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Effect of Textile Wastewater Irrigation on Heavy Metals Accumulation in Post-harvest Soils

Monoara Begum [a*], Md. Nasimul Gani [b++] and Md. Didar-ul-Alam [c]

[a] Department of Soil, Water and Environment, University of Barisal, Barisal, Bangladesh.
[b] Bangladesh Jute Research Institute, Dhaka, Bangladesh.
[c] Department of Soil, Water and Environment, University of Dhaka, Dhaka, Bangladesh.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Textile wastewater is used as an alternative irrigation source where freshwater is limited, but repeated application may alter soil heavy-metal status. This study evaluated heavy-metal accumulation in post-harvest soils under a vegetables-jute-T. Aman crop rotation at the Bangladesh Jute Research Institute, Central Station, Dhaka. Six treatments were evaluated: T1 control, T2 sole RDF plus freshwater, and T3–T6 50% RDF combined with 25%, 50%, 75%, and 100% textile wastewater, respectively. Post-harvest soil samples were collected after each crop, digested using aqua regia and H_2O_2, and analysed for Zn, Cu, Ni, Fe, Cd, Cr, Pb, and Mn by flame atomic absorption spectrophotometry. Heavy-metal concentrations generally increased with increasing textile wastewater concentration, and the highest values were consistently observed in T6. Under T6, concentrations of Zn, Cu, Ni, Fe, Cd, Cr, Pb, and Mn were 30.31, 0.93, 24.74, 239.55, 0.255, 34.03, 33.79, and 2.80 ppm after jute cultivation and 38.20, 1.79, 36.22, 303.70, 0.345, 41.15, 40.22, and 6.00 ppm after red amaranth cultivation, respectively. The results indicate progressive

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[++] *Chief Scientific Officer & Head of the Fiber Quality Improvement Division;*
**Corresponding author: E-mail: monoarabegum819@gmail.com;*

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accumulation of the measured metals across the studied crop sequence under 100% textile wastewater irrigation. Regular monitoring of wastewater quality and post-harvest soil metal concentrations is therefore warranted when textile wastewater is considered for irrigation.

Keywords: *Textile wastewater; wastewater irrigation; heavy metals; soil contamination; jute; T. Aman rice; red amaranth; heavy-metal accumulation.*

1. Introduction

Heavy metals are principally referred to as metals that have high densities and atomic weights or atomic numbers. In metallurgy, heavy metals are defined on the basis of density; in physics, on the basis of atomic number; and in chemistry, on the basis of chemical behaviour. In biochemistry, heavy metals may be defined on the basis of the Lewis acid (electron-pair acceptor) behaviour of their ions in aqueous solution (Li *et al.*, 2019). Heavy metals, when present in trace concentrations, are needed for the proper functioning of plants; however, at higher concentrations, they can cause serious harm to plants and animals. Metals such as copper, manganese, cobalt, zinc, nickel, and iron are micronutrients that are vital for plant growth. Other metals such as mercury, cadmium, lead, and arsenic, however, have no known biological function and are toxic even at low concentrations. It has been well documented that various metals such as manganese, iron, chromium, cobalt, selenium, and nickel are needed at trace concentrations and are therefore known as essential nutrients. Their non-availability for plant uptake has been linked to various deficiency diseases (Fazekašová & Fazekaš, 2019). In Bangladesh, textile industrial wastes and effluents are discharged randomly without treatment directly into soil, canals, and rivers. They contain heavy metals such as Cu, Zn, Pb, Cr, Cd, As, Hg, Mn, and Fe. Some are toxic to plants, whereas others are toxic to both plants and animals. They pollute soils and natural water systems, as well as groundwater, endangering human health, aquatic life, and crop production (Begum *et al.,* 2011; Chhonkar *et al.*, 2000; Faryal *et al.*, 2007). In recent years, wastewater reuse has increased rapidly in different parts of the world. Volumes of wastewater reuse have increased by 10-29% per year in Europe, the United States, and China, and by up to 41% in Australia (Aziz & Farissi, 2014). More than 80% of treated wastewater is reused for agriculture in Israel (Angelakis & Snyder, 2015). In areas where freshwater is scarce, farmers are compelled to use industrial wastewater for irrigation without knowing the direct and long-term impacts of wastewater irrigation (Christou *et al.,* 2014; Kiziloglu *et al.*, 2007; Singh *et al.*, 2012). In recent years, this practice has been increasing in Bangladesh. Industrial wastewater irrigation has also been associated with heavy-metal deposition in farm soils in Bangladesh, supporting the need to assess metal accumulation where wastewater is repeatedly used for irrigation (Islam *et al.*, 2020). Recent studies further show that wastewater irrigation can contribute to the accumulation of potentially toxic elements in soil-vegetable systems, including systems irrigated with textile wastewater (Ruan *et al.*, 2023; Hassan *et al.*, 2024).

