTP at 40 cm depth (51.63 μg/L) than at 30 cm depth (22.97 μg/L). Comparative Analysis of Metals: Certain metals, such as mercury (Hg), are detected in relatively high concentrations across the TWW sources (e.g., 49.56 μg/L in Assamra WWTP at 40 cm) when compared to rainwater (5.93 μg/L at 40 cm). Conversely, metals like thorium (Th) are mostly absent in the samples, with the exception of Al-Salt WWTP and rainwater-irrigated soils, where they appear at lower concentrations. Standard Deviations (SD): The SD values reflect the variability in the measurements. High SD values (for example, selenium (Se) from Assamra WWTP at 40 cm depth, SD = 4.08) indicate inconsistent distribution or potential heterogeneity in the soil composition. Notable Trends by Elements: Arsenic (As): Found in high concentrations in Assamra WWTP samples, while lower in Al-Salt and rainwater. Cadmium (Cd) concentrations are highest in the As-Samra WWTP, measuring 44.66 μg/L at a depth of 40 cm, while they are significantly lower in soils irrigated with rainwater. Aluminum (Al) levels remain relatively stable across different samples, showing only a slight decrease in rainwater-irrigated soils. Titanium (Ti) and Thorium (Th) are either minimal or completely absent in several samples, indicating limited contamination from these elements. Rainwater-Irrigated Soils: In general, soils irrigated with rainwater show lower levels of heavy metals, suggesting they are less contaminated compared to those irrigated with treated wastewater. Potential Implications: The differences in heavy metal concentrations indicate that the type of treated wastewater used for irrigation plays a significant role in soil contamination. Variations in depth may suggest that metal leaching or accumulation is influenced by soil characteristics and irrigation methods. Certain metals, such as cadmium and mercury, raise environmental and health concerns due to their elevated levels in soils irrigated with wastewater.

Table 2: The concentration of Heavy Metals in Soils Irrigated with Treated Wastewater and Rain Water

Elements	Za'atri WWTP,				As-Samra WWTP				Al-Salt WWTP				Rain Water			
	30 cm depth		40 cm depth		30 cm depth		40 cm		30 cm		40 cm depth		30 cm depth		40 cm	
	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD	Avre, (μg/L)	SD
Thorium (Th)	0	0	0	0	2.37	1.06	0	0	0	0	0	0	0.63	0.61	0.68	0.47
Titanium (Ti)	0	0	0	0	16.27	3.18	0	0	0	0	0	0	0.49	0.54	2.23	2.05
Aluminium (Al)	12.87	2.02	42.95	2.42	35.35	3.95	32.71	2.48	13.62	3.55	12.57	2.2	6.6	3.25	17.9	2.463
Antimony (Sb)	3.27	1.72	19.60	3.15	4.87	2.08	2.96	1.69	3.3	1.98	3.6	1.93	0.40	0.29	1.4	0.8
Arsenic (As)	10.17	1.67	42.74	2.67	16.64	3.27	9.53	1.49	7.67	2.65	15.27	4.13	3.83	1.55	4.27	1.85
Barium (Ba)	3	1.34	25.2	1.95	1.67	1.25	1.27	0.96	4.65	2.35	5.87	2.02	0.63	0.45	1.63	1.07
Berylium (Be)	3.93	2.07	20.58	2.56	N.D	N.D	0	0	1	0.57	2.54	1.36	0	0	0.62	0.55
Bismuth (Bi)	2.23	0.9	18.87	2.14	4.49	1.8	7.67	2.57	0.7	0.4	3.74	2.29	1.37	0.76	0.67	0.50
Boron (Br)	9.83	2.1	36.95	2.88	13.08	2.17	4.57	2.594	6.22	1.82	15.24	1.58	2.33	1.11	3.43	1.76
Cadmium (Cd)	17.67	3.12	44.66	3.93	24.97	2	10.90	2.55	13.21	2.85	20.29	1.72	1.47	0.86	1.27	1.0
Chromium (Cr)	13.27	1.76	37.66	1.64	9.37	1.6	9.23	1.90	7.35	1.95	26.51	3.24	1.07	1.00	1.67	1.46

