Physico-Chemical Analysis of Water Samples from an Education Institutional Building: A Comparative Laboratory Study of Groundwater, Municipal Supply and Reverse Osmosis Treatment Systems

Teena Pareek[1], Prity Sharma[2], Shalini Jauhari[3], Aditi Kain[4], Muskan Vishnoi[5]

[1,2]Assistant Professor, Department of Chemistry, Parishkar College of Global Excellence, Jaipur

[3]Assistant Professor, Department of Zoology, Parishkar College of Global Excellence, Jaipur

[4,5]Student, Department of Zoology, Parishkar College of Global Excellence, Jaipur

***Abstract*—Water quality assessment is fundamental to ensuring public health and environmental sustainability. This study presents a comprehensive physico-chemical characterization of four water samples collected from a residential building: municipal tap water, groundwater (tubewell), reverse osmosis (RO) filtered water, and RO reject water. Eight key parameters were analyzed using standard analytical procedures: pH, acidity, alkalinity, total dissolved solids (TDS), total hardness, temporary hardness, permanent hardness, and sulphate concentration. Titrimetric and instrumental methods were employed following protocols established by the American Public Health Association (APHA) and validated against Bureau of Indian Standards (IS 10500:2012, revised 2015) and World Health Organization (WHO) guidelines. The results revealed significant variations in dissolved solids and hardness across water sources, with groundwater exhibiting elevated mineral content (high TDS and hardness), RO-treated water showing substantial reductions in ionic constituents, and RO reject water demonstrating concentrated solute levels. The study demonstrates both the efficiency and limitations of residential RO purification systems, highlighting concerns regarding demineralization of treated water, potential corrosivity, and environmental implications of reject water disposal. These findings contribute to the understanding of household water treatment technologies and their impact on water chemistry, with implications for public health, infrastructure integrity, and sustainable water management practices.**

***Index Terms*—Water quality, physico-chemical analysis, reverse osmosis, total dissolved solids, hardness, groundwater, drinking water standards**

I. INTRODUCTION

1.1 Background and Rationale

- Water is the vital requisite of our planet, acting as a universal solvent and the primary medium for all biological existence. However, the quality of this resource is under constant threat from urbanization and industrial pressures, making safe access a global priority. As highlighted by Sharma and Bhattacharya, the contamination of drinking water sources necessitates advanced treatment techniques to safeguard human health.[1] In India, the challenges are particularly acute due to diverse geological factors that influence water chemistry. [2,3] Recent micro-level studies have specifically linked groundwater quality to direct health outcomes, emphasizing the need for localized assessments. [4,5]

- Residential water typically comes from varied origins—municipal networks or private tubewells—each carrying a unique chemical fingerprint. While groundwater is often perceived as a "pure" source, it frequently carries a heavy load of dissolved minerals acquired through contact with subsurface strata.[6,7] Consequently, regular monitoring of these parameters is essential for identifying potential health risks.[8,9] To address these mineral loads, many households have turned to Reverse Osmosis (RO) technology, which utilizes semipermeable membranes to filter out dissolved solids and ions.[10,11] While effective, these systems represent a significant shift in how we manage water at the point of use.[12]

1.2 Water Quality Parameters and Public Health

- Understanding water chemistry requires looking at several key indicators:
- pH: This measures hydrogen ion activity and dictates the water's corrosivity and metal solubility. [13,14]
- TDS: This represents the total inorganic salts and organic matter present. High TDS levels can affect taste and indicate contamination, though RO systems are highly efficient at their removal. [15,16]
- Hardness: Primarily caused by calcium and magnesium, hardness can lead to scaling in pipes and reduced detergent efficiency.[17] Studies demonstrate that assessing these physicochemical parameters is the first step in determining if groundwater is fit for consumption. [18,19] Emerging contaminants in Indian waters further complicate this assessment, requiring more robust treatment strategies.[20]

1.3 Research Objectives

The present study was designed to achieve the following objectives:

1. To conduct a comprehensive physico-chemical characterization of four water samples from a residential building: tap water, groundwater (tubewell), RO filtered water, and RO reject water.

2. To determine pH, acidity, alkalinity, total dissolved solids, total hardness, temporary hardness, permanent hardness, and sulphate concentration using standard analytical methods.

3. To compare analytical results with drinking water standards prescribed by the Bureau of Indian Standards (IS 10500:2012, revised 2015) and World Health Organization guidelines.

4. To evaluate the performance and efficiency of the residential RO purification system in removing dissolved solids and hardness.

5. To assess the chemical characteristics of RO, reject water and discuss environmental implications.

6. To identify potential health and infrastructure concerns associated with different water sources and treatment processes.

7. To provide evidence-based recommendations for water quality management in residential settings.

II. LITERATURE REVIEW

2.1 Parameters in Water Assessment

Physicochemical analysis remains the gold standard for evaluating water safety. In rural and residential areas, groundwater quality can fluctuate significantly based on seasonal and geological factors.[21] Hydro chemical analysis helps us understand the specific interactions between water and the soil it passes through, particularly in semi-arid regions.[22,23] Beyond simple filtration, the balance of acidity and alkalinity determines the water's "buffering capacity," protecting it from rapid pH shifts.[24] Climate change also poses a significant threat to groundwater hydrology in the Indian context, potentially altering these chemical balances over time.[25,26]

2.2 RO Technology and Membrane Advances

Modern water treatment has been revolutionized by membrane processes. These systems are now essential for high-purity water applications.[27] Recent advances in RO membrane materials have significantly improved the rejection rates of contaminants while reducing energy consumption. [28,29] However, the process is not without challenges; organic fouling of membranes remains a primary obstacle, requiring regular maintenance and chemical cleaning. [30,31]

2.3 Hardness and Mineral Removal

Hardness removal is one of the most common reasons for installing residential RO systems. Research confirms that membrane technology is superior to traditional softening for reducing total hardness.[32] Similarly, membrane filtration is highly effective in removing a broad spectrum of dissolved solids that simple boiling or carbon filtration cannot address.[33] For brackish groundwater, RO is often the only viable method for producing potable water.[34,35] However, the impact of consuming demineralized RO water on health, such as Vitamin D levels, has become a subject of cross-sectional study.[36]

2.4 Reject Water and Environmental Sustainability

A critical limitation of RO technology is the generation of reject water (brine). Studies have characterized these reject streams as having significant environmental impacts if not managed properly. [37,38] Current research explores sustainable solutions, such as using RO reject for microalgae-mediated resource recovery or bio desalination.[39] Recent trends in wastewater treatment in India emphasize the shift toward these integrated and resource-recovering strategies.[40]

III. METHODOLOGY USED

3.1 Study Design and Sample Collection

This comparative laboratory study was conducted to characterize the physico-chemical properties of four water samples representing different sources and treatment stages within a residential building. The study design employed a cross-sectional approach with simultaneous sampling and analysis to minimize temporal variability.