Soil is one of the vital components of the ecosystem. The vulnerability of soil to heavy-metal pollution is associated with its emission and absorption potentials. The occurrence of heavy metals in soil has been attributed to various natural and anthropogenic sources associated with industrialisation, urbanisation, and agricultural activities (Bayraklı *et al.*, 2023; Inobeme *et al.*, 2023). Industrial effluent-contaminated soils have likewise been reported to contain heavy metals together with altered physicochemical characteristics (Okafor *et al.*, 2022). Accordingly, the specific gap addressed in this study is the accumulation pattern of multiple heavy metals in post-harvest soils across successive crops under graded textile wastewater irrigation within the vegetables-jute-T. Aman rotation. Therefore, in the present study, different dilutions of textile wastewater were used as irrigation water in a vegetables-jute-rice cropping pattern to determine the accumulation of heavy metals in post-harvest soils after crop harvest.

2. Materials and Methods

A field experiment was conducted at the Bangladesh Jute Research Institute, Central Station, Dhaka, to determine the effect of textile wastewater irrigation on the accumulation of heavy metals in post-harvest soils after crop harvest. In this field experiment, for the Vegetables-Jute-T. Aman crop rotation, high-yielding jute variety Tossa (O-795), T. Aman rice Binashail, BJRI deshi pat shak-1 and red amaranth variety Lolita were cultivated. The soil samples were collected after crop harvest using a steel auger. According to the treatments, each subplot was considered for sample collection. The samples were kept in polythene bags and tagged by treatment. The soil was air-dried, ground and sieved through a 0.5 mm sieve for physical and chemical analysis.

Heavy metal analysis: A flame atomic absorption spectrophotometer equipped with deuterium-lamp background correction and hollow-cathode lamps was used for the analysis of the heavy metals Fe, Zn, Mn, Cu, Co, Ni, Cd, Cr and Pb (Addis & Abebaw, 2017). Aqua regia (prepared at a 3:1 ratio of 35–38% HCl and 65–68% HNO_3) and 30% H_2O_2 were used for sample digestion. A wet digestion method was used to digest the soil samples. The digested samples were analysed for the concentrations of heavy metals (Fe, Zn, Mn, Cu, Co, Ni, Cd, Cr and Pb) using a flame atomic absorption spectrophotometer. Final concentrations of the metals in the soil samples were calculated using the following formula (Uwah *et al.,* 2012):

$$\text{Concentration (mg/kg)} = \frac{\text{Concentration (mg/ L)} \times V}{W}$$

Where, V = Final volume (50 ml) of solution, and W = Initial weight (0.5 g) of sample measured.

For irrigation, textile wastewater was collected from the Gazipur district, where many textile mills are situated. One litre of textile wastewater was also collected in a plastic bottle. The physical and chemical characteristics of the soil and water were then determined. Standard methods were followed for the determination of the following properties:

