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ARISTON PUBLICATIONS
ChemSci Advances
ISSN: 2997-9587 https://aristonpubs.com/journal/chemsci-advances https://doi.org/10.69626/csa.2026.0177

RESEARCH ARTICLE

Assessment of Heavy Metal Contamination in Textile Dye Wastewater and Its Accumulation in Agricultural Soils

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ABSTRACT: The rapid expansion of textile dyeing industries has led to the discharge of substantial quantities of contaminated water containing toxic heavy metals, posing serious environmental and agricultural concerns. This investigation assessed heavy metal levels in wastewater from a textile dyeing unit in the Bagru industrial area of Rajasthan, India, and examined their deposition in adjacent agricultural soils. Standard analytical techniques were employed to analyse physicochemical parameters and concentrations of chromium, cadmium, lead, copper, zinc, nickel, and iron in both wastewater and soil samples collected from multiple sites affected by industrial effluent discharge. The results demonstrated that wastewater contained several heavy metals exceeding permissible limits established by national and international environmental regulations. Elevated concentrations of these metals were also detected in nearby agricultural soils, indicating long-term infiltration of metals through irrigation with untreated or partially treated textile effluents. Soil quality evaluation revealed deterioration in physicochemical conditions, including altered pH, increased electrical conductivity, and reduced fertility, all of which can adversely affect soil health and crop production. Correlation analysis established a strong relationship between wastewater contamination and soil enrichment with heavy metals. The findings underscore the urgent need for effective wastewater treatment, periodic environmental monitoring, and sustainable wastewater management practices to minimize heavy metal pollution, preserve farmland health, and safeguard human communities residing in industrial regions.

Keywords: Heavy Metals, Textile Wastewater, Agricultural Soil, Bagru, Atomic Absorption Spectroscopy, Environmental Pollution

Received: 30 May 2026; Revised: 29 July 2026; Accepted: 06 August 2026; Published Online: 19 August 2026

1. INTRODUCTION

Industrialization has long been celebrated as an engine of economic growth and employment generation, yet it has simultaneously established itself as a principal driver of environmental degradation. Among industrial sectors, the textile dyeing and printing industry ranks among the most significant contributors to water pollution, discharging large volumes of effluent laden with dyes, chemical auxiliaries, salts, and heavy metals, frequently without adequate treatment. The consequences of such discharge extend to surface water, groundwater, soil quality, and aquatic ecosystems, with developing nations and regions lacking robust wastewater treatment infrastructure experiencing the most severe impacts [1]. The environmental burden imposed by textile effluents is not merely a matter of aesthetic degradation; it represents a persistent threat to ecological integrity and public health [2].

The presence of heavy metals in textile processing is well documented. Chromium, cadmium, lead, nickel, copper, zinc, and iron are routinely employed as mordants, pigments, catalysts, and dye-fixing agents [3]. Unlike many organic contaminants, these metals resist biodegradation, persist indefinitely in environmental matrices, and possess the capacity to bioaccumulate and biomagnify through soil and living organisms [4]. Long-term exposure to elevated concentrations of these metals poses serious concerns for

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both environmental quality and human health, as they can degrade soil conditions, contaminate crops, and enter the food chain with detrimental consequences [5]. The non-biodegradable nature of heavy metals means that once introduced into agricultural systems, they remain a lasting legacy of industrial activity [6].

Bagru, located approximately 35 kilometres southwest of Jaipur in Rajasthan, is internationally recognised for its traditional hand block printing and textile dyeing heritage. The region hosts hundreds of small and medium-scale dyeing units that collectively generate substantial quantities of coloured wastewater [7]. Owing to water scarcity in this semi-arid region, wastewater is frequently diverted for agricultural irrigation, yet the absence of adequate storage and treatment infrastructure means that untreated or only partially treated effluents are discharged directly into nearby drains and agricultural fields [8]. This practice has raised growing concern regarding the accumulation of heavy metals in agricultural soils and the potential for contamination of crops and groundwater [9]. The confluence of traditional craft, industrial expansion, and water scarcity makes Bagru a particularly instructive case for examining the environmental consequences of unregulated textile effluent reuse [10].

