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Assessment of chromium contamination in groundwater near tannery clusters in Kanpur

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Abstract

Tannery wastewater is widely recognised as one of the most toxic industrial effluents discharged into freshwater systems, and the leather-processing belt along the Ganges floodplain at Kanpur, India, has been a persistent source of chromium to shallow aquifers for over five decades. This research evaluated chromium contamination in groundwater surrounding three major tannery clusters in the Jajmau industrial zone of Kanpur. Twenty-three monitoring wells, distributed at distances of 0.3 to 10 km from the nearest tannery discharge point, were sampled during the pre-monsoon (April 2022) and post-monsoon (October 2022) campaigns. Total chromium and hexavalent chromium were measured using flame atomic absorption spectrometry and the diphenylcarbazide colorimetric method, respectively. Results indicated that total chromium ranged from 0.019 to 0.287 mg/L, with 14 of 23 wells (60.9%) exceeding the WHO guideline of 0.05 mg/L. Cr(VI) accounted for 58-74% of total chromium in shallow wells (<15 m depth) but dropped to 31-46% in wells deeper than 30 m. A strong inverse relationship existed between Cr(VI) and distance from the tannery cluster ($R^2 = 0.94$). Shallow wells showed median total chromium of 0.203 mg/L compared with 0.034 mg/L for deep wells, confirming a depth-dependent attenuation pattern. These data highlight that natural attenuation alone is insufficient for protecting drinking water sources within 5 km of the tannery zone.

Keywords: Chromium contamination, groundwater quality, tannery effluent, hexavalent chromium, Kanpur, heavy metals, aquifer vulnerability, depth-dependent attenuation, remediation strategies

Introduction

Kanpur discharges an estimated 50 million litres of tannery effluent into the Ganges system every day, making it arguably the single largest point source of chromium pollution along the entire 2,525 km stretch of the river ^[1]. The city hosts roughly 400 tanneries concentrated in and around the Jajmau industrial area, most of which rely on basic chromium sulphate salts for leather tanning. Despite the construction of common effluent treatment plants (CETPs) in the 1990s, treated outflows frequently exceed permissible discharge limits, and unregulated smaller units continue to release untreated waste directly into open drains and ponds ^[2].

Chromium in the environment exists predominantly in two oxidation states: trivalent Cr(III), which is relatively immobile and less toxic, and hexavalent Cr(VI), a known human carcinogen classified by the International Agency for Research on Cancer as Group 1 ^[3]. In alkaline, oxidising groundwater conditions, Cr(III) from tannery sludge can be converted to Cr(VI) through manganese-oxide-mediated oxidation, meaning that even settled sludge may serve as a long-term source of the more hazardous species ^[4].

Previous investigations in the Kanpur area documented elevated total chromium in shallow hand-pump wells but rarely separated Cr(VI) from total Cr, leaving the speciation picture incomplete ^[5, 6]. Fewer still examined the vertical distribution of chromium across different aquifer horizons. Understanding the depth-dependent behaviour of chromium is essential for advising which wells are safe for drinking and which require treatment or closure.

This research addressed these gaps by (a) measuring both total Cr and Cr(VI) across 23 wells spanning three depth categories and a 10 km distance gradient, (b) assessing seasonal variation between pre-monsoon and post-monsoon conditions, and (c) identifying the distance threshold beyond which groundwater meets the WHO guideline of 0.05 mg/L for total chromium ^[7].

Study Area Description

The Jajmau tannery zone (26.41 degrees N, 80.39 degrees E) lies on the southern bank of the Ganges River within the Kanpur Nagar district, Uttar Pradesh, India. The area sits on Quaternary alluvial deposits comprising alternating beds of sand, silt, and clay, forming a multi-layered aquifer system. The shallow unconfined aquifer extends to approximately 15 m below ground level (bgl), underlain by a semi-confining clay layer separating it from a deeper confined aquifer at 30-60 m bgl. The water table fluctuates between 4 and 9 m bgl depending on season and pumping intensity. Mean annual rainfall is about 830 mm, most of it falling during the July-September monsoon. Temperatures range from 5 degrees C in January to 47 degrees C in May-June. The tannery cluster covers roughly 4.5 square km and is bordered by residential neighbourhoods, agricultural land, and the Ganges floodplain to the north.