Cobalt (Co)	13.03	3.03	40.91	2.16	11.29	1.68	8.31	3.00	11.25	2.00	26.39	3.65	2.73	1.53	3.05	1.43
Table 2 (Cont.): The concentration of Heavy Metals in Soils Irrigated with Treated Wastewater and Rain Water																
Lead (pb)	22.97	1.97	51.63	3.52	20.71	2.06	15.31	2.00	6.6	1.22	32.51	1.3	4.83	2.47	3.87	2.09
Lithium (Li)	18.03	2.04	25.85	2.68	7.8	2.14	9.58	2.49	2.92	1.23	11.93	2.48	3.23	2.10	4.33	3.0
Mercury (Hg)	35.9	2.41	49.56	2.58	37.98	2.14	17.57	2.54	7.94	1.32	24.93	2.02	5.84	2.47	5.93	3.38
Molybdenum (Mo)	N.D	N.D	20.7	2.71	5.27	1.71	3.67	2.61	0	0	7.91	2.09	2.4	1.61	3.42	2.18
Nickel (Ni)	7.7	1.93	15.64	2.39	7.99	2.03	8.65	1.66	0	0	1.57	1.11	0.83	0.55	1.01	0.47
Palladium (Pd)	3.77	2.15	17.87	2.51	3.39	1.85	3.2	2.14	0	0	1.23	0.69	0.92	1.03	0.87	0.54
Platinum (Pt)	8.53	1.97	12.97	2.64	4.51	1.84	7.67	2.47	0	0	0.53	0.29	2.17	1.21	0.06	0.04
Scandium (Sc)	6.2	2.49	5.65	2.94	3.44	1.8	7.13	1.94	0	0	2.57	1.06	0.48	0.39	0.64	0.59
Selenium (Se)	4.13	2.13	46.23	4.08	5.83	1.77	6.03	2.70	0	0	8.17	1.59	0.54	0.66	1	1.13
Silver (Ag)	8.27	1.67	37.56	2.98	10.54	0.59	9.47	1.91	0	0	12.27	1.55	3.2	2.05	4.17	2.20
Strontium (Sr)	5.87	2.44	30.33	2.12	35.38	2.41	12.94	2.54	0	0	0	0	3.77	1.19	3.57	2.37

Table 3 shows the levels of heavy metals in plants that were irrigated with TWW from three treatment plants (Za'atri, Assamra, Al-Salt) and rainwater. Plants watered with wastewater from Za'atri WWTP typically show higher heavy metal concentrations than those watered with rainwater. For instance: Cadmium (Cd):

Table 3: The concentration of Heavy Metals in the Irrigated Plants with Treated Wastewater of Different Wastewater Treatment Plants (WWTP) and Rain Water

WWTP	**Za'atri,**		**Assamra**		**Al-Salt,**				**Rain Water**	
Irrigated Plant	**Fodder**		**Fodder**		**Olive trees**		**Lemon trees**		**Olive trees**	
Elements	**Average Concentration (µg/L)**	**SD**	**Average Concentration (µg/L)**	**SD**	**Average Concentration (µg/L)**	**SD**	**Average Concentration (µg/L)**	**SD**	**Average Concentration (µg/L)**	**SD**
Thorium (Th)	0	0	0	0	0	0	0	0	0	0
Titanium (Ti)	0	0	0	0	0	0	0	0	0	0
Aluminium (Al)	4.27	1.20	4.33	2.00	3.33	2.00	2.45	1.34	6.9	2.14
Antimony (Sb)	0	0	0.87	0.93	1.07	1.03	0	0	0.77	0.61
Arsenic (As)	2.00	1.31	1.33	1.21	1.17	1.17	1.03	1.00	0.7	0.62
Barium (Ba)	4.47	2.47	1.20	1.58	1.33	1.38	0	0	0	0
Berylium (Be)	1.27	1.61	0	0	0	0	0	0	0	0
Bismuth (Bi)	0	0	0.73	0	0.9	0	0	0	0	0
Boron (Br)	2.93	1.46	1.33	1.02	1.39	0.79	0	0	0.53	0.40
Cadmium (Cd)	6.57	1.10	3.37	2.20	4.37	2.10	0.77	0.66	3	2.1
Chromium (Cr)	5.37	1.79	1.57	1.61	1.93	1.59	1	1.08	1.65	1.33
Cobalt (Co)	3.13	1.35	4.77	2.65	4.67	1.96	0	0	0.7	0.55

