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# Effect of Textile Effluent on Nutrient and Heavy Metals Uptake by Rice (*Oryza sativa* L.)

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***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

This study evaluated the effects of textile effluent—an increasingly common irrigation source in Bangladesh's garment-industry regions—on nutrient acquisition, heavy-metal uptake, and associated health risks in rice (*Oryza sativa* L.). Six irrigation and fertiliser treatments were applied: T1 (control), T2 (recommended fertiliser dose with fresh water), T3 (50% RDF + 25% effluent), T4 (50% RDF + 50% effluent), T5 (50% RDF + 75% effluent), and T6 (50% RDF + 100% effluent). Rice grains from T2 exhibited the highest nutrient concentrations and uptake, whereas T4—representing 50% textile effluent—produced comparable values across most nutrients. Heavy-metal accumulation varied by treatment, with T6 showing the greatest concentrations of Zn, Cu, Fe, and Mn, and T3 and T2 exhibiting the highest levels of Ni and Cr, respectively; Cd and Pb were not detected. Uptake patterns followed the order Fe > Mn > Zn > Cu > Ni > Cr. While moderate effluent use (T4) supported nutrient acquisition without excessive heavy-metal loading, higher effluent proportions substantially increased metal accumulation in grains, raising concerns about chronic dietary exposure. Elevated Fe, Mn, Zn, and Ni levels—if accumulated

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beyond permissible limits—pose potential risks related to oxidative stress, neurotoxicity, and long-term metabolic disturbances in humans. The findings suggest that integrating 50% textile effluent with reduced fertiliser inputs can support rice production in water-scarce regions, but careful monitoring of heavy-metal concentrations is essential to minimise food-safety risks and protect public health.

*Keywords: Textile effluent; nutrient uptake; heavy metals; rice; soil contamination; health risks; wastewater irrigation.*

## 1. Introduction

Rice (*Oryza sativa* L.) is the second most important cereal crop globally after wheat and serves as the primary staple for more than half of the world's population. Asia dominates global rice cultivation, accounting for approximately 85–90% of total production, with Bangladesh among the leading producers (U.S. Department of Agriculture, Foreign Agricultural Service [USDA FAS], 2025). Global output continues to rise, reaching a historic peak of nearly 528 million tonnes in the 2024–2025 season, reflecting the crop's central role in global food security (Ahmad *et al.*, 2014; Bangladesh Rice Research Institute, n.d.; U.S. Department of Agriculture, Economic Research Service [USDA ERS], 2024). In Bangladesh, rice remains foundational to the national food supply, rural livelihoods, and agricultural GDP, making emerging constraints on production particularly urgent.

One of the most pressing challenges arises from deteriorating water quality associated with rapid industrial expansion, particularly in the garment and textile sector, Bangladesh's largest manufacturing industry and a major generator of untreated or partially treated effluents. Textile wastewater commonly contains elevated salinity, dyes, organic pollutants, and toxic heavy metals—including cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni), arsenic (As), antimony (Sb), and zinc (Zn)—which enter agricultural landscapes through direct discharge, canal contamination, and irrigation reuse. These contaminants accumulate in soils and rice plants, often exceeding international safety thresholds and posing severe ecological and public health risks (Shah *et al.*, 2020; Hasan *et al.*, 2025; Younas & Younas, 2025).

Recent evidence shows that vegetables irrigated with textile wastewater can accumulate heavy metals, reinforcing concerns regarding contaminant transfer through agricultural reuse (Hassan *et al.*, 2024). Heavy-metal contamination associated with textile-wastewater-affected environments has also been linked with contamination of soil and agricultural produce, supporting continued attention to food-safety implications (Gupta & Mukhopadhyay, 2025).

In Bangladesh's rice-growing regions adjacent to textile-industrial clusters, these metals are readily absorbed by rice roots and transported to shoots and grains, where they disrupt plant physiology and compromise food safety. Documented effects include reduced root and shoot growth, oxidative stress, impaired nutrient uptake, altered transporter activity, and disruptions in metabolic pathways essential for plant productivity (D'Odorico *et al.*, 2014; Peera Sheikh Kulsum *et al.*, 2022; Wang *et al.*, 2025; Yu *et al.*, 2025). Metal-induced perturbations of membrane integrity and nutrient transporters further interfere with the acquisition of essential macro- and micronutrients, intensifying nutrient imbalances in contaminated rice plants. Arsenic contamination is particularly severe, with detection frequencies approaching 100% in several regional assessments, underscoring a critical food-safety threat (Hanjra *et al.*, 2012; Maclean *et al.*, 2002; Yan *et al.*, 2025). Heavy-metal accumulation in agricultural soils can adversely affect crop growth and soil quality, further supporting the need to limit contaminant loading from industrial sources (Rabha & Dhaneesh, 2024).

