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Assessing pollution vulnerability in groundwater: A case study of Kala Shah Kaku industrial complex

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ABSTRACT

Various factors, such as industrialization, population growth, and urbanization, have caused water quality and availability to decline worldwide, resulting in water crises in many regions and millions of annual deaths from water-related diseases. The study aimed to assess the groundwater quality in Kala Shah Kaku, an industrial area in central Punjab, Pakistan. Groundwater samples from six locations were analyzed for physical and chemical parameters and heavy metals. The results revealed that Kala Shah Kaku's groundwater is unsuitable for drinking due to exceeding the physical and chemical parameters range. The study identified industrial effluents from nearby industries as the primary source of pollution in the area's groundwater. These findings emphasize the urgent need for remedial measures to address industrial pollution and protect groundwater resources in Kala Shah Kaku.

Key words: groundwater contamination, heavy metals, industrial effluent, industrialization, physical–chemical parameters

HIGHLIGHTS

- Water scarcity threatens human survival.
- Global water crisis and health impact.
- Groundwater quality in Kala Shah Kaku.
- Industrial effluents as major pollutants.
- Importance of remedial measures.

1. INTRODUCTION

Water is the essential element for the survival of every organism on Earth. Approximately 71% of the Earth's surface is composed of water, out of which approximately 97% is sea water and 2.5% is fresh water, from which groundwater comprises 0.63% (Noortheen *et al.* 2016; Miletto *et al.* 2017). Despite its smaller proportion, groundwater is significant in sustaining life on Earth (Lautze & Manthrithilake 2014). Due to the increasing population and increasing water requirements for this growing population, groundwater resources have been under great stress for several decades in many global geographies (WHO 2010). In present times, due to industrialization, high exponential growth of the population, urbanization and increasing demands of the people, water quality, quantity, and availability are severely being deteriorated (Snel 2004; Anwar *et al.* 2024). According to an estimate, about 7.4 billion people face water crises in terms of quality, quantity, and lack of access to proper sanitation in the near future (Rasul 2015).

World Health Organization – WHO (2011) highlights the global issue of inadequate sanitation and water-related diseases, with 2.5 billion lacking proper sanitation and 6 million annual deaths. Groundwater is the sole water source in countries like Malta, Denmark, and Saudi Arabia (Vyas *et al.* 2018). Some European cities rely on it strictly for domestic use (Brindha & Schneider 2019). In Asia, 80% of the population lacks sanitation facilities, resulting in an accumulation of excessive fecal coliform bacteria in Asian rivers and contributing to waterborne diseases (Lal 2008). These bacteria and pathogenic microbes enter the drinking water, thus leading to waterborne diseases. Groundwater contamination, caused by various factors, is a significant problem in Asia, Latin America, and Africa, often exacerbated by industrial effluent discharge in rapidly industrializing areas

(Egboka *et al.* 1989; Tellman *et al.* 2018). Li *et al.* (2014) assessed groundwater pollution and its impact on human health in an industrial area, in North West China. The results of the water quality assessment revealed that half of the collected groundwater samples were of poor quality and thus required proper treatment before human consumption. Groundwater contamination mainly results from industrial waste, domestic waste, agricultural activities, and mining (Khan *et al.* 2013).

