ISSN: 0973-4929, Vol. 20, No. (1) 2025, Pg. 368-384

Current World Environment

www.cwejournal.org

Impact of Industrial Effluents on Groundwater Quality in Semi-Arid Regions: A Case Study from RIICO Industrial Area in Eastern Rajasthan, India

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Abstract

As awareness of the importance of drinking water for public health and the effect of water quality on aquatic life increases, the assessment of water quality has become more essential. This study focused on the investigation of the impact of industrial effluents on the groundwater quality of the RIICO industrial area of Dholpur district, Eastern Rajasthan, India. In this study analysis of Physico-chemical parameters and heavy metal ions {Fe, Cu, Zn, Mn, Pb, Cd, Cr, Hg} in groundwater samples, collected from selected different locations of RIICO industrial area of Dholpur were done during pre-monsoon, monsoon and post-monsoon seasons of three years (2021-2024). The physico-chemical parameters include pH, water temperature, color, electrical conductivity {EC}, total alkalinity {TA}, turbidity, total hardness {TH}, chloride, sulphate, fluoride, sodium, potassium, calcium, magnesium, dissolved oxygen {D.O.}, nitrate, total dissolved solids {T.D.S.}, and chemical oxygen demand {COD}. The result of this study reveals that most of the physico-chemical parameters {total alkalinity, total hardness, fluoride, nitrate, TDS and EC} and heavy metal ion {Fe, Cd and Pb} obtained surpassing than the permissible limit of WHO and BIS. Seasonal variations of this study showed that higher concentrations of contaminants were observed in the post rainfall season. So due to effect of industrial effluents the groundwater of this industrial area is contaminated, so it is almost unfit for human consumption (drinking) but it is useful for irrigation and domestic purposes. In addition, the results suggest that there is an urgent need for better effluent treatment systems and more stringent monitoring regimes in these industrial zones in order to protect groundwater resources and public health.

Article History
Received: 05 December 2024
Accepted: 25 February 2025

Keywords
Groundwater Contamination;
Physico-Chemical Parameters;
Public Health;
Heavy Metal Ion.

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Doi: https://dx.doi.org/10.12944/CWE.20.1.28

Introduction

Environmental pollution in general and water contamination in particular are among the most important environmental problems of our time. The era of rapid industrialization and urban technological revolution characterized by unprecedented exploitation of natural resources is responsible for extreme environmental degradation in the USA and Europ.[1] India has plentiful groundwater, and almost 53% of population depends on it for drinking water and 81% of rural population is dependent on it.[2]

In the area with intensive industrial activities and shallow groundwater table, the problem of groundwater quality deterioration is becoming especially acute. The RIICO {Rajasthan State Industrial Development and Investment Corporation} industrial area of Dholpur district in Eastern Rajasthan are presented as a critical case study of this phenomenon. Due to rapid industrial growth in this area different industries like Dairy plants, Manufacturing units, Chemical plants and Oil mills releasing large number of industrial effluents.

Recent studies have shown that heavy metals, hazardous compounds and other toxic substances in industrial effluents are now posing serious groundwater quality threats.[3] However, industrial activities in Rajasthan now contaminate groundwater resources making this an additional challenge to sustainable development and public health in the context of Rajasthan, where water scarcity is already of high concern.[4]

Several studies have been reported about the impact of industrial effluents on the quality of groundwater in Rajasthan. The groundwater of the state is high in fluoride and other contaminants, It has also been established that the threat to human health posed by contaminated groundwater in the arid and semi-arid regions of the state is on the rise.[5,6]

The study area suffers from this problem particularly because of poor wastewater treatment infrastructure and improper disposal practices that have allowed industrial effluents to percolate into ground water aquifers. Previous investigations of similar industrial zones have shown such contamination to have long term environmental and health impacts.[7] Groundwater that contains heavy metals and other toxic compounds not only affect drinking water quality but also enter the agricultural productivity and soil health.[8]

Despite the growing concern over groundwater contamination in industrial area, there has been limited comprehensive research focusing specifically on the RIICO industrial area of Dholpur district. This study seeks to address the existing research gap by undertaking a comprehensive evaluation of groundwater quality in these areas, with particular emphasis on:

- Evaluating the concentration of various physico-chemical parameters in groundwater samples from different locations within the study area
- Analyzing seasonal variations in groundwater quality during the pre-monsoon, monsoon, and post-monsoon phases.
- Assessing the spatial distribution of contaminants and their relationship with industrial activities.
- Assessing the suitability of groundwater for potability and agricultural uses.
- Proposing mitigation measures to address groundwater contamination in these industrial zones.

This study will contribute to the existing knowledge base on industrial pollution of groundwater resources and offer valuable insights into industrial pollution of groundwater resources for the policymakers and environmental managers. In addition, the research will assist in designing targeted interventions to preserve groundwater resources in fast industrializing regions of Rajasthan.

With growing industrial development in this region and the rising concern for water security in Rajasthan, this investigation is particularly timely. Outcomes of the study will be important to develop strategies that can balance industrial growth with environmental protection and public health concerns.[9] This research is in line with the national efforts to enhance groundwater management and protect water resources from industrial contamination.[10]

Literature Review

Groundwater Contamination in Industrial Areas: A Global Perspective

In industrial area different industries are a major source of groundwater contamination worldwide. This problem has been shown to be becoming more serious in rapidly industrializing regions in recent studies. According to Jones (2021), worldwide 39174 m^3 of wastewater is generated each year, of which only 52% undergoes appropriate treatment. Consequently, huge quantities of untreated industrial effluents find their way into the groundwater systems.[11]

The composition and impact of industrial effluents are highly variable, related to industry type, and local geological conditions. In recent studies it was found that industrial wastewater discharge patterns in developing countries have upward trend, with hot spots mainly located in areas of rapid industrial growth. Zhang & others (2020) found that industrial structure, the degree of sector nationalization and environmental protection policies are important variables that explain regional variations in effluent discharge.[12]

Heavy Metal Contamination in Groundwater

Heavy metal contamination is one of the most serious threats for groundwater quality in industrial areas. It was found that our groundwater near industrial zones contains high levels of heavy metals iron {Fe}, manganese {Mn} and chromium {Cr} which account for 43% of all metals in water, as shown in a recent study. The study concluded that chromium contamination was responsible for the largest carcinogenic risk, contributing 95.45% of the total health risk in the industrial areas.[13]

Recent research's asserts that the geogenic sources contribute around 30.9% of groundwater pollution in case of developing nations, and anthropogenic sources comprising industrial activities account for 31.3%. They analysed 243 groundwater samples and found worrying levels of arsenic, manganese, lead and iron above WHO guidelines.[14]

Groundwater Quality Studies in Rajasthan

Several studies have specifically focused on groundwater contamination in Rajasthan's industrial areas. In recent research it was reported that elevated levels of heavy metals in groundwater samples from industrial zones, with particularly high concentrations of iron and copper and indicated that industrial activities significantly contributed to deteriorating groundwater quality.[7] In a comprehensive study of groundwater quality in Rajasthan's industrial regions by a researcher it was found that Fluoride contamination was prevalent in many industrial areas and heavy metals concentration exceeded permissible limits in 40% of samples.[5]

Industrial Impact on Groundwater in RIICO Areas

Studies specific to RIICO industrial areas have shown varying levels of contamination. Sheikh & others (2022) found significant levels of organophosphate pesticides in groundwater samples from industrial zones. It was reported that industrial effluents significantly impacted groundwater quality, though their impact varied during the COVID-19 pandemic period due to reduced industrial activity.[8]

Seasonal Variations in Groundwater Quality

Research has shown significant seasonal variations in groundwater contamination levels. This was observed that: Pre-monsoon periods showed moderate contamination levels, Dilution effects were observed during monsoon seasons and Contaminant concentrations typically peaked during post-monsoon period.[4]

Limitations in Current Research

Although the existing literature offers valuable insights into groundwater contamination in industrial regions, several knowledge gaps persist.

