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Hydrochemical Characteristics of Groundwater in Aquaculture-Dominated Regions: A Review

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Abstract: *Aquaculture has emerged as a major contributor to global food security; however, its rapid expansion has raised concerns regarding its influence on groundwater quality and hydrochemical characteristics. Among the key water quality parameters, alkalinity and hardness play significant roles in maintaining the chemical stability and biological productivity of aquaculture systems. Adequate alkalinity acts as a buffering agent that stabilizes pH, minimizes the toxicity of ammonia and carbon dioxide, and supports efficient biofiltration through enhanced nitrification. Similarly, water hardness, primarily governed by calcium and magnesium ions, reduces the toxicity of heavy metals such as copper and zinc, thereby improving aquatic organism health. Nevertheless, imbalances in these parameters can adversely affect aquatic ecosystems. In waters characterized by high alkalinity but low calcium concentrations, intensive photosynthetic activity may elevate pH to levels that become harmful to fish and other aquatic organisms. Furthermore, excessive alkalinity can alter ecosystem functioning and reduce biodiversity. The expansion of aquaculture, particularly in coastal regions, has also been associated with groundwater salinization caused by seawater intrusion and the seepage of saline aquaculture effluents, leading to significant changes in alkalinity, hardness, salinity, and other physicochemical parameters. This review synthesizes recent findings on the interactions between aquaculture practices and groundwater quality, with particular emphasis on alkalinity, hardness, salinity, and their ecological implications. It also highlights the need for sustainable aquaculture management practices to minimize groundwater contamination and ensure long-term environmental sustainability.*

Keywords: Aquaculture, groundwater contamination, alkalinity, hardness, salinity, biofiltration, nitrification, photosynthesis, aquatic ecosystem, water quality

1. Introduction

Water quality is one of the most critical determinants of successful aquaculture production, directly influencing the growth, survival, and health of cultured organisms. Among the various physicochemical parameters, **alkalinity** and **hardness** play indispensable roles in maintaining the chemical stability and biological productivity of aquatic ecosystems. These parameters are largely controlled by the geological characteristics of a region, the weathering of carbonate-bearing rocks, and the interaction of rainwater and surface water with subsurface formations. Naturally acidic rainwater enhances the dissolution of carbonate minerals such as limestone and dolomite, resulting in groundwater enriched with bicarbonate, carbonate, calcium, and magnesium ions. Consequently, groundwater sources in carbonate-rich regions generally exhibit higher alkalinity and hardness than surface waters, making them suitable for aquaculture applications due to their relatively stable physicochemical properties and lower risk of microbial contamination [1–7].

Groundwater has long been recognized as a preferred water source for aquaculture because of its minimal seasonal fluctuations in temperature and water chemistry. However, groundwater used in aquaculture, particularly in coastal areas, is often characterized by elevated salinity and dissolved mineral concentrations resulting from natural geological processes or seawater intrusion. These hydrochemical characteristics significantly influence water buffering capacity, nutrient cycling, and aquatic ecosystem functioning. Therefore, understanding the interactions between groundwater chemistry and aquaculture operations is essential for sustainable water resource management.

Alkalinity represents the capacity of water to neutralize acids and resist changes in pH. This buffering capacity is primarily attributed to bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and hydroxide ions present in water. Stable pH conditions are essential in aquaculture systems because biological and biochemical processes continuously alter the acid-base balance. Carbon dioxide produced during respiration forms carbonic acid, increasing hydrogen ion concentration and lowering pH, whereas ammonia excreted by aquatic organisms tends to increase pH through proton consumption. The equilibrium between ammonia (NH_3) and ammonium (NH_4^+) is strongly influenced by pH; under acidic conditions, the less toxic ammonium form predominates, whereas alkaline conditions favor the more toxic un-ionized ammonia. Consequently, maintaining an optimal pH range of approximately **7.0–8.0** is considered ideal for minimizing the toxic effects of both ammonia and carbon dioxide in aquaculture systems [5,11].