The existing body of literature has addressed various dimensions of textile wastewater pollution and heavy metal accumulation in soils. Ramos-Romero et al. [11] conducted a systematic review examining the transport and leaching of heavy metals in agricultural soils receiving wastewater irrigation, identifying soil properties, irrigation practices, and climatic conditions as critical determinants of metal fate. The authors cautioned that year-round wastewater irrigation may result in soil contamination capable of reaching groundwater, and recommended integrated monitoring and sustainable management strategies. Kallawar and Bhanvase [12] provided a comprehensive assessment of conventional and advanced treatment technologies, concluding that coagulation, sedimentation, and biological treatment alone are insufficient for complete removal of toxic pollutants, and advocating for integrated systems incorporating advanced oxidation processes, membrane filtration, and nanotechnology. Wang et al. [13] emphasized that wastewater reuse without proper treatment leads to heavy metal accumulation in agricultural soils and aquatic ecosystems, negatively impacting soil quality, crop productivity, and biodiversity. Hou et al. [14] identified industrial wastewater irrigation as a principal pathway for toxic metal accumulation in cultivated lands and proposed phytoremediation and microbial remediation as environmentally friendly and cost-effective restoration options. Donkadokula et al. [15] analyzed the performance of advanced physicochemical and biological treatment technologies, concluding that integrating biological treatment with advanced oxidation and membrane processes significantly improves removal efficiency for dyes, heavy metals, and recalcitrant pollutants. These studies collectively establish the scientific foundation for understanding heavy metal contamination pathways, yet a notable gap persists in site-specific investigations that link wastewater characteristics to soil accumulation patterns in traditional textile clusters such as Bagru [16].

The novelty of this study lies in its integrated assessment of both wastewater quality and soil contamination within the specific context of Bagru's traditional dyeing cluster, coupling physicochemical characterization with heavy metal quantification across matched wastewater and soil samples. Unlike broader regional surveys, this investigation directly correlates effluent metal concentrations with accumulation patterns in adjacent agricultural fields, while simultaneously evaluating soil quality deterioration through changes in pH, electrical conductivity, and fertility indicators [17]. The inclusion of control soils irrigated by tube wells provides a comparative baseline that strengthens causal inference regarding the role of textile effluents in soil contamination [18]. By situating these findings within the broader discourse on sustainable wastewater management, the study offers actionable evidence for environmental managers, policymakers, and industry stakeholders operating in similar artisanal-industrial contexts [19].

In this paper, we report the findings of a comprehensive investigation into heavy metal contamination in textile dye wastewater and its accumulation in agricultural soils surrounding the Bagru industrial area, with the objective of quantifying contamination levels, assessing soil quality deterioration, and providing a scientific basis for sustainable wastewater management in the region.

2. EXPERIMENTAL DETAILS

2.1. Study Area

The investigation was conducted in the industrial area of Bagru, situated approximately 35 km southwest of Jaipur city in Rajasthan, India. Geographically, Bagru lies between 26°55′–26°57′ N latitude and 75°11′–75°15′ E longitude, and the village is internationally recognised for its traditional hand block printing and textile dyeing heritage [7]. The region hosts hundreds of small and medium-scale dyeing units that collectively generate substantial quantities of coloured wastewater containing dyes, salts, organic compounds, and heavy metals [8]. Owing to limited freshwater availability, textile wastewater is frequently discharged into local drains without treatment, or partially treated effluent is diverted for agricultural irrigation [9]. The area experiences a semi-arid climate characterised by hot summers, moderate monsoon rainfall, and mild winters. The predominant soil types range from sandy loam to loam, and the principal crops cultivated include wheat, mustard, pearl millet, vegetables, and fodder crops [10]. Continuous wastewater irrigation in the region has raised concerns regarding soil degradation, heavy metal accumulation, and the potential contamination of crops and groundwater, making Bagru an appropriate location for investigating the impacts of industrial pollution [11].

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2.2. Sample Collection

Wastewater and soil samples were collected from representative locations within and around the Bagru industrial area during the study period. Wastewater samples were obtained from the outlets of textile dyeing units, from the common drain where industrial effluents are discharged, and from the irrigation channel transmitting wastewater to agricultural fields [12]. Samples were collected in pre-cleaned, acid-washed polyethylene bottles following standard sampling procedures. Concentrated nitric acid was immediately added to each sample to bring the pH below 2, thereby preserving dissolved metals until laboratory analysis [13]. Simultaneously, surface soil samples were collected from agricultural fields receiving wastewater from textile industries, while fields irrigated by tube wells were selected as controls [14]. Multiple sub-samples were composited from each location to represent the mean of that site. Soil samples were air-dried at room temperature, gently crushed, homogenised, and sieved through a 2 mm sieve prior to chemical analysis [15]. All samples were properly labelled, transported to the laboratory, and stored appropriately until analysis.