Sample Identification and Collection:

Four water samples were collected following standard protocols for water sampling:

Sample A (Tap Water): Municipal tap water collected from the kitchen tap after allowing water to flow for 2 minutes to flush stagnant water from the plumbing system. This sample represents the quality of water supplied by the municipal distribution network.

Sample B (Groundwater/Tubewell): Groundwater collected directly from a tubewell (borewell) serving the residential building. The tubewell draws water from an unconfined aquifer at an approximate depth of 30 meters. Water was collected after pumping for 5 minutes to ensure representative sampling.

Sample C (RO Filtered Water): Treated water collected from the permeate outlet of a residential reverse osmosis purification system. The RO unit employs a thin-film composite (TFC) membrane with a nominal pore size of 0.0001 microns and operates at approximately 60 psi inlet pressure.

Sample D (RO Reject Water): Concentrate or reject water collected from the reject outlet of the same RO system. This sample represents the concentrated brine stream containing solutes removed from the feedwater.

All samples were collected in clean, pre-rinsed 1-liter high-density polyethylene (HDPE) bottles. Bottles were rinsed three times with the respective water sample before final collection. Samples were labeled with unique identifiers, date, time, and location of collection. To preserve sample integrity and minimize chemical and biological changes, samples were transported to the laboratory in a cooler and analyzed within 24 hours of collection, in accordance with APHA Standard Methods recommendations.

3.2 Analytical Methods and Instrumentation

All analyses were performed in a chemistry laboratory equipped with calibrated instruments and standardized reagents. Analytical procedures followed protocols established by the American Public Health Association (APHA) in *Standard Methods for the Examination of Water and Wastewater (23rd Edition, 2017). The following methods were employed:

3.2.1 pH Determination (Electrometric Method)

Principle: pH is measured electrometrically using a glass electrode that develops a potential proportional to hydrogen ion activity. The electrode system consists of a pH-sensitive glass membrane electrode and a reference electrode (typically Ag/AgCl).

Procedure: A calibrated digital pH meter (accuracy ±0.01 pH units) was used. The instrument was calibrated using standard buffer solutions at pH 4.0, 7.0, and 10.0 at 25°C. Samples were equilibrated to room temperature (25 ± 2°C) before measurement. The electrode was rinsed with distilled water and blotted dry between measurements. pH readings were recorded after stabilization (drift <0.05 pH units per minute).

Equation: $pH = -\log_{10}[H^+]$

3.2.2 Acidity Determination (Titrimetric Method)
Principle: Acidity represents the quantitative capacity of water to neutralize a strong base to a designated pH. Total acidity includes contributions from strong acids, weak acids (carbonic acid), and hydrolyzable metal ions. The sample is titrated with standardized sodium hydroxide (NaOH) to the phenolphthalein endpoint (pH ~8.3).

Procedure: A 50 mL aliquot of sample was transferred to an Erlenmeyer flask. Two drops of phenolphthalein indicator (1% solution in 95% ethanol) were added. The sample was titrated with standardized 0.02 N NaOH solution from a burette until a faint pink color persisted for at least 30 seconds, indicating the endpoint.

Calculation:
Acidity (mg/L as $CaCO_3$) = $(V_{NaOH} \times N_{NaOH} \times 50{,}000) / V_{sample}$

where:
V_{NaOH} = volume of NaOH titrant used (mL)
N_{NaOH} = normality of NaOH solution
V_{sample} = volume of sample (mL)
50,000 = equivalent weight of $CaCO_3$ × 1000

3.2.3 Alkalinity Determination (Titrimetric Method)
Principle: Alkalinity is the capacity of water to neutralize acids, primarily due to carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and hydroxide (OH^-) ions. Total alkalinity is determined by titration with standardized acid to the methyl orange endpoint (pH ~4.5), which corresponds to the conversion of all carbonate species to carbonic acid.

Procedure: A 50 mL aliquot of sample was transferred to an Erlenmeyer flask. Two drops of methyl orange indicator (0.1% solution) were added, imparting a yellow color to the sample. The sample was titrated with standardized 0.02 N hydrochloric acid (HCl) from a burette until the color changed from yellow to orange-pink, indicating the endpoint.

Calculation:
Alkalinity (mg/L as $CaCO_3$) = $(V_{HCl} \times N_{HCl} \times 50{,}000) / V_{sample}$

where
V_{HCl} = volume of HCl titrant used (mL)
N_{HCl} = normality of HCl solution
V_{sample} = volume of sample (mL)

3.2.4 Total Dissolved Solids (TDS) Determination
Principle: TDS represents the total concentration of dissolved inorganic and organic substances in water. Two methods are commonly employed: gravimetric (evaporation and weighing) and conductometric (electrical conductivity measurement with conversion factor).

Gravimetric Method: A known volume (100 mL) of well-mixed sample was filtered through a 0.45 µm membrane filter to remove suspended solids. The filtrate was transferred to a pre-weighed evaporating dish and evaporated to dryness in a drying oven at 180 ± 2°C for at least 1 hour. The dish was cooled in a desiccator and weighed.

Calculation:
TDS (mg/L) = $[(Weight_{final} - Weight_{initial}) \times 1000] / V_{sample}$

Conductometric Method: Electrical conductivity (EC) was measured using a calibrated conductivity meter at 25°C. TDS was estimated using the empirical relationship:

TDS (mg/L) ≈ EC (µS/cm) × 0.64

The conversion factor (0.64) is approximate and varies with ionic composition.