Nitrogen transformation processes further emphasize the importance of alkalinity in aquaculture. Fish and crustaceans excrete nitrogen primarily as ammonia, which must be converted into less toxic nitrate through biological nitrification. This process is carried out by autotrophic nitrifying bacteria in two sequential steps: oxidation of ammonia to nitrite, followed by oxidation of nitrite to nitrate. Nitrification consumes alkalinity and generates carbonic acid, thereby reducing the buffering capacity of the water. Insufficient alkalinity inhibits nitrifying bacterial activity, leading to the accumulation of toxic ammonia and nitrite. Therefore, maintaining adequate alkalinity is essential not only for pH stabilization but also for sustaining efficient biofiltration and nitrogen removal in intensive aquaculture systems [5].

Although alkalinity does not exert direct physiological effects on fish and crustaceans, it strongly influences their aquatic environment. Biological activities such as respiration, photosynthesis, and microbial metabolism continuously modify carbon dioxide concentrations and pH. During daylight hours, phytoplankton consume carbon dioxide through photosynthesis, causing pH to increase, whereas respiration during nighttime releases carbon dioxide, lowering pH. In waters with inadequate buffering capacity, these diurnal fluctuations can become severe enough to stress aquatic organisms and impair microbial processes such as nitrification. Aeration can partially alleviate excessive carbon dioxide accumulation, but adequate alkalinity remains the primary mechanism for maintaining pH stability and supporting biological productivity.

The availability of inorganic carbon for photosynthesis is also closely linked to alkalinity. Waters containing alkalinity above approximately **20 mg L^{-1}** generally provide sufficient bicarbonate and carbonate ions to sustain phytoplankton growth, whereas lower alkalinity can limit primary productivity due to carbon deficiency. In commercial aquaculture, alkalinity levels exceeding **80–100 mg L^{-1}** are generally recommended to ensure effective buffering, promote nitrification, and improve fertilizer efficiency. Nevertheless, excessively high alkalinity may alter aquatic ecosystem functioning, reduce species diversity, and modify the bioavailability and toxicity of heavy metals and agricultural contaminants [5]. Groundwater commonly exhibits substantially higher alkalinity than surface waters because of prolonged contact with carbonate minerals, with concentrations often exceeding **500 mg L^{-1}** in carbonate-rich aquifers.

Water hardness is another fundamental parameter governing aquaculture water quality. Hardness is primarily determined by dissolved divalent cations, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}), which originate from the dissolution of carbonate and sulfate minerals. Calcium plays an essential role in skeletal development, exoskeleton formation, osmoregulation, muscle contraction, nerve transmission, blood clotting, and numerous metabolic processes in aquatic organisms. Freshwater fish generally exhibit optimal growth and health when total hardness is maintained near **100 mg L^{-1}** as calcium carbonate. Magnesium, the second most abundant cation in seawater after sodium, contributes significantly to total hardness and participates in several physiological and biochemical processes [8,10].

In addition to its nutritional significance, hardness reduces the toxicity of several heavy metals, including copper, zinc, cadmium, and lead, by decreasing their bioavailability to gill-breathing organisms. Consequently, waters with adequate hardness provide greater protection against metal toxicity and environmental stress. Similar benefits have also been reported for crustaceans, where calcium availability supports successful moulting and shell formation. Beyond aquaculture, calcium and magnesium are also essential constituents of drinking water and contribute to human health. Although moderate concentrations are considered beneficial, excessive hardness is often associated with elevated dissolved solids that may adversely affect water quality and usability [4,9].

The rapid expansion of aquaculture has intensified concerns regarding groundwater quality, particularly in coastal regions where saline aquaculture practices may promote seawater intrusion and the seepage of mineral-rich pond effluents into surrounding aquifers. Such processes alter groundwater hydrochemistry by increasing salinity, alkalinity, hardness, and dissolved ion concentrations, potentially affecting agricultural productivity, freshwater availability, and ecosystem health. Despite considerable research on individual water quality parameters, a comprehensive synthesis of the interactions among alkalinity, hardness, groundwater chemistry, and aquaculture practices remains limited.