The concentration of heavy metals in groundwater exceeds the standard limits in various cities of Pakistan. It is estimated that only 51% of the population of Pakistan has access to safe drinking water and it is reported that 60% of the children die each year due to polluted water (Soomro *et al.* 2011) The industries that largely contribute in groundwater pollution are mainly the leather industries, textile and sugar industries, petrochemicals, and tanneries. The effluents that are discharged from these industries contain large amounts of toxic metals such as chromium, copper, lead, manganese, iron, arsenic, and nickel. Punjab is the most populous province of Pakistan, with abundant fertile land, various climatic conditions, and ample freshwater resources (Mazhar *et al.* 2021, 2022; Perveen & Haque 2023). Punjab faces serious sanitation issues, including mixed sewer pipelines and open drains, leading to pollution from temporary wastewater disposal stations (Soomro *et al.* 2011; Asolekar & Gopichandran 2012). In three major cities of Pakistan, including Karachi, Sialkot, and Kasur, the Leather tannery industry is a significant industrial activity where about 600 tanneries are concentrated. The industrial discharge from these zones results in groundwater contamination, resulting in various waterborne diseases such as cholera, dysentery, and skin and eye allergies. Sindh Industrial Estate and Korangi industrial estate in Karachi have no proper wastewater treatment plants. They dispose of their waste containing oil and heavy metals directly into the nearby water bodies and harbor. It is estimated from the analysis that due to the high toxicity of heavy metals in water, there is a decrease in shrimp and fish production.

Lahore, the provincial capital and Pakistan's second-largest city, is expected to reach a population of 22 million by 2025, but it faces declining groundwater levels (Rana & Bhatti 2018; Siddiqui & Siddiqui 2018; Fida *et al.* 2022; Tariq & Mushtaq 2023). While there are numerous industrial complexes in Lahore, there is a lack of appropriate research studies regarding groundwater quality conducted in these regions. The present research focuses on the Kala Shah Kaku industrial complex. The study's core objectives are: (i) analyzing groundwater samples through laboratory testing, (ii) assessing the impact of industrial effluents on groundwater quality, and (iii) recommending remedial measures to reduce groundwater contamination.

2. DATA AND METHODS

2.1. Study area

Kala Shah Kaku, located 17 km from Lahore, is known as an 'Industrial Complex', hosting many manufacturing industries, including metals, paper, leather, textiles, printing, ceramics, and chemicals. This area was established without the proper planning of the urban planners. It has a flat topography with semi-arid climatic conditions. In the beginning, the Sahgal group of companies established their industrial complex in the area. Simultaneously, colonies were developed to start with everyday activities. Many large-scale popular industries are in the Kala Shah Kaku Industrial Zone. This industrial complex is most vulnerable to environmental pollution due to massive industrialization and increasing urbanization. In addition, not only is the environment under threat but the groundwater quality is also declining gradually.

The level of groundwater contamination becomes more acute as the wastewater being discharged from various industries directly fall into the Deg Nallah which ultimately becomes part of River Ravi. Moreover, the municipal wastewater gets mixed up with the industrial discharge thus polluting the sewage and making it unfit for irrigation purposes. The pollution vulnerability of groundwater and surface bodies due to untreated direct discharge of industrial effluents has become a great matter of concern. Furthermore, no significant studies have been carried out to investigate the prevailing level of contamination to anticipate its future consequences. Refer to Figure 1 for details on the study area and site locations. This paper emphasizes that industries in the Kala Shah Kaku industrial complex discharge effluents into an unlined surface drainage system, leading to soil percolation and groundwater contamination, which is the primary water source for the local population. The area lacked urban planning and was selected for its strategic location in a flat, semi-arid region with alluvial terrain along the seasonal 'Nallah Deg' drain, which only carries water during the monsoon season.