- Limited long-term studies tracking changes in groundwater quality over extended periods
- Insufficient research on the combined effects of multiple contaminants
- Lack of comprehensive studies specifically focusing on RIICO area of Dholpur (Rajasthan)
- Limited understanding of the relationship between industrial processes and specific contaminant profiles
- Need for more detailed investigation of seasonal variations in contamination patterns

Theoretical Framework

This study builds upon existing research methodologies while addressing identified gaps. The theoretical framework incorporates.

- Multiple parameter analysis for comprehensive groundwater quality assessment
- Seasonal variation analysis to understand temporal changes
- Risk assessment methods to evaluate potential health impacts

The literature review reveals a clear need for detailed investigation of groundwater contamination in RIICO industrial area of Dholpur district. This study is oriented to address the identified research gaps while building upon established methodologies and findings from previous studies.

Materials and Methods
Overview of the Study Area
Dholpur RIICO Industrial Area

Dholpur district, located in the north-eastern region of Rajasthan, located between 26.7235 northern latitude and 77.8837 eastern longitude and encompassing an area of 3,033 square kilometers, situated at an elevation of 183 meters above sea level. The study area is bounded by Agra district (Uttar Pradesh) to the northeast, Morena district (Madhya Pradesh) to the south, and Sawai Madhopur and Bharatpur districts to the west and north, respectively. The region experiences a dry climate with extreme temperatures in both summer and winter seasons. The Chambal River, flowing through the southeast, represents the only perennial water source in the district. RIICO industrial area of Dholpur is rapidly developing area and covers around 2.18 square kilometers area and there are many Dairy plants, Manufacturing industries, Oil mills and other type of industries are working regularly so due to geographical features and these working industries Government has allowed this area as a industrial area and almost 8400 people lives in this area and these people use this groundwater for fulfilment of their daily needs.

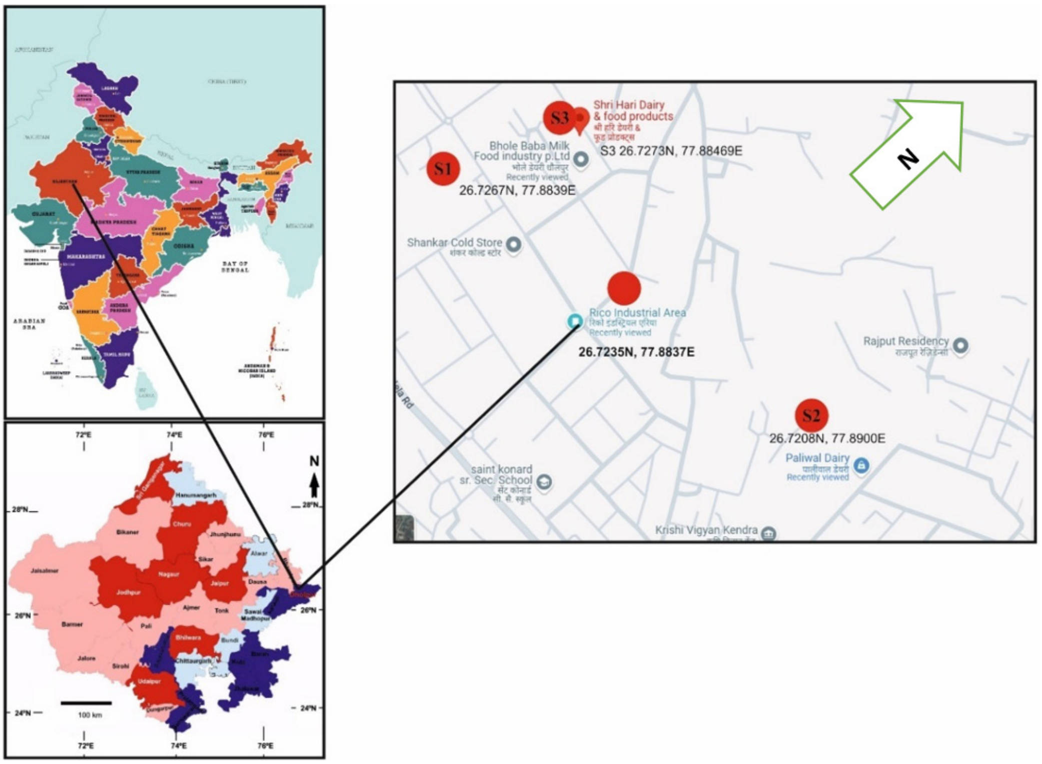

Fig. 1: Location of study area and sampling sites

Sampling Design and Collection
Sampling Locations

- Three sampling sites were selected across the Dholpur RIICO industrial area (26.7235N, 77.8837E) and these are named as S1, S2 and S3
- S_1 = Groundwater sample of nearby of Bhole Baba Dairy, Dholpur (26.7267N, 77.8839E)
- S_2 = Groundwater sample of nearby of Paliwal Dairy, Dholpur (26.7208N,77.8900E)
- S_3 = Groundwater sample of nearby of Hari Dairy, Dholpur (26.7273N,77.8846E)

These sampling points were chosen based on:
- Proximity to industrial units
- Groundwater usage patterns
- Accessibility and reliability of sampling
- Representative coverage of the study area

Sampling Period and Frequency

Samples were collected month-wise from the depth of 220 to 250 F of Borewell of over three years (2021-2024) during three distinct seasons.
- Pre-monsoon (March-June)
- Monsoon (July-October)
- Post-monsoon (November-February)

Sample Collection Procedure
- Water samples were collected in high-quality narrow-mouth screw-capped polypropylene bottles (2L capacity)
- Bottles were pre-cleaned with dilute nitric acid and rinsed with demineralized water
- Three rinses with sample water were performed before collection
- Samples were properly labeled with location, depth, source, and collection date
- Field parameters (pH, temperature) were measured in situ
- Samples were stored at 4°C during transport to the laboratory

Analytical Methods

Standard methods published by APH15 were used for determination of physico-chemical parameters which are following.

Physical Parameters
- Temperature: Measured using calibrated thermometer
- pH: Electrometric method (4500-H^+ B, APHA)
- Electrical Conductivity (EC): Conductivity meter (Method 2510 B)
- Total Dissolved Solids (TDS): Gravimetric method (1030 F)
- Turbidity: Nephelometric method (2130 B)

Chemical Parameters
- Total Hardness: EDTA titrimetric method (2340 C)
- Total Alkalinity: Titration method (2320 B)
- Chloride: Argentometric method (4500-Cl- B)
- Fluoride: Ion-selective electrode method (4500-F- C)
- Nitrate: Ion-selective electrode method (4500-NO_3-D)
- Sulphate: Turbidimetric method (4500-SO42- E)
- Sodium: Flame Emission Photometric method no (3500-Na-D)
- Potassium: Flame Emission Photometric method no (3500-K- D)
- Magnesium Hardness: EDTA Titration method (3500-Mg-E)
- Calcium Hardness: EDTA Titration method (3500-Ca-D)
- Dissolve Oxygen {D.O.}: Winkler-azide Method (4500-O-C)
- Chemical Oxygen Demand {C.O.D.}: Closed reflux titrametric method (5220- C)

Heavy Metals Analysis

The analysis of heavy metals was conducted using an Atomic Absorption Spectrophotometer {AAS} following the prescribed methodology 3111 {APHA}:
- Sample preparation: Acidification with concentrated HNO_3
- Filtration through 0.45 µm Millipore filter
- Analysis for Fe, Cu, Zn, Mn, Pb, Cd, Cr, and Hg

Statistical Analysis

Statistical analysis was carried out using SPSS-PASW 27.0 and Microsoft Excel 2022:-
- Descriptive statistics
- Correlation analysis

Data Interpretation and Visualization
- Seasonal variation analysis table through average values of all sites (S1, S2 and S3)
- Generation of plots and graphs using MS Excel

This methodology was designed to ensure comprehensive analysis of groundwater quality and the impact of industrial effluents in the study area. The multiple analytical approaches and quality control measures enhance the reliability and validity of the results.