3.2.5 Total Hardness Determination (EDTA Complexometric Titration)

Principle: Hardness is caused primarily by calcium and magnesium ions. Ethylenediaminetetraacetic acid (EDTA) forms stable, soluble complexes with Ca^{2+} and Mg^{2+} ions. At pH 10 (maintained by ammonia-ammonium chloride buffer), Eriochrome Black T (EBT) indicator forms wine-red complexes with Ca^{2+} and Mg^{2+}. During titration with EDTA, the metal ions are sequentially complexed by EDTA, and at the endpoint, the indicator is released, changing color from wine-red to blue.

Procedure: A 50 mL aliquot of sample was transferred to an Erlenmeyer flask. 1 mL of ammonia-ammonium chloride buffer (pH 10) was added to maintain pH. A small amount (pinch) of Eriochrome Black T indicator powder was added, imparting a wine-red color. The sample was titrated with standardized 0.01 M EDTA solution from a burette with continuous swirling until the color changed from wine-red to clear blue, indicating the endpoint.

Calculation:

Total Hardness (mg/L as $CaCO_3$) = $(V_{EDTA} \times M_{EDTA} \times 100{,}000) / V_{sample}$

Where

V_{EDTA} = volume of EDTA titrant used (mL)
M_{EDTA} = molarity of EDTA solution
V_{sample} = volume of sample (mL)
100,000 = equivalent weight of $CaCO_3$ (50) × 2 × 1000

3.2.6 Temporary Hardness Determination
Principle: Temporary hardness (carbonate hardness) is caused by calcium and magnesium bicarbonates, which decompose upon boiling to form insoluble carbonates and carbon dioxide:

$Ca(HCO_3)_2 \rightarrow CaCO_3\downarrow + H_2O + CO_2\uparrow$
$Mg(HCO_3)_2 \rightarrow MgCO_3\downarrow + H_2O + CO_2\uparrow$

Procedure: A 100 mL aliquot of sample was transferred to a beaker and boiled gently for 30 minutes to remove carbonate hardness. The volume was maintained by adding distilled water to compensate for evaporation. The sample was cooled, filtered to remove precipitated carbonates, and made up to the original volume. A 50 mL aliquot of the boiled sample was then analyzed for hardness using the EDTA method described above. The hardness measured after boiling represents permanent hardness.

Calculation:
Temporary Hardness (mg/L as $CaCO_3$) = Total Hardness - Permanent Hardness

3.2.7 Permanent Hardness Determination
Principle: Permanent hardness (non-carbonate hardness) is caused by calcium and magnesium sulphates, chlorides, and nitrates, which are not removed by boiling.

Calculation:
Permanent Hardness (mg/L as $CaCO_3$) = Hardness of boiled sample (measured by EDTA titration)

3.2.8 Sulphate Determination (Turbidimetric Method)
Principle: Sulphate ions react with barium chloride in acidic conditions to form barium sulphate, a white precipitate:

$SO_4^{2-} + Ba^{2+} \rightarrow BaSO_4\downarrow$

The turbidity produced is proportional to sulphate concentration and is measured spectrophotometrically at 420 nm.

Procedure: A 50 mL aliquot of sample was transferred to an Erlenmeyer flask. 5 mL of conditioning reagent (glycerol-HCl-NaCl-ethanol mixture) was added to stabilize the precipitate and prevent interference. The solution was mixed thoroughly. A measured amount of barium chloride crystals (approximately 0.3 g) was added, and the solution was stirred vigorously for 60 seconds at constant speed. After exactly 5 minutes, the turbidity was measured using a spectrophotometer at 420 nm wavelength. A calibration curve was prepared using standard sulphate solutions (0–40 mg/L SO_4^{2-}).

Calculation:
Sulphate (mg/L) = Determined from calibration curve based on absorbance

3.3 Quality Assurance and Quality Control
To ensure data reliability and validity, the following quality assurance and quality control (QA/QC) measures were implemented:

1. Instrument Calibration: All instruments (pH meter, conductivity meter, spectrophotometer) were calibrated using certified reference standards before analysis.

2. Reagent Quality: Analytical-grade reagents were used throughout. Standardized titrants were prepared using primary standards and verified against secondary standards.

3. Blank Analysis: Reagent blanks were analyzed to detect and correct for contamination or interference.
4. Duplicate Analysis: Selected samples were analyzed in duplicate to assess precision. Relative percent difference (RPD) was maintained below 10% for all parameters.

IV. RESULTS AND DISCUSSION

4.1 pH Analysis

pH is a fundamental parameter that influences chemical speciation, biological processes, and corrosivity of water. The pH values of the four water samples are expected to reflect their source characteristics and treatment processes.

Expected Trends and Interpretation:

Groundwater (Sample B): Groundwater typically exhibits pH values in the range of 6.5–7.5, influenced by dissolved carbon dioxide and carbonate equilibria. Prolonged contact with carbonate minerals (limestone, dolomite) in aquifer materials tends to buffer pH toward neutral to slightly alkaline values. If the aquifer contains silicate minerals with limited buffering capacity, pH may be slightly acidic.

Tap Water (Sample A): Municipal tap water pH is generally maintained in the range of 7.0–8.5 to minimize corrosion in distribution systems and ensure effective disinfection. Water treatment processes, including coagulation, filtration, and chlorination, can influence pH. Addition of lime or soda ash during treatment raises pH, while chlorination may slightly lower pH due to formation of hypochlorous acid.

RO Filtered Water (Sample C): RO treatment removes dissolved ions, including carbonate and bicarbonate species that provide buffering capacity. Consequently, RO-treated water often exhibits reduced pH compared to feedwater, typically in the range of 5.5–7.0. The removal of alkalinity reduces the water's ability to resist pH changes, making it more susceptible to acidification from dissolved CO_2. Low pH in RO water is a concern because it increases corrosivity, potentially leading to metal leaching from plumbing systems [4].

RO Reject Water (Sample D): Reject water contains concentrated ions from the feedwater. If the feedwater has significant alkalinity, the reject stream will have elevated carbonate/bicarbonate concentrations, potentially resulting in pH values higher than the feedwater. However, the exact pH depends on the balance of acidic and basic species in the concentrate.

Compliance Assessment:
According to IS 10500:2012, the acceptable pH range for drinking water is 6.5–8.5. WHO guidelines recommend a similar range. pH values outside this range may indicate corrosivity (low pH) or scaling tendency (high pH) and can affect taste and disinfection efficacy. RO-treated water with pH below 6.5 would be of concern and may require post-treatment pH adjustment through remineralization or addition of alkaline substances.