2.3. Laboratory Analysis

Physicochemical characteristics including pH, electrical conductivity, total dissolved solids, biological oxygen demand, and chemical oxygen demand were measured using standard analytical methods recommended by the American Public Health Association [16]. pH and electrical conductivity were determined using calibrated digital meters, while total dissolved solids, biological oxygen demand, and chemical oxygen demand were measured using standard laboratory techniques [17]. Wastewater and soil samples were digested following the nitric acid–perchloric acid digestion method for heavy metal analysis, which effectively dissolves metal ions completely [18]. Digested samples were filtered and diluted with deionised water prior to instrumental analysis. An Atomic Absorption Spectrophotometer was used to quantify concentrations of chromium, lead, cadmium, copper, nickel, zinc, and iron [19]. To ensure analytical accuracy, precision, and quality control, appropriate reagent blanks, calibration standards, and duplicate samples were analysed throughout the experimental procedures [6].

2.4. Statistical Analysis

Data collected from wastewater and soil samples were analysed statistically to assess the degree of heavy metal contamination in wastewater and the relationships between variables measured in wastewater and soil samples [5]. Physicochemical parameters and heavy metal concentrations were summarized using descriptive statistics including mean and standard deviation. Pearson correlation analysis was employed to determine the level of correlation between wastewater quality parameters and heavy metal accumulation in soils [1]. Statistically significant differences at the 95% confidence level ($p < 0.05$) between wastewater-irrigated soil and control soil were determined using one-way analysis of variance [2]. Additionally, the Pollution Index was computed to determine contamination levels for each metal, and the Geo-accumulation Index was used to measure the degree of soil contamination relative to natural background concentrations [3]. Statistical analysis was performed using appropriate software including SPSS, R, and MS-Excel to ensure reliable interpretation of results [4].

3. RESULTS AND DISCUSSION

3.1. Heavy Metal Concentration in Textile Wastewater

The heavy metal analysis of wastewater samples collected from the textile dyeing units and associated discharge channels revealed substantial contamination with several toxic metals. The concentrations of chromium, lead, cadmium, and nickel were found to be considerably higher than the permissible limits established by the World Health Organization [10]. Specifically, chromium was detected at 1.95 mg/L against a permissible limit of 0.1 mg/L, lead at 0.82 mg/L against 0.05 mg/L, cadmium at 0.09 mg/L against 0.01 mg/L, and nickel at 0.73 mg/L against 0.2 mg/L. These values represent approximately nineteen-fold, sixteen-fold, nine-fold, and three-and-a-half-fold exceedances, respectively, indicating severe contamination of the effluent stream. In contrast, copper, zinc, and iron were present at concentrations below their respective permissible limits, with copper at 0.56 mg/L against 2.0 mg/L, zinc at 1.80 mg/L against 5.0 mg/L, and iron at 4.65 mg/L against 5.0 mg/L [13]. Although these three metals did not exceed regulatory thresholds, their continuous discharge into the environment remains a concern owing to the potential for long-term accumulation in receiving soils and water bodies.

The elevated chromium concentration is most plausibly attributable to the extensive use of chromium-based mordants and dyes in the dyeing and printing processes that characterise the Bagru textile cluster [7]. Chromium compounds are widely employed to fix dyes onto fabrics and to impart colour fastness, and inadequate treatment of spent dye baths results in their direct release into the effluent stream. The presence of lead and cadmium at concentrations exceeding permissible limits is likely linked to the use of metal-based pigments, dye stabilisers, and chemical additives employed in textile production processes [8]. Nickel contamination may originate from the use of nickel-containing catalysts and metal complex dyes. The

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physicochemical characterization of the wastewater further corroborated the presence of a heavily polluted effluent stream, with elevated electrical conductivity, total dissolved solids, chemical oxygen demand, and biological oxygen demand values indicating high concentrations of dissolved salts, organic matter, and industrial pollutants [12]. These findings demonstrate that the untreated or partially treated textile effluents from the Bagru industrial area possess considerable pollution potential for agricultural soils, groundwater quality, and the food chain [9].