Therefore, this review critically examines the current understanding of alkalinity and hardness in aquaculture systems, emphasizing their hydrochemical controls, ecological significance, effects on aquatic organisms, and their role in groundwater quality deterioration. The review also discusses the environmental implications of aquaculture-induced groundwater contamination and highlights sustainable management strategies aimed at protecting groundwater resources while supporting the continued growth of aquaculture.

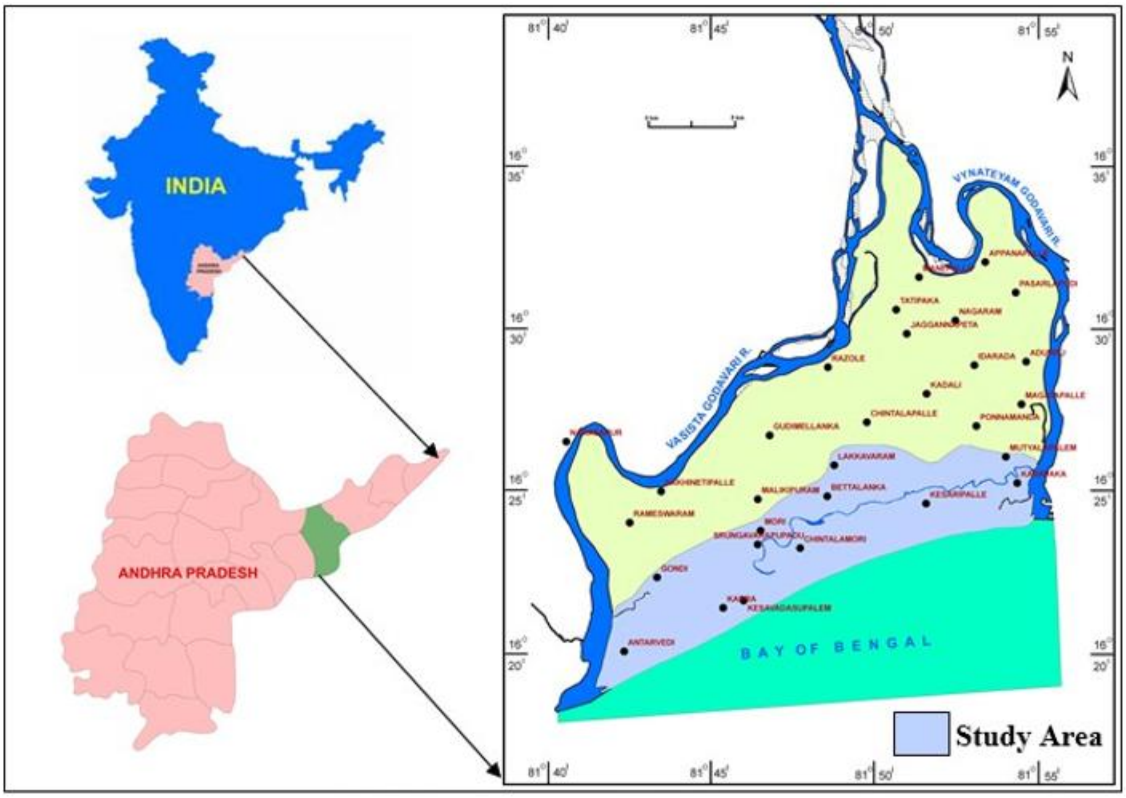

Figure 1: Location Map of the Study Area

2. Study Area

Several studies investigating the influence of aquaculture on groundwater quality have been conducted in the coastal regions of the Godavari delta, one of India's most productive aquaculture belts. Located along the eastern coast of India in the present-day **Andhra Pradesh**, the deltaic region is characterized by extensive brackish water aquaculture, fertile alluvial plains, and a dense network of distributaries of the Godavari River. The coastal zone between the Vasista Godavari and Vainateyam Godavari distributaries has received considerable attention owing to its rapid expansion of shrimp and fish farming and the associated concerns regarding groundwater salinization and hydrochemical alterations.