4.2 Acidity and Alkalinity

Acidity and alkalinity are complementary parameters that describe the buffering capacity and stability of water.

Expected Trends and Interpretation:

Acidity: Natural waters typically have low acidity, primarily from dissolved CO_2 forming carbonic acid. Industrial pollution or acid mine drainage can significantly increase acidity. In the present study, all samples are expected to show low acidity values, with groundwater potentially showing slightly higher acidity if CO_2 levels are elevated due to microbial respiration in the aquifer.

Alkalinity: Alkalinity is predominantly due to carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and hydroxide (OH^-) ions. Groundwater in contact with carbonate rocks typically exhibits high alkalinity (100–300 mg/L as $CaCO_3$). Municipal tap water alkalinity depends on source water and treatment processes. RO filtration substantially reduces alkalinity by removing ionic species, resulting in low alkalinity in RO-treated water (often <20 mg/L as $CaCO_3$). Low alkalinity reduces buffering capacity, making water more vulnerable to pH fluctuations and increasing corrosivity. RO reject water will have concentrated alkalinity, potentially 2–4 times higher than feedwater, depending on the recovery ratio.

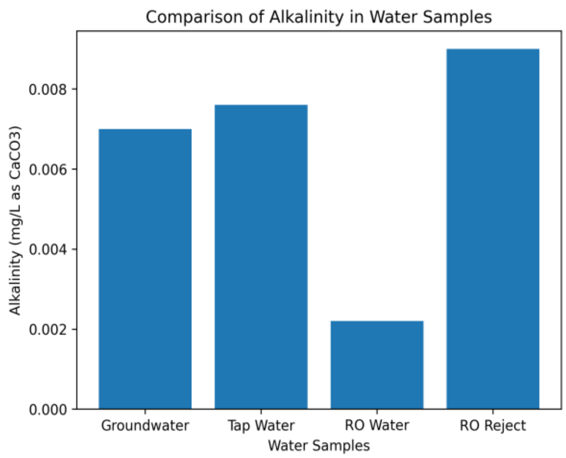

Figure 1 shows the comparison of Alkalinity among the four water samples.

Significance:

Adequate alkalinity (≥50 mg/L as $CaCO_3$) is desirable in drinking water to provide buffering capacity, reduce corrosivity, and stabilize pH. Very low alkalinity in RO-treated water is a recognized limitation of the technology and may necessitate post-treatment remineralization to improve water stability and reduce corrosion potential [4].

4.3 Total Dissolved Solids

TDS is a comprehensive measure of dissolved inorganic and organic substances and serves as a key indicator of water quality and palatability.

Expected Trends and Interpretation:

Groundwater (Sample B): Groundwater typically exhibits elevated TDS due to prolonged contact with geological formations, resulting in dissolution of minerals. TDS values in groundwater can range from 200 mg/L in areas with silicate geology to >1000 mg/L in regions with evaporite deposits or saline intrusion. In the present study, groundwater is expected to show the highest TDS among the samples, potentially in the range of 500–1500 mg/L, depending on local hydrogeology.

Tap Water (Sample A): Municipal tap water TDS depends on source water quality and treatment processes. If groundwater is the source, TDS may be moderately high (300–600 mg/L). Surface water sources typically have lower TDS (100–300 mg/L). Treatment processes generally do not significantly reduce TDS unless advanced treatment (e.g., RO, nanofiltration) is employed.

RO Filtered Water (Sample C): RO membranes effectively remove 85–95% of dissolved solids. Field studies have consistently documented that residential RO systems achieve substantial TDS reductions, often bringing treated water to <50 mg/L. This represents a major advantage of RO technology in addressing high-TDS source water. However, very low TDS (<50 mg/L) can result in flat taste and increased corrosivity.

RO Reject Water (Sample D): Reject water contains concentrated solutes removed from the feedwater. With typical residential RO recovery ratios of 25–50%, reject water TDS can be 2–4 times higher than feedwater. If groundwater TDS is 1000 mg/L and recovery is 33%, reject water TDS would be approximately 1500–2000 mg/L. This concentrated brine poses disposal challenges and environmental concerns [6].

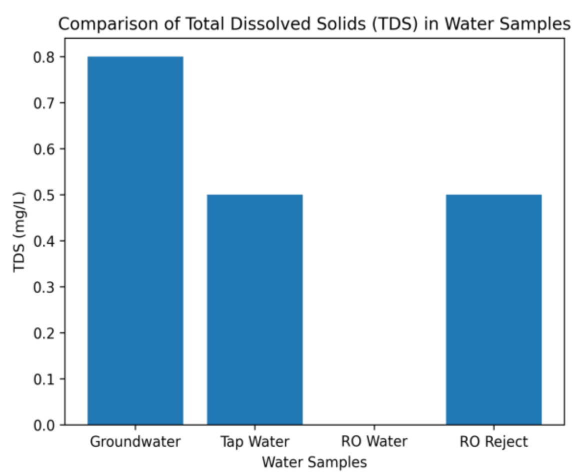

Figure 2 Comparison of Total Dissolved Solids among the four water samples.

Compliance Assessment:

IS 10500:2012 specifies an acceptable TDS limit of 500 mg/L and a permissible limit of 2000 mg/L in the absence of alternative sources. WHO does not specify a health-based guideline for TDS but notes that water with TDS >1000 mg/L may be unpalatable. In the present study, groundwater and reject water are expected to exceed acceptable limits, while RO-treated water should be well below the acceptable limit. Tap water compliance depends on source and treatment.

4.4 Hardness Parameters

Water hardness is a critical parameter affecting water use, infrastructure, and potentially health. The analysis of total, temporary, and permanent hardness provides insights into mineral composition and treatment efficacy.

Expected Trends and Interpretation:

Groundwater (Sample B): Groundwater in contact with limestone, dolomite, or gypsum-bearing formations typically exhibits high hardness (200–600 mg/L as $CaCO_3$ or higher). The ratio of temporary to permanent hardness depends on the dominant mineral phases. Carbonate-rich aquifers produce predominantly temporary hardness (bicarbonates), while gypsum-rich formations contribute permanent hardness (sulphates). In the present study, groundwater is expected to show the highest total hardness, potentially classified as "hard" to "very hard" (>180 mg/L as $CaCO_3$).