Table 1. Heavy Metal Concentration in Textile Wastewater and Comparison with WHO Permissible Limits

Metal	Concentration (mg/L)	WHO Limit (mg/L)	Exceedance Factor
Cr	1.95	0.1	19.5×
Pb	0.82	0.05	16.4×
Cd	0.09	0.01	9.0×
Cu	0.56	2.0	Below limit
Ni	0.73	0.2	3.65×
Zn	1.80	5.0	Below limit
Fe	4.65	5.0	Below limit

The bar chart presented in Figure 1 provides a visual comparison of the measured heavy metal concentrations against the corresponding WHO permissible limits. The graphic clearly illustrates the pronounced exceedances for chromium, lead, cadmium, and nickel, while copper, zinc, and iron remain within acceptable bounds. The magnitude of the chromium exceedance is particularly striking and underscores the urgent need for effective treatment interventions.

3.2. Heavy Metal Accumulation in Agricultural Soils

The analysis of agricultural soil samples revealed that heavy metal concentrations in wastewater-irrigated soils were substantially higher than those in control soils irrigated by tube wells. Chromium was detected at 92 mg/kg in wastewater-irrigated soil compared with 36 mg/kg in control soil, representing approximately a two-and-a-half-fold enrichment [11]. Lead was present at 65 mg/kg against 19 mg/kg in controls, cadmium at 3.8 mg/kg against 0.9 mg/kg, copper at 52 mg/kg against 24 mg/kg, nickel at 49 mg/kg against 18 mg/kg, zinc at 98 mg/kg against 42 mg/kg, and iron at 16,800 mg/kg against 14,100 mg/kg in control soils [14]. The consistent elevation of all seven metals in wastewater-irrigated soils relative to controls provides compelling evidence that long-term irrigation with textile effluents is the principal driver of heavy metal accumulation in these agricultural lands.