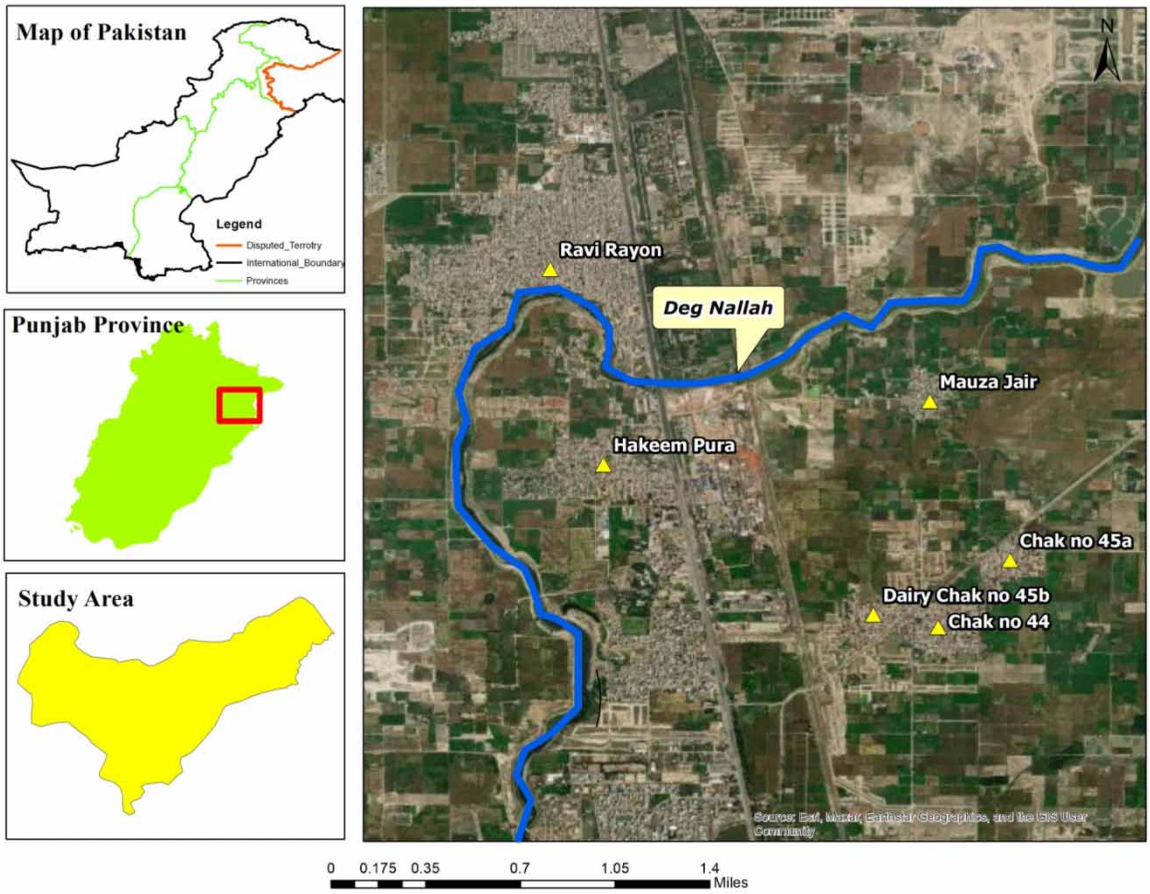

Figure 1 | Study area map. Yellow pin symbols denote the sample sites.

2.2. Sampling

A pilot study was carried out in the Kala Shah Kaku Industrial Complex and its surrounding areas to determine the industrial effluent discharge into the water bodies and the quality of groundwater. A total of six sample sites were selected for the research analysis. All these six areas were selected along the industrial zones of Kala Shah Kaku. For this purpose, six groundwater samples were collected from selected sample sites. Tube well water samples were collected, ranging from 75 to 80 m in depth. All the groundwater samples were collected in polyethylene sample bottles of size 500 ml and were further taken to the laboratory for testing.

2.3. Analytical methods and laboratory testing

The selected groundwater samples were tested for physical and chemical parameters. The preservation and analysis of samples were based on American Public Health Association (APHA) methods. Major cations like Ca^{2+}, Mg^{2+}, and Na^{+} were analyzed with ion chromatography (IC). Heavy metals were analyzed by atomic absorption spectrometry (AAS). IC and AAS measurements were analyzed at the Environmental Science Laboratory of Kinnaird College and the Soil and Water Testing Laboratory, Agriculture Department, Thokar Niaz Beg, Lahore. Particularly, HCO_3^- was calculated from the alkalinity and this was analyzed through titration with 0.01 M sulfuric acid in the laboratory immediately after receiving the samples from the sites. Table 1 summarizes the analytical methods and corresponding equipment used in this study.