The study region covers approximately **125 km²** and extends nearly **5 km inland from the Bay of Bengal coastline**, encompassing several villages in the **Konaseema district** (formerly part of East Godavari district), including Antarvedi, Mori, Chintalamori, Kesanapalli, Karavaka, Mutyalapalem, Lakkavaram, Battelanka, Visweswarapuram, Gudapalli, Katrenipadu, Toorpupalem, Sankaraguptham, Kesavadasupalem, and Gondi. Geographically, the region lies between **16°18′–16°23′ N latitude** and **81°42′–81°57′ E longitude**, corresponding to Survey of India toposheets **65H/11** and **65H/15**.

The hydrogeology of this coastal delta is dominated by unconsolidated alluvial sediments comprising sand, silt, clay, and shell deposits. The shallow aquifers are highly vulnerable to seawater intrusion, tidal influences, and the seepage of saline aquaculture pond effluents. Consequently, groundwater quality in this region exhibits considerable spatial and seasonal variability, making it an important natural laboratory for evaluating the impacts of intensive aquaculture on groundwater hydrochemistry.

3. Scope and Objectives

Groundwater serves as a vital resource for domestic consumption, agriculture, and aquaculture in many coastal regions. However, the rapid expansion of intensive shrimp and fish farming has raised significant concerns regarding groundwater contamination through salinity intrusion, nutrient enrichment, and changes in hydrochemical composition. Among the various water quality parameters, **alkalinity** and **hardness** are of particular importance because they influence buffering capacity, pH stability, nutrient cycling, metal toxicity, and the physiological well-being of cultured aquatic organisms.

This review aims to synthesize current knowledge on the hydrochemical characteristics of groundwater in aquaculture-dominated coastal regions, with particular emphasis on the role of alkalinity and hardness. The review also evaluates the influence of aquaculture practices on groundwater quality, discusses the environmental implications of hydrochemical alterations, and highlights sustainable management strategies for protecting groundwater resources. In addition, the significance of these parameters is examined not only from the perspective of aquaculture productivity but also with regard to drinking water quality and public health.

The specific objectives of this review are to:

- Critically evaluate the hydrochemical processes controlling groundwater alkalinity and hardness in coastal aquifers;

- Review the influence of aquaculture activities on groundwater quality, particularly salinity, alkalinity, hardness, and associated physicochemical parameters;
- Examine the ecological and physiological significance of alkalinity and hardness in fish and shrimp culture;
- Discuss the implications of groundwater quality deterioration for environmental sustainability and human health; and
- Identify knowledge gaps and recommend sustainable groundwater management practices for aquaculture-intensive regions.

4. Methodological Approach

This review is based on a comprehensive assessment of published scientific literature concerning groundwater quality in aquaculture regions. Relevant peer-reviewed journal articles, conference proceedings, government reports, technical publications, and institutional documents were critically evaluated to synthesize current knowledge on the hydrochemistry of groundwater affected by aquaculture activities.

The reviewed studies commonly employed systematic groundwater sampling from dug wells, bore wells, hand pumps, and monitoring wells distributed across aquaculture-dominated coastal areas. Sampling locations were generally geo-referenced using **Global Positioning System (GPS)** instruments to facilitate spatial analysis. Most investigations included seasonal monitoring during **pre-monsoon**, **monsoon**, and, in some cases, **post-monsoon** periods to evaluate temporal variations in groundwater quality.

Laboratory analyses reported in the reviewed literature typically included the determination of major physicochemical parameters such as **pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, total alkalinity, total hardness, chloride, sulphate, nitrate, nitrite, ammonia, sodium, potassium, calcium, and magnesium** using standard analytical procedures recommended by the **American Public Health Association**, **World Health Organization**, and the **Bureau of Indian Standards**. Several studies further applied hydrochemical indices, ionic ratio analyses, statistical methods, and geospatial techniques to assess groundwater quality, identify contamination sources, and evaluate the extent of aquaculture-induced hydrochemical changes.

The synthesis presented in this review integrates findings from these studies to provide a comprehensive understanding of the relationships among aquaculture practices, groundwater hydrochemistry, alkalinity, hardness, and environmental sustainability.

