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Trace metal distribution in wastewater in semi-arid Rajasthan: seasonal presence of zinc, chromium, manganese, and rare copper detection

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Abstract

This study assesses the distribution of heavy metals—Zinc (Zn), Chromium (Cr), Manganese (Mn), and Copper (Cu)—in wastewater from four wastewater bodies in Sardarshahar, a semi-arid city in the state of Rajasthan, across pre-monsoon, monsoon, and post-monsoon seasons. Results show Zn, Cr, and Mn are consistently present. Zn and Cr showed significant seasonal and spatial variations, whereas Mn showed significant temporal variation only. Cu was detected only once during the monsoon at a single site. Notably, chromium concentrations exceeded the permissible limits set by the Central Pollution Control Board (CPCB), indicating potential environmental and public health risks. Lead (Pb), Mercury (Hg), and Cadmium (Cd) were absent in all samples, which suggests limited inputs of these toxic metals. The findings emphasise the need for targeted wastewater management and continuous monitoring to mitigate heavy metal contamination in semi-arid wastewater bodies.

Keywords: Heavy metals, wastewater, semi-arid region, Sardarshahar, chromium contamination

Introduction

Heavy metal pollution in wastewater is a growing global environmental concern due to the toxic effects of these metals on ecosystems and human health. Anthropogenic activities, like industrial discharges, agricultural runoff, and urbanisation, contribute significantly to the accumulation of heavy metals in water bodies worldwide (Tchounwou *et al*., 2012) [13]. Metals like lead (Pb), cadmium (Cd), and mercury (Hg) are extremely toxic even at low concentrations because of their stability, tendency to bioaccumulate, and harmful effects. Meanwhile, metals such as zinc (Zn), chromium (Cr), manganese (Mn), and copper (Cu) require careful monitoring because they serve as essential micronutrients but can become toxic when found in excess (Jarup, 2003).

The assessment of heavy metal contamination in wastewater in semi-arid regions is critical, as these environments are vulnerable to water scarcity and pollution accumulation due to low dilution capacity and variable hydrological cycles (Elgallal *et al*., 2016) [5]. Semi-arid regions like Sardarshahar in Rajasthan, India, face extensive seasonal variations that influence water quality, including trace metal concentrations. Wastewater bodies in these regions not only pose ecological risks but also threaten public health by contaminating groundwater and surface water used for agriculture and domestic applications.

This study focuses on four urban wastewater storage ponds (WSP1-WSP4) in Sardarshahar, Rajasthan. These ponds are key components of local wastewater management infrastructure and have differential exposure to wastewater inputs and seasonal hydrological changes. The rationale for studying these ponds is to understand the temporal and spatial distribution of trace metals to inform environmental monitoring and management practices in semi-arid contexts (CPCB, 2018).

Health and environmental concerns associated with the metals detected in this study are multifaceted. Zinc, chromium, and manganese are essential elements for biological functions but can have toxic effects beyond threshold concentrations (Prasad, 2012). Chromium, particularly in its hexavalent form, is a known carcinogen (IARC, 2012). Copper, while vital, induces oxidative stress and toxicity at elevated levels (Liu *et al*., 2020) [10]. Notably, the absence of highly toxic metals such as lead, mercury, and cadmium in all samples presents a relatively lower pollution burden by these hazardous metals in this locale, allowing for focused attention on the metals present and their seasonal dynamics.

In sum, this paper aims to characterise the trace metal distribution in wastewater ponds of semi-arid Rajasthan, emphasising the seasonal presence of Zn, Cr, Mn, and the rare detection of Cu. This assessment is crucial for developing targeted wastewater management and pollution mitigation strategies to safeguard aquatic ecosystems and public health in water-stressed regions.

Materials and Methods

The study was conducted in the semi-arid region of Sardarshahar, located in the northern part of Rajasthan, India (28°26′26″N latitude and 74°29′28″E longitude), characterised by low rainfall and high evaporation rates (IMD, 2010). Four wastewater storage ponds (WSP1, WSP2, WSP3, and WSP4) were selected based on their significance in local wastewater management and varying exposure to effluent discharge. WSP1 is located in a densely populated area. WSP2 lies next to a commercial hub, whereas WSP3 and WSP4 are on the extremity of the city, with WSP3 near an industrial area. These ponds represent typical wastewater bodies in terms of size, usage, and catchment characteristics and are integral to understanding heavy metal dynamics in this water-scarce region.