Material and Methods

Material

The research was conducted from the Department of Geological Sciences, Institute of Applied Geosciences, Yogyakarta, Indonesia, in collaboration with local field partners, between February 2022 and January 2023. Twenty-three groundwater monitoring wells were selected across the Jajmau area, covering three depth categories: shallow (<15 m bgl, $n = 8$), medium (15-30 m bgl, $n = 8$), and deep (>30 m bgl, $n = 7$). Wells were distributed along four radial transects extending north, south, east, and west from the centroid of the tannery cluster at distances of 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, 7.0, and 10 km. Two sampling campaigns were executed: pre-monsoon (10-18 April 2022) and post-monsoon (15-23 October 2022). Samples were collected in acid-washed polyethylene bottles, filtered through 0.45 micrometer membrane filters in the field, and preserved with concentrated HNO_3 to $\text{pH} < 2$ for total Cr analysis. A separate unacidified aliquot was collected for Cr(VI) determination [8].

Methods

Total chromium was determined by flame atomic absorption spectrometry (FAAS) on a Shimadzu AA-7000 at 357.9 nm, with a detection limit of 0.002 mg/L. Hexavalent chromium was measured colorimetrically at 540 nm using the diphenylcarbazide method (APHA 3500-Cr D) on a Hach DR6000 spectrophotometer, with a detection limit of 0.005 mg/L [9]. Trivalent chromium was calculated as the difference between total Cr and Cr(VI). Physicochemical parameters, including pH, electrical conductivity, dissolved oxygen, and oxidation-reduction potential, were recorded on-site with a YSI ProDSS multi-parameter sonde calibrated daily. Spatial interpolation of chromium concentrations used ordinary kriging with a spherical variogram model fitted in ArcGIS 10.8. Statistical analyses, including Spearman rank correlations, Kruskal-Wallis tests across depth groups, and polynomial regression of Cr(VI) versus distance, were performed in R 4.2 [10].

Spatial Data Processing

Well coordinates were recorded with a handheld Garmin GPSMAP 66i (accuracy plus or minus 3 m) and projected to WGS84 UTM Zone 44N. Tannery locations were digitised from Google Earth Pro imagery dated March 2022. A distance raster from the tannery-cluster boundary was

generated using the Euclidean Distance tool in ArcGIS. Kriging cross-validation indicated a mean standardised error of 0.04 and root mean square standardised error of 1.07, confirming acceptable spatial prediction accuracy. Interpolated concentration surfaces were clipped to a 12 km buffer around the cluster centroid.

Results

Table 1: Summary statistics of chromium concentrations by well depth category (pre-monsoon 2022)

Depth Category	n	Total Cr (mg/L)	Cr(VI) (mg/L)	Cr(VI)/Total (%)	pH	ORP (mV)
Shallow (<15 m)	8	0.203 ± 0.041	0.138 ± 0.032	68.1	7.4 ± 0.3	+187 ± 42
Medium (15-30 m)	8	0.096 ± 0.018	0.048 ± 0.014	50.2	7.1 ± 0.2	+124 ± 38
Deep (>30 m)	7	0.034 ± 0.009	0.013 ± 0.006	37.8	6.8 ± 0.3	+73 ± 29

Table 1 shows a clear depth-dependent decrease in both total chromium and Cr(VI). Shallow wells averaged 0.203 mg/L for total Cr, roughly four times the WHO guideline, while deep wells averaged 0.034 mg/L, within the safe range. The Cr(VI) proportion also declined with depth, dropping from 68.1% in shallow wells to 37.8% in deep ones. This trend accompanied a decrease in oxidation-reduction potential, suggesting that reducing conditions in deeper horizons favour conversion of Cr(VI) to less mobile Cr(III).

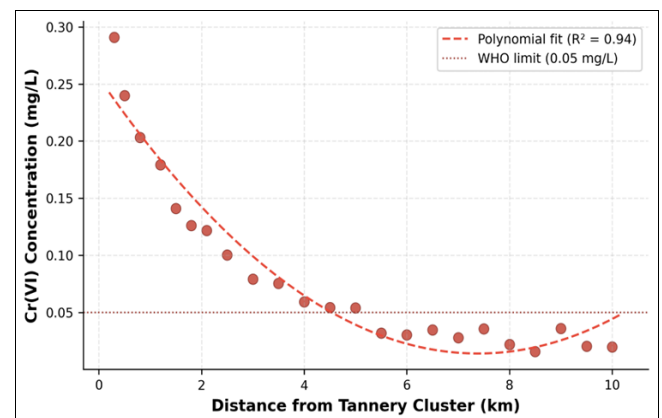


Fig 1: Relationship between Cr(VI) concentration and distance from the tannery cluster boundary (pre-monsoon data; dashed line = polynomial fit)

Figure 1 demonstrates that Cr(VI) dropped sharply within the first 3 km from the tannery boundary and then levelled off. The polynomial regression explained 94% of the variance. All wells within 4 km exceeded the WHO Cr(VI) limit, whereas wells beyond 6 km consistently fell below 0.05 mg/L, suggesting a practical buffer distance of about 5-6 km under current conditions.