Results and Discussion

Variations in contamination levels and water quality parameters within locations and seasons were analysed using groundwater samples from RIICO industrial area of Dholpur. Detailed findings of physical parameters, chemical characteristics and heavy metal concentrations and their significance to water quality and human health are then presented as the results of this study.

Table 01:- Average value of different Physico-chemical parameters for Groundwater of RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023-24

Sr. No	Parameters	Years	Seasons		
			Pre Monsoon	Monsoon	Post Monsoon
1	Temperature	2021-22	23.22	22.33	25.43
		2022-23	23.47	22.2	25.52
		2023-24	23.37	22.17	25.65
		Average	**23.35**	**22.23**	**25.53**
2	pH	2021-22	7.42	7.57	7.49
		2022-23	7.42	7.55	7.48
		2023-24	7.42	7.63	7.52
		Average	**7.42**	**7.58**	**7.50**
3	Colour	2021-22	26.33	31.33	24.67
		2022-23	24.83	31.17	24.17
		2023-24	25.17	31.67	24.33
		Average	**25.44**	**31.39**	**24.39**
4	Turbidity in (NTU)	2021-22	4.75	7.08	6.42
		2022-23	4.52	6.98	6.17
		2023-24	4.52	6.85	5.87
		Average	**4.59**	**6.97**	**6.15**
5	Fluoride in (mg/L)	2021-22	2.94	3.26	3.10
		2022-23	2.94	3.24	3.35
		2023-24	2.94	3.23	3.39
		Average	**2.94**	**3.24**	**3.28**
6	Potassium in (mg/L)	2021-22	1.65	0.90	1.32
		2022-23	2.30	1.20	1.68
		2023-24	2.43	1.35	1.85
		Average	**2.12**	**1.15**	**1.61**
7	Nitrate in (mg/L)	2021-22	95.33	113.17	130.33
		2022-23	96.33	115.83	131.17
		2023-24	92.17	119.67	105.00
		Average	**94.61**	**116.22**	**122.16**
8	Sulphate in (mg/L)	2021-22	34.62	23.75	26.50
		2022-23	33.60	22.5	18.56
		2023-24	35.07	22.8	21.00
		Average	**34.43**	**23.01**	**22.02**
9	Calcium in (mg/L)	2021-22	95.10	109.92	100.60
		2022-23	99.85	116.05	106.26
		2023-24	90.68	110.65	100.15
		Average	**95.21**	**112.2**	**102.33**
10	Magnesium in (mg/L)	2021-22	61.17	72.05	63.23
		2022-23	76.22	88.30	78.15
		2023-24	66.70	76.82	69.03
		Average	**68.03**	**79.05**	**70.13**

11	Sodium in(mg/L)	2021-22	282.00	232.50	257.87
		2022-23	291.83	248.18	277.37
		2023-24	286.67	246.83	271.00
		Average	**286.83**	**242.5**	**268.74**
12	TDS in (mg/L)	2021-22	2154.67	2314.83	2441.33
		2022-23	2126.33	1933.83	2069.33
		2023-24	2107.17	2231.33	2268.67
		Average	**2129.39**	**2160.00**	**2259.77**
13	EC in (µS/cm)	2021-22	4323.33	4598.33	4887.5
		2022-23	4262.17	3860.83	4135.67
		2023-24	4208.83	4459.17	4525.17
		Average	**4264.77**	**4306.11**	**4516.11**
14	Total Hardness in (mg/L)	2021-22	513.17	601.33	537.67
		2022-23	497.50	576.33	520.00
		2023-24	480.67	569.17	513.17
		Average	**497.11**	**582.27**	**523.61**
15	Total Alkalinity in (mg/L)	2021-22	678.50	625.33	648.17
		2022-23	678.50	632.00	655.17
		2023-24	687.33	625.83	660.00
		Average	**681.44**	**627.72**	**654.44**
16	Chloride (mg/L)	2021-22	633.83	473	551.5
		2022-23	662.17	705.83	740.33
		2023-24	640.00	520.83	658.17
		Average	**645.33**	**566.55**	**650.00**
17	Dissolve Oxygen (DO)	2021-22	5.48	5.84	6.14
		2022-23	5.53	5.95	6.26
		2023-24	5.79	6.09	6.31
		Average	**5.60**	**5.96**	**6.24**
18	Chemical Oxygen Demand (COD)	2021-22	5.46	5.05	4.90
		2022-23	5.11	4.95	4.78
		2023-24	5.27	5.06	4.89
		Average	**5.13**	**4.94**	**5.07**

Physico-Chemical Study

The physico-chemical parameters of groundwater from RIICO industrial area of Dholpur analyzed over the period from 2021-22 to 2023-2024 reveals significant variations as following

Temperature (^{O}C)

The groundwater temperature shows considerable seasonal variation, with the highest average value recorded during the post monsoon season (25.53 °C) and the lowest in monsoon season (22.23°C) across all over sites during three years. This fluctuation can be attributed to seasonal climatic variations, with cooler temperatures during the monsoon due to rainfall and higher humidity, and warmer temperatures post-monsoon as the region dries up.

pH

The average value of pH of groundwater samples lies between 7.42 and 7.58, all over the seasons across three years, indicating slightly basic nature of water. The highest average pH values were recorded during the monsoon seasons (average of 7.58), likely due to the dilution effects of rainfall, which reduces the concentration of acidic or alkaline substances in the groundwater and lowest average pH value were recorded (7.42) during pre-monsoon season. The consistent pH levels across the years suggest that there is no significant acidic or alkaline contamination in the groundwater, making it suitable for most domestic aquatic health and agricultural purposes.

Color (Hazen Unit)

Color values,which indicate the presence of dissolved organic and inorganicsubstances, were highest in the monsoon season, with a maximum average value of 31.39 Hazen units, suggesting increased organic material and sediment load during this period. Lower average color value of 24.39 Hazen units observed in post monsoon season.

Turbidity (mg/L)

Turbidity of groundwater samples followed a similar trend like color with maximum average value of 6.97 NTU during the monsoon season reflecting higher suspended solids, likely due to runoff and inflow during the monsoon. The lowest turbidity of 4.59 NTU was observed in Pre monsoon season, indicating clearer water.

Fluoride (mg/L)

The highest average fluoride concentration of 3.28 mg/L was observed in post monsoon phase, and the lowest average of 2.94 mg/L in pre monsoon season. The observed fluoride levels exceed the acceptable thresholds defined by BIS and WHO, ensuring that a natural source of fluoride contamination that may need to be addressed, particularly if the water is used for drinking because Fluoride is a naturally occurring mineral, but excessive levels in drinking water can lead to dental and skeletal fluorosis.

