STM JOURNALS

Journal of
Water Pollution &
Purification Research

ISSN: 2394-7306
Volume 12, Issue 2, 2025
September–December
DOI (Journal): 10.37591/JoWPPR

https://journals.stmjournals.com/jowppr

Research JoWPPR

Tackling Water Hardness: Understanding the Issue for Sustainable Development

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Abstract

Hard water poses a serious threat to human health and industrial operations. The pervasiveness of water hardness, characterized by elevated concentrations of calcium and magnesium ions, originates from seepage and runoff from soils, as well as polyvalent metallic ions from sedimentary rocks. These minerals, while essential in moderate amounts, can become problematic when consumed in excess. Epidemiological studies have established correlations between excessive consumption of calcium and magnesium and increased risks of coronary artery disease, insulin resistance, colorectal cancer, hypertension, stroke, osteoporosis, and nephrolithiasis. Moreover, magnesium deficiency has been implicated in the pathophysiology of hypertension, as evidenced by numerous experimental studies demonstrating a negative relationship between serum magnesium levels and blood pressure. This research paper presents a comprehensive analysis of water hardness in various samples collected from the Sitapura Industrial area of Jaipur using the EDTA titration method. Our findings reveal alarmingly high water hardness levels throughout the region, significantly exceeding the WHO permissible limits, thus highlighting an urgent need for intervention strategies.

Keywords: Water hardness, Human Health, Diseases, EDTA titration, Magnesium and Calcium Contamination

INTRODUCTION

Water hardness refers to the concentration of dissolved calcium and magnesium ions present in water samples. The quantification of water hardness is typically expressed in milligrams per liter (mg/L) as calcium carbonate ($CaCO_3$), representing the cumulative concentration of divalent cations in the water matrix. From a biochemical perspective, calcium arguably constitutes the most significant factor in hardness determination, particularly in aquatic ecosystems, as elevated calcium levels can impede the respiratory function of aquatic organisms by reducing water permeability through gill structures [1].

The geological composition of Rajasthan, characterized by extensive limestone and dolomite formations, contributes significantly to the region's pervasive water hardness issues. Rajasthan stands as one of the most endemic states in India, plagued by elevated concentrations of various pollutants in subsurface water across the majority of its districts [2]. The financial implications of this water quality crisis are substantial, as numerous successfully excavated bore wells have been decommissioned for human consumption due to the presence of contaminants exceeding the acceptable limits established by the Bureau of Indian Standards (BIS) [3].

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Received Date: May 08, 2025
Accepted Date: May 16, 2025
Published Date: June 03, 2025

Citation: Nupur Jain, Prayatna Gupta, Pulkit Vijayvargiya, Yuvraj Saini. Tackling Water Hardness: Understanding the Issue for Sustainable Development. Journal of Water Pollution & Purification Research. 2025; 12(2): 73–79p.

Table 1. Hardness of water.

Calcium carbonate (PPM)	Designation
0–43	Soft
43–150	Slightly hard
150–300	Moderately hard
300–450	Hard
450	Very hard

The classification of water based on hardness levels, as presented in Table 1, provides a standardized framework for assessing water quality in both domestic and industrial contexts. One of the most endemic states, Rajasthan is plagued by a high concentration of pollutants in the subsurface water in the majority of the districts [3]. Many successfully dug bore wells have been stopped for human consumption because to the presence of impurities over the acceptable limit of BIS, which has cost the nation money [4]. Table 1 gives us information about the hardness of water [5].

LITERATURE REVIEW

Water hardness has been extensively studied across various geographical contexts, with researchers identifying significant correlations between hardness levels and both human health and industrial efficiency. Sharma (2007) [1] conducted a comprehensive analysis of groundwater quality in selected villages of Rajasthan, with a particular focus on fluoride concentrations, but also documented concerning levels of hardness throughout the region [4]. Building upon this foundation, Vikas et al. (2009) [2] investigated the hydrochemical status of groundwater in Ajmer district, noting a strong correlation between geological formations and hardness levels [5].

Mudgal et al. (2009) [3] performed a hydrochemical analysis of drinking water quality in Alwar district, identifying numerous locations where hardness exceeded permissible limits [6]. Similarly, Yadav et al. (2011) assessed groundwater quality in areas adjacent to the Bhiwari industrial zone in Alwar, documenting the industrial contribution to increased hardness levels [7].