3. RESULTS

3.1. Groundwater quality

The determination of the groundwater quality is based on its sustainability for drinking and domestic use. The criteria for this purpose are that the water should be low in hardness and should be free from all the hazardous toxic substances and sediments that are dangerous for health. In order to investigate the groundwater quality

Table 1 | Analytical methods and equipment's used for the analysis of water quality parameters

Parameters	Instruments	APHA reference method[a]	WHO standards	Standard value (S_i) (ug/mg)
Electric conductivity (EC)	EC meter (Eutech PC 510)	2510-A	1,000 μs/cm	300
Calcium (Ca^+) Magnesium (Mg^+)	(Ca–Mg) EDTA Titrimetric method	3500-CaB 3500-MgB	50 mg/l	200,000 100,000
Sodium (Na)	Flame photometer	3500-NaB	200 mg/l	200,000
Chloride (Cl)	Silver nitrate titration			1,000,000
Chromium (Cr)	Atomic absorption spectrometer (Buck Scientific)	APHA311B	50 μg/l	50
Cadmium (Cd)	Atomic absorption spectrometer	APHA311B	30 μg/l	3
Lead (Pb)	Atomic absorption spectrometer	APHA311B	10 μg/l	10
Nickel (Ni)	Atomic absorption spectrometer	APHA311B	20 μg/l	20

[a]APHA reference methods are in line with Alawadi *et al.* (2023). S_i values are obtained from Boum-Nkot *et al.* (2023).

samples were collected from the study area. The spatial distribution and the concentrations of various physical and chemical parameters of groundwater samples collected from the Industrial Complex of Kala Shah Kaku and its surrounding area are presented respectively in the form of Interpolated Distance Weighted Maps. In order to investigate the groundwater quality, samples were collected from the study area. A single sampling strategy was adopted to cover six major zones surrounding the Industrial Complex. This method was adopted as it is easy to design and administer.

3.2. Distribution of physical and chemical parameters

Table 2 shows the concentration of physical and chemical parameters along the sample sites which were found to be within the permissible limits of WHO except that of electric conductivity which was found to be exceeding in residential areas of Hakeem Pura and Ravi Rayon. These residential zones were surrounded by the major industrial units along the study area including a chemical complex which is the major producer of acetate yarn (cloth, fiber), private chemical industries (caustic soda, chlorine, hydrochloric acid, sulfuric acid, sodium hydrochloride, and zinc sulfate) and a paint industry which is a major manufacturer of paints and varnishes. The values of EC ranged from 805 to 1,908 μs/cm. Some of the values of groundwater samples exceeded the prescribed range of WHO (1,000 μs/cm). The maximum value of EC was found at Ravi Rayon, which was 1,908 μs/cm. It is worth mentioning that the above-mentioned two private chemical industries lie in a close proximity to Ravi Rayon and Hakeem Pura.

Table 2 | Groundwater quality of the sampling sites of Kala Shah Kaku Industrial Complex (here TB, HP, and MP stand for tube well, hand pump, and motor pump, respectively)

Sample_site	Source	EC (μs/cm)	Ca^{2+} (mg/l)	Mg^{2+}	Na^+ (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	Cr (μg/l)	Cd (μg/l)	Pb (μg/l)	Ni (μg/l)
Chak No 45 (b)	TB	1,025	45	17	5.0	6.4	3.4	52	34	5	19
Chak No 44	HP	1,108	50	11	5.2	5.8	3.1	23	12	8	8
Chak No 45 (a)	HP	926	45	12	3.3	5.6	2.9	51	36	2	18
Mauza Jair	MP	805	60	8	4.1	5.2	1.6	42	34	9	12
Ravi Rayon	TB	1,908	84	32	12.4	7.8	8.8	120	58	15	38
Hakeem Pura	MP	1,320	88	30.5	6.3	8.6	3.8	180	74	12	32
WHO standards		**1,000**	**75**	**30**	**200**			**50**	**30**	**10**	**20**