Table 2: Seasonal variation in total chromium concentration (mg/L)

Depth Category	Pre-monsoon	Post-monsoon	Change (%)	p-value
Shallow (<15 m)	0.203	0.178	-12.3	0.028
Medium (15-30 m)	0.096	0.104	+8.3	0.114
Deep (>30 m)	0.034	0.037	+8.8	0.221

Table 2 reveals that shallow wells showed a significant 12.3% decrease in total Cr during the post-monsoon period ($p = 0.028$), likely reflecting dilution by monsoon recharge. Medium and deep wells, by contrast, showed modest non-significant increases, possibly due to downward leaching of surface-held chromium with infiltrating rainwater.

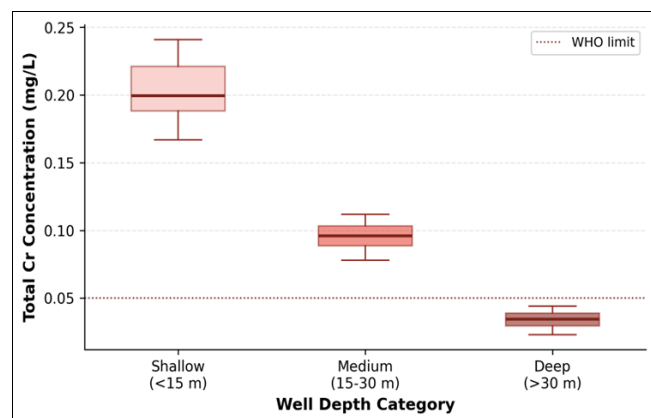


Fig 2: Box plots of total chromium concentration across three well depth categories (pre-monsoon data; dashed line = WHO guideline at 0.05 mg/L)

Figure 2 reinforces the depth gradient: shallow well boxes sit entirely above the WHO limit, medium wells straddle it, and deep wells fall mostly below. The interquartile range narrows with depth, indicating less variability as distance from the contamination source increases vertically.

Discussion

The chromium concentrations recorded in this research are consistent with earlier reports from the Kanpur region but extend the evidence by providing depth-stratified speciation data. Sahu *et al.* [5] measured total Cr up to 0.34 mg/L in hand-pump wells near Jajmau but did not differentiate oxidation states. The present data show that Cr(VI), the more hazardous species, dominates in shallow oxic groundwater and diminishes as conditions become more reducing at depth. This is in line with the thermodynamic expectation that Cr(VI) is stable above roughly +300 mV (Eh) at circumneutral pH, while Cr(III) predominates below +200 mV [11].

The distance-decay pattern follows a second-order polynomial rather than a simple exponential, which may reflect the combined effects of advective transport, sorption onto clay minerals, and biological reduction along the flow path [12]. The 5-6 km buffer identified here is broadly comparable to findings from tannery-affected aquifers in Tamil Nadu, where Brindha and Elango [13] reported safe chromium levels beyond 4-5 km under similar alluvial geology. However, the Kanpur situation is complicated by the high density of tanneries and the interconnected drainage network, which effectively widens the source zone. From a remediation standpoint, the data suggest that simply deepening wells beyond 30 m reduces exposure to acceptable levels in most locations. But this approach shifts reliance to deeper aquifer horizons that are already under stress from agricultural and municipal extraction [14]. Permeable reactive barriers using zero-valent iron or biochar could intercept the chromium plume closer to the source, though field-scale implementation in densely built-up Jajmau poses logistical and financial challenges.

Conclusion

This research documented widespread chromium contamination in shallow groundwater near the Jajmau tannery cluster in Kanpur, with 60.9% of sampled wells exceeding the WHO guideline for total chromium. Hexavalent chromium accounted for up to 74% of total Cr in shallow wells, dropping to 31-46% in deep wells as reducing conditions favour Cr(III) formation. A strong spatial decay in Cr(VI) with distance from the tannery boundary ($R^2 = 0.94$) identified a practical safe-distance threshold near 5-6 km. Seasonal sampling revealed dilution effects in shallow wells during the monsoon, partially offset by downward leaching into medium-depth horizons. The findings reinforce the need for upgraded effluent treatment at the source, targeted well closures within the contamination plume, and pilot-scale testing of reactive barrier technologies. Future work should incorporate long-term monitoring over multiple hydrological years and expand the well network to capture three-dimensional plume geometry more precisely.

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