Seasonal sampling was conducted to record temporal variability. Sampling campaigns were carried out across three distinct seasons: pre-monsoon, monsoon, and post-monsoon during the year 2024-25. At each pond, samples were collected from multiple representative points in the early morning to minimise diurnal variations and transported in acid-washed polyethene bottles to the laboratory for analysis.

Fig. 1: Location of four wastewater bodies studied (labelled WSP1- WSP4) (Source- Google Earth Pro 7.3.6.10441)

Standard protocols for sample collection and preservation were followed to ensure data reliability (APHA, 2017) [1]. Samples were filtered using 0.45 µm membrane filters and acidified with ultrapure nitric acid to pH < 2 immediately after collection to prevent metal precipitation and microbial activity. Samples were preserved by cooling at 4°C and analysed within 48 hours of collection to ensure sample integrity. Concentrations of Zinc (Zn), Chromium (Cr), Manganese (Mn), Copper (Cu), Lead (Pb), Mercury (Hg), and Cadmium (Cd) were quantified using Atomic Absorption Spectrometry (AAS) following strictly standardised protocols (USEPA, 2007). Calibration was done using certified standard solutions.

Data were analysed using Microsoft Excel 2021. Descriptive statistics (mean, standard deviation) characterised heavy metal distributions. Inferential statistics included two-way ANOVA to assess the effects of sampling season and pond location on metal concentrations, with significance determined at $p < 0.01$ and $p < 0.05$. Interaction effects between season and site were also explored to understand complex spatial-temporal dynamics

Results

Zinc concentrations across all ponds ranged from 0.027 mg/L to 0.043 mg/L (Fig. 2), well below the CPCB permissible limit of 5.0 mg/L. Significant spatial and seasonal differences ($p < 0.01$) were observed, with the highest zinc levels generally occurring during the monsoon season.

Chromium concentrations in all ponds exceeded the CPCB limit of 0.05 mg/L, with measured values ranging from 0.342 mg/L to 0.608 mg/L (Fig. 3), indicating significant chromium contamination in these wastewater bodies. Statistical analysis revealed significant spatial and seasonal variations ($p < 0.01$).

Manganese was detected at concentrations ranging from 0.039 to 0.068 mg/L (Fig. 4), below the CPCB limit of 0.1 mg/L. Seasonal variation was significant ($p < 0.01$), while spatial differences were not statistically significant ($p > 0.05$).

Copper was detected only once during the monsoon season at pond WSP3, with a concentration of 0.032 mg/L, well below the CPCB limit of 3.0 mg/L. All other samples showed copper levels below detection limits.

Lead, mercury, cadmium, and nickel were absent in all samples across ponds and seasons, indicating negligible contamination by these toxic heavy metals in the study area.

Table 1: Summary of the measured concentrations of different heavy metals (mg/L) across sites and seasons.

Parameter	CPCB standard Limit	WSP1 (Pre-monsoon, monsoon post-monsoon)	WSP2 (Pre-monsoon, monsoon post-monsoon)	WSP3 (Pre-monsoon, monsoon post-monsoon)	WSP4 (Pre-monsoon, monsoon post-monsoon)	Statistical Significance (p-values)
Zinc	5.0 mg/L	0.034±0.005 0.073±0.019 0.051±0.024	0.027±0.009 0.036±0.007 0.032±0.011	0.036±0.005 0.057±0.015 0.043±0.004	0.043±0.007 0.047±0.005 0.042±0.002	Sample Effect: p=0.007** Season Effect: p=0.003** Interaction: ns
Total Chromium	0.05 mg/L	0.608±0.027 0.413±0.097 0.461±0.117	0.511±0.021 0.342±0.024 0.381±0.029	0.507±0.024 0.417±0.095 0.474±0.112	0.602±0.074 0.571±0.089 0.486±0.019	Sample Effect: p=0.003** Season Effect: p=0.0006** Interaction: ns
Manganese	0.1 mg/L	0.048±0.003 0.057±0.012 0.043±0.028	0.046±0.004 0.051±0.003 0.043±0.006	0.042±0.003 0.058±0.008 0.039±0.002	0.056±0.008 0.068±0.009 0.048±0.003	Sample Effect: ns; Season Effect: p=0.004** Interaction: ns
Copper	3.0 Mg/L	BDL	BDL	BDL 0.032 mg/ L (Monsoon)	BDL	Detected only once in the monsoon at WSP3
Lead (Pb)	0.01 mg/L	BDL	BDL	BDL	BDL	Not detected
Mercury (Hg)	0.001 mg/L	BDL	BDL	BDL	BDL	Not detected
Cadmium (Cd)	0.01 mg/L	BDL	BDL	BDL	BDL	Not detected
Nickel (Ni)	0.02 mg/L	BDL	BDL	BDL	BDL	Not detected