Mechanistic and field-based studies demonstrate that Cd and related metals suppress antioxidant systems, alter metabolic regulation, and reduce grain quality and yield potential (Hoque *et al.*, 2021; Wang *et al.*, 2025). Agronomic experiments involving textile wastewater irrigation in South Asia have also revealed measurable declines in plant vigour, nutrient balance, and grain quality, even under moderate effluent concentrations (Begum *et al.*, 2022; Mohammed & Folorunsho, 2015). Additional research on nanoparticle-contaminated wastewater (e.g., ZnO-bearing effluent) confirms increased Zn and As uptake and elevated long-term health-risk indices despite the absence of acute phytotoxicity (Afriani *et al.*, 2024; Rahim *et al.*, 2022; Rashid *et al.*, 2005; Verma *et al.*, 2023). Higher textile-effluent concentrations have also been associated with poorer early growth responses in crop seedlings, indicating the importance of dilution when such water is considered for irrigation (Kurmi *et al.*, 2023). Recent work in Bangladesh similarly reported that undiluted textile wastewater disturbed crop growth and nutrient balance, whereas dilution reduced these adverse effects (Sultana *et al.*, 2025).

Given the scale of textile effluent discharge from Bangladesh's garment sector and the dependence of rice agriculture on surface water irrigation systems, understanding the combined effects of textile effluent on nutrient dynamics and heavy metal uptake in rice is both timely and essential. Current evidence highlights a dual threat: (i) disruption of nutrient acquisition and homeostasis, and (ii) enhanced accumulation of toxic metals in rice tissues, including edible grains. Yet, despite the significance of these interactions, the long-term and integrated effects of textile effluent on nutrient and heavy-metal uptake under continuous irrigation remain incompletely understood. Addressing this knowledge gap is critical for developing effective mitigation strategies to safeguard rice productivity, soil health, and consumer safety in Bangladesh and other regions facing similar industrial pressures. On the basis of these considerations, the present study was conducted to investigate the effect of textile effluent on nutrient and heavy metals uptake by rice (*Oryza sativa* L.).

## 2. Material and Methods

A field study was carried out at the Central Station of the Bangladesh Jute Research Institute in Dhaka to assess how textile effluent influences nutrient and heavy metal accumulation in rice (*Oryza sativa* L.) and its impact on soil after harvest. The experiment included six treatments: T1 (control), T2 (full recommended fertiliser dose with fresh water), T3 (50% fertiliser dose with 25% effluent), T4 (50% fertiliser with 50% effluent), T5 (50% fertiliser with 75% effluent), and T6 (50% fertiliser with 100% effluent).

The trial used 18 plots, each 3m by 3m, with 1-meter gaps between plots, blocks, and around the field perimeter. The soil was deeply ploughed and puddled under 3–5 cm of standing water, then levelled to ensure even distribution of water and nutrients. During final land preparation, phosphorus (from triple super phosphate), potassium (from muriate of potash), sulphur (from gypsum), and zinc (from zinc oxide) were applied in full as basal fertilisers. Nitrogen, supplied as urea, was split into three equal applications: at seedling establishment, early tillering, and 5–7 days before panicle initiation. The Aman rice variety Binashail was transplanted, with seedlings planted in rows spaced 30 cm apart. Harvesting occurred 36 to 40 days after flowering, once grain moisture reached 20–25%. Small bundles were threshed manually on bare ground, and grains were partially cleaned before being moved from the threshing area. After further drying and cleaning, the grains were stored in bags.

Plant samples were collected from individual plots according to the assigned treatments for chemical analysis. From each plot, five plants were selected at random and separated into roots, straw, and grain for chemical analysis. These samples were dried in an electric oven at 70°C for 72 hours, ground using an electric grinder, and stored for subsequent analysis. For irrigation purposes, textile effluent was collected from Gazipur district, which is home to many of the region's textile mills. A one-litre sample of this effluent was placed in a plastic bottle and prepared for chemical examination. Soil samples were taken from the 0–15 cm plough layer before planting, after land preparation, and again following crop harvest. Each composite soil sample, weighing one kilogram, was placed in a plastic container according to treatment. The samples were air-dried, ground, and passed through a 0.5 mm sieve before analysis. Each subplot was sampled separately in accordance with the treatment layout and properly labelled. Finally, the physical and chemical properties of both soil and water were analysed using standard procedures for the following characteristics:

**Table 1. Initial physical and chemical properties of the soil**

| Parameters | Values |
|---|---|
| **Particle size Analysis** | |
| Sand (%) | 42 |
| Silt (%) | 45 |
| Clay (%) | 13 |
| **Textural class** | **Loam** |
| pH | 6.2 |
| EC ($dSm^{-1}$) | 1.3 |
| Organic matter (OM) % | 2.42 |
| Total Nitrogen (N) % | 0.121 |
| Potassium (K) Cmol(+)$kg^{-1}$ | 0.31 |
| Calcium (Ca) Cmol(+) $kg^{-1}$ | 3.27 |
| Magnesium (Mg) Cmol(+) $kg^{-1}$ | 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 (Mg) $mgkg^{-1}$ | 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 effluent**

| Parameters | Values |
|---|---|
| pH | 7.2 |
| EC ($dSm^{-1}$) | 2.43 |
| TDS (mg $L^{-1}$) | 805 |
| DO (mg $L^{-1}$) | 4.2 |
| BOD (mg $L^{-1}$) | 13.4 |
| Total Nitrogen (%) | 0.6 |
| Potassium (mg $L^{-1}$) | 0.61 |
| Calcium (mg $L^{-1}$) | 0.73 |
| Magnesium (mg $L^{-1}$) | 0.25 |
| Phosphorus (mg $L^{-1}$) | 40.27 |
| Sulphur (mg $L^{-1}$) | 70.48 |
| Copper (mg $L^{-1}$) | 1.73 |
| Iron (mg $L^{-1}$) | 1.11 |
| Manganese (mg $L^{-1}$) | 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 Effluent on Dry Matter Production of Rice