Lead (pb)	6.27	0.97	4.7	2.71	4.7	2.70	0.8	0.62	2.98	2.02
Lithium (Li)	2.17	1.05	0.90	0.99	1.38	1.47	0	0	0.7	0.6
Table 3(Cont.): The concentration of Heavy Metals in the Irrigated Plants with Treated Wastewater of Different Wastewater Treatment Plants (WWTP) and Rain Water										
Mercury (Hg)	5.2	1.1	3.13	1.10	3.53	1.33	0.51	0.34	2.67	1.52
Molybdenum (Mo)	0	0	0.8	0	1.57	0.86	0	0	0	0
Nickel (Ni)	6.64	1.41	0.73	0.68	1.37	1.34	0	0	0	0
Palladium (Pd)	3.3	1.15	1.03	1.21	1.4	1.13	0	0	0	0
Platinum (Pt)	0	0	1.23	0.95	1.29	0.91	0	0	0	0
Scandium (Sc)	0	0	2.63	1.86	3.26	2.26	0	0	0	0
Selenium (Se)	7.17	2.99	2.7	1.9	1.6	1	0	0	3.6	1.47
Silver (Ag)	4.67	2.09	0	0	0	0	0	0	2.97	1.33
Strontium (Sr)	0	0	0	0	0	0	0	0	0	0

The highest concentration is found in plants irrigated by Za'atri WWTP (6.57 µg/L), compared to 3 µg/L in those irrigated with rainwater. Nickel (Ni): Detected at a notable level in Za'atri WWTP-irrigated plants (6.64 µg/L), while absent in rainwater-irrigated plants. Rainwater: Generally, lower concentrations of heavy metals are noted. For example: Arsenic (As): The lowest levels are in rainwater-irrigated plants (0.7 µg/L), compared to 2 µg/L in those from Za'atri WWTP. Cobalt (Co): Very low levels are found in rainwater-irrigated plants (0.7 µg/L), compared to 3.13 µg/L in Za'atri. Variation Across Plant Types: Fodder Plants (Za'atri WWTP and As-Samra WWTP): These show higher concentrations of many elements compared to trees irrigated from other sources. Olive Trees: Generally accumulate fewer heavy metals than fodder plants, particularly when watered with rainwater. Arsenic (As): Present across all irrigation sources but significantly lower in rainwater-irrigated plants. Cadmium (Cd) and Lead (Pb): Higher levels are found in wastewater-irrigated plants, raising concerns about potential health risks. Beryllium (Be), Titanium (Ti), and Thorium (Th): Not detected or found at negligible levels in all plants. Standard Deviations: Some metals show high variability (e.g., selenium in Za'atri WWTP-irrigated plants, SD = 2.99), suggesting inconsistent uptake or varying contamination levels in the environment. Potential Implications: Health Risks: Increased levels of heavy metals like cadmium, lead, and mercury in fodder plants could pose risks for livestock and human health.

4.1 Correlation Between Soil Heavy Metal Levels and Their Uptake by Plants

4.1.1 As-Samra WWTP

The data shown in Figure 1, display the concentration of various heavy metals in soil at depths of 30 cm and 40 cm, and in plant samples collected from the As-Samra Wastewater Treatment Plant (WWTP). As seen in most of the cases, concentration of heavy metals seems to be greater at 30 cm depth than at 40 cm depth. This indicates that possibly heavy metals are more likely to be found in the upper layers of the soil rather than the lower layers because of the direct contact with the treated wastewater and slight downward leaching. For example, Aluminium concentration was higher at 30cm for 12.87 µg/L as compared to 40cm which had 2.02 µg/L whereas also for Lead concentration of 22.97 µg/L was at 30cm while 1.97 was at 40cm depth. In relation to the uptake of heavy metals by the irrigated plants, there are heavy metals present that plants tend to significantly absorb as seen with Titanium having a concentration of 4.33 µg/L in plants and none in both depths of soil, or Chromium with 4.77 concentration in plants and 13.27 at 30cm depth. With this it can be implied that these metals are bioavailable and can cause harm through the food chain. A case in point: Mercury. Even though its concentration is high in soils (35.9 µg/L at 30 cm) its uptake by plants is very low (0.8 µg/L). This may be attributed to lower bioavailability or specific plant resistance mechanisms.