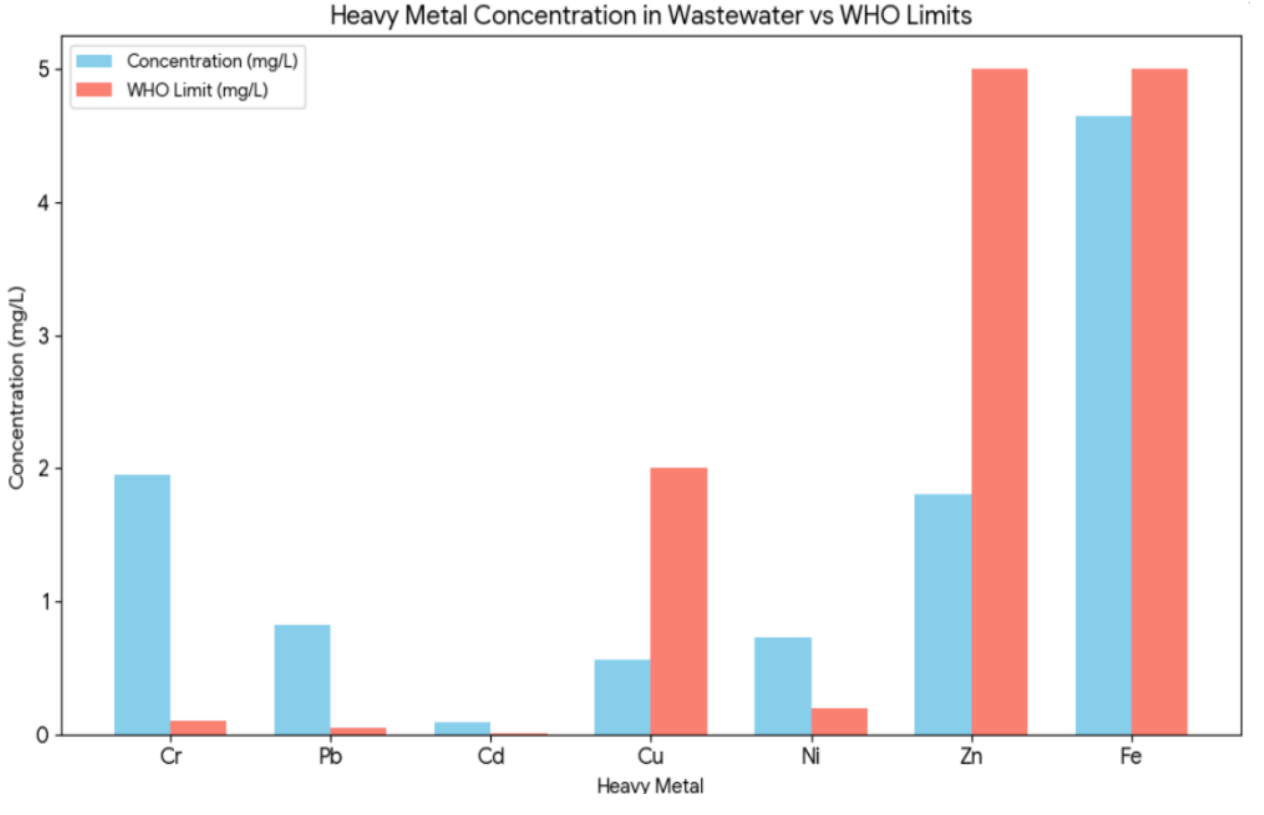

Fig. 1. Comparative representation of heavy metal concentrations in textile wastewater against WHO permissible limits.

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The highest enrichment factors were observed for cadmium and lead, which exhibited approximately four-fold and three-and-a-half-fold increases over control values, respectively. Although cadmium was present at a relatively low concentration in the wastewater (0.09 mg/L), its accumulation in soil is particularly concerning owing to its high toxicity, long environmental persistence, and propensity for uptake by crops [15]. Chromium, which was present at the highest concentration in wastewater among the toxic metals, showed substantial accumulation in soil, consistent with its widespread use in dyeing and mordanting operations. Iron was present at the highest absolute concentration in both irrigated and control soils, reflecting its natural abundance in the sandy loam to loam soils of the region, yet the difference between irrigated and control soils (2,700 mg/kg) indicates an anthropogenic contribution superimposed upon the geological background [18]. The observed differences between wastewater-irrigated and control soils were statistically significant at the 95% confidence level, supporting the conclusion that textile effluents constitute a substantial source of heavy metals in the agricultural environment.

Table 2. Heavy Metal Concentration in Agricultural Soils Irrigated with Textile Wastewater and Control Soils

Metal	Wastewater Irrigated Soil (mg/kg)	Control Soil (mg/kg)	Enrichment Factor
Cr	92	36	2.56
Pb	65	19	3.42
Cd	3.8	0.9	4.22
Cu	52	24	2.17
Ni	49	18	2.72
Zn	98	42	2.33
Fe	16,800	14,100	1.19

Figure 2 presents a side-by-side comparison of heavy metal concentrations in wastewater-irrigated and control soils. The chart graphically demonstrates the consistent enrichment of all metals in the irrigated soils, with cadmium and lead showing the most pronounced relative increases. The dominance of iron in both soil categories is visually apparent, although the absolute difference between irrigated and control soils remains environmentally significant.

3.3. Discussion of Heavy Metal Contamination in Textile Wastewater

The results of the present investigation establish that textile dye wastewater from the Bagru industrial area is severely polluted with toxic heavy metals and exhibits poor physicochemical quality [1]. The concentrations of chromium, lead, cadmium, and nickel exceeded the permissible limits recommended by the World Health Organization, indicating a high level of environmental pollution and a potential threat to public health [10]. These elevated concentrations are primarily attributable to the widespread application of metal-based dyes, mordants, pigment dyes, and chemical auxiliaries in textile dyeing and printing operations [3]. The high values of electrical conductivity, total dissolved solids, chemical oxygen demand, and biological oxygen demand further indicate the presence of significant quantities of dissolved salts, organic matter, and industrial pollutants in the effluent stream [5]. The continuous discharge of untreated or partially treated textile effluents into nearby drains and irrigation channels poses a direct threat to surface water, groundwater, and agricultural lands [6]. These findings highlight the inadequacy of existing wastewater management systems in the study area and underscore the need for effective effluent treatment infrastructure and systematic environmental monitoring to mitigate heavy metal pollution [4].