Potassium (mg/L)

Potassium is a crucial nutrient for plant development, yet its excessive presence can stimulate algal blooms, resulting in oxygen depletion and detrimental effects on aquatic organisms. The observed potassium levels with maximum and minimum average values respectively 2.12 mg/L in pre monsoon phase and 1.15 mg/L in rainy period. This could be due to the dilution effect of the monsoon rains. This trend suggests that potassium is more concentrated in the groundwater when rainfall is low, likely due to reduced dilution and increased evaporation, which concentrates the existing ions in the water.

Seasonal variation of various Physico-chemical parameters {Temperature, pH, Turbidity, Fluoride, Potassium and Colour}, {Nitrate, Sulphate, Calcium, Magnesium, Sodium}, {TDS, EC, TH, TA and Chloride} and {DO and COD} of groundwater of RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024 can be represented by following (Fig. 02, 03, 04, 05) respectively.

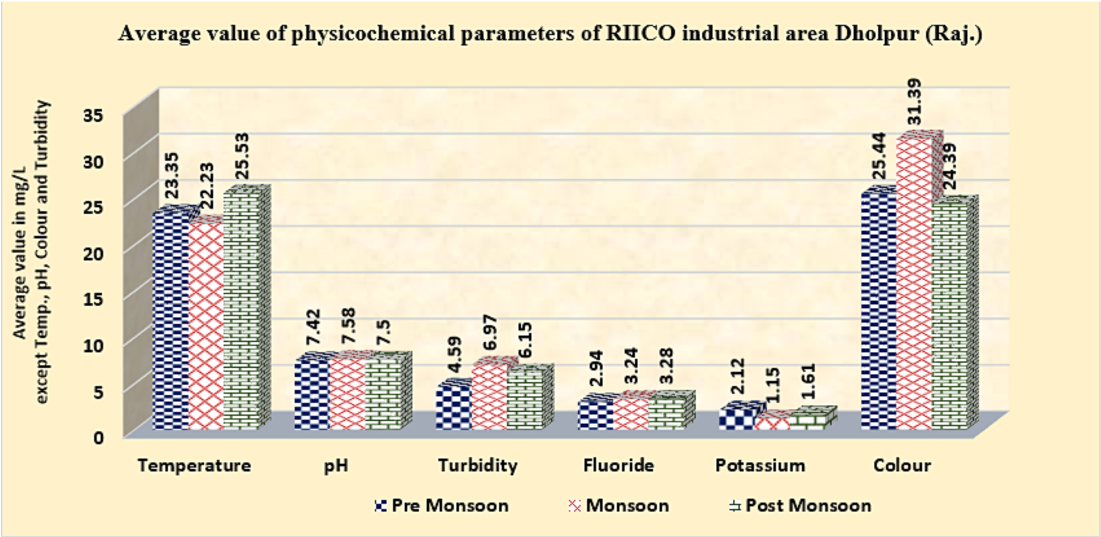

Fig. 2: Seasonal Changes in various Physico-chemical parameters of RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024.

Nitrate (mg/L)

The maximum average nitrate concentration of 122.16 mg/L was recorded in post monsoon period, while the lowest average of 94.61mg/L was observed in pre rainy season. This peak is likely due to the runoff from agricultural fields during the rainy season, washing fertilizers into the groundwater.

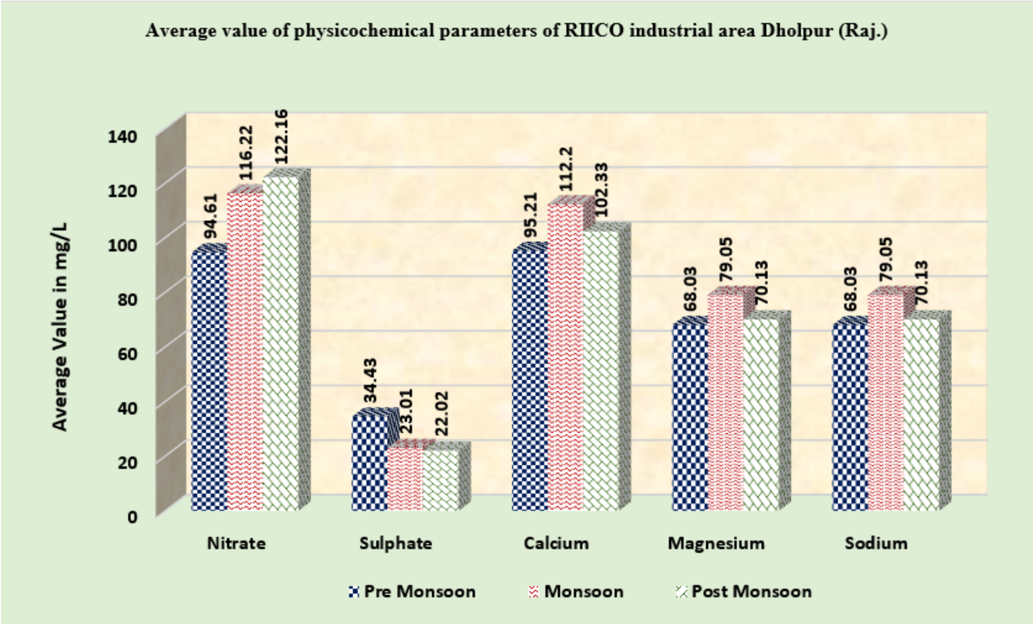

Fig. 3: Seasonal changes in various Physico-chemical parameters of groundwater RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024.

Sulphate (mg/L)

Sulphate is often found in minerals and can contribute to the hardness of water. This study reveals that the highest average sulphate level 34.43 mg/L was consistently recorded during the pre-rainy periods, while the lowest average level 22.02 mg/L was observed during post-rainfall season, these seasonal variation suggests that sulphate concentrations are influenced by the dilution effect of rainwater and subsequent concentration post-monsoon.

Calcium (mg/L)

Calcium is an important parameter that influences the ionic composition of water, i.e. hardness of water which can affect the osmoregulation processes in aquatic organisms. This study reveals that average highest and lowest value of calcium concentration respectively 112.2 mg/L during monsoon season and 95.21 mg/L during pre-monsoon season across three years in sample sites. The fluctuation across seasons suggests that calcium levels are influenced by both dilution during the monsoon and concentration as water evaporates post-monsoon. The Calcium levels within safe limit and suitable for aquatic animals.

Magnesium (mg/L)

Magnesium, like calcium, contributes to water hardness. The study shows that the highest average value was 79.05 mg/L recorded in rainy period and lowest 68.03 mg/L in pre monsoon season. Elevated magnesium levels indicate a rise in organic pollution, reflecting the quantity of organic matter present in the water.

Sodium (mg/L)

Sodium levels varied across the seasons, with the maximum concentration observed in the pre-monsoon season (average of 286.83 mg/L), while the lowest values were in monsoon season (average of 242.50 mg/L). The seasonal variation suggests that sodium levels are influenced by external factors such as runoff during the monsoon, which introduces more salts into the groundwater.

Total Dissolved Solids (mg/L)

TDS is an important parameter to indicate the presence of various salts and minerals in water. The study reveals that TDS values are generally higher during the post-monsoon period average of 2259.77 mg/L while the minimum average of 2129.39 mg/L was observed in pre monsoon season, due to the dilution effect of rainwater. High TDS levels can affect the taste of water and may pose health risks over prolonged consumption.