5. Results and Discussion

The relationship between **alkalinity** and **hardness** has been widely recognized as an important indicator of groundwater hydrochemistry, particularly in aquaculture-intensive coastal regions. A review of published studies indicates that these parameters are closely associated because both are largely controlled by the dissolution of carbonate minerals and the presence of common ionic constituents, particularly calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) ions. In many groundwater systems, alkalinity and hardness exhibit comparable concentrations, although alkalinity is often reported to be slightly higher, generally ranging from **1.0 to 2.0 times** the hardness values (Table 1). Such hydrochemical conditions are characteristic of groundwater influenced by the dissolution of calcium carbonate and other carbonate-bearing minerals, where carbonate hardness is chemically equivalent to the bicarbonate fraction of alkalinity. However, numerous studies conducted in aquaculture-dominated coastal areas have reported groundwater with **significantly higher alkalinity than hardness** (Table 2), suggesting that alkalinity is additionally influenced by biological processes, organic matter decomposition, bicarbonate enrichment, sodium bicarbonate, and saline aquaculture effluents. Intensive fish and shrimp farming enhances microbial respiration and carbon dioxide production, which subsequently increases bicarbonate concentrations and groundwater alkalinity. Elevated alkalinity improves buffering capacity, stabilizes pH, and supports biological nitrification; however, excessive alkalinity may increase pH during periods of intense photosynthesis, thereby enhancing ammonia toxicity and affecting aquatic ecosystem health. Conversely, a few groundwater samples have been reported with **hardness values exceeding alkalinity** (Table 3), indicating the occurrence of **non-carbonate hardness**, where calcium and magnesium are associated with sulphate, chloride, nitrate, or other non-carbonate anions. This condition is commonly attributed to seawater intrusion, evaporite mineral dissolution, agricultural inputs, or anthropogenic contamination in coastal aquifers. Overall, the relative proportions of alkalinity and hardness provide valuable information on groundwater evolution, carbonate equilibrium, and the extent of aquaculture-induced hydrochemical changes. Their combined assessment is therefore essential for evaluating groundwater suitability for aquaculture, drinking, and irrigation purposes, as well as for developing sustainable groundwater management strategies in coastal aquaculture regions.

Table 1: Groundwater Samples Showing Comparable Alkalinity and Hardness (Alkalinity ≈ 1.0–2.0 × Hardness)

S. No.	Village	Alkalinity (mg L^{-1} as $CaCO_3$)	Total Hardness (mg L^{-1} as $CaCO_3$)	Alkalinity/Hardness Ratio
1	Gondi	1212	836	1.45
2	Visweswarapuram	452	272	1.66
3	Battelanka	412	204	2.02
4	Adavipalem	252	172	1.47
5	Mori	228	136	1.68
6	Lakkavaram	208	120	1.73

Interpretation: Groundwater chemistry in these villages is predominantly influenced by carbonate mineral dissolution, resulting in comparable alkalinity and hardness values.

Table 2: Groundwater Samples with Significantly Higher Alkalinity than Hardness (Alkalinity > 2 × Hardness)

S. No.	Village	Alkalinity (mg L^{-1} as $CaCO_3$)	Total Hardness (mg L^{-1} as $CaCO_3$)	Alkalinity/Hardness Ratio
1	Mutyalapalem	1060	132	8.03
2	Gubbalapalem	716	116	6.17
3	Antarvedi	696	296	2.35
4	Gudapalli	312	100	3.12
5	Toorpupalem	304	68	4.47

Interpretation: The predominance of alkalinity over hardness suggests bicarbonate enrichment resulting from biological activity, carbonate dissolution, and aquaculture-related hydrochemical processes.

Table 3: Groundwater Samples with Hardness Exceeding Alkalinity (Non-Carbonate Hardness Dominance)

S. No.	Village	Alkalinity (mg L^{-1} as $CaCO_3$)	Total Hardness (mg L^{-1} as $CaCO_3$)	Hardness/Alkalinity Ratio
1	Kesavadasupalem	360	396	1.1
2	Padamatipalem	220	320	1.45
3	Katrenipadu	100	264	2.64
4	Karavaka	70	82	1.17

Interpretation: These groundwater samples indicate the occurrence of non-carbonate hardness, likely resulting from dissolved chloride and sulphate salts associated with seawater intrusion or other anthropogenic influences.