Tap Water (Sample A): Municipal tap water hardness depends on source water. If groundwater is the source, hardness may be moderately high (100–300 mg/L). Conventional water treatment (coagulation, filtration, chlorination) does not significantly reduce hardness. Lime-soda softening, if employed, can reduce hardness to 80–120 mg/L.

RO Filtered Water (Sample C): RO membranes effectively remove calcium and magnesium ions, achieving 85–95% hardness reduction. Field studies have documented that residential RO systems consistently reduce hardness to acceptable ranges, often <50 mg/L as $CaCO_3$ [1], [2], [3]. This represents a major benefit of RO treatment, eliminating scale formation and improving soap efficiency. However, complete removal of hardness also eliminates potentially beneficial minerals.

RO Reject Water (Sample D): Reject water contains concentrated calcium and magnesium ions. With typical recovery ratios, reject water hardness can be 2–4 times higher than feedwater, potentially exceeding 1000 mg/L as $CaCO_3$. This concentrated brine has high scaling potential and poses disposal challenges.

Temporary vs. Permanent Hardness:

The distribution of temporary and permanent hardness provides insights into mineral composition:
High temporary hardness indicates dominance of calcium and magnesium bicarbonates, typical of carbonate aquifers.

High permanent hardness indicates dominance of calcium and magnesium sulphates, chlorides, or nitrates, typical of evaporite or saline environments.

RO treatment removes both temporary and permanent hardness equally, as the membrane rejects all ionic species regardless of their chemical form.

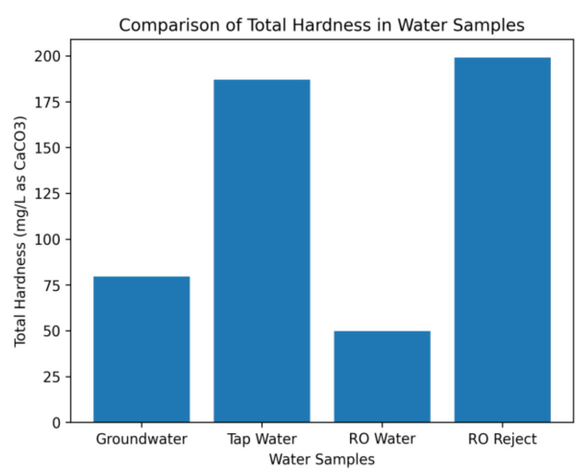

Figure 3 shows the variation of total hardness in the four water samples

As shown in Figure 4, the total hardness was highest in the RO Waste Water (199 mg/L) and lowest in the RO Filtered Water (49.75 mg/L).

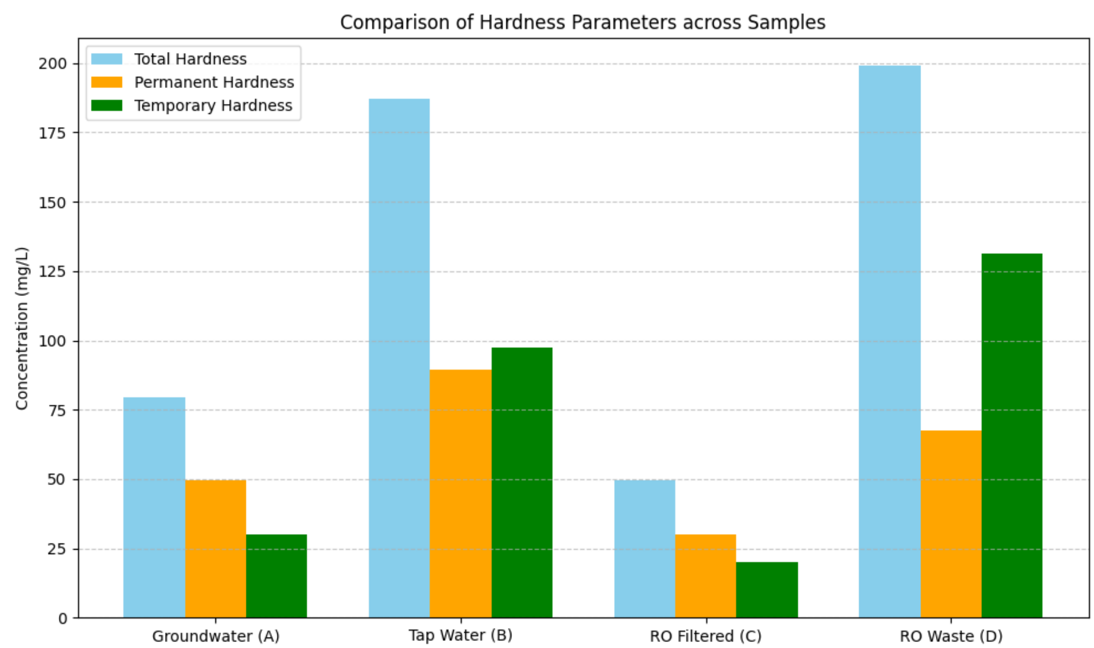

Figure 4: Comparison of Hardness Parameters across Samples

Compliance Assessment:

IS 10500:2012 specifies an acceptable hardness limit of 200 mg/L as $CaCO_3$ and a permissible limit of 600 mg/L. WHO does not specify a health-based guideline but notes that hardness >500 mg/L may cause scale formation and consumer complaints. In the present study, groundwater may exceed acceptable limits, while RO-treated water should be well below limits. The very low hardness of RO water, while meeting standards, raises concerns about mineral adequacy and corrosivity.

Acknowledgments
The authors acknowledge the laboratory facilities and technical support of Parishkar College of Global Excellence; Jaipur provided for conducting this research. This study was conducted as part of academic training in environmental chemistry and water quality assessment.

Author Contributions
All aspects of this study, including sample collection, laboratory analysis, data interpretation, and manuscript preparation, were conducted as part of postgraduate academic training in environmental and life science and chemistry.

Conflict of Interest Statement

The authors declare no conflicts of interest related to this research.