Electrical Conductivity (μS/cm)

Electrical Conductivity levels in groundwater indicate the presence of different type of ions in the water. The highest average value of Electrical Conductivity 4516.11 μS/cm was observed in post monsoon phase, while the lowest average of 4264.77 μS/cm was recorded in pre-monsoon phase. This trend of seasonal variation is consistent across three years which indicates that the groundwater of Dholpur RIICO region has a high mineral content, due to effect of industrial effluents which might not be ideal for drinking without proper treatment.

Total Hardness (mg/L)

Water hardness is primarily attributed to the presence of calcium and magnesium salts. The study shows that total hardness (TH) was highest during the rainy season i.e. average of 582.27 mg/L and lowest in the Early monsoon phase i.e. average of 497.11 mg/L. indicating the water's capacity to buffer against pH changes and the presence of calcium and magnesium ions. This trend of seasonal variation is consistent across three years which indicates that the groundwater of Dholpur RIICO region has a high mineral content, due to effect of industrial effluents by which it can be undesirable for daily use.

Total Alkalinity (mg/L)

This study shows that the highest average value of total alkalinity is obtained 681.44 mg/L during Early-monsoon period that will indicate significant buffering capacity, which helps maintain pH stability and lowest average alkalinity of 627.72 mg/L recorded in rainy season. High alkalinity indicating severe contamination resulting from unregulated industrial activities and poor waste management practices not only makes the water unsafe for drinking and irrigation but also threatens the broader ecosystem.[16]

Chloride (mg/L)

This study shows that the highest average value of chloride concentration is obtained 650.00 mg/L during Post-rainfall period, while the lowest average of 566.55 mg/L was observed in monsoon period. The observed chloride levels are within safe limits, ensuring that the water remains conducive for aquatic life.

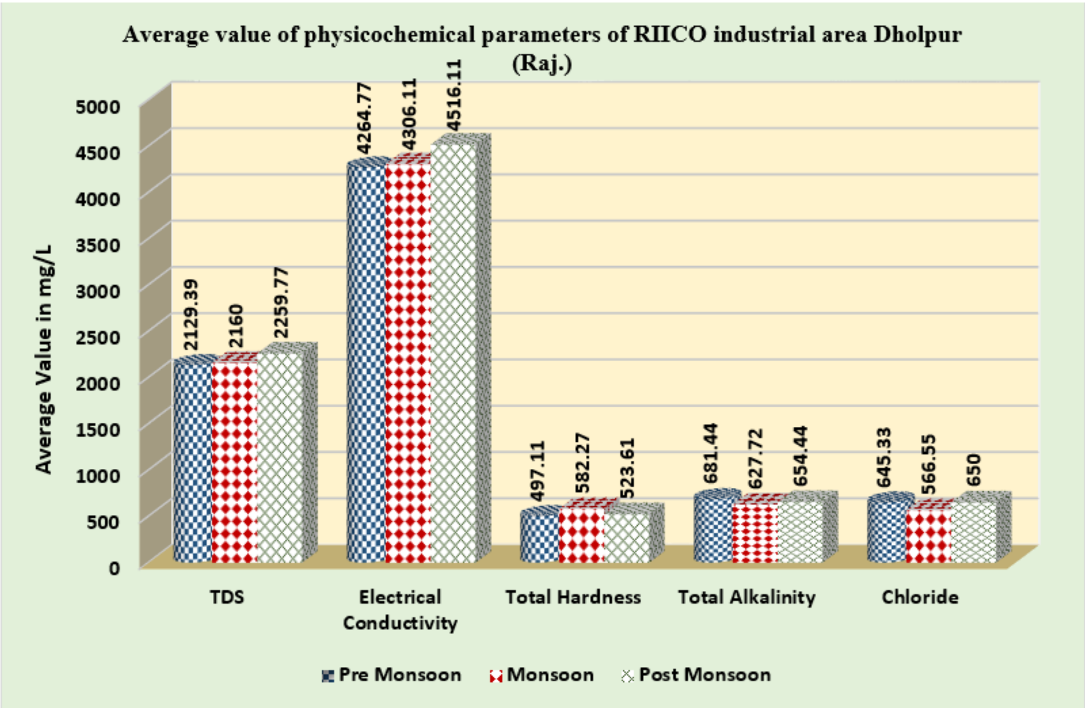

Fig. 4: Seasonal Variation of different Physico-chemical parameters of RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024.

Dissolved Oxygen (mg/L)

Dissolved oxygen is a critical indicator of water quality, as it reflects the ability of water to support aquatic life. Dissolved oxygen (DO) levels were highest in the post monsoon season 6.24 mg/L, which is crucial for respiration of aquatic life, while minimum value 5.60 mg/L was observed in Pre-rainfall season, possibly due to higher temperatures and increased biological activity. The observed DO levels are within safe limits, ensuring the suitability of water for aquatic life. The highest DO levels were observed in the post-monsoon period, which is likely due to the influx of fresh water from rains, which is usually higher in oxygen content.

Chemical Oxygen Demand (mg/L)

COD is a metric that quantifies the amount of oxygen needed to chemically oxidize both organic and inorganic substances present in water. Higher COD levels indicate higher levels of pollution, particularly from organic matter. This study shows that COD values of groundwater were under the permissible limit. The highest average of 5.13 ppm observed in pre rainfall season, and the lowest average value of 4.94 ppm in monsoon period. High COD indicate increased organic pollution in water.

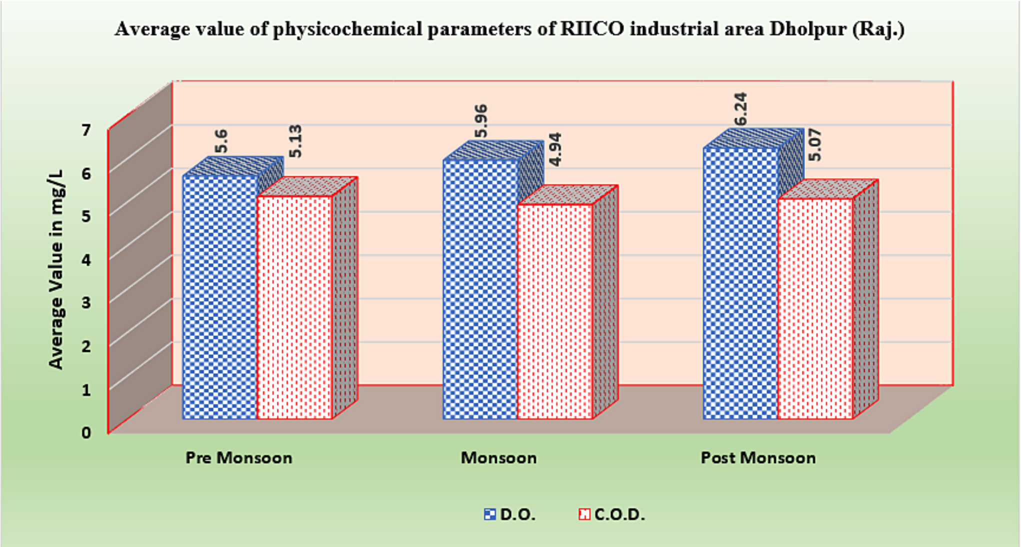

Fig. 5: Seasonal changes in various Physico-chemical parameters of groundwater RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024.