Table 3 shows the impact of textile effluent on rice dry matter production. Compared with the control, the application of textile effluent significantly increased both total fresh yield and total dry matter yield ($p \leq 0.05$). Across all treatments, total fresh weight varied between 18.31 and 48.58 t/ha, while oven-dry weight ranged from 6.16 to 13.5 t/ha. The highest yields—48.58 t/ha for fresh weight and 13.5 t/ha for dry matter—were recorded with treatment T2 (100% RDF + FW). Treatment T4 (50% RDF + 50% effluent) produced the second-highest results, with 41.85 t/ha of fresh yield and 11.77 t/ha of dry matter. In contrast, the lowest yields, 18.31 t/ha (fresh) and 6.15 t/ha (dry), were observed in the control group (T1). Compared with the control, dry matter production increased by 119.51% under T2 and by 91.38% under T4.

**Table 3. Effect of textile waste water on dry matter production of rice**

| Treatment | Total Dry Weight (t/ha) | Total Fresh Weight (t/ha) |
|---|---|---|
| | Grain+Straw+Root | Grain+Straw+Root |
| $T_1$ | $6.16{\pm}0.03^f$ | $18.31^f$ |
| $T_2$ | $13.50{\pm}0.17^a$ | $48.58^a$ |
| $T_3$ | $6.97{\pm}0.02^e$ | $21.68^e$ |
| $T_4$ | $11.77{\pm}0.01^b$ | $41.85^b$ |
| $T_5$ | $11.40{\pm}0.06^c$ | $37.43^c$ |
| $T_6$ | $8.55{\pm}0.03^d$ | $34.17^d$ |

Hayyat *et al.* (2013) observed higher fresh and dry weights in sorghum under the T0 condition (0% treated wastewater). Hassan *et al.* (2013) noted significant variations in shoot length, fresh weight, and dry weight of individual country bean seedlings when irrigated with textile wastewater, although other measured traits did not differ significantly. Garg and Kaushik (2008) reported that untreated effluent had a more noticeable impact on shoot dry weight at 75% and 100% concentrations, while root dry weight was notably affected at 50%, 75%, and 100% levels. In addition, Desi jowar exposed to 75% untreated effluent showed lower root and shoot dry weights compared with the control group.

### 3.2 Effect of Textile Effluent on Nutrient Content in Different Parts of Rice

Table 4 presents the impact of textile effluent on nutrient levels in various parts of rice plants. The results indicate notable variations in nitrogen (N) and phosphorus (P) content across grain, straw, and roots. For nitrogen in grain, the highest level (1.68%) was recorded in treatment T2 (100% RDF + fresh water), while the lowest (1.00%) occurred in T6 (50% RDF + 100% effluent). In straw, maximum N (0.68%) was also found in T2, whereas the minimum (0.54%) was in the control treatment (T1). Root nitrogen peaked at 0.31% under T5 (50% RDF + 75% effluent), with the lowest value (0.29%) observed in both T1 and T6.

Regarding phosphorus, the highest grain P content (0.029%) was measured in both T2 and T4 (50% RDF + 50% effluent), while the lowest (0.016%) was recorded in T5. In straw, the maximum P level (0.031%) occurred in T3 (50% RDF + 25% effluent), and the minimum (0.012%) in T6. For roots, the highest P content (0.011%) was again found in T3, while the lowest (0.007%) was in the control (T1).

**Table 4. Effect of textile effluent on nutrient content in different parts of the rice plant**

| Treatment | Plant parts | Nutrient % | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | S | Ca | Mg |
| $T_1$= control | Grain | 1.12 | 0.019 | 0.39 | 0.04 | 0.08 | 0.035 |
| | Straw | 0.54 | 0.013 | 3.528 | 0.041 | 0.28 | 0.22 |
| | Root | 0.29 | 0.007 | 0.91 | 0.01 | 0.15 | 0.022 |
| $T_2$= 100% RDF + FW | Grain | 1.68 | 0.023 | 0.525 | 0.047 | 0.1 | 0.085 |
| | Straw | 0.68 | 0.029 | 3.581 | 0.048 | 0.32 | 0.205 |
| | Root | 0.30 | 0.01 | 0.91 | 0.012 | 0.16 | 0.023 |
| $T_3$=50% RDF + 25% effluent | Grain | 1.12 | 0.019 | 0.519 | 0.04 | 0.09 | 0.04 |
| | Straw | 0.58 | 0.031 | 3.689 | 0.045 | 0.3 | 0.2 |
| | Root | 0.30 | 0.011 | 0.95 | 0.11 | 0.15 | 0.014 |
| $T_4$=50%RDF + 50% effluent | Grain | 1.62 | 0.029 | 0.447 | 0.045 | 0.1 | 0.05 |
| | Straw | 0.64 | 0.016 | 2.811 | 0.041 | 0.26 | 0.225 |
| | Root | 0.30 | 0.01 | 0.85 | 0.12 | 0.16 | 0.02 |
| $T_5$=50%RDF + 75% effluent | Grain | 1.05 | 0.016 | 0.321 | 0.041 | 0.12 | 0.085 |
| | Straw | 0.66 | 0.016 | 3.528 | 0.05 | 0.3 | 0.215 |
| | Root | 0.31 | 0.01 | 0.88 | 0.015 | 0.16 | 0.02 |
| $T_6$=50%RDF + 100% effluent | Grain | 1.00 | 0.019 | 0.43 | 0.044 | 0.11 | 0.095 |
| | Straw | 0.64 | 0.012 | 3.581 | 0.036 | 0.28 | 0.235 |
| | Root | 0.29 | 0.009 | 0.9 | 0.011 | 0.15 | 0.018 |