More recent studies by Rupali et al. (2019) specifically examined groundwater quality in Jaipur district, highlighting the Sitapura industrial area as a hotspot for elevated hardness [8]. Nisha et al. (2014) conducted a comprehensive groundwater quality assessment of Jaipur city, corroborating these findings and establishing a baseline for temporal comparison [9]. Aditi et al. (2018) investigated hardness levels in packaged drinking water in West Bengal, providing methodological insights for hardness determination that informed our analytical approach [10]. The extensive literature consistently demonstrates that water hardness represents a significant challenge across Rajasthan, with industrial areas exhibiting particularly concerning levels. However, a dedicated investigation of the Sitapura industrial area, employing standardized EDTA titration methodology and comprehensive spatial sampling, has been lacking. Our study addresses this research gap.

EXPERIMENTAL DETAILS

Sampling Points

Water samples were carefully collected in clean, rinsed bottles from different parts of the Sitapura Industrial Area in the Jaipur District. Four to five samples were taken from each type of source, including collected groundwater, closed bore wells, and open wells. Eight to 10 samples were thus taken from each. For at least a year, the samples were drawn at random from pre-fixed locations (Figure 1).

Sampling Method

In this experiment, a known concentration of EDTA (Ethylene di Amine Tetra Acetic Acid) is used to calculate the concentrations of Ca^{2+} and Mg^{2+} ions. The big molecule EDTA attaches many connections to a single metal ion in order to trap it. The complex of metal-EDTA is stable, and one mole of metal ions interacts with one mole of EDTA to generate one mole of the metal–EDTA complex. This reaction occurs in a regulated 1:1 mole ratio [6, 7]. This can be explained by the following steps as shown in Figure 2.

Journal of Water Pollution & Purification Research
Volume 12, Issue 2
ISSN: 2394-7306