Table 1. Initial physical and chemical properties of the soil

Parameters	Values
Particle size analysis (Bouyoucos, 1962)	
Sand (%)	42
Silt (%)	45
Clay (%)	13
Textural class	Loam
pH (Jackson, 1973)	6.2
EC (dSm^{-1})	1.3
Organic matter (OM) % (Walkley and Black 1934)	2.42
Total Nitrogen (N) % (Jackson, 1973)	0.121
Potassium (K) $Cmol(+)K^{-1}$	0.31
Calcium (Ca) $Cmol(+)K^{-1}$	3.27
Magnesium (Mg) $Cmol(+)K^{-1}$	0.93
Available phosphorus (P) $mgkg^{-1}$	26.51
Available Sulphur (S) $mgkg^{-1}$	29.11
Available copper (Cu) $mgkg^{-1}$	0.74
Available iron (Fe) $mgkg^{-1}$	199.80
Available manganese (Mn) $mgkg^{-1}$	2.42
Available zinc (Zn) $mgkg^{-1}$	20.15
Available lead (Pb) $mgkg^{-1}$	29.78
Available cadmium (Cd) $mgkg^{-1}$	0.238
Available nickel (Ni) $mgkg^{-1}$	23.48
Available chromium (Cr) $mgkg^{-1}$	31.12

Table 2. Chemical characteristics of textile wastewater

Parameters	Values
pH	7.2
EC (dSm^{-1})	2.43
TDS ($mgkg^{-1}$)	805
DO ($mgkg^{-1}$)	4.2
BOD ($mgkg^{-1}$)	13.4
Total Nitrogen (%)	0.6
Potassium ($mgkg^{-1}$)	0.61
Calcium ($mgkg^{-1}$)	0.73
Magnesium ($mgkg^{-1}$)	0.25
Phosphorus ($mgkg^{-1}$)	40.27
Sulphur ($mgkg^{-1}$)	70.48
Copper ($mgkg^{-1}$)	1.73
Iron ($mgkg^{-1}$)	1.11
Manganese ($mgkg^{-1}$)	0.069
Zinc ($mgkg^{-1}$)	0.10
Lead ($mgkg^{-1}$)	0.0001
Cadmium ($mgkg^{-1}$)	0.0032
Nickel ($mgkg^{-1}$)	0.351
Chromium ($mgkg^{-1}$)	0.152

3. Results and Discussion

3.1 Effect of Textile Wastewater on Heavy Metal Concentration of Post-harvest Soil after Jute Cultivation

The heavy metal concentrations in post-harvest soil are presented in Table 3. It was observed that as the concentration of textile wastewater increased, heavy metal concentrations in post-harvest soil gradually increased.

The concentrations of Zn and Cu in post-harvest soil increased significantly ($P \le 0.05$) in all treatments compared with the control. The highest concentrations of Zn and Cu in post-harvest soil were 30.31 and 0.93 ppm, respectively, and were found with 100% textile wastewater irrigation along with 50% RDF (T_6). The lowest concentrations of Zn and Cu were 20.10 and 0.70 ppm, respectively, and were found in T_1 (control).

The concentration of Ni in post-harvest soil increased significantly ($P \le 0.05$) in T_2 (100% RDF + 0% TWW), T_5 (50% RDF + 75% TWW) and T_6 (50% RDF + 100% TWW) compared with the control. The highest concentration of Ni in post-harvest soil, 24.74 ppm, was observed in T_6, where 100% textile wastewater was used for irrigation. The lowest Ni concentration, 23.40 ppm, in post-harvest soil was observed in T_1 (control).

The Fe concentration in post-harvest soil differed significantly ($P \leq 0.05$) among all treatments (Table 3). Compared with T_1 (199.79 ppm), Fe was significantly higher in T_2 (202.32 ppm), T_5 (223.80 ppm) and T_6 (239.55 ppm), but significantly lower in T_3 (195.59 ppm) and T_4 (199.38 ppm), as indicated by the distinct significance letters in the table. The highest Fe concentration was observed in T_6, whereas the lowest was observed in T_3.