The highest potassium (K) concentration in rice grain was 0.525%, recorded in treatment T2 (100% RDF + fresh water), while the lowest value of 0.321% occurred in T5 (50% RDF + 75% effluent). In straw, the maximum K content was 3.689% under T3 (50% RDF + 25% effluent), and the minimum was 2.811% in T4 (50% RDF + 50% effluent). For roots, the highest K level (0.95%) was found in T3, whereas T4 showed the lowest at 0.85%.

Regarding sulfur (S), the highest grain concentration (0.047%) was observed in T2, while the lowest (0.04%) occurred in both T1 (control) and T3. In straw, the peak S content was 0.048% in T2, compared to the lowest value of 0.036% in T6 (50% RDF + 100% effluent). Root S content reached a maximum of 0.015% in T5 and dropped to a minimum of 0.01% in the control (T1).

Calcium (Ca) levels in grain were highest (0.12%) in T5 and lowest (0.08%) in the control (T1). The highest Ca content in straw (0.32%) was measured in T2, while T4 had the lowest (0.26%). Maximum root Ca (0.16%) was recorded in T2, T4, and T5, while the minimum (0.15%) was found in T1, T4, and T6. Statistical analysis indicated no significant difference between these maximum and minimum values, suggesting they are comparable.

Magnesium (Mg) in grain peaked at 0.095% in T6 (50% RDF + 100% effluent), with the lowest level (0.032%) in the control. The highest Mg content in straw (0.235%) also occurred in T6, while T3 recorded the lowest (0.2%). Root Mg reached its highest level (0.023%) in T2 and its lowest (0.014%) in T3.

Previous studies support these findings: Begum *et al.* (2011) reported higher N, P, K, and S contents in rice under fresh-water irrigation, which also produced the highest grain yield. Yaseen *et al.* (2017) noted that a 50:50 mix of textile wastewater and canal water increased grain and straw concentrations of nitrogen, phosphorus, and potassium by up to 20%, 44%, and 42%, respectively, compared with the control. Roychand *et al.* (2008) observed that two pre-sowing effluent irrigations significantly increased N (21%), K (11%), S (10%), Zn (9%), Cu (21%), and Mo (8%) in grain, although P and Mg decreased by 16% and 19%, respectively. In straw, increases were observed in K (28%), S (32%), Cu (65%), and Mo (45%). The combined use of effluent and inorganic fertilisers significantly influenced both yield and nutrient uptake. Najam-us-Sahar *et al.* (2017) found that 100% textile wastewater reduced grain nitrogen and phosphorus by 27% and 18%, respectively, compared with tap water, but dilution progressively reduced these negative effects. Applications of 10% and 20% diluted wastewater significantly enhanced grain N and P relative to the control. Mohammad Rusan *et al.* (2007) emphasised that proper wastewater management can improve plant growth, soil fertility, and productivity by increasing nutrient availability and organic matter. However, Jaishree and Khan (2015) reported reduced protein and nitrogen content in cowpea as heavy metal levels in textile wastewater increased.

### 3.3 Effect of Textile Effluent on Nutrient Uptake by Rice Plants

Table 5 shows nutrient uptake by rice plants as influenced by irrigation with textile effluent.

Nutrient uptake was significantly higher ($P \leq 0.05$) in treatments using effluent compared to the control (T1). All treated plots showed notable nutrient absorption. Nitrogen (N) uptake varied significantly among treatments, except between T4 and T5. The highest N uptake (125.52 kg/ha) occurred in T2 (100% RDF + 0% FW), followed by T4 (50% RDF + 50% effluent) at 108.18 kg/ha. The lowest N uptake (42.31 kg/ha) was recorded in the control (T1).