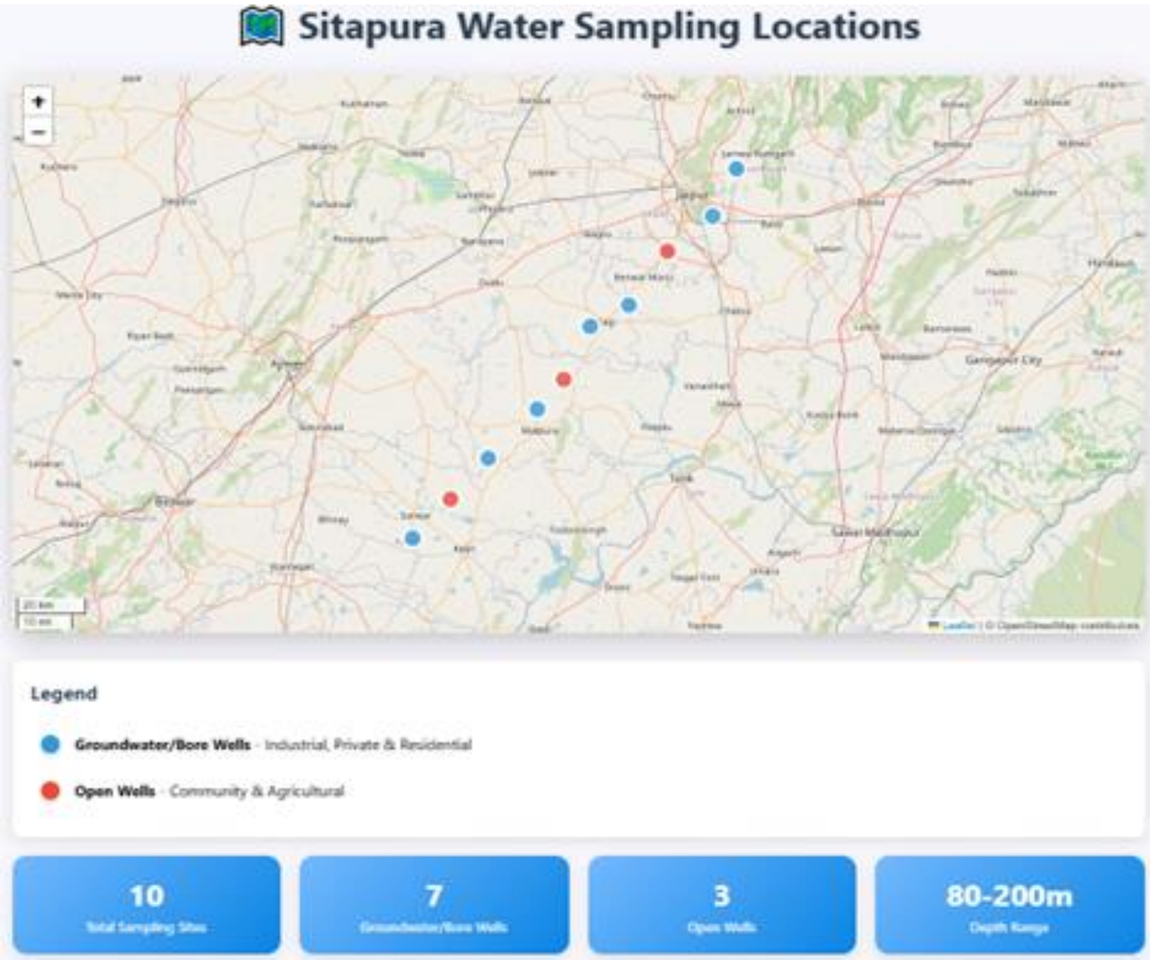

Figure 1. Sample location map.

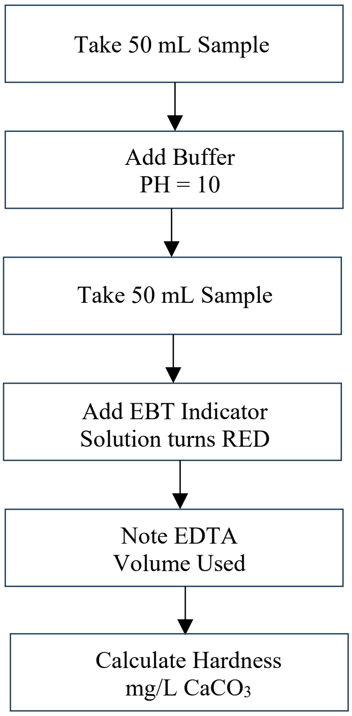

Figure 2. Experimental steps.

Note: Repeat those same steps for boiled water to calculate the hardness.

Table 2. Sample location point and their characteristics.

S.N.	Sample no.	Location	Latitude	Longitude	Sample type	Source description
1	S1	Sitapura	26.002	75.004	Groundwater	Industrial bore well, depth ~150m
2	S2	Sitapura	26.105	75.113	Open well	Community well, depth ~80m
3	S3	Sitapura	26.214	75.223	Groundwater	Private bore well, depth ~120m
4	S4	Sitapura	26.346	75.365	Groundwater	Industrial bore well, depth ~180m
5	S5	Sitapura	26.423	75.442	Open well	Agricultural well, depth ~100m
6	S6	Sitapura	26.564	75.521	Groundwater	Residential bore well, depth ~140m
7	S7	Sitapura	26.621	75.633	Groundwater	Industrial bore well, depth ~200m
8	S8	Sitapura	26.764	75.746	Open well	Community well, depth ~90m
9	S9	Sitapura	26.855	75.878	Groundwater	Private bore well, depth ~160m
10	S10	Sitapura	26.980	75.947	Groundwater	Industrial bore well, depth ~170m

Here, Table 2 shows the location of the points from where the samples were collected.

Note: Table 2 provides detailed information about each sampling location, including the type of water source (groundwater from bore wells vs. open wells), approximate depth of the source, and primary usage (industrial, residential, community, or agricultural). This classification helps explain the variation in hardness levels observed across different sample points, as deeper groundwater sources and those in industrial zones typically exhibit higher mineral concentrations due to prolonged contact with geological formations and potential industrial influences.

RESULTS AND DISCUSSION

Samples collection from various places of Sitapura has been analyzed for hardness of water and analytical results reported in Table 3.

According to the values of hardness of samples, it is clear that the level of hardness in the water at Sitapura industrial area is too high. The average value of hardness is about 1582 mg/l there [8].