Table 3. Effect of textile waste water on heavy metal concentration of post harvest soil for jute cultivation

Treatment	Zn	Cu	Ni	Fe	Cd	Cr	Pb	Mn
	(ppm)							
T_1=control	20.10 f	0.70 e	23.40 c	199.79 d	0.235 c	30.33 f	29.45 f	2.41 e
T_2=100% RDF + 0%TWW	26.25 c	0.81 c	24.11 b	202.32 c	0.250 a	30.79 e	30.22 d	2.55 d
T_3=50% RDF + 25%TWW	23.16 e	0.77 d	23.52 c	195.59 f	0.242 b	31.07 d	30.10 e	2.45 e
T_4=50% RDF + 50%TWW	25.18 d	0.82bc	23.60 c	199.38 e	0.244 b	33.21 c	31.37 c	2.63 c
T_5=50% RDF + 75%TWW	27.22 b	0.85 b	24.21 b	223.80 b	0.253 a	33.90 b	32.07 b	2.71 b
T_6=50% RDF+100%TWW	30.31 a	0.93 a	24.74 a	239.55 a	0.255 a	34.03 a	33.79 a	2.80 a

The concentrations of Cd, Cr and Pb in post-harvest soil increased significantly ($P \leq 0.05$) in all treatments compared with the control. The highest concentrations of Cd, Cr and Pb in post-harvest soil were 0.255, 34.03 and 33.79 ppm, respectively, and were observed in T_6, where 100% textile wastewater was used for irrigation. The lowest concentrations of Cd, Cr and Pb in post-harvest soil were 0.235, 30.33 and 29.45 ppm, respectively, and were observed in T_1 (control).

The concentration of Mn in post-harvest soil also increased significantly ($P \leq 0.05$) in all treatments compared with the control, except T_3 (50% RDF + 25% TWW). The highest concentration of Mn in post-harvest soil, 2.80 ppm, was observed in T_6, where 100% textile wastewater was used for irrigation. The lowest concentration of Mn in post-harvest soil, 2.41 ppm, was observed in T_1 (control).

3.2 Effect of Textile Effluent on Heavy Metal Concentration in Post-harvest Soil after Rice Cultivation

The concentrations of heavy metals in post-harvest soil of the rice field are presented in Table 4. Across the graded textile-effluent treatments (T_3-T_6), the concentrations generally increased, but the statistical response differed among metals and treatments.

The concentrations of Zn and Cu in post-harvest soil of the rice field were significantly higher ($P \leq 0.05$) in all treatments than in the control. Zn and Cu concentrations ranged from 18.22 to 33.59 ppm and from 0.63 to 0.98 ppm, respectively. For Cu, T_2 and T_4 shared the same significance letter and therefore did not differ significantly from each other; the remaining Cu treatment means were in different significance groups. The highest Zn and Cu concentrations were observed in T_6, whereas the lowest were observed in T_1 (control).

Table 4. Effect of textile effluent on heavy metal concentration of post harvest soil for rice cultivation

Treatment	Zn	Cu	Ni	Fe	Cd	Cr	Pb	Mn
	(ppm)							
T_1=control	18.22 f	0.63 e	22.59 e	202.11 e	0.224 d	30.10 f	29.30 f	2.30 c
T_2=100% RDF +FW	29.35 c	0.87 c	26.77 d	207.57 c	0.262 a	30.90 e	30.70 e	3.07 b
T_3=50% RDF + 25% effluent	26.74 e	0.80 d	26.77 d	203.75 d	0.247 c	31.22 d	30.92d	2.79bc
T_4=50% RDF + 50% effluent	29.20 d	0.85 c	27.05 c	207.50 c	0.251 c	33.89 c	31.75 c	2.91bc
T_5=50% RDF + 75% effluent	30.35 b	0.91 b	27.23 b	230.78 b	0.257 b	34.25 b	32.44 b	3.11ab
T_6=50% RDF+ 100% effluent	33.59 a	0.98 a	27.50 a	245.03 a	0.262 a	35.90 a	34.27 a	3.50 a

The concentration of Ni in post-harvest soil of the rice field increased significantly ($P \leq 0.05$) in all treatments compared with the control. The highest concentration of Ni in post-harvest soil, 27.50 ppm, was observed in T_6, where 100% textile wastewater was used for irrigation. The lowest Ni concentration, 22.59 ppm, in post-harvest soil was observed in T_1 (control). The Ni concentration in post-harvest soil was the same (26.77 ppm) in T_2 and T_3. All treatments showed a slight increase in Ni compared with the control.