Table 2: Yearwise variation in concentration of different Heavy Metal ions in groundwater samples of RIICO industrial area Dholpur

Sr. no.	Parameters (Heavy Metal ions)	Permissible limit in mg/L as per BIS :2012	Average values years		
			2021-22	2022-23	2023-24
1	Iron in {mg/L}	0.30	0.56	0.44	0.66
2	Copper in {mg/L}	1.50	0.54	0.52	0.60
3	Zinc {mg/L}	15.0	2.19	2.10	2.29
4	Manganese {mg/L}	0.30	0.07	0.07	0.08
5	Lead {mg/L}	0.01	0.02	0.01	0.02
6	Cadmium {mg/L}	0.003	0.003	0.000	0.006
7	Chromium {mg/L}	0.05	0.003	0.000	0.013
8	Mercury {mg/L}	.001	0.00	0.00	0.00

Heavy Metal ion Study

Concentration of diverse heavy metal ions in groundwater samples of RIICO area of Dholpur District obtained different across three years and for selected sites, Iron stand between average value of 0.44 mg/L to 0.66 mg/L, Copper stand between 0.52 mg/L to 0.60 mg/L, Zinc stand between 2.10 mg/L to 2.29 mg/L, Manganese stand between 0.07 mg/L to 0.08 mg/L, Lead stand between 0.01 mg/L to 0.02 mg/L, Cadmium stand between 0.003 mg/L to 0.006 mg/L, Chromium stand between 0.003 mg/L to 0.013 mg/L and Mercury was absent in all water samples throughout this study.

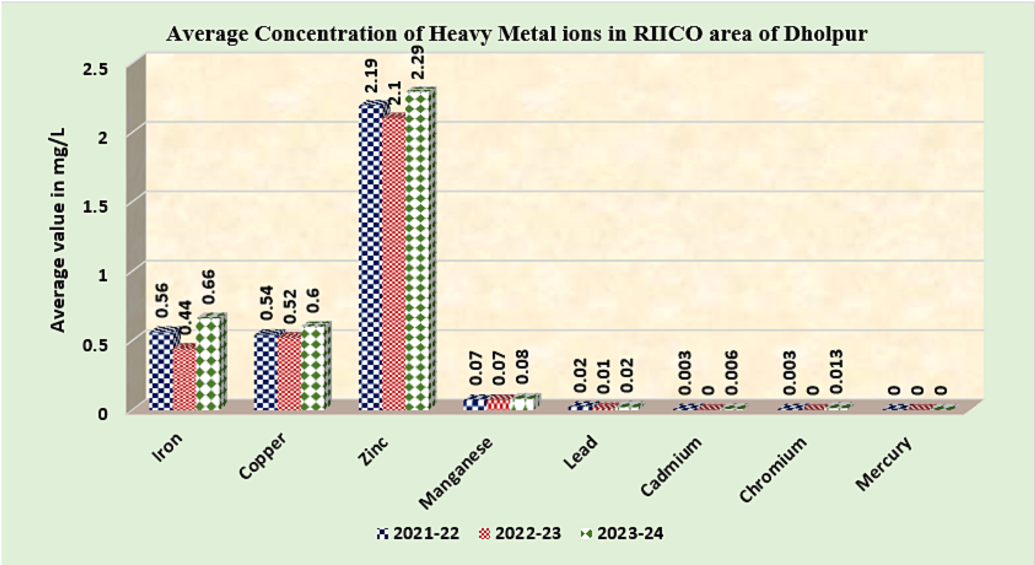

Fig. 6: Variation in concentration of different Heavy Metal ions present in groundwater of RIICO industrial area Dholpur (Rajasthan) during 2021-22 to 2023- 2024.

Seasonal Trends in Water Quality

The seasonal analysis showed different patterns in contamination levels. Higher concentrations of most parameters were observed during the post rainfall period, in Dholpur. This trend indicates that the leaching of contaminants from industrial areas is intensified during this period. Rainfall diluted the concentrations during the monsoon season, while pre-monsoon readings were moderate.

The statistical analysis was carried out of these groundwater samples to establish the relationships between the dependent variable which is found more than permissible limit (e.g., total alkalinity, total hardness, fluoride, nitrate and TDS) and the independent variables (e.g., pH, EC, Temperature) across different seasonal conditions (pre monsoon, monsoon and post monsoon) through following descriptive analysis

Descriptive Statistics

Mean Values

The average values for each variable across the three seasons were calculated. These mean values provide insight into the central tendency of the data.

Standard Deviations

Standard deviation was computed to measure the amount of variation or dispersion in the dataset. A low standard deviation signifies that the data points are clustered near the mean, while a high standard deviation indicates greater variability.

Table 3a: Statistical Analysis of Pre -Monsoon, Monsoon and Post -Monsoon, 2021-22, 2022-23 and 2023-24 at Dholpur Location

S. No.	Season	Pre - Monsoon		Monsoon		Post - Monsoon		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	pH	7.42	0.19	7.58	0.20	7.50	0.15	7.50	0.18
2	Temp	23.35	0.63	22.23	0.27	25.53	0.32	23.70	0.40
3	EC	4264.77	18.65	4306.11	9.02	4516.11	5.94	4362.33	11.13
4	TDS	2129.41	6.24	2160.00	4.57	2259.71	7.12	2183.06	6.24
5	Total Alkalinity	681.44	3.92	627.72	2.56	654.44	3.71	654.53	4.22
6	Total Hardness	497.11	4.57	582.27	2.59	523.61	2.75	534.33	4.51
7	Fluoride	2.94	0.11	3.24	0.06	3.28	0.46	3.15	0.22
8	Nitrate	94.61	4.26	116.22	5.73	122.16	5.23	110.99	6.49

Table 3b: Correlation analysis of Dholpur Location values

Parameters	Sig.	pH	Electrical Conductivity	Temperature
Total Alkalinity	r Value	.012	-.463**	.014
	p Value	.937	.001	.928
Total Hardness	r Value	.084	.824**	-.057
	p Value	.585	.000	.711
TDS	r Value	.275	1.000**	.060
	p Value	.067	.000	.697
Fluoride	r Value	.189	-.357*	.086
	p Value	.214	.016	.573
Nitrate	r Value	.280	.787**	.095
	p Value	.062	.000	.535