The analytical data reveals alarmingly elevated hardness levels across all sampling points within the Sitapura Industrial Area. The total hardness values range from 1470 mg/L to 1810 mg/L, with an average concentration of approximately 1582 mg/L. This average exceeds the WHO-recommended permissible limit of 500 mg/L for total hardness in drinking water, categorizing the entire area's water supply as "Very Hard" according to standard classification criteria.

Temporary hardness, attributable to bicarbonate and carbonate compounds that can be removed through boiling, ranged from 840 mg/L to 1075 mg/L, with a mean value of 969 mg/L. The permanent hardness, caused primarily by sulfate and chloride compounds that persist after boiling, exhibited values between 510 mg/L and 750 mg/L, with an average of 623 mg/L.

The ratio between temporary and permanent hardness across sampling points maintains relative consistency, suggesting a common geological origin for the dissolved minerals. The significantly higher proportion of temporary hardness indicates the predominance of bicarbonate compounds in the mineral composition, typical of limestone-rich geological formations.

Table 3 shows the hardness of water collected water sample from different sample point. Temporary hardness, attributable to bicarbonate and carbonate compounds that can be removed through boiling, ranged from 840 mg/L to 1075 mg/L, with a mean value of 969 mg/L. The permanent hardness, caused primarily by sulfate and chloride compounds that persist after boiling, exhibited values between 510 mg/L and 750 mg/L, with an average of 623 mg/L (Figure 3).

Table 3. Results of hardness of different sample point.

Sample no.	Temporary hardness	Permanent hardness	Total hardness
S1	980 mg/l	540 mg/l	1520 mg/l
S2	860 mg/l	630 mg/l	1490 mg/l
S3	1000 mg/l	655 mg/l	1655 mg/l
S4	990 mg/l	690 mg/l	1680 mg/l
S5	1075 mg/l	510 mg/l	1585 mg/l
S6	910 mg/l	620 mg/l	1530 mg/l
S7	1060 mg/l	750 mg/l	1810 mg/l
S8	840 mg/l	630 mg/l	1470 mg/l
S9	1055 mg/l	545 mg/l	1600 mg/l
S10	920 mg/l	660 mg/l	1580 mg/l
Average	*969*	*623*	*1592*

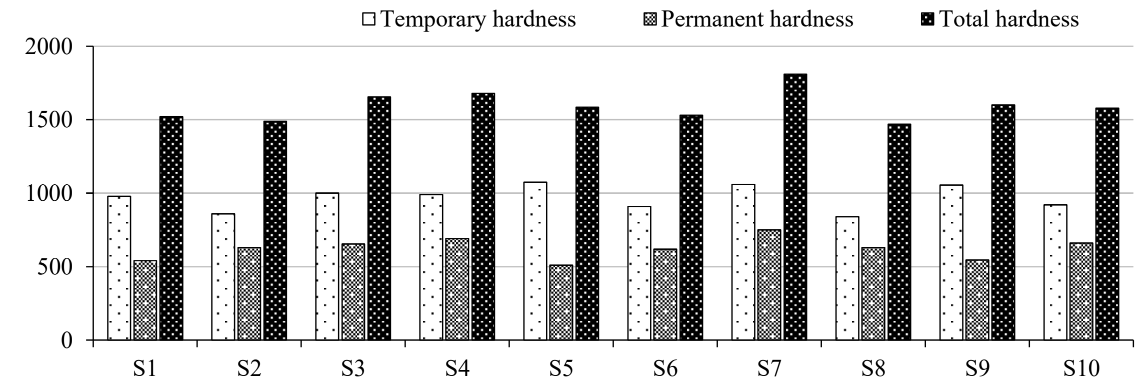

Figure 3. Graphical representation of hardness.

Hardness, while often associated with strength and durability, can also present drawbacks. One significant drawback is that excessively hard materials may become brittle, making them prone to fracture or shattering under certain conditions of stress. This brittleness reduces the material's ability to deform plastically, potentially compromising its performance in applications where resilience and flexibility are required. Additionally, extremely hard surfaces can be challenging to machine or process, increasing production costs and complexity. Moreover, the increased wear resistance of hard materials can lead to accelerated wear on mating components, causing compatibility issues and reducing overall system efficiency. Therefore, achieving an optimal balance between hardness and other mechanical properties is essential for ensuring the suitability and longevity of materials in various engineering applications [11].