The Fe content in post-harvest soil of the rice field increased significantly ($P \leq 0.05$) in all treatments compared with the control. The Fe concentration in post-harvest soil ranged from 202.11 to 245.03 ppm among the treatments. The highest concentration of Fe in post-harvest soil, 245.03 ppm, was observed in T_6, where 100% textile effluent was used for irrigation. The lowest concentration of Fe in post-harvest soil, 202.11 ppm, was found in T_1, where no fertiliser or textile effluent was used. Statistically similar Fe contents were found in T_2 and T_4.

The concentrations of Cd, Cr and Pb in post-harvest soil of the rice field were significantly higher ($P \leq 0.05$) in all treatments than in the control (Table 4). For Cd, T_2 and T_6 were statistically similar, and T_3 and T_4 were statistically similar, whereas T_5 belonged to a separate significance group. For Cr and Pb, each treatment had a distinct significance letter, indicating significant differences among all treatments. The highest concentrations of Cd, Cr and Pb were 0.262, 35.90 and 34.27 ppm, respectively, in T_6, whereas the lowest were 0.224, 30.10 and 29.30 ppm, respectively, in T_1 (control).

The Mn content in post-harvest soil of the rice field did not increase significantly in every treatment relative to the control. Based on the significance letters in Table 4, Mn was significantly higher ($P \leq 0.05$) in T_2, T_5 and T_6 than in T_1, whereas T_3 and T_4 were not significantly different from T_1 because their letter groupings overlapped with that of the control. T_2, T_3, T_4 and T_5 shared the letter b and therefore did not differ significantly from one another; T_5 and T_6 also shared the letter a. The highest Mn concentration was 3.50 ppm in T_6, and the lowest was 2.30 ppm in T_1.

3.3 Effect of Textile Wastewater on Heavy Metal Concentration of Post-harvest Soil after Jute Leaf Vegetable (pat shak) Cultivation

The heavy metal concentrations in post-harvest soil after jute leaf vegetable cultivation are presented in Table 5. It was observed that as the concentration of textile wastewater increased, heavy metal concentrations in post-harvest soil did not increase at a very high rate across the treatments.

The concentrations of Zn and Cu in post-harvest soil after jute leaf vegetable cultivation were significantly higher ($P \leq 0.05$) in all treatments than in the control. The highest Zn and Cu concentrations were 35.21 and 1.01 ppm, respectively, in T_6, whereas the lowest were 17.50 and 0.57 ppm, respectively, in T_1. For Zn, T_2 and T_5 were statistically similar. For Cu, T_2 and T_4 were statistically similar, and T_3 and T_5 were statistically similar, as indicated by their shared significance letters.

The Ni concentration in post-harvest soil after jute leaf vegetable cultivation was significantly higher ($P \leq 0.05$) in all treatments than in the control. T_2 and T_3 were statistically similar. T_4 shared significance letters with T_2, T_3 and T_5 and therefore did not differ significantly from those treatments. T_5 differed significantly from T_2 and T_3 but not from T_4, whereas T_6 was significantly higher than all other treatments. The highest Ni concentration was 32.11 ppm in T_6, and the lowest was 21.50 ppm in T_1.

Table 5. Effect of textile waste water on heavy metal concentration of post harvest soil for jute leaves vegetable plant (pat shak) cultivation

Treatment	Zn	Cu	Ni	Fe	Cd	Cr	Pb	Mn
	(ppm)							
T_1=control	17.50 e	0.57 d	21.50 d	200.77 e	0.200 b	27.55 d	27.33 f	2.22 d
T_2=100% RDF + 0%TWW	32.52 b	0.93 b	28.95 c	250.10 b	0.266 a	32.75 c	32.42 e	3.89 ab
T_3=50% RDF + 25%TWW	29.22 d	0.85 c	27.75 c	237.33 d	0.250 a	32.08 c	33.08 d	2.97 c
T_4=50% RDF + 50%TWW	31.70 c	0.92 b	29.22 bc	243.50 c	0.258 a	34.11 b	34.93 c	3.44 bc
T_5=50% RDF + 75%TWW	32.72 b	0.86 c	30.07 b	251.90 b	0.266 a	36.05 a	35.11 b	3.90 ab
T_6=50% RDF+ 100%TWW	35.21 a	1.01 a	32.11 a	260.21 a	0.275 a	37.11 a	35.90 a	4.07 a

The concentration of Fe in post-harvest soil increased significantly ($P \leq 0.05$) in all treatments compared with the control. The highest concentration of Fe in post-harvest soil, 260.21 ppm, was observed in T_6, where 100% textile wastewater was used for irrigation. The lowest concentration of Fe in post-harvest soil, 200.77 ppm, was observed in T_1 (control). The Fe contents in post-harvest soil in T_2 and T_5 were statistically similar.