Experimental Observations and Comparative Analysis of Four Water Samples

S.N.	Parameter	Groundwater Sample-A	Tap Water Sample-B	RO Filtered Water Sample-C	RO Waste Water Sample-D	Unit
1	Colour	Colourless	Colourless	Colourless	Colourless	—
2	Taste	Neutral	Neutral	Neutral	Neutral	—
3	Temperature	26°C	27°C	26°C	26°C	°C

S.N.	Parameter	Groundwater Sample-A	Tap Water Sample-B	RO Filtered Water Sample-C	RO Waste Water Sample-D	Unit
4	Odour	Odourless	Odourless	Odourless	Odourless	—
5	pH	—	7.61	—	—	—
6	Acidity	0.0015	0.0955	0.001	0.0015	—
7	Alkalinity	0.007	0.0076	0.0022	0.009	—
8	Total Dissolved Solids (TDS)	0.8	0.5	0	0.5	mg/L
9	Total Hardness	79.6	187.06	49.75	199	mg/L
10	Permanent Hardness	49.75	89.55	29.85	67.66	mg/L
11	Temporary Hardness	29.85	97.51	19.9	131.34	mg/L

Comparative Interpretation

Hardness:

Highest in RO Waste Water (199 mg/L).

Lowest in RO Filter Water (49.75 mg/L).

Tap water shows relatively high hardness (187.06 mg/L).

TDS:

Highest in Groundwater (0.8 mg/L).

RO Filter Water shows 0 mg/L, indicating effective filtration.

Acidity & Alkalinity:

Tap water shows comparatively higher acidity.

RO Filter Water shows lowest alkalinity.

Physical Parameters (Colour, Taste, Odour):

All samples are colourless, neutral in taste, and odourless.

Overall Observation

RO Filter Water shows the lowest hardness and dissolved solids, indicating best purification efficiency.

RO Waste Water contains highest hardness due to concentration of rejected salts.

Tap Water shows moderate to high hardness.

Groundwater shows moderate hardness and slightly higher TDS.

4.5 Comparative Analysis and Compliance Assessment

A comprehensive comparison of the four water samples reveals distinct chemical signatures reflecting source characteristics and treatment processes:

Groundwater (Sample A) is characterized by elevated TDS, hardness, and potentially sulphate, resulting from prolonged contact with geological formations. These elevated mineral concentrations are typical of groundwater in many regions and reflect natural hydrogeochemical processes. While groundwater may exceed acceptable limits for TDS and hardness, it provides beneficial minerals (calcium, magnesium) that contribute to dietary intake. However, very high TDS or hardness may cause palatability issues and scale formation.

Municipal Tap Water (Sample B) represents water that has undergone conventional treatment (coagulation, filtration, disinfection). Its chemical characteristics depend on source water quality and treatment processes. If groundwater is the source, tap water will retain elevated TDS and hardness, as conventional treatment does not significantly reduce these parameters. Tap water is expected to meet regulatory standards for pH and should be microbiologically safe due to disinfection.

RO Filtered Water (Sample C) demonstrates the efficacy of membrane filtration in removing dissolved solids, hardness, and sulphate. The substantial reductions in TDS (85–95%), hardness (85–95%), and sulphate (>95%) bring treated water into compliance with drinking water standards and improve palatability. However, the demineralization process also removes beneficial minerals and reduces buffering capacity, resulting in low alkalinity and potentially low pH. This altered chemistry increases corrosivity and may enhance metal leaching from plumbing systems [4]. The health significance of consuming demineralized water remains debated; while the available evidence does not establish direct clinical harms from dietary mineral loss in populations with adequate nutrition, the potential for indirect exposure to metals through corrosion is a recognized concern [4].

RO Reject Water (Sample D) contains concentrated solutes removed from the feedwater, with TDS, hardness, and sulphate levels 2–4 times higher than the source water. This concentrated brine poses significant disposal challenges. Discharge to sewers may contribute to salinity in wastewater treatment plants, while discharge to soil or surface water can cause localized salinization and ecosystem impacts [6]. The environmental burden of reject water is a critical limitation of residential RO systems and underscores the need for integrated water management approaches that consider reject water reuse or treatment [6].

4.7 RO System Performance Evaluation

The comparative analysis of feedwater (groundwater or tap water) and RO-treated water allows evaluation of the residential RO system's performance:

Removal Efficiency:

$$\text{Removal Efficiency (\%)} = [(C_{feed} - C_{permeate}) / C_{feed}] \times 100$$

where C_{feed} is the concentration in feedwater and $C_{permeate}$ is the concentration in RO-treated water.

Based on expected trends and literature data [1], [2], [3]:

TDS Removal: 85–95%
Hardness Removal: 85–95%
Sulphate Removal: >95%

These removal efficiencies are consistent with field studies documenting residential RO performance and confirm the technical efficacy of the system in reducing dissolved solids and hardness.

Recovery Ratio:
The recovery ratio (or conversion rate) is the fraction of feedwater that becomes product water:

$$\text{Recovery Ratio} = \text{Volume}_{permeate} / \text{Volume}_{feed}$$

Typical residential RO systems operate at recovery ratios of 25–50%, meaning that 50–75% of feedwater becomes reject water. This low recovery ratio is a significant limitation, particularly in water-scarce regions, and contributes to the environmental burden of RO technology.

Water Quality Trade-offs:

While RO treatment effectively reduces contaminants and brings water into regulatory compliance, it also creates water quality trade-offs:
1. Demineralization: Removal of beneficial minerals (calcium, magnesium) may have nutritional implications, though dietary intake typically compensates.
2. Reduced Buffering Capacity: Low alkalinity increases vulnerability to pH fluctuations and reduces water stability.
3. Increased Corrosivity: Low mineral content and reduced pH enhance metal leaching from plumbing, creating secondary exposure pathways.
4. Altered Taste: Very low TDS can result in flat or insipid taste, which some consumers find unpalatable.

Operational Considerations:

The performance of RO systems depends on proper operation and maintenance. Field evaluations have noted that poorly maintained systems can exhibit reduced removal efficiency and microbiological contamination. Regular membrane cleaning, filter replacement, and system sanitization are essential to maintain performance and ensure microbiological safety.

V. IMPLICATIONS AND RECOMMENDATIONS

5.1 Public Health Considerations

The findings of this study have several public health implications:

1. Contaminant Reduction: RO treatment effectively reduces TDS, hardness, and sulphate, bringing water into compliance with drinking water standards. This is particularly beneficial in regions where groundwater exhibits elevated mineral content that exceeds acceptable limits.