The relationship between alkalinity, hardness, and calcium concentration has been extensively discussed in the literature owing to its significant influence on groundwater quality and aquaculture productivity. Although high alkalinity is often associated with carbonate mineral dissolution, several studies have reported situations where elevated alkalinity is primarily caused by **sodium bicarbonate ($NaHCO_3$)** rather than calcium carbonate. Under such conditions, groundwater may exhibit **high alkalinity but relatively low hardness and low calcium concentrations**, indicating that alkalinity alone cannot be used as an indicator of calcium availability. A low **$CaCO_3$ hardness** value generally reflects low calcium content, whereas high total hardness does not necessarily imply high calcium concentrations because hardness may be predominantly contributed by magnesium ions (Table 5; Figures 3a and 3b). Calcium is an essential constituent of aquaculture waters, playing a critical role in osmoregulation, skeletal and exoskeletal development, blood coagulation, muscle function, and several metabolic processes in fish and crustaceans. Moreover, adequate concentrations of ionic calcium reduce the loss of essential electrolytes such as sodium and potassium from body fluids and significantly decrease the toxicity of heavy metals, ammonia, and hydrogen ions. Previous investigations have demonstrated that **calcium hardness provides effective protection against copper toxicity**, whereas magnesium hardness offers comparatively little protective effect. Consequently, determination of calcium hardness is recommended before the application of copper sulphate in aquaculture ponds, particularly in waters with low alkalinity. Hardness also influences the physical characteristics of water by promoting the rapid settling of suspended soil particles, thereby improving water clarity. Conversely, excessive alkalinity resulting from elevated concentrations of dissolved carbonates and bicarbonates may increase turbidity through the suspension of fine mineral particles. Seasonal variations further influence groundwater hydrochemistry, with several studies reporting an increase in alkalinity from the **pre-monsoon (summer) to monsoon season** (Table 4; Figure 2), primarily due to enhanced dissolution of carbonate minerals and increased recharge carrying bicarbonate-rich water into the aquifer. These observations collectively highlight the importance of evaluating alkalinity, hardness, and calcium concentrations simultaneously for assessing groundwater suitability for aquaculture and understanding the hydrochemical processes governing coastal aquifers.

Table 4: Seasonal Variation in Groundwater Alkalinity During Pre-Monsoon and Monsoon Seasons

S. No.	Village	Pre-Monsoon Alkalinity (mg L^{-1} as $CaCO_3$)	Monsoon Alkalinity (mg L^{-1} as $CaCO_3$)	Seasonal Trend
1	Gondi	1265	1212	Slight decrease
2	Mori	1040	696	Decrease
3	Antarvedikara	838	816	Slight decrease
4	Antarvedi	720	696	Slight decrease
5	Visweswarapuram	613	457	Decrease
6	Toorpupalem	444	304	Decrease
7	Lakkavaram	393	208	Decrease
8	Gudapalli	365	196	Decrease
9	Chintala Mori	343	312	Slight decrease
10	Adavipalem	258	252	Nearly unchanged
11	Kesanapalli	140	136	Nearly unchanged
12	Katrenipadu	140	200	Increase
13	Padamatipalem	185	220	Increase
14	Karavaka	241	300	Increase
15	Kesavadasupalem	337	360	Slight increase
16	Battelanka	180	412	Significant increase
17	Gubbalapalem	258	716	Significant increase
18	Mutyalapalem	855	1060	Increase

Note: Alkalinity values are expressed as **mg L⁻¹ (ppm) as $CaCO_3$**. Seasonal variations indicate the influence of recharge, carbonate dissolution, aquaculture activities, and groundwater–seawater interactions on groundwater hydrochemistry.