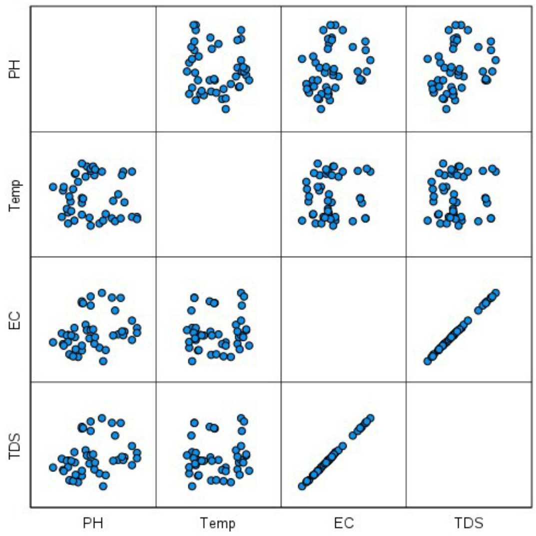

Fig. 7: Scattered plot between independent variable vs TDS

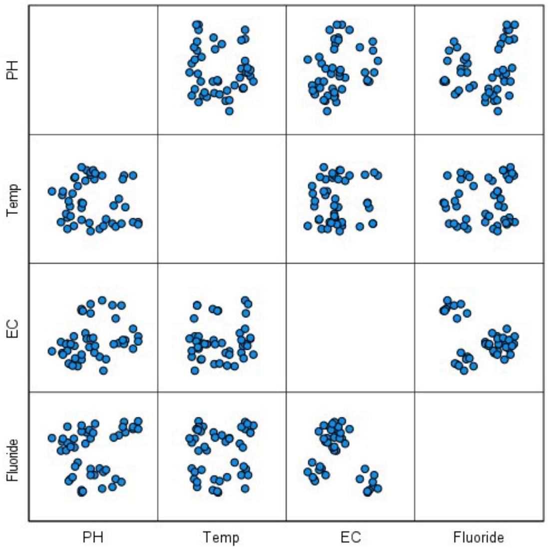

Fig. 8 : Scattered plot between independent variable vs Fluoride

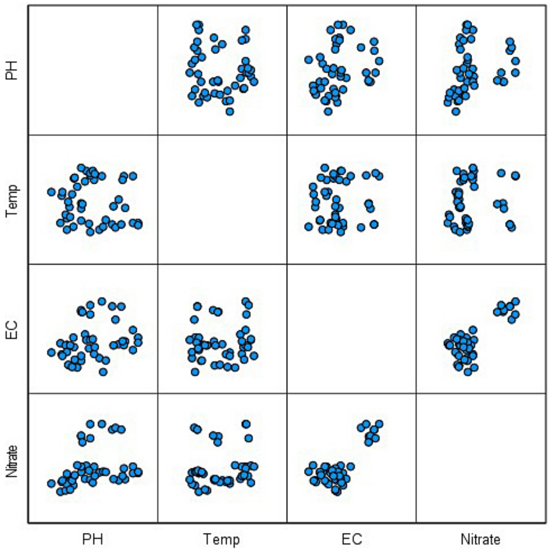

Fig. 9 : Scattered plot between independent variable vs Nitrate

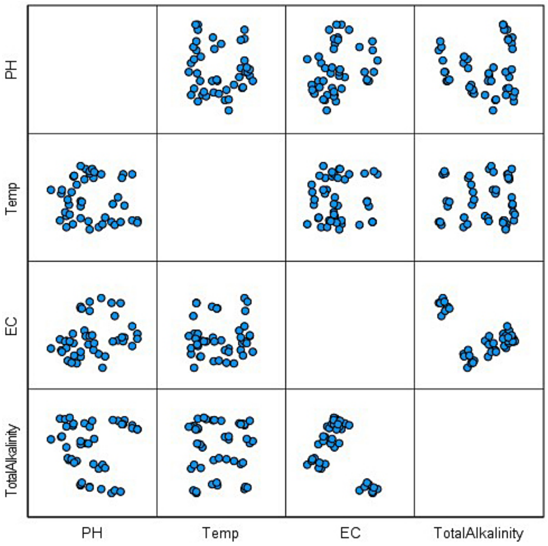

Fig.10 : Scattered plot between independent variable vs Total Alkalinity

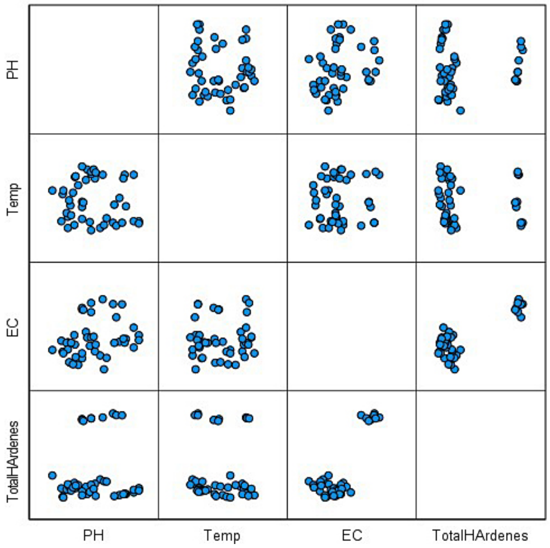

Fig. 11 : Scattered plot between independent variable vs Total Hardness

Above data (Table 3a & 3b) and fig. no. 7 to 11 explain that among independent variables (temperature, pH and electrical conductivity), electrical conductivity shows strong corelation with all dependent variable in which negative corelation with fluoride ($r = -0.357$, $p = .016$) and total alkalinity ($r = -0.463$, $p = .001$) and positive corelation with total hardness, ($r = 0.824$, $p = .000$) TDS ($r = 1.000$, $p = .000$) and nitrate ($r = .787$, $p = .000$) while pH and temperature shows weak corelation with all dependent variable (TDS, total alkalinity, total hardness, fluoride and nitrate because $p > .05$ for each parameter.

Interpretation of Groundwater Contamination

The analysis of groundwater quality in the RIICO industrial area of Dholpur demonstrates that some physico-chemical parameters such as Total Alkalinity, Total Hardness, Fluoride, Nitrate, TDS and EC were obtained exceeding the permissible limit of BIS (2012) and WHO (2003) which shows high level of contamination of water due to adverse effect of industrial effluents. The concentration level of heavy metal ions iron (Fe), cadmium (Cd) and lead (Pb) were obtained exceeding the permissible limit of WHO (2003) and BIS (2012) but mercury (Hg) was absent in all water samples, reflecting large scale industrial contamination in groundwater. This accords with the work of Kumar & others,[7] they found similar patterns of heavy metal contamination in industrial zones. This study refers that higher concentration of heavy metal ions shows higher concentrations of industrial activity, and poorer practices regarding the effective management of effluents. These findings show different level of industrial impact in this region, which is its own distinguishing features that are related to the intensity of industrial activities and the local hydrogeological conditions. In terms of spatial distribution of contaminants, a clear correlation is found between industrial density and groundwater deterioration. Similarly, Singh & others[3] finds strong correlations between groundwater contamination and industrial clusters. A clear causative relationship between industrial activities and the groundwater quality deterioration is indicated by the decrease with distance from industrial sources of the contamination levels.

Temporal Variations and Seasonal Impacts

Seasonal variations of contamination levels provide important information on the dynamics of pollutant transport and accumulation. Contaminant concentration trends are also in accordance with Tanwer [17] findings for industrial areas in Rajasthan, with seasonal trends in contaminant concentrations, especially in post monsoon of RIICO area in Dholpur. One reason for this trend is the leaching of accumulated contaminants during monsoon rains and subsequent concentration in groundwater resources. The observed results also indicate that climatic factors contribute to the distribution of contaminants. We show that rainfall patterns control the distribution and concentration of pollutants through a dilution effect in monsoon months and a concentration effect in post monsoon months. Characterizing these seasonal variations also serves the important role of a basis for developing monitoring and management strategies that can accommodate these seasonal contamination levels.

Industrial Impact and Environmental Sustainability

The study reveals a marked tension between industrial development and environmental sustainability in these regions. This three years study of industrial area show different levels of contamination, which shows how much industrial waste management methods can affect groundwater quality. But this implies that groundwater quality of RIICO area in Dholpur is poor, because proper environmental safeguards must have been in place before vandals got to the groundwater. The presence of correlation between industrial densities and groundwater contamination calls for improvement of the industrial waste management practice. Manoj Shanmugamoorthy[8] says that proper treatment and disposal practices can be used to check industrial effluent impact on groundwater. So, it is suggested that local factors such as waste management practices and regulatory enforcement are significant determinants in the extent of groundwater contamination.