While barium organic plant compounds can be synthesized and enhanced by bacteria in the soil ecosystems, metals such as Beryllium and Strontium are seldom found in plants effectively illustrating their biogeochemical behavior as non mobile elements in the soils or poorly available organic compounds. On the contrary, it would also seem that when present similarly to or with lesser ratios than these first two metals, Boron and Cadmium display relatively greater concentrations in plants than the rest of the metals suggesting Potassium, Phosphorus and Nitrogen complexes could facilitate the transportation of lean Cadmium Precipitation in plants."

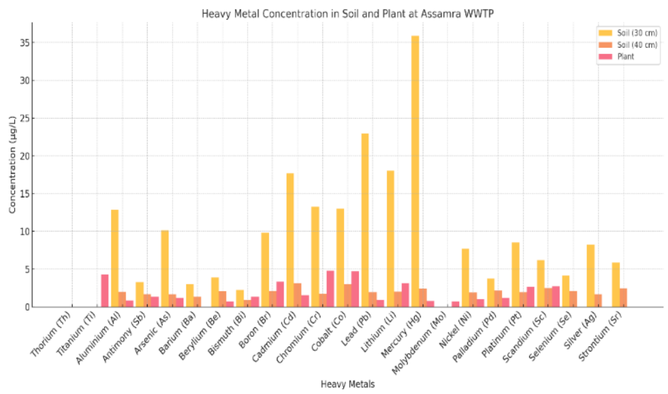

Figure 1: Heavy metal concentrations in irrigated soil and plants at As-Samra WWTP

Concerning the environmental and health implications, presence of heavy metals in the soil will cause negative effects on the area's soil structure and quality. Also a potential to cause pollution down in the groundwater can be drawn from the high concentrations noted in lead, cadmium and mercury contamination in the upper horizon of the soil 30 centimeters below the surface. However, it is possible that the aforementioned three metals can also be harmful to human health when ingested from agricultural products as seen in the case of Titanium, Boron, and cadmium for example. Therefore, regular monitoring should be made in order to reduce the danger posed to human beings, plants, and soil, it is important to constantly measure the concentration of heavy metals in treated wastewater as well as in soil and plants. Additionally, development and modifications of the sewage treatment chemical process will enable a reduction in the concentration of heavy metals in treated effluents. Plants that can absorb heavy metals and immobilize then would be good means of exploring and possibly reclaiming the contaminated ecosystems from the soils.

The above results emphasize the necessity of controlling heavy metals during agriculture with treated wastewater in order to retain farm and environment quality.

4.1.2 Al-Salt WWTP (Wadi Shoab site)

The data presented in Figure 2 displays the concentration of various heavy metals in soil at depths of 30 cm and 40 cm and in plant samples collected from the Al-Salt Wastewater Treatment Plant (WWTP). Heavy metal concentrations tend to be higher at the 40 cm depth compared to 30 cm, as illustrated by metals like Arsenic (As) (7.67 mg/kg at 30 cm vs. 15.27 mg/kg at 40 cm) and Cadmium (Cd) (13.21 mg/kg at 30 cm vs. 20.29 mg/kg at 40 cm). This indicates a downward movement and leaching of metals into deeper soil layers, likely influenced by irrigation practices and infiltration processes.

Metal Uptake by Plants: The concentration of metals in plants is significantly lower than in the soil. For example: Arsenic (As): Moderate levels in soil (15.27 mg/kg at 40 cm) contrast with low uptake in plants (2.00 mg/kg). Lead (Pb): High levels in soil (32.51 mg/kg at 40 cm) but limited absorption by plants (6.27 mg/kg). This suggests that certain metals have reduced bioavailability or that plants possess natural resistance mechanisms to limit metal absorption.