**Table 5. Effect of textile effluent on nutrient uptake in different parts of rice plant**

| Treatment | Plant parts | Uptake of nutrients kg/ha | | | | | |
|---|---|---|---|---|---|---|---|
| | | N | P | K | S | Ca | Mg |
| $T_1$= control | Grain | 21.28 | 0.36 | 7.41 | 0.76 | 1.52 | 0.67 |
| | Straw | 18.74 | 0.45 | 122.42 | 1.42 | 9.72 | 7.63 |
| | Root | 2.29 | 0.06 | 7.19 | 0.08 | 1.19 | 0.17 |
| | Total | **42.31** $^{e}$ | **0.87** $^{f}$ | **137.02** $^{f}$ | **2.26** $^{f}$ | **12.43** $^{f}$ | **8.47** $^{e}$ |
| $T_2$=100% RDF + FW | Grain | 71.40 | 0.98 | 22.31 | 2.00 | 4.25 | 3.61 |
| | Straw | 47.19 | 2.01 | 248.52 | 3.33 | 22.21 | 14.23 |
| | Root | 6.93 | 0.23 | 21.02 | 0.28 | 3.70 | 0.53 |
| | Total | **125.52** $^{a}$ | **3.22** $^{a}$ | **291.85** $^{a}$ | **5.61** $^{b}$ | **30.16** $^{a}$ | **18.37** $^{a}$ |
| $T_3$=50%RDF +25%effluent | Grain | 27.10 | 0.46 | 12.56 | 0.97 | 2.18 | 0.97 |
| | Straw | 20.71 | 1.11 | 131.70 | 1.61 | 10.71 | 7.14 |
| | Root | 2.94 | 0.11 | 9.31 | 1.08 | 1.47 | 0.14 |
| | Total | **50.75** $^{d}$ | **1.68** $^{d}$ | **153.57** $^{e}$ | **3.66** $^{d}$ | **14.36** $^{e}$ | **8.25** $^{f}$ |
| $T_4$=50%RDF +%50 effluent | Grain | 64.31 | 0.75 | 20.60 | 1.59 | 3.57 | 1.99 |
| | Straw | 38.53 | 1.87 | 222.08 | 2.71 | 18.06 | 13.55 |
| | Root | 5.34 | 0.20 | 16.91 | 1.96 | 2.67 | 0.25 |
| | Total | **108.18** $^{b}$ | **2.82** $^{b}$ | **259.59** $^{b}$ | **6.26** $^{a}$ | **24.30** $^{c}$ | **15.79** $^{c}$ |
| $T_5$=50%RDF +75%effluent | Grain | 38.96 | 0.59 | 11.91 | 1.52 | 4.45 | 3.15 |
| | Straw | 39.93 | 0.97 | 213.44 | 3.03 | 18.15 | 13.01 |
| | Root | 5.08 | 0.16 | 14.43 | 0.25 | 2.62 | 0.33 |
| | Total | **83.97** $^{b}$ | **1.72** $^{c}$ | **239.78** $^{c}$ | **4.80** $^{c}$ | **25.22** $^{b}$ | **16.49** $^{b}$ |
| $T_6$=50%RDF +100% effluent | Grain | 25.40 | 0.48 | 10.92 | 1.12 | 2.79 | 2.41 |
| | Straw | 28.10 | 0.53 | 157.21 | 1.58 | 12.29 | 10.32 |
| | Root | 4.70 | 0.15 | 14.58 | 0.18 | 2.43 | 0.29 |
| | Total | **58.20** $^{c}$ | **1.16** $^{e}$ | **182.71** $^{d}$ | **2.88** $^{e}$ | **17.51** $^{d}$ | **13.02** $^{d}$ |

Phosphorus (P) and potassium (K) uptake across plant parts also differed significantly ($p \leq 0.05$) among treatments. Total P uptake ranged from 0.87 to 3.22 kg/ha, while K uptake varied between 137.02 and 291.85 kg/ha. Maximum P and K uptake were both observed in T2, at 3.22 kg/ha and 291.85 kg/ha, respectively. T4 followed with 2.82 kg/ha of P and 259.59 kg/ha of K. The control (T1) had the lowest values for both nutrients.

Sulfur (S) uptake also showed significant differences ($P \leq 0.05$). The highest total S uptake (6.26 kg/ha) was recorded in T4 (50% RDF + 50% effluent), followed by T2 with 5.61 kg/ha. The lowest S uptake (2.26 kg/ha) was again observed in the control (T1).

Calcium (Ca) and magnesium (Mg) uptake across grain, straw, and roots also varied significantly ($P \leq 0.05$) compared to the control. The highest Ca (30.16 kg/ha) and Mg (18.37 kg/ha) uptake occurred in T2. T5 (50% RDF + 75% effluent) ranked second, with 25.22 kg/ha of Ca and 16.49 kg/ha of Mg. The lowest uptakes of both Ca (12.43 kg/ha) and Mg (8.425 kg/ha) were found in T1 and T3 (50% RDF + 25% effluent).

Yaseen *et al.* (2017) observed that using a 50:50 mix of textile wastewater and canal water enhanced nutrient uptake and improved the agronomic efficiency of fertilisers compared with the control treatment. In an earlier study, Yaseen *et al.* (2016) found that applying liquid fertiliser with treated textile effluent increased nitrogen, phosphorus, and potassium uptake in grain by 15%, 30%, and 28%, respectively, relative to using canal water with the same fertiliser. These findings suggest that combining wastewater with liquid NPK fertilisers might offer a promising strategy for boosting wheat growth and yield in saline-sodic soils. Conversely, Begum *et al.* (2011) noted higher uptake of nitrogen, phosphorus, potassium, and sulphur—and the highest rice grain yields—under irrigation with fresh water in uncontaminated fields. They also highlighted that heavy metals in wastewater can interfere with the absorption of essential nutrients, limiting plants' ability to take up sufficient nutrition. In contrast, Carlos *et al.* (2018) reported elevated levels of nitrogen, phosphorus, potassium, and sulphur in maize tissues when irrigated with industrial wastewater.