Regulatory and Management Implications

The implications of these findings for regulatory frameworks and management practices in industrial area is important. For the level of contamination observed, especially in Dholpur, current regulatory mechanisms may not be feasible to protect groundwater resources. This aligns with the observations made by Sheikh & others,[9] which point out gaps regarding the industrial pollution control measures in the industrial zones of Rajasthan.

According to the study results, there is a need to enhance the monitoring and the enforcement of environmental regulations. So more effective application of pollution control measures could improve groundwater quality significantly. This is especially important due to the importance of groundwater for industrial activity and community needs in this semi-arid region.

Conclusion

The results of this three-year study (2021-2024) reveals significant groundwater contamination in the RIICO industrial area of Dholpur, Rajasthan. Some of the key parameters found in the groundwater are several times above the safe drinking water standards set by WHO (2003) and BIS (2012), such as the total alkalinity, total hardness, fluoride, nitrate, total dissolved solids (TDS) and electrical conductivity. During this study Iron (Fe), cadmium (Cd) and lead (Pb) concentration in groundwater were found more than permissible limit among heavy metals.

Contamination patterns indicated that contamination was the highest during the post-monsoon season as the rain-washed industrial pollutants into the groundwater sources. This pollution has an industrial origin since the conductivity of the water bears a strong correlation with different contaminants.

Groundwater quality within the industrial zone varies by location, with the closest areas to industrial facilities having the most contaminated water. This implies that current waste management and regulatory enforcement practices are incapable of protecting water resources in this semi-arid area, suggesting an urgent need for improved and better-monitored industrial waste treatment systems. Though this groundwater is unfit for drinking, it is still usable for irrigation and domestic purposes with necessary precautions.

Industries must adopt better effluent treatment practices, and regulatory authorities must enforce monitoring and control more effectively. These are essential actions for safeguarding public health and environmental sustainability in an area where groundwater is such an important resource for industrial and community uses.

Acknowledgement

We appreciate the support provided by PHED Department Bharatpur, and Soil Science Department Bharatpur Rajasthan.

Funding Sources

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest

“The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research work from the PHED Department Bharatpur, and Soil Science Department Bharatpur Rajasthan.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from other Sources

Not Applicable

Author Contributions

Deshmukh Singh, Manoj Kumar Singh and Magan Prasad contribute in writing original draft and formal analysis of this research work

References

1. Bhardwaj, S., & Shukla, D. P. Policy and regulatory framework for inorganic contaminants. *Inorganic Pollutants in Water.* 2020; 53-67.https://doi.org/10.1016/B978-0-12-818965-8.00004-4
2. Chinchmalatpure, A. R., Gorain, B., Kumar, S., Camus, D. D., & Vibhute, S. D. Groundwater pollution through different contaminants: Indian scenario. *Research Developments in Saline Agriculture.* 2019; 347-371.https://doi.org/10.1007/978-981-13-5832-6_15
3. Singh, K. K., Tewari, G., Kumar, S., Busa, R., Chaturvedi, A., Rathore, S. S., Singh, R. K., & Gangwar, A. Understanding urban groundwater pollution in the Upper Gangetic Alluvial Plains of northern India with multiple industries and their impact on drinking water quality and associated health risks. *Groundwater for Sustainable Development.* 2023; 21: 100902.https://doi.org/10.1016/j.gsd.2023.100902

4. Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S., & Khosla, B. Assessment of groundwater potability and health risk due to fluoride and nitrate in groundwater of Churu District of Rajasthan, India. *Environmental Geochemistry and Health.* 2023a; 45: 1485-1502.https://doi.org/10.1007/s10653-023-01485-z
5. Choubisa, S. L., Choubisa, D., & Choubisa, A. Fluoride contamination of groundwater and its threat to health of villagers and their domestic animals and agriculture crops in rural Rajasthan, India. *Environmental Geochemistry and Health.* 2023; 45: 1267-1280.https://doi.org/10.1007/s10653-022-01267-z
6. Pandey, S., Mohapatra, G., & Arora, R. Groundwater quality, human health risks and major driving factors in arid and semi-arid regions of Rajasthan, India. *Journal of Cleaner Production.* 2023; 382: 139149. https://doi.org/10.1016/j.jclepro.2023.139149
7. Kumar, A., Singh, M. V., Bhatt, N., Jayaswal, P., Sethi, M., Burcar, E., & Wang, Z. The perils of heavy metal contamination in groundwater: Impacts on human health in the northeastern region of Jhunjhunu, Rajasthan. *ES Food & Agroforestry.* 2024; 16: 1079. https://doi.org/10.30919/esfaf1079
8. Manoj Shanmugamoorthy, Subbaiyan, A., Elango, L., & Velusamy, S. Groundwater contamination monitoring for pollution measurement and transmission applying WQI approaches from a region of the Erode District, Tamilnadu, India. *Journal of Water Chemistry and Technology.* 2023; 45(2): 91-99. https://doi.org/10.3103/s1063455x23020091
9. Sheikh, S., Kuldeep, K., Mathur, A. K., & Kamboj, P. Assessment of organophosphate pesticides residue in groundwater of Kota region of Rajasthan, India. *ECS Transactions.* 2022; 107(1): 3845. https://doi.org/10.1149/10701.3845ecst
10. Munoth, N., & Prabha, C. Root causes of groundwater contamination for analyzing resource management and policy framework. *Contaminants of Emerging Concerns and Reigning Removal Technologies.* 2022; 325-340. https://doi.org/10.1201/9781003247869-17
11. Jones, E. R., Van Vliet, M. T. H., Qadir, M., & Bierkens, M. F. P. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth System Science Data.* 2021; 13(2): 237-254. https://doi.org/10.5194/essd-13-237-2021
12. Zhang, P., Yang, D., Zhang, Y., Li, Y., Liu, Y., Cen, Y., Zhang, W., Geng, W., Rong, T., Liu, Y., & Shao, J. Re-examining the drive forces of China's industrial wastewater pollution based on GWR model at provincial level. *Journal of Cleaner Production.* 2020; 262: 121309. https://doi.org/10.1016/j.jclepro.2020.121309
13. Wang, L., Tao, Y., Su, B., Wang, L., & Liu, P. Environmental and health risks posed by heavy metal contamination of groundwater in the Sunan coal mine, China. *Toxics*. 2022; 10(7): 390. https://doi.org/10.3390/toxics10070390
14. Ullah, Z., Rashid, A., Lee, J. Y., Shakoor, M. B., & Kwon, K. D. Groundwater contamination through potentially harmful metals and its implications in groundwater management. *Frontiers in Environmental Science.* 2022; 10: 1021596.https://doi.org/10.3389/fenvs.2022.1021596
15. APHA, AWWA, WEF (American Public Health Association, American Water Works Association, Water Environment Federation) Standard Methods for the examination of Water and Wastewater. 23rd edition. Edited by: Baird R.B., Eaton A.D., &Rice E. W. APHA, WashingtonDC.2017. https//doi.org/10.2105/SMWW.2882.214
16. Hameed, M. S., & Kumar, B. S. Analysis of Water Quality Parameters of Surface Water in Tiruchirapalli District, Tamil Nadu, India. *International Journal of Engineering Research and Technology*. 2018; 4(25): 1-4.
17. Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S., & Khosla, B. Fluoride and nitrate in groundwater: A comprehensive analysis of health risk and potability of groundwater of Jhunjhunu district of Rajasthan, India. *Environmental Monitoring and Assessment.* 2023b; 195(2): 1-19.https://doi.org/10.1007/s10661-022-10886-z