The results of major cations including calcium and magnesium values ranged from 45 to 88 mg/l and 8 to 32 mg/l, respectively. Groundwater samples collected from Ravi Rayon and Hakeem Pura were found to have exceeding values of WHO standards (75 and 30 mg/l for calcium and magnesium, respectively. Similar findings were concluded by Sharma & Rout (2011) in which calcium values ranged 18.71–82.5 mg/l while magnesium values ranged from 10.34 to 28.98 mg/l. Chlorides of calcium and magnesium mainly contribute to hardness of water, thus making it unhealthy for consumption.

The values of sodium are shown ranging from 3.3 to 12.4 mg/l. The maximum value of Na was found at Ravi Rayon, which was 12.4 mg/l, while the minimum value was found at Chak No 45 (a), which was 43.3 mg/l. The values of bicarbonate are shown ranging from 5.2 to 8.6 mg/l. All groundwater sample values were within the prescribed range of WHO (125–350 mg/l). The maximum value of bicarbonates was found at Hakeem Pura, which was 8.6 mg/l, while the minimum value was found at Mauza Jair, which was 5.2 mg/l. The maximum value of chloride was found at Chak No 45 (a), which was 3.4 mg/l, while the minimum value was found at Mauza Jair, which was 1.6 mg/l.

3.3. Heavy metal concentration along sample sites

Figure 2 shows the spatial distribution of Cr, Cd, and Pb, respectively. The highest chromium levels were detected in Hakeem Pura due to its proximity to three industrial zones. Ravi Rayon also had elevated chromium levels due to nearby industries, while Chak 44 and Muaza Jair had the lowest concentrations, being farther from industrial areas. Excessive Cr concentration was due to increased infiltration of water and leachate from dumpsites along with the disposal of metal products. These observations are similar to the findings of Edokpayi *et al.* (2018). Similarly, the maximum lead and nickel concentrations were found in Ravi Rayon and Hakeem Pura, both surrounded by industrial zones. Chak 44 and Dairy Chak No 45 (b) had the lowest levels, away from industrial areas. Cadmium is a toxic metal primarily sourced from mining, smelting, and various industrial applications, including plastics, pigments, and batteries. Nickel shows a peak value of 38 μg/l in Ravi Rayon and shows the lowest value of 8 μg/l in Chak 44.