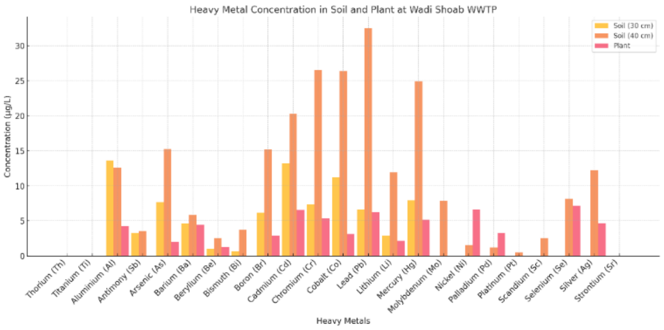

Figure 2: Heavy metal concentrations in irrigated soil and plants at Al-Salt (Wadi shoab) WWTP

Metals with High Bioavailability: Metals such as Cadmium (Cd) (6.57 mg/kg), Chromium (Cr) (5.37 mg/kg), and Selenium (Se) (7.17 mg/kg) show significant concentrations in plants relative to their levels in soil. This indicates that these metals are highly bioavailable, which raises concerns about potential bioaccumulation in the food chain. Low Uptake or Immobility: Elements like Thorium (Th) and Titanium (Ti) are either absent or present in negligible amounts in both soil and plants, suggesting immobility or low availability in the studied ecosystem. Metals like Nickel (Ni) and Palladium (Pd), while found in soil, show limited uptake by plants, reflecting their restricted mobility. Potential Environmental and Health Impacts: Cadmium (Cd): High concentrations in both soil and plants indicate a significant risk of bioaccumulation, which could impact crop safety and human health. Lead (Pb): Elevated levels in soil, despite limited plant uptake, pose long-term risks to soil health and potential groundwater contamination. Selenium (Se): Its notable presence in plants suggests it could enter the food chain, potentially affecting animal health.

Za'atri WWTP

The data in Figure 3 display the concentration of various heavy metals in soil at depths of 30 cm and 40 cm, and in plant samples collected from the Za'atari (WWTP).

Heavy metal levels in soil at a depth of 40 cm are consistently higher than those at 30 cm, suggesting that metals may leach into deeper layers over time. For instance: Arsenic (As) shows a concentration of 10.17 µg/L at 30 cm, increasing to 42.74 µg/L at 40 cm. Lead (Pb) is measured at 22.97 µg/L at 30 cm, rising to 51.63 µg/L at 40 cm. Concentration in Treated Wastewater (TWW): The metal concentrations in TWW are generally lower than those found in soil, likely due to the accumulation of metals in the soil over extended irrigation periods. Noteworthy elements such as cadmium (Cd) and lead (Pb) are present at moderate levels in TWW (16.75 µg/L and 19.55 µg/L, respectively), which is important for irrigation water quality. Metal Uptake by Plants: Plants show lower concentrations of heavy metals compared to both soil and TWW, indicating either partial uptake or resistance to certain metals. For example: Aluminium (Al) is found at 12.87 µg/L in soil (30 cm depth) versus 4.27 µg/L in plants. Cadmium (Cd) levels are 17.67 µg/L in soil (30 cm depth) compared to 6.57 µg/L in plants. Absent or Negligible Metals: Elements like thorium (Th), titanium (Ti), and platinum (Pt) are either negligible or completely absent in soil, TWW, and plants. Specific Heavy Metals: Cadmium (Cd): Soil shows high levels of cadmium, with significant uptake by plants (6.57 µg/L).

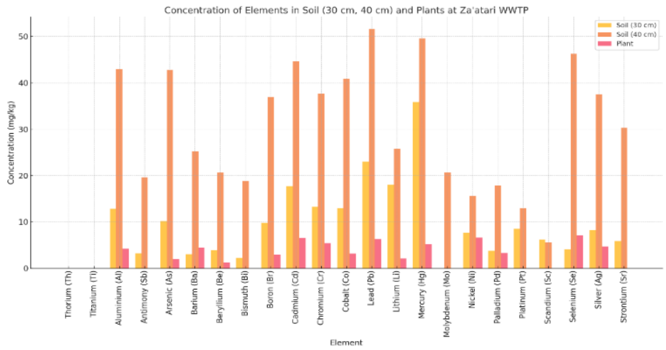

Figure 3: Heavy metal concentrations in irrigated soil and plants at Za'atri WWTP

Cd is known to be toxic and raises environmental and health concerns. Mercury (Hg): High concentrations are found in soil (35.9 µg/L at 30 cm, 49.56 µg/L at 40 cm) but are relatively lower in plants (5.2 µg/L). Arsenic (As): Moderate levels are detected in soil and TWW, but significantly lower in plants (2.00 µg/L). Lead (Pb): There is substantial accumulation in soil, with moderate uptake in plants (6.27 µg/L).