The Cd concentration in post-harvest soil after jute leaf vegetable cultivation was significantly higher ($P \leq 0.05$) in T_2-T_6 than in the control. The highest Cd concentration was 0.275 ppm in T_6, whereas the lowest was 0.200 ppm in T_1. All treated plots from T_2 to T_6 shared the same significance letter and therefore did not differ significantly from one another. Cd concentrations in the treated plots were numerically close to the initial soil value, while the control value was lower than the initial soil value.

The concentrations of Cr and Pb in post-harvest soil after jute leaf vegetable cultivation were significantly higher ($P \leq 0.05$) in all treatments than in the control. The highest Cr and Pb concentrations were 37.11 and 35.90 ppm, respectively, in T_6, whereas the lowest were 27.55 and 27.33 ppm, respectively, in T_1. For Cr, T_2 and T_3 were not significantly different, and T_5 and T_6 were not significantly different. For Pb, all treatments had distinct significance letters and therefore differed significantly from one another.

The Mn concentration in post-harvest soil after jute leaf vegetable cultivation was significantly higher ($P \leq 0.05$) in all treatments than in the control. The highest Mn concentration was 4.07 ppm in T_6, whereas the lowest was 2.22 ppm in T_1. T_2, T_5 and T_6 shared the letter a and therefore did not differ significantly from one another. T_4 shared a significance letter with T_2, T_3 and T_5, but not with T_6; T_3 did not differ significantly from T_4 but differed significantly from T_2, T_5 and T_6.

3.4 Effect of Textile Wastewater on Heavy Metal Concentration of Post-harvest Soil after Red Amaranth Cultivation

The effect of textile wastewater on heavy metal concentrations in post-harvest soil after red amaranth cultivation is presented in Table 6. Based on the significance letters, all measured metal concentrations in T_2-T_6 differed significantly ($P \leq 0.05$) from the control (T_1). However, treatment-to-treatment responses were not uniformly monotonic because T_2 represented 100% RDF with freshwater rather than a graded textile-wastewater treatment.

Table 6. Effect of textile waste water on heavy metal concentration of post harvest soil for red amaranth cultivation

Treatment	Zn	Cu	Ni	Fe	Cd	Cr	Pb	Mn
	(ppm)							
T_1=control	15.90 e	0.51 f	20.55 f	200.02 f	0.191 e	25.10 f	26.00 f	2.01 f
T_2=100% RDF + 0%TWW	34.88 b	1.22 c	30.50 d	277.90 c	0.290 c	37.37 c	38.02 c	4.05 d
T_3=50% RDF + 25%TWW	30.50 d	0.97 e	29.11 e	250.45 e	0.273 d	33.22 e	35.54 e	3.27 e
T_4=50% RDF + 50%TWW	32.79 c	1.08 d	30.90 c	271.43 d	0.295 c	36.80 d	37.30 d	4.45 c
T_5=50% RDF + 75%TWW	34.90 b	1.47 b	33.51 b	292.50 b	0.311 b	39.45 b	39.50 b	5.02 b
T_6=50% RDF+ 100%TWW	38.20 a	1.79 a	36.22 a	303.70 a	0.345 a	41.15 a	40.22 a	6.00 a

The concentrations of Zn and Cu in post-harvest soil after red amaranth cultivation were significantly higher ($P \leq 0.05$) in T_2-T_6 than in the control. For Zn, T_2 and T_5 shared the same significance letter and did not differ significantly from each other; all other Zn treatment comparisons were in different significance groups. For Cu, all treatments had distinct significance letters, indicating significant differences among all treatment means. The highest Zn and Cu concentrations were 38.20 and 1.79 ppm, respectively, in T_6, whereas the lowest were 15.90 and 0.51 ppm, respectively, in T_1.