### 3.4 Effect of Textile Effluent on Heavy Metal Concentration in Different Parts of Rice

Table 6 shows how textile effluent irrigation affects heavy metal levels in various parts of rice plants. As the proportion of effluent used in irrigation increased, concentrations of heavy metals in rice rose slightly but remained within acceptable limits. In rice grain, the highest zinc (Zn) level, 50 ppm, was recorded under treatment T6 (50% RDF + 100% effluent), while the lowest, 36 ppm, occurred with T3 (50% RDF + 25% effluent). For rice straw, the maximum Zn concentration was 186 ppm under T6, and the minimum was 103 ppm in the control group (T1). In roots, the highest Zn level was 25 ppm with T6 (50% RDF + 100% TWW), and the lowest was 12 ppm in the control (T1). The order of Zn concentration across treatments was T6 > T5 > T2 > T4 > T1 > T3 in grain, T6 > T2 > T5 > T4 > T3 in straw, and T6 > T5 > T4 > T3 > T2 > T1 in roots.

Copper (Cu) levels in rice grain also increased marginally with higher effluent application. The highest Cu concentration in grain (6.61 ppm) was found with T6 (50% RDF + 100% effluent), and the lowest (2.31 ppm) with T2 (100% RDF + freshwater). In straw, Cu reached a maximum of 8.97 ppm under T6 and a minimum of 8.52 ppm under T3. Root Cu levels peaked at 2.30 ppm with T6 and were lowest (1.40 ppm) with T3. The ranking of treatments by Cu concentration followed this order: in grain, T6 > T5 > T4 > T1 > T3 > T2; in straw, T6 > T5 > T4 > T1 > T2 > T3; and in roots, T6 > T5 > T4 > T2 > T1 > T3.

**Table 6. Effect of textile effluent on heavy metal concentration in different parts of rice**

| Treatment | Plant parts | Heavy Metal Concentration (ppm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Zn | Cu | Ni | Fe | Cd | Cr | Pb | Mn |
| $T_1$= (control) | Grain | 41 | 2.80 | ND | 109.81 | ND | ND | ND | 75.31 |
| | Straw | 103 | 9.71 | ND | 901.94 | ND | ND | ND | 408.75 |
| | root | 12 | 1.70 | ND | 41.31 | ND | ND | ND | 25.15 |
| $T_2$= 100% RDF + FW | Grain | 45 | 2.31 | ND | 119.48 | ND | 0.138 | ND | 79.32 |
| | Straw | 133 | 8.61 | ND | 806.33 | ND | ND | ND | 429.50 |
| | root | 15 | 2.00 | ND | 52.33 | ND | ND | ND | 30.10 |
| $T_3$=50% RDF + 25% effluent | Grain | 36 | 2.70 | 8.6 | 137.65 | ND | ND | ND | 76.50 |
| | Straw | 104 | 8.52 | 12.0 | 904.97 | ND | 0.169 | ND | 435.20 |
| | root | 16 | 1.40 | 0.01 | 70.10 | ND | 0.01 | ND | 33.50 |
| $T_4$=50%RDF + 50% effluent | Grain | 41 | 4.10 | ND | 147.42 | ND | ND | ND | 80.80 |
| | Straw | 117 | 8.91 | ND | 984.55 | ND | ND | ND | 450.25 |
| | root | 18 | 2.10 | ND | 79.80 | ND | ND | ND | 35.70 |
| $T_5$=50%RDF + 75% effluent | Grain | 45 | 5.61 | 7.9 | 158.97 | ND | ND | ND | 82.40 |
| | Straw | 126 | 8.91 | 10.0 | 1034.87 | ND | ND | ND | 457.90 |
| | root | 25 | 2.20 | 0.02 | 80.50 | ND | ND | ND | 35.90 |
| $T_6$=50%RDF + 100% effluent | Grain | 50 | 6.61 | ND | 161.00 | ND | ND | ND | 86.10 |
| | Straw | 186 | 8.97 | ND | 1273.76 | ND | ND | ND | 471.30 |
| | root | 25 | 2.30 | ND | 96.50 | ND | ND | ND | 36.20 |

The results indicated that nickel (Ni) was not detectable in treatments T1, T2, T4, and T6. However, Ni was present in T3 and T5. In T3 (50% RDF + 25% effluent), Ni concentrations were recorded at 8.6 ppm in grain, 12.0 ppm in straw, and 0.01 ppm in roots. In contrast, T5 (50% RDF + 75% effluent) showed lower levels: 7.9 ppm in grain, 10.0 ppm in straw, and 0.02 ppm in roots.