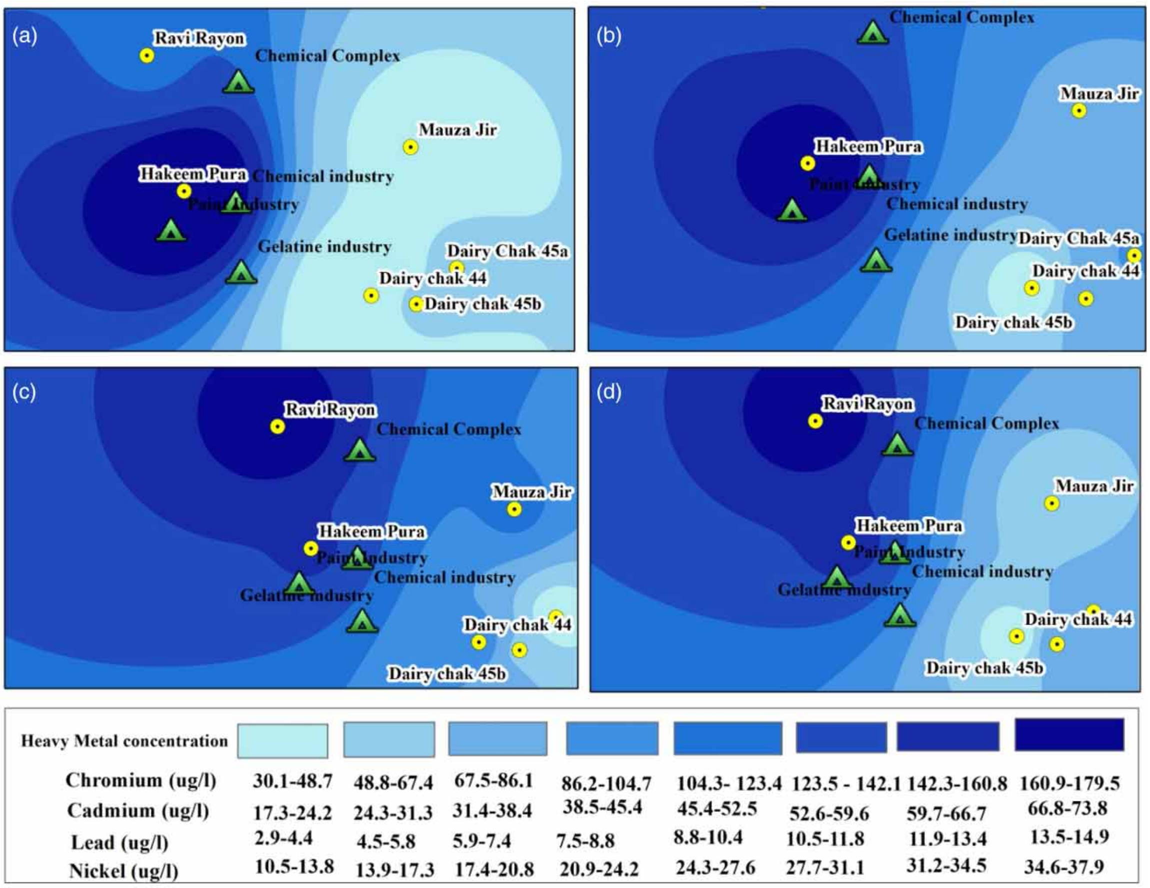

Figure 2 | Spatial concentration of heavy metals along the study area. (a) Chromium, (b) Cadmium, (c) Lead, and (d) Nickel.

4. DISCUSSION

The study on groundwater quality in the Industrial Complex of Kala Shah Kaku and its surrounding area highlights several crucial findings regarding water contamination and its potential health implications. The investigation focused on physical and chemical parameters, including electrical conductivity (EC), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), bicarbonate (HCO_3), chloride (Cl), chromium (Cr), cadmium (Cd), lead (Pb), and nickel (Ni). The results indicate that while most parameters fall within the World Health Organization's (WHO) permissible limits, elevated levels of EC were observed in residential areas near major industrial units. These industrial units mainly consist of chemical industries. It is evident from the results that the industries, especially chemical industries have a large impact on the groundwater quality in their proximity. Table 3 presents the water quality parameters of the four major industries, which are marked in Figure 2. These values are obtained from various literature (Ahmad *et al.* 2012; Tariq *et al.* 2020), and online resources (https://www.scribd.com/document/693493233/No, last access June 20, 2024, and https://doi.punjab.gov.pk/system/files/DPIS_Sheikhupura_0.pdf, last access June 20, 2024).

Table 3 | Groundwater characteristics of major manufacturing industries located in Kala Shah Kaku Industrial Complex

Industry	TDS (mg/l)	pH	Suspended solids (mg/l)	Settleable solids (mg/l)	Discharge (m^3/d)
Chemical industry	1,245	11.5	730	5.0	3,000
Chemical complex	1,100	5	371–8,033	6–17	6,300
Paint industry	1,054	7.4	4,600	60–200	7,400
Gelatine industry	980	6.5	1,600	3–10	16,000