The Ni concentration in post-harvest soil after red amaranth cultivation differed significantly ($P \leq 0.05$) among all treatments. All T_2-T_6 values were significantly higher than the control, and the distinct significance letters for T_1-T_6 indicate that every treatment mean differed significantly from the others. The highest Ni concentration was 36.22 ppm in T_6, whereas the lowest was 20.55 ppm in T_1.

The Fe concentration in post-harvest soil after red amaranth cultivation differed significantly ($P \leq 0.05$) among all treatments. All T_2-T_6 values were significantly higher than the control, and the distinct significance letters for T_1-T_6 indicate significant differences among every treatment mean. The highest Fe concentration was 303.70 ppm in T_6, whereas the lowest was 200.02 ppm in T_1.

The Cd concentration in post-harvest soil after red amaranth cultivation was significantly higher ($P \leq 0.05$) in T_2-T_6 than in the control. T_2 and T_4 shared the same significance letter and did not differ significantly from each other; all other Cd treatment comparisons were in different significance groups. The highest Cd concentration was 0.345 ppm in T_6, whereas the lowest was 0.191 ppm in T_1.

The concentrations of Cr and Pb in post-harvest soil after red amaranth cultivation were significantly higher ($P \leq 0.05$) in T_2-T_6 than in the control. For both Cr and Pb, all treatments had distinct significance letters, indicating significant differences among every treatment mean. The highest Cr and Pb concentrations were 41.15 and 40.22 ppm, respectively, in T_6, whereas the lowest were 25.10 and 26.00 ppm, respectively, in T_1.

The Mn concentration in post-harvest soil after red amaranth cultivation differed significantly ($P \leq 0.05$) among all treatments. All T_2-T_6 values were significantly higher than the control, and each treatment had a distinct significance letter. The highest Mn concentration was 6.00 ppm in T_6, whereas the lowest was 2.01 ppm in T_1.

The concentrations of heavy metals in post-harvest soils after jute, rice, jute leaf vegetable and red amaranth cultivation under treatment T_6 are shown in Fig. 1. The results showed that heavy metal concentrations in post-harvest soil from the same field gradually increased after harvesting each crop under 100% textile wastewater irrigation. After completion of the Vegetables-Jute-T. Aman crop rotation under 100% textile wastewater irrigation, the concentrations of Zn, Cu, Ni, Fe, Cd, Cr, Pb and Mn in post-harvest soil increased from 30.31 to 38.20, 0.93 to 1.79, 24.74 to 36.22, 239.55 to 303.70, 0.255 to 0.345, 34.03 to 41.15, 33.79 to 40.22 and 2.8 to 6.0 ppm, respectively.