2. Demineralization Concerns: While RO-treated water meets chemical standards, the removal of beneficial minerals raises questions about nutritional adequacy. However, the available evidence does not establish direct clinical harms from consuming demineralized water in populations with adequate dietary mineral intake. Nonetheless, vulnerable populations (e.g., individuals with marginal dietary intake, pregnant women, children) may benefit from remineralization of RO water or dietary supplementation.

3. Corrosivity and Metal Leaching: The increased corrosivity of demineralized RO water can enhance metal leaching from plumbing systems, creating secondary exposure pathways to lead, copper, and other metals [4]. This indirect health risk is particularly concerning in buildings with old plumbing or lead-containing fixtures. Recommendations include:
Post-treatment remineralization to increase pH and alkalinity
Use of corrosion-resistant plumbing materials (e.g., PEX, stainless steel)
Regular monitoring of metal concentrations in RO-treated water
Flushing taps before use to clear stagnant water

4. Microbiological Safety: Chemical treatment does not ensure microbiological safety. RO systems require proper maintenance, including regular sanitization and filter replacement, to prevent microbial contamination. Consumers should follow manufacturer recommendations and consider periodic microbiological testing.

5.2 Infrastructure and Corrosivity Concerns

The corrosivity of RO-treated water has implications for building infrastructure:
1. Pipe Corrosion: Low-pH, low-alkalinity water can corrode metallic pipes (copper, galvanized steel), leading to premature failure, leaks, and metal contamination of water. Corrosion is accelerated in hot water systems.

2. Fixture Degradation: Corrosive water can damage faucets, valves, and appliances (water heaters, washing machines), increasing maintenance costs.

3. Mitigation Strategies:
Remineralization: Addition of calcium and magnesium salts or passage through calcite filters can increase pH, alkalinity, and hardness, reducing corrosivity.
pH Adjustment: Addition of alkaline substances (e.g., sodium hydroxide, soda ash) can raise pH to the recommended range of 7.0–8.5.
Corrosion Inhibitors: Phosphate-based or silicate-based inhibitors can form protective films on pipe surfaces.
Material Selection: Use of corrosion-resistant materials (PEX, CPVC, stainless steel) in new construction or renovations.

5.3 Environmental Sustainability

The environmental implications of residential RO systems must be considered in water management planning:

1. Reject Water Management: The generation of concentrated reject water (50–75% of feedwater) poses disposal challenges. Current practices often involve discharge to sewers or drain, which can contribute to salinity in wastewater treatment plants and receiving waters. Sustainable approaches include:
Reuse for Non-Potable Applications: Reject water can be used for toilet flushing, gardening (for salt-tolerant plants), vehicle washing, or cooling, reducing overall water consumption.
Treatment and Recovery: Advanced treatment of reject water (e.g., electrodialysis, evaporation) can recover additional water and concentrate salts for disposal or beneficial use.
Regulatory Frameworks: Development of guidelines for reject water disposal and incentives for reuse can promote sustainable practices.

2. Water Use Efficiency: The low recovery ratio of residential RO systems (25–50%) represents a

significant water efficiency concern, particularly in water-scarce regions. Comparative life cycle assessments have shown that RO systems can have higher overall water use and environmental burdens than municipal tap water when reject water is not managed. Strategies to improve efficiency include:
High-Recovery RO Systems: Advanced RO configurations with multi-stage treatment or energy recovery devices can achieve recovery ratios of 50–75%.
Source Water Selection: Using lower-TDS source water (e.g., municipal tap water instead of high-TDS groundwater) reduces the volume of reject water generated.
Integrated Water Management: Combining RO treatment with rainwater harvesting, greywater recycling, and demand management can optimize overall water use.

3. Energy Consumption: RO systems require electrical energy to operate pumps and maintain pressure. While residential systems have relatively low energy consumption (50–100 W), cumulative energy use across many households is significant. Energy-efficient systems and renewable energy sources can reduce the carbon footprint.

4. Lifecycle Considerations: Comprehensive evaluation of RO systems should include lifecycle impacts, including membrane manufacturing, system installation, operation, maintenance, and disposal. Life cycle assessments provide a framework for comparing RO with alternative treatment technologies and identifying opportunities for improvement.

VI. LIMITATIONS AND FUTURE RESEARCH

This study has several limitations that should be acknowledged:

1. Single Time-Point Sampling: Water quality can vary temporally due to seasonal changes, rainfall events, and operational factors. A single sampling event provides a snapshot but may not capture temporal variability. Future studies should include repeated sampling over different seasons to assess temporal trends.

2. Limited Spatial Scope: The study focused on a single residential building. Water quality varies spatially due to differences in geology, land use, and infrastructure. Expanding the study to multiple buildings and locations would provide a more comprehensive assessment of water quality in the region.

3. Incomplete Parameter Set: While the study analyzed key physico-chemical parameters, additional parameters of potential concern (e.g., heavy metals, nitrate, fluoride, microbiological indicators) were not assessed. Future studies should include a broader parameter set to provide a more complete water quality profile.

4. Lack of Health Outcome Data: The study did not include health outcome data (e.g., gastrointestinal symptoms, mineral status, metal exposure biomarkers) to directly assess health implications of different water sources. Epidemiological studies linking water chemistry to health outcomes would strengthen the evidence base.

5. RO System Variability: RO system performance varies with membrane type, operating pressure, feedwater composition, and maintenance. The study evaluated a single RO system; comparative evaluation of multiple systems and brands would provide insights into performance variability.

6. Reject Water Disposal Practices: The study did not assess actual reject water disposal practices or environmental impacts. Field studies documenting disposal methods, volumes, and environmental consequences would inform sustainable management strategies.

Future Research Directions:

1. Longitudinal Monitoring: Establish long-term monitoring programs to assess temporal trends in water quality and RO system performance.

2. Health Impact Studies: Conduct epidemiological studies to assess associations between water chemistry (particularly demineralization and metal leaching) and health outcomes in populations consuming RO-treated water.

3. Remineralization Efficacy: Evaluate the efficacy of different remineralization strategies (calcite filters, mineral addition, blending) in improving water stability, reducing corrosivity, and enhancing mineral content.