IMPLICATIONS OF EXTREME WATER HARDNESS

The high hardness levels reported in the Sitapura Industrial Area pose complex challenges to both industrial processes and public health. Industrially, these high mineral levels enhance scale formation in boilers, heat exchangers, and cooling systems, greatly lowering thermal efficiency and raising maintenance costs. Precipitation of calcium and magnesium compounds in pipelines limits flow capacity and raises pumping energy demands, further degrading operational efficiency [12].

From a public health perspective, although calcium and magnesium are nutrients, their overconsumption in the form of water with very high hardness levels can lead to several health issues. Epidemiological evidence indicates correlations between chronic intake of highly hard water and higher prevalence of urolithiasis (kidney stones), especially in areas with high ambient temperatures such as Rajasthan, where chronic mild dehydration is prevalent [13].

In addition, the interaction between hard water minerals and detergents or soaps diminishes cleaning effectiveness, resulting in higher usage of these materials and more environmental impact from surfactants in wastewater. This economic effect continues to household appliances, as scale formation shortens the life of water heaters, washing machines, and dishwashers [14].

The environmental consequences are changed soil chemistry in land irrigated with water that is very hard, which may influence agricultural production. The intricate dynamics among water hardness, soil type, and crop physiology require specialized study in the context of Sitapura's peri-urban farming [15].

MITIGATION STRATEGIES

Mitigation of the Sitapura Industrial Area's very hard water requires an integrated approach that brings together technological measures, policy support, and community response. The possible mitigation strategies are:

1. *Industrial scale treatment:* For industrial processes involving high levels of water intake, ion-exchange water-softening treatment systems are the cost-effective method. These use the exchange of sodium ions on beds of resin against calcium and magnesium ions to markedly decrease hardness. For complete demineralization processes, reverse osmosis treatment systems have the capability, although at elevated operational expense.
2. *Domestic water treatment:* In a household setting, smaller ion exchange softeners or polyphosphate-based sequestering systems work well to limit hardness effects. For drinking water alone, reverse osmosis or nanofiltration treatment systems give wide-ranging treatment, although attention has to be given to the long-term health implications of drinking wholly demineralized water.
3. *Municipal infrastructure:* Long-term solutions can involve the creation of centralized water softening plants as part of the municipal water treatment system. Lime-soda ash softening processes can be applied at scale to lower hardness prior to distribution, yielding systemic advantages throughout the industrial zone.
4. *Regulatory frameworks:* Improved monitoring and regulatory control over groundwater extraction operations, especially in industrial areas, would enhance the prevention of further water quality decline. Installation of discharge standards for treated industrial effluents would minimize mineral loading in groundwater systems in the long run.

CONCLUSION

The exhaustive water sample analysis from the Sitapura Industrial Area presents widespread and intense hardness across the area, with every sample way above WHO allowable values. The dominance of temporary hardness indicates that carbonate-type minerals are the main contributors to total hardness, an indicator of the underlying geology's prevalence of limestone in the area.

The significance of these results transcends water quality measurements, touching on economic effects on industrial processes, public health concerns for the residents, and environmental implications for the ecosystem within. The economic cost of untreated water hardness is realized in terms of enhanced equipment degradation, greater maintenance needs, and compromised operational efficiency throughout industrial processes.

Mitigating this water quality issue necessitates a multi-pronged intervention that integrates technological measures at both the industrial and domestic levels, complemented with supportive regulatory schemes and public awareness campaigns. The use of water softening technology, from ion-exchange plants to reverse osmosis systems, is a key intervention aimed at reducing the negative implications of excessive water hardness.

Further investigation is needed to examine the specific health effects of long-term exposure to very hard water in the Sitapura setting, specifically taking into account the distinctive demographic and environmental factors typical of the area. Examining the potential relationship between industrial processes and hardness levels could further guide targeted regulation.

The results of this research highlight the imperative for integrated water quality management plans in fast-industrializing areas, where geologic susceptibility meets anthropogenic stress to present key environmental threats. By adopting evidence-informed interventions guided by intensive scientific assessment, interested parties in the Sitapura Industrial Area can attempt sustainable solutions to reconcile economic growth with environmental protection and human health safety.

Acknowledgment
The authors thank Poornima Institute of Engineering & Technology, Jaipur, for providing the necessary support to carry out this work.

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