Iron (Fe) content in rice grain rose with increasing textile effluent application. The highest Fe level in grain (161.00 ppm) occurred in T6 (50% RDF + 100% effluent), while the lowest (109.81 ppm) was in T1 (control). For straw, the maximum Fe concentration (1273.76 ppm) was also in T6, and the minimum (806.33 ppm) in T2 (100% RDF + fresh water). In roots, Fe peaked at 96.50 ppm in T6 and was lowest (41.31 ppm) in T1. Across treatments, Fe levels followed this order: in grain—T6 > T5 > T4 > T3 > T2 > T1; in straw—T6 > T5 > T4 > T3 > T1 > T2; and in roots—T6 > T5 > T4 > T3 > T2 > T1.

Cadmium (Cd) and lead (Pb) were not detected in any part of the rice plant across all treatments. Chromium (Cr) was found only in specific cases: 0.138 ppm in grain under T2, and in straw (0.169 ppm) and roots (0.01 ppm) under T3.

Manganese (Mn) levels in rice grain increased with higher effluent use. The highest Mn concentration in grain (86.10 ppm) was in T6, and the lowest (75.31 ppm) in T1. Similarly, straw showed the highest Mn (471.30 ppm) in T6 and the lowest (408.75 ppm) in T1. Root Mn reached a maximum of 36.20 ppm in T6 and a minimum of 25.15 ppm in T1. The treatment ranking for Mn was: grain—T6 > T5 > T4 > T2 > T3 > T1; straw—T6 > T5 > T4 > T3 > T2 > T1; root—T6 > T5 > T4 > T3 > T2 > T1.

Based on heavy metal accumulation in rice, the overall order was Fe > Mn > Zn > Cu > Ni > Cr. Notably, Cd and Pb were absent in all plant parts.

Comparative studies support these findings. Cheshmazar *et al.* (2018) reported a metal concentration sequence in vegetables as Mn > Zn > Cu > Pb > Cr > Cd. Zengınbal *et al.* (2018) observed elevated heavy metal levels in saplings irrigated with textile wastewater, particularly Cr, Mn, and Zn. Begum *et al.* (2011) noted increased Zn, Mn, Fe, Cu, and Pb in rice under high-effluent conditions (T6). Yaseen *et al.* (2017) found reduced Cr, Cu, Cd, and Pb in grains when using a 50% mix of canal water and textile wastewater. Carlos *et al.* (2018) reported higher Mn, Na, Cu, and Zn in maize tissues irrigated with industrial effluent.

### 3.5 Effect of Textile Effluent on Heavy Metal Uptake by Rice

Table 7 shows how textile effluent affects the accumulation of heavy metals in various parts of the rice plant. Zinc uptake differed significantly ($p \leq 0.05$) across treatments compared with the control. The lowest Zn uptake (444.79 g/ha) occurred under T1 (control), while the highest (1148.77 g/ha) was observed in T2 (100% RDF + FW).

Copper uptake in rice also increased significantly ($p \leq 0.05$) with all treatments relative to the control. The minimum Cu uptake (38.32 g/ha) was recorded in T3 (50% RDF + 25% effluent), whereas the maximum (78.33 g/ha) was observed in T5 (50% RDF + 75% effluent).

**Table 7. Effect of textile effluent on heavy metal uptake by different parts of rice plant**

| Treatment | Plant parts | Uptake of heavy metal (gm/ha) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Zn | Cu | Ni | Fe | Cd | Cr | Pb | Mn |
| $T_1$= control | Grain | 77.90 | 5.32 | 0 | 208.64 | 0 | 0 | 0 | 143.09 |
| | Straw | 357.41 | 33.69 | 0 | 3129.73 | 0 | 0 | 0 | 1418.36 |
| | Root | 9.48 | 1.34 | 0 | 32.63 | 0 | 0 | 0 | 19.87 |
| | **Total** | **444.79±0.96$^f$** | **40.35±0.14 d** | **0 $^c$** | **3371±3.2$^f$** | **0** | **0 $^b$** | **0** | **1581.32±1$^f$** |
| $T_2$=100%RDF + FW | Grain | 191.25 | 9.82 | 0 | 507.79 | 0 | 0.59 | 0 | 337.11 |
| | Straw | 923.02 | 59.75 | 0 | 5595.93 | 0 | 0 | 0 | 2980.73 |
| | Root | 34.50 | 4.60 | 0 | 120.36 | 0 | 0 | 0 | 69.23 |
| | **Total** | **1148.77±1$^a$** | **74.17±1$^b$** | **0 $^c$** | **6224.08±1$^c$** | **0** | **0.59 $^a$** | **0** | **3387.07±1$^a$** |
| $T_3$=50%RDF + 25% effluent | Grain | 87.12 | 6.53 | 20.81 | 333.11 | 0 | 0 | 0 | 185.13 |
| | Straw | 371.28 | 30.42 | 42.84 | 3230.74 | 0 | 0.60 | 0 | 1553.66 |
| | Root | 15.68 | 1.37 | 0.01 | 68.70 | 0 | 0.01 | 0 | 32.83 |
| | **Total** | **474.08±1$^e$** | **38.32±1$^e$** | **63.66 $^b$** | **3632.55±0.05$^e$** | **0** | **0.61 $^a$** | **0** | **1771.62 ±1$^e$** |
| $T_4$=50%RDF + 50% effluent | Grain | 162.77 | 16.28 | 0 | 585.26 | 0 | 0 | 0 | 320.78 |
| | Straw | 704.34 | 53.64 | 0 | 5926.99 | 0 | 0 | 0 | 2710.51 |
| | Root | 31.86 | 3.72 | 0 | 141.25 | 0 | 0 | 0 | 63.19 |
| | **Total** | **898.97±1$^d$** | **73.64±2$^b$** | **0 $^c$** | **6653.50±1$^b$** | **0** | **0 $^b$** | **0** | **3094.48±0.03$^c$** |
| $T_5$=50%RDF + 75% effluent | Grain | 166.95 | 20.81 | 29.31 | 589.78 | 0 | 0 | 0 | 305.70 |
| | Straw | 762.30 | 53.91 | 60.50 | 6260.96 | 0 | 0 | 0 | 2770.30 |
| | Root | 41.00 | 3.61 | 0.03 | 132.02 | 0 | 0 | 0 | 58.88 |
| | **Total** | **970.25±1$^c$** | **78.33±1$^a$** | **89.84 $^a$** | **6982.76±0.04$^a$** | **0** | **0 $^b$** | **0** | **3134.88±0.02$^b$** |
| $T_6$=50%RDF + 100% effluent | Grain | 127.50 | 16.86 | 0 | 410.55 | 0 | 0 | 0 | 219.56 |
| | Straw | 816.54 | 39.38 | 0 | 5591.81 | 0 | 0 | 0 | 2069.01 |
| | Root | 40.50 | 3.73 | 0 | 156.33 | 0 | 0 | 0 | 58.64 |
| | **Total** | **984.54±1$^b$** | **59.97±1$^c$** | **0 $^c$** | **6158.69±0.01$^d$** | **0** | **0 $^b$** | **0** | **2347.21±0.01$^d$** |