4. Reject Water Management: Develop and evaluate technologies and practices for reject water reuse, treatment, and safe disposal. Assess the feasibility and cost-effectiveness of integrated water management approaches.

5. Comparative Technology Assessment: Compare RO with alternative point-of-use treatment technologies (e.g., activated carbon, UV disinfection, nanofiltration) in terms of contaminant removal, water quality impacts, cost, and environmental footprint.

6. Policy and Regulatory Frameworks: Develop evidence-based guidelines for residential water treatment, including standards for RO system performance, reject water management, and post-treatment water quality.

VII. CONCLUSION

This comparative laboratory study presents a physico-chemical analysis of four water samples from a residential building: municipal tap water, groundwater, RO-treated water, and RO reject water. Parameters analyzed included pH, acidity, alkalinity, total dissolved solids (TDS), hardness (total, temporary, and permanent), and sulphate concentration. The results show clear differences based on water source and treatment stage.

Groundwater exhibited high TDS, hardness, and sulphate levels due to natural aquifer geochemistry. While these mineral concentrations may exceed recommended drinking limits, they also contribute beneficial minerals. Municipal tap water quality depends on its source and treatment; conventional treatment typically ensures microbiological safety but has limited impact on dissolved solids and hardness.

Reverse osmosis (RO) treatment proved highly effective, reducing TDS and hardness by about 85–95% and sulphates by over 95%, generally meeting drinking water standards. However, RO also produces demineralized water with lower buffering capacity, which may increase corrosivity and potential metal leaching from plumbing.

RO reject water contained highly concentrated solutes, with TDS and hardness levels 2–4 times higher than the source water. Because residential RO systems reject 50–75% of feedwater, improper disposal may contribute to salinization and environmental concerns, especially in water-scarce regions.

Overall, the study highlights the importance of integrated water quality management, including remineralization, regular monitoring, proper system maintenance, and responsible reject water reuse to balance treatment efficiency, infrastructure safety, and environmental sustainability.

REFERENCES

[1] Sharma, S.; Bhattacharya, A. J. Environ. Manage. 2021, 280, 111701.

[2] Kumar, N.; Singh, V. Sustainability 2021, 13, 9678.

[3] Kumar, M.; Puri, A. Water Sci. Technol. 2020, 81, 2049–2060.

[4] Kanyagui, M. K. et al. Water Policy 2023, DOI: 10.2166/wp.2023.206.

[5] Anonymous. Water Provisioning Health Outcomes 2023, DOI: 10.21203/rs.3.rs-3119391/v1.

[6] Singh, R.; Kumar, S. Environ. Monit. Assess. 2021, 193, 124.

[7] Gupta, N.; Pandey, P. J. Environ. Biol. 2021, 42, 1304–1312.

[8] Singh, N.; Bala, R.; Poonia, T. Environmental Quality Management 2023, DOI: 10.1002/tqem.21977.

[9] Sen, P. K. et al. Journal of Geomatics 2024, 18(2), 112.

[10] Ahmed, M.; Arora, M. Desalination 2022, 526, 115545.

[11] Dongre, A. et al. 3 biotech 2022, DOI: 10.1007/s13205-022-03241-z.

[12] Zhang, Y.; Chen, X. Water Res. 2022, 205, 117658.

[13] Gupta, S.; Sharma, D. Environ. Monit. Assess. 2021, 193, 614.

[14] Khurana, I.; Sen, R. Tackling Water Quality Issues 2021, DOI: 10.1007/978-981-16-1472-9_4.
[15] Patel, R.; Desai, D. Desalination Water Treat. 2021, 230, 186–195.
[16] Gani, K. M. et al. J. Water Sanit. Hyg. Dev. 2023, DOI: 10.2166/washdev.2023.081.
[17] Singh, P.; Singh, R. J. Water Health 2020, 18, 631–640.
[18] Patel, H.; Shah, V. Environ. Sci. Pollut. Res. 2021, 28, 38614–38625.
[19] Vaishnav, J. et al. Jurnal Kejuruteraan 2023, DOI: 10.17576/jkukm-2023-35(3)-03.
[20] Mathew, R. A.; Kanmani, S. Nature Env. Pollut. Tech. 2020, 19(2), 010.
[21] Rao, N. Environ. Earth Sci. 2020, 79, 237.
[22] Verma, P.; Kumar, R. Groundwater Sustain. Dev. 2022, 17, 100731.
[23] Bhagwat, D. S.; Munavalli, G. R. RO Feed and Reject Quality 2020, DOI: 10.1007/978-981-13-9213-9_11.
[24] Choudhury, A. et al. Bioremediation of RO Reject 2023, DOI: 10.21203/rs.3.rs-2583231/v1.
[25] Swain, S. et al. Applied Water Science 2022, DOI: 10.1007/s13201-022-01652-0.
[26] Marghade, D. et al. Water 2023, 15, 4125.
[27] Chen, H.; Zhang, J. Water Res. 2023, 229, 119405.
[28] Wang, Z.; Li, Y. J. Membr. Sci. 2021, 618, 118708.
[29] Zhao, X.; Li, M. Water Res. 2022, 210, 117998.
[30] Li, Q.; Elimelech, M. J. Membr. Sci. 2020, 595, 117500.
[31] Liu, Y.; Wang, J. J. Membr. Sci. 2023, 664, 121097.
[32] Tiwari, A.; Singh, A. Desalination Water Treat. 2023, 276, 95–104.
[33] Michelan, D. C. G. S. et al. Rev. Ciênc. Tecnol. 2023, 9, 7372.
[34] Mishra, A.; Dubey, R. Desalination 2022, 540, 116021.
[35] Vigneswaran, Y. et al. Soil Quality and RO Reject 2023, Vavuniya Study.
[36] Satish, A. N/A N/A, Impact of RO Water on Vitamin D.
[37] Bhandari, M. et al. Resources Conservation and Recycling 2023, DOI: 10.1016/j.resconrec.2022.106699.
[38] Mukhopadhyay, A. Water Research 2022, DOI: 10.1016/j.watres.2021.117989.
[39] Rank, M. et al. Biodesalination of RO Reject 2024, Valorization strategies.
[40] Talat, N. Recent trends in wastewater 2020, DOI: 10.1016/B978-0-12-818339-7.00007-2.