BDL= <0.01 mg/L

* = significance at $p < 0.05$

** = significance at $p < 0.01$

ns = not significant ($p > 0.05$)

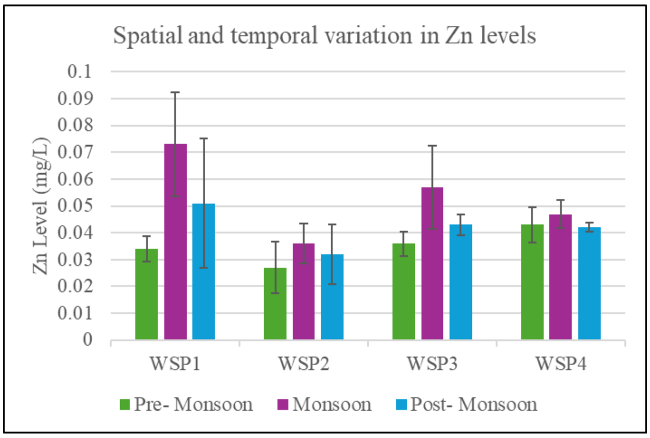

Fig 2: Graph showing spatial and temporal variation in zinc levels in four wastewater bodies

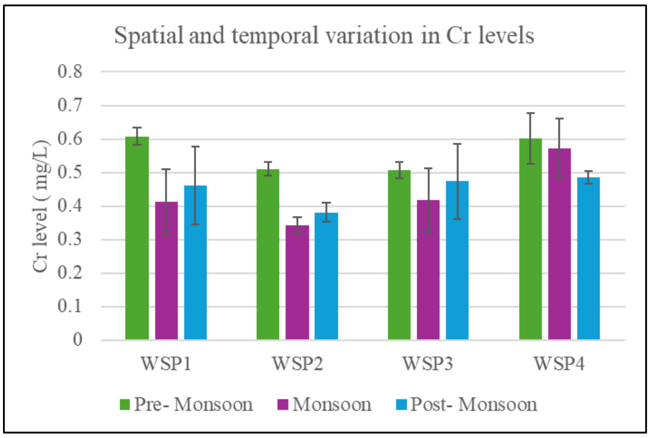

Fig 3: Graph showing spatial and temporal variation in Chromium levels in four wastewater bodies

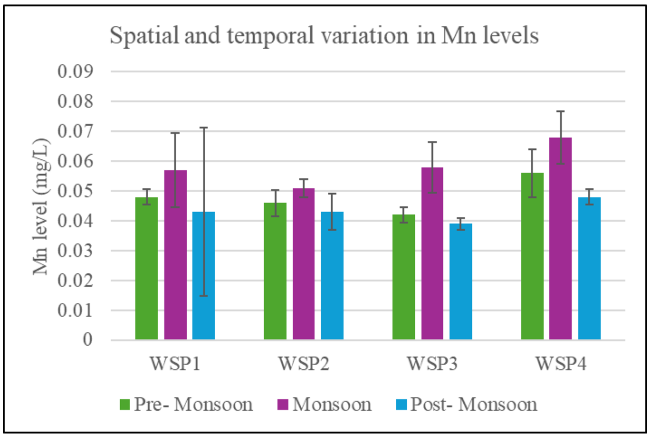

Fig 4: Graph showing spatial andtemporal variation in Manganese levels in four wastewater bodies

Statistical Significance of Variations

Two-way ANOVA indicated significant effects of pond location and season on zinc and chromium concentrations, while manganese exhibited significant seasonal but not spatial variation. No significant interactions between pond and season were detected for any of the analysed metals, suggesting that spatial and temporal factors independently influenced the metal concentrations.