A recent study having similar industrial conditions (Rashid *et al.* 2023) also revealed the exceeded values of EC which ranged between 1,200 and 1,500 μs/cm. Similar statistics were reported in research conducted by Popoola *et al.* (2019) where EC values of 1,190.0 μs/cm were found to exceed permissible levels in groundwater samples present along industrial sites. Industries were found to be a significant source of groundwater contamination. Positive loadings EC (399–1,700 μs/cm) were observed by Kumar *et al.* (2023) in Patna Region of Bihar. TDS and EC were determined to be greater than the limit range of WHO, which are significant in terms of salinity. The increased salinity was due to the dissolution of soluble salts and minerals into groundwater, evaporation of groundwater and anthropogenic activities (Zhai *et al.* 2022). In addition to EC, the concentration of heavy metals in drinking water is also directly influenced by nearby industries. Rahman *et al.* (2020) revealed that the spatial concentration of heavy metals was found to be high along the North East side of the Meghna Ghat industrial area, Bangladesh where industries were located. The highest concentration of Pb (0.4008 mg/l) was found along the salt industry. The highest chromium values (0.121 mg/l) were found along the coal industry. The cadmium values exceeded (0.016 mg/l). Egun (2010) reported that industrial effluents are among the chief sources of water pollution. According to Reza & Singh (2010), the basic man-made sources of heavy metal pollution are the disposal of partially treated or untreated effluents into nearby water bodies from various industries.

This suggests a potential correlation between industrial activities and groundwater contamination, with EC exceeding WHO standards, consistent with previous research findings. Furthermore, the presence of heavy metals such as chromium, cadmium, lead, and nickel, particularly in areas proximal to industrial zones, underscores the impact of industrial effluents on water quality.

The study's findings emphasize the urgent need for effective pollution prevention strategies, stakeholder involvement, and stricter regulations to mitigate groundwater contamination. To address this issue, the community should implement water pollution prevention strategies, focus on removing pollutants at the source, and encourage industries to recycle their waste rather than dispose of it directly into water bodies to improve groundwater quality standards. Some proposed remedial measures to improve groundwater quality are:

- Corporate approach with stakeholder participation for groundwater quality protection.
- It requires emphasis on practical performance alongside theoretical work.
- Launch effective awareness programs through media and NGOs.
- Adopt a sustainable development strategy with pollution control and wastewater reduction.
- Enforce strict rules to prevent industrial and municipal wastewater discharge.

- Develop proper solid waste management strategies to prevent water body pollution.
- Implement regular monitoring and enhance staff, technology, and laboratory resources.
- To address environmental concerns, promote water conservation in water-intensive industries like textiles, leather, sugar, paper, and pulp.

Addressing groundwater contamination requires a comprehensive approach, including pollution prevention strategies, stakeholder involvement, strict regulations, sustainable development, and effective awareness programs.

5. CONCLUSION

Groundwater is a significant source of drinking water in Kala Shah Kaku, but research analysis indicates that its quality is unfit for consumption. This contamination primarily results from untreated effluents discharged by nearby industries, particularly in areas like Hakeem Pura and Ravi Rayon. These industrial activities lead to high levels of electric conductivity and increased metal content in the groundwater, making it unsuitable for drinking.

The key findings of the research are as follows:

(1) The physical analysis of groundwater revealed a higher concentration of EC along the Hakeem Pura and Ravi Rayon industrial units. These exceeding values of EC are the major determinants of salinity.
(2) The results of major anions and cations revealed the exceeding values of (Ca^{2+} and Mg^{2+}) which are the major determinants of hardness in water thus making it unfit for human consumption, whereas Na^+, Cl^-, and HCO_3^2 were found to be within the permissible limit of WHO standards.
(3) The spatial concentration of the heavy metals revealed that sites located near the chemical industrial area (Hakeem Pura and Ravi Rayon) were more vulnerable to heavy metal contamination while the sites located far from the industrial area (Mauza Jair, Chak No 44, Chak No 45 (a), and Chak No 45 (b)) were less polluted.

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DATA AVAILABILITY STATEMENT

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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