Salinity:

The data in Table 4 presents the total dissolved solid concentration in the TWW from the three WWTPs as well as the salinity of the irrigated soils in the plants and the calculate sodium adsorption ratio SAR.

Table 4: dissolved solid concentration in the treated wastewater from the studies plants and the salinity of soils irrigated with this water

WWTP	WW, TDS mg/l	EC, µs/cm		Jordanian Standard	SAR	Jordanian Standard
		30 cm	40 cm			
Za'atri	1100	2049	2163	2300	4.3	6
Al-Salt	1600	3600	4200		3.1	
As-Samra	1500	2150	2240		2.8	

Electrical Conductivity (EC) is an indicator of salt concentration in soil, with crops demonstrating varying responses to salt stress (Shrivastava and Kumar, 2015). The EC of soil is closely tied to salinity, which refers to the presence of soluble salts within the soil. High salinity levels not only reduce the agricultural productivity of most crops but also affect soil physicochemical properties and disrupt the ecological balance of the region. Salinity's consequences include reduced crop yields, lower economic returns, and soil erosion (Hu and Schmidhalter, 2004). For soil to be considered productive, its EC should be below 150 µs/cm (Reid and Dirou, 2004). Additionally, soil pH likely influences salt solubility and moisture retention, with alkaline soils typically containing less soluble salt (Mohd-Aizat et al., 2014). The results illustrated in Table 4 show that in soil samples from Al-Salt WWTP, EC values were significantly higher than the acceptable range for productive soil, and the Jordanian standard. This can be attributed to the low treatment efficiency in the plant due to hydraulic and organic overloading. The EC measurements for upper and lower soils were 3600 µs/cm and 4200 µs/cm, respectively (Table. 4). In contrast, soil samples from As-Samra and Za'atri WWTPs exhibited lower EC values of 2150 and 2049 µs/cm in the upper soil and 2240 and 2163 µs/cm in lower soil respectively. The soil salinity in areas irrigated with TWW from As-Samra and Za'atri WWTPs is below the allowable limits in Jordanian standards. It is highly recommended to leach the soil with fresh water periodically to avoid salt accumulation and high salinity values.

5. Conclusions

Water Quality and Standards: Treated wastewater from all the studied wastewater treatment plants (WWTPs) contained heavy metals that exceeded permissible limits, such as cadmium, lead, and mercury. This highlights the urgent need for advanced treatment technologies. The differences in heavy metal concentrations among the WWTPs are likely attributed to variations in the sources of influent water, whether domestic or industrial. Soil Impacts: Soil that was irrigated with treated wastewater

(TWW) showed higher salinity and accumulation of heavy metals compared to soil irrigated with rainwater. Metal concentrations were generally found to be higher in deeper soil layers, suggesting potential leaching and long-term contamination risks. The high salinity levels observed at the Al-Salt WWTP point to inefficiencies in the treatment processes. Plant Uptake and Bioavailability: Metals such as cadmium and selenium were identified as bioavailable, raising concerns about their potential for bioaccumulation in the food chain. Certain metals, including titanium and thorium, demonstrated limited uptake, indicating their low bioavailability or immobility in the soil.

RECOMMENDATIONS

It is advisable to periodically leach the soil with fresh water to manage salinity levels and mitigate metal accumulation. Implementing enhanced pre-treatment processes for industrial wastewater before it enters WWTPs is crucial for reducing heavy metal content in effluents. Regular monitoring of heavy metals in treated wastewater, soil, and plants is essential to protect environmental and public health. Promoting plants that absorb metals could be a viable remediation strategy.

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