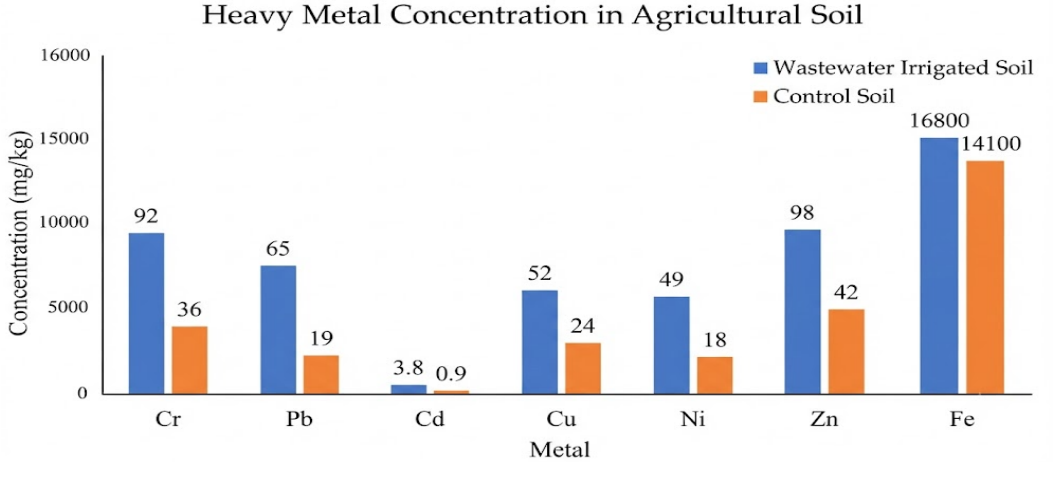

Fig. 2. Comparative representation of heavy metal concentrations in wastewater-irrigated and control agricultural soils.

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The physicochemical parameters measured in the wastewater merit particular attention because they influence the mobility and bioavailability of heavy metals in receiving environments. Elevated electrical conductivity and total dissolved solids reflect high concentrations of dissolved salts, which can alter soil osmotic potential and affect nutrient uptake by crops [17]. High chemical oxygen demand and biological oxygen demand values indicate substantial organic loading, which upon decomposition can create anaerobic conditions in receiving waters and soils, potentially enhancing the solubility and mobility of certain heavy metals [19]. The combination of high organic load and elevated heavy metal concentrations creates a synergistic pollution burden that is particularly challenging to remediate through conventional treatment approaches [2].

3.4. Discussion of Heavy Metal Accumulation in Agricultural Soils

The analysis of agricultural soil samples demonstrated that heavy metal levels in wastewater-irrigated soils were significantly higher than those in tube-well irrigated control soils [11]. This finding confirms that long-term application of untreated or partially treated textile effluents has resulted in the gradual accumulation of toxic metals in the soil profile [7]. The highest enrichment was observed for chromium, which is extensively used in textile dyeing, printing, and mordanting processes [8]. Elevated concentrations of lead and cadmium were also detected, likely originating from pigments, dye stabilisers, and various chemical additives employed in textile production [9]. Copper, nickel, zinc, and iron also showed significant increases in wastewater-irrigated soils, suggesting ongoing deposition from repeated irrigation events [12]. These heavy metals may eventually modify soil physicochemical characteristics, reduce microbial activity, and decrease nutrient availability, thereby adversely affecting soil fertility and crop productivity [13]. Heavy metal pollution also poses a continuing threat to the uptake of these elements by agricultural produce, creating risks for both environmental and human health [14]. These results emphasise the importance of continuous monitoring of wastewater-irrigated soils and the adoption of sustainable wastewater management practices [15].

The enrichment factors calculated for the study area provide insight into the relative contribution of anthropogenic versus geogenic sources. Cadmium exhibited the highest enrichment factor at 4.22, followed by lead at 3.42, nickel at 2.72, chromium at 2.56, zinc at 2.33, copper at 2.17, and iron at 1.19 [16]. The relatively low enrichment factor for iron reflects its predominantly geogenic origin, with the anthropogenic contribution representing a smaller fraction of the total soil burden. In contrast, the elevated enrichment factors for cadmium, lead, and chromium indicate substantial anthropogenic inputs from textile processing activities. These findings are consistent with those reported by other researchers investigating heavy metal contamination in textile-industrial regions of Rajasthan and elsewhere [18, 19].