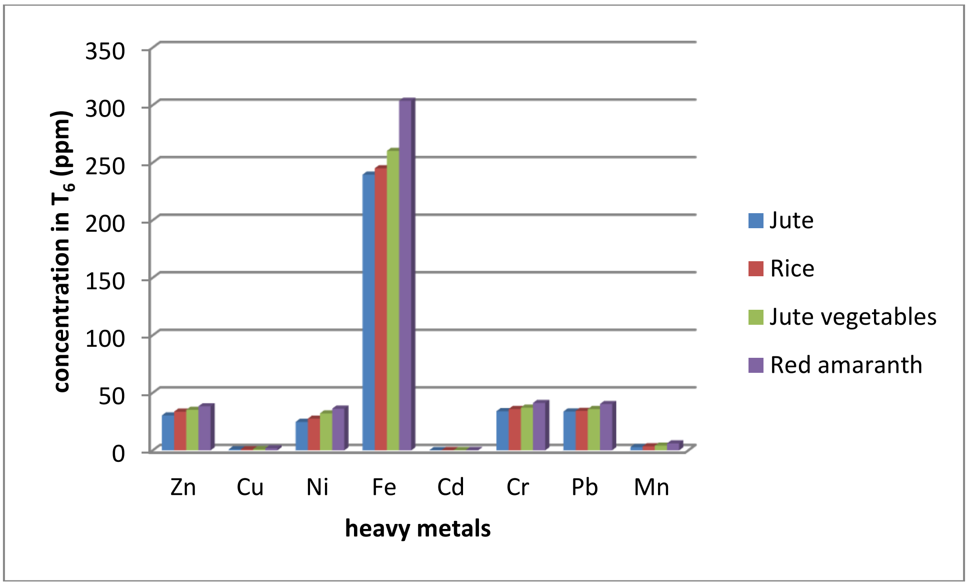

Fig. 1. Concentration of heavy metals in past harvest soils of Jute, Rice, Jute leaves and Red amaranth with treatment T_6

In the post-harvest soils after jute, rice, jute leaf vegetable and red amaranth cultivation, heavy metal concentrations increased with higher concentrations of textile wastewater irrigation and were reported to be within the permissible values of WHO (2006). The maximum concentrations of Zn, Cu, Ni, Fe, Cd, Cr, Pb and Mn were found in treatment T_6, where 100% textile wastewater was used for irrigation, whereas the minimum concentrations of Zn, Cu, Ni, Fe, Cd, Cr, Pb and Mn were found in treatment T_1 (control) in the post-harvest soils after all crops. The results are consistent with the findings of the following studies:

Uniyal *et al.* (2024) found that heavy metals tend to accumulate over time and are difficult to degrade once they are in the soil. Heavy metals are retained in soil for a longer period than in air or water because soil is a heterogeneous, complex material with a biochemical and geochemical composition.

Lekshmi and Rajani (2017) observed that the regular and periodic addition of industrial effluent causes undesirable changes in soil parameters. Even a small concentration over a short period can cause a substantial change from normal parameter values, indicating the toxicity of the effluent. Shammi *et al.* (2016) reported that wastewater irrigation increased salinity and that heavy metals accumulated in agricultural land. Najam *et al.* (2015) reported that long-term use of industrial wastewater causes heavy metals to accumulate in soil. Alrawiq *et al.* (2014) observed that the average concentrations of heavy metals, except Cd, were higher in soil irrigated with recycled water than in soil irrigated with non-recycled water. Bhatti *et al.* (2016) reported that the use of NPK fertilisers and other agrochemicals further contaminates soil with heavy metals. Various NPK fertilisers can act as sources of heavy metals such as Cd, As, Pb, Cr, Ni and Cu. Yaseen *et al.* (2016) observed that textile wastewater contains relatively high amounts of sodium and heavy metals, including Zn, Cu, Pb, Ni, Cr and Cd, depending on the associated activities; these can accumulate in soil during wastewater irrigation and exert toxic effects on plants.

4. Conclusions

Textile wastewater irrigation increased the concentrations of Zn, Cu, Ni, Fe, Cd, Cr, Pb, and Mn in post-harvest soils under the studied vegetables–jute–T. Aman rice cropping sequence. The highest accumulation was observed where 100% textile wastewater was applied with 50% recommended fertiliser dose. Heavy metal concentrations increased across the crop sequence, with the highest values generally recorded after red amaranth cultivation. Although the measured values were reported within permissible limits in the manuscript, continued use of textile wastewater may contribute to gradual heavy metal build-up in soil. Regular monitoring of wastewater quality and post-harvest soil heavy-metal status is therefore necessary before recommending textile wastewater for irrigation.

5. Limitation

This study was conducted at a single experimental location therefore, the findings may not fully represent variations in soil properties and textile wastewater composition across other locations or industrial sources. The investigation focused primarily on the accumulation of selected heavy metals in post-harvest soils under a vegetables–jute–T. Aman cropping sequence and did not directly assess heavy-metal uptake by the harvested crops, their transfer through the food chain, or associated human health risks. In addition, the observations were limited to the studied crop sequence. Further long-term, multi-location studies incorporating crop-tissue analysis and periodic assessment of wastewater quality would provide a more comprehensive evaluation of the environmental and agricultural risks associated with textile wastewater irrigation.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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