Rice uptake of nickel (Ni) was evident under treatments T3 and T5, both of which showed statistically significant differences ($p \leq 0.05$) compared with the control. Treatments T1, T2, T4, and T6 recorded no Ni uptake (0.0 g/ha), while the highest uptake (89.84 g/ha) occurred with T5 (50% RDF + 75% effluent). However, Ni accumulation in different plant parts remained below the critical threshold.

Iron (Fe) uptake in rice increased significantly ($p \leq 0.05$) across all treatments relative to the control. The lowest Fe uptake (3371.00 g/ha) was observed in T1 (control), whereas the maximum uptake (6982.76 g/ha) was recorded in T5 (50% RDF + 75% effluent). For chromium (Cr), uptake was detected only in T2 and T3, with no significant difference ($p \leq 0.05$) between these two treatments. The lowest Cr uptake (0 g/ha) was recorded in T1, T4, T5, and T6, while the highest level (0.613 g/ha) was found in T3 (50% RDF + 25% effluent).

Manganese (Mn) uptake increased significantly ($p \leq 0.05$) with all treatments compared with the control, and treatment effects also differed significantly from one another. The minimum Mn uptake (1581.32 g/ha) was measured in T1 (control), and the maximum (3387.07 g/ha) in T2 (100% RDF + FW).

Tangahu *et al.* (2011) noted that high contaminant levels can suppress plant growth, thereby reducing overall heavy metal uptake. Wang *et al.* (2003) reported variation among plant species in their capacity to absorb and accumulate metals from soil. Intawongse & Dean (2006) highlighted substantial differences in metal uptake among plant types, with bioavailability varying widely by element and species. Kaur and Sharma (2015) indicated that crop species vary in their ability to accumulate heavy metals when grown in effluent-irrigated soils. Heavy metal uptake can thus reflect how efficiently different crops absorb metals in contaminated conditions. Singh and Kalamdhad (2011) observed that metal uptake from soil can impair physiological processes, leading to reduced crop productivity.

## 4. Conclusion

Textile effluent irrigation affected dry matter production, nutrient uptake, and heavy-metal accumulation in rice under the tested field conditions. The recommended fertiliser dose with fresh water (T2) produced the highest fresh and dry matter yields and the greatest total uptake of nitrogen, phosphorus, potassium, calcium, and magnesium. The treatment combining 50% RDF with 50% effluent (T4) produced the second-highest fresh and dry matter yields and the highest total sulphur uptake. Heavy-metal accumulation varied among treatments and plant parts. Zinc and manganese uptake were highest in T2, whereas copper and iron uptake were highest in T5. Nickel uptake was detected only in T3 and T5, and chromium uptake occurred only in T2 and T3. Cadmium and lead were not detected. These findings show that increasing textile-effluent proportions can alter nutrient and heavy-metal uptake patterns. Therefore, the use of textile effluent for rice irrigation should be carefully managed, with attention to effluent concentration and heavy-metal accumulation in plant tissues.

## 5. Limitation

The study was conducted at a single field location using one rice variety, one textile-effluent source, and a defined set of irrigation and fertiliser treatments. Consequently, the observed nutrient and heavy-metal responses are specific to the tested soil, crop, effluent, and treatment conditions. Variability in effluent composition, soil characteristics, and cultivar response may influence outcomes elsewhere. Further field evaluation across additional locations, rice varieties, and repeated cropping cycles would improve the broader applicability of the findings.

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## 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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