Discussion

The presence of Zinc (Zn), Chromium (Cr), and Manganese (Mn) in the wastewater ponds of semi-arid Rajasthan reflects both natural geochemical background and anthropogenic influences. Zinc is an essential micronutrient involved in biological processes, but can accumulate in the environment due to industrial discharge, agricultural runoff, including fertilisers, and domestic wastewater (Prasad, 2012). The observed levels, though below regulatory limits, exhibited significant spatial and seasonal variability, likely influenced by local variations in effluent sources and hydrological factors affecting dilution and deposition during the post-monsoon season.

Chromium concentrations in the ponds notably exceeded the CPCB permissible limits, indicating substantial contamination. Chromium contamination is commonly linked to tannery effluents, metal plating industries, and textile dyeing processes prevalent in parts of Rajasthan and surrounding regions (IARC, 2012). Higher chromium concentrations may be attributed to lower water volumes, which concentrate pollutants, followed by runoff-based inputs during rainfall (Cederkvist *et al*., 2013; Zhang *et al*., 2023; Chen *et al*., 2024) [2, 4, 16]. Hexavalent chromium, a known carcinogen, poses significant ecological and human health risks, underscoring the need for targeted remediation strategies in these ponds (Jarup, 2003).

Manganese, detected at concentrations below regulatory thresholds, is ubiquitous in natural waters due to soil and rock weathering processes. Its seasonal increase in post-monsoon waters may be related to redox changes under varying oxygen conditions and to organic matter input, which affect metal mobility (Narayanan *et al*., 2025) [11]. While biologically essential, elevated manganese levels can cause neurotoxicity with prolonged exposure (Erikson *et al*., 2004) [6].

The rare mono-seasonal detection of copper (Cu) in only one pond (WSP3) during the monsoon suggests localised or episodic pollution events possibly linked to urban runoff or corrosion of copper-containing plumbing and industrial inputs (Vargas *et al*., 2017) [15]. Copper's environmental presence is concerning due to its toxicity to aquatic organisms at elevated levels, although measured concentrations were well below CPCB limits.

Compared with other regions, the absence of lead (Pb), mercury (Hg), Nickel (Ni), and cadmium (Cd)—highly toxic and persistent pollutants—suggests limited inputs or effective natural attenuation mechanisms in this region. The findings align partially with other regional studies showing variable heavy metal contamination patterns influenced by industrialisation levels and hydrological factors (Tchounwou *et al*., 2012).

Environmental implications include potential risks to aquatic life and human health through direct contact or use of contaminated water for irrigation, exacerbated by semi-arid conditions that limit dilution and promote pollutant accumulation. The elevated chromium levels call for urgent pollution control measures and continuous monitoring. Wastewater treatment improvements and regulatory enforcement are critical for mitigating heavy metal risks in such water-scarce settings.

Limitations of this study include analysing only dissolved metal fractions without speciation data, which could elucidate metal bioavailability and toxicity. Future research should incorporate sediment analysis, speciation studies, and expanded spatial coverage to provide a more comprehensive risk assessment.

Conclusion

This study investigated the distribution of trace metals—Zinc (Zn), Chromium (Cr), Manganese (Mn), and Copper (Cu)—in wastewater from four storage ponds (WSP1-WSP4) in the semi-arid region of Sardarshahar, Rajasthan. The key findings indicate that Zn, Cr, and Mn were consistently present across the ponds with significant seasonal variability. At the same time, Cu was detected only once during the monsoon season at a single site. Notably, Chromium concentrations exceeded the CPCB-set permissible limits, highlighting potential pollution concerns. Lead (Pb), Mercury (Hg), Nickel (Ni), and Cadmium (Cd), highly toxic metals, were absent in all samples.

These findings highlight the urgent need for effective wastewater management and pollution control in semi-arid regions, where limited water availability worsens environmental risks caused by pollutant accumulation. The seasonal fluctuations observed suggest that wastewater treatment and monitoring programs must be adaptive and account for temporal variations to ensure sustainable water quality management.

Ongoing monitoring of heavy metal concentrations, particularly chromium due to its toxicity and regulatory exceedance, is essential. Future research should incorporate sediment and speciation analyses and evaluate the efficacy of existing wastewater treatment practices. Such efforts will contribute to safeguarding aquatic ecosystems and public health in semi-arid environments confronted with complex water quality challenges.

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