3.5. Environmental and Agricultural Implications

Heavy metal contamination of agricultural soils produces significant environmental and agricultural consequences, particularly in areas where untreated industrial wastewater is routinely used for irrigation [1]. Elevated concentrations of chromium, lead, cadmium, nickel, and other metals can adversely affect soil microbial communities responsible for organic matter decomposition, nutrient cycling, and the maintenance of soil fertility [2]. Heavy metal accumulation also alters soil physicochemical properties, leading to reduced nutrient availability and negative impacts on plant growth and crop production [3]. Furthermore, there exists the potential for heavy metal uptake by crop roots and translocation to edible plant parts, thereby introducing these toxic elements into the human food chain [4]. Excessive intake of contaminated plant-based foods can cause serious health problems including kidney damage, neurological disorders, liver dysfunction, and carcinogenic effects [5]. Groundwater contamination may also occur through leaching from polluted soils, leading to deterioration of water quality [6]. These environmental consequences reveal the necessity for sustainable wastewater management, frequent monitoring of soil and water quality, and the implementation of effective measures to control water pollution in order to protect agricultural productivity, ecosystem health, and public health in the Bagru industrial area [7].

The soil quality deterioration observed in this study, manifested as altered pH, increased electrical conductivity, and reduced fertility, has direct implications for agricultural sustainability in the region [8]. Changes in soil pH can affect the mobility and bioavailability of heavy metals, with acidic conditions generally increasing metal solubility and plant uptake [9]. Increased electrical conductivity indicates the accumulation of soluble salts, which can impair seed germination and crop growth [10]. Reduced soil fertility, reflected in decreased nutrient availability, directly threatens crop yields and the economic viability of farming in the affected area [11]. These interrelated effects create a cycle of declining soil health and agricultural productivity that can only be reversed through concerted management interventions [12].

The findings of this study underscore the critical need for a comprehensive environmental management approach to address heavy metal contamination in the Bagru industrial area [13]. The indiscriminate discharge of effluents from textile industries into adjacent agricultural lands demonstrates the necessity for the installation and effective operation of effluent treatment plants to ensure that industrial

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discharges meet ecological norms before release [14]. Regular monitoring of wastewater, agricultural soils, groundwater, and crop quality is essential to identify contamination trends and enable timely corrective actions [15]. Moreover, compliance with effluent discharge standards depends on the rigorous enforcement of environmental regulations by pollution control authorities [16]. Agricultural practices that utilise alternative water sources or appropriately treated wastewater for irrigation should be encouraged to reduce heavy metal accumulation in soils [17]. Public awareness programmes and capacity-building initiatives can help educate industry operators and communities about the environmental and health impacts of heavy metal contamination [18]. These management measures, implemented collectively, will help maintain soil fertility, protect groundwater resources, improve agricultural productivity, minimise ecological degradation, and safeguard human health, thereby contributing to long-term environmental sustainability in the Bagru industrial area [19].

4. CONCLUSION

The present study confirms that textile dye wastewater generated from the Bagru industrial area constitutes a significant source of heavy metal pollution in the surrounding environment. The analysis demonstrated that concentrations of chromium, lead, cadmium, and nickel were substantially elevated in the wastewater, exceeding the permissible limits prescribed by the World Health Organization. Furthermore, the concentrations of these metals were significantly higher in agricultural soils exposed to wastewater irrigation compared with control soils irrigated by tube wells. This accumulation of toxic metals is primarily attributed to the long-term application of untreated or partially treated effluents, resulting in the gradual deterioration of soil quality and persistent environmental contamination. The elevated values of physicochemical parameters including electrical conductivity, total dissolved solids, chemical oxygen demand, and biological oxygen demand further indicate the poor quality of textile wastewater and its potential to adversely affect the agricultural ecosystem. The accumulation of heavy metals in soils over time can diminish soil fertility, interfere with microbial activity, facilitate the uptake of metals by crops, impair groundwater quality, and create health risks for humans through the food chain. From the results of this study, it is evident that developing an effective wastewater management system in the Bagru industrial area is urgently required. The installation and efficient operation of effluent treatment plants, frequent monitoring of effluent and soil quality, enforcement of environmental regulations, and adoption of sustainable irrigation practices are essential to reduce heavy metal pollution. These measures will help mitigate soil degradation, conserve water resources, and promote sustainable environmental management in textile-producing regions.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

No funding.

Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Authors' contributions

All authors contributed equally to this work,

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