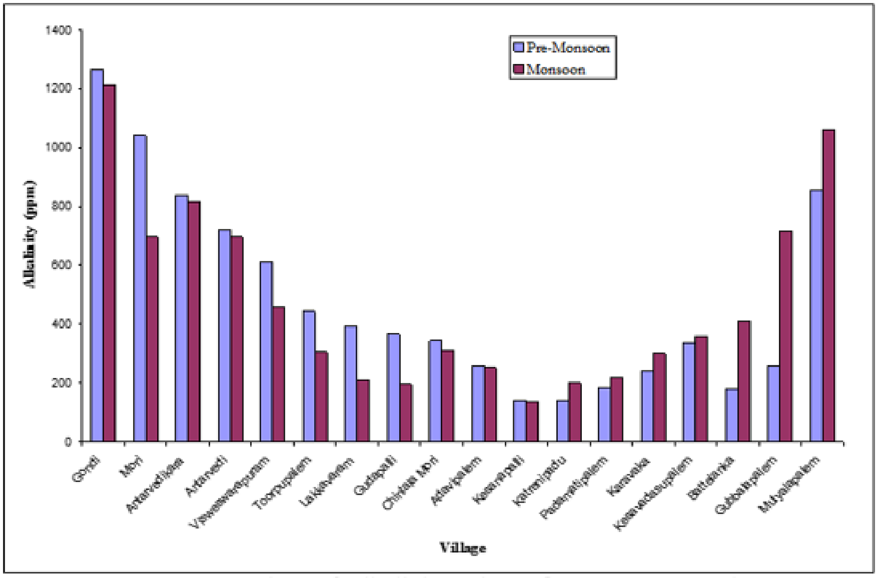

Fig 2: Comparison of Alkalinity values of pre-Monsoon and Monsoon of ground water samples in the study area

Table 5: Seasonal Variation of Calcium and Magnesium Concentrations in Groundwater

S. No.	Village	Pre-Monsoon Calcium (Ca^{2+}) (mg L⁻¹)	Pre-Monsoon Magnesium (Mg^{2+}) (mg L⁻¹)	Monsoon Calcium (Ca^{2+}) (mg L⁻¹)	Monsoon Magnesium (Mg^{2+}) (mg L⁻¹)
1	Toorpupalem	25.6	17.2	2.4	12.4
2	Antarvedi Kara	17.6	65.2	3.2	93.6
3	Karavaka	17.6	21.2	4.8	30.4
4	Antarvedi	16	18	6.4	56
5	Kesavadasupalem	25.6	75.2	6.4	76.6
6	Sankaraguptham	24	14	6.4	25.6
7	Gondi	25	138.4	6.4	163.2
8	Chintala Mori	16	18	8	30.4
9	Padamatipalem	17.6	23.2	9.6	25.6
10	Kesanapalli	16	2	11.2	7.2
11	Mutyalapalem	11.2	4.4	12.8	20
12	Battelanka	14.4	12.8	13.6	34
13	Gudapalli	14.4	30.8	14.4	12.8
14	Katrenipadu	14.4	2.6	14.4	12
15	Adavipalem	14.4	6.8	16	26.4
16	Lakkavaram	12.8	13.6	16.8	15.6
17	Gubbalapalem	17.6	9.2	19.2	13.6
18	Visweswarapuram	12.8	15.2	20.8	44

Note: Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) concentrations are expressed in **mg L⁻¹ (ppm)**. Seasonal variations reflect the influence of groundwater recharge, carbonate mineral dissolution, seawater intrusion, and aquaculture activities on groundwater hydrochemistry.

Seasonal variations in groundwater chemistry indicate that **seawater intrusion and monsoon recharge** are the two major factors controlling groundwater quality in the study area. An increase in **magnesium (Mg^{2+})** concentrations during the monsoon season suggests enhanced seawater intrusion into the coastal aquifers. As a result, **total hardness** increased from an average of **177.11 mg L⁻¹** in the pre-monsoon season to **218.19 mg L⁻¹** during the monsoon. Hardness exceeded **300 mg L⁻¹** in at least three villages, indicating a significant contribution of magnesium salts, particularly magnesium sulphate. Sulphate concentrations also showed a slight increase, with the average value rising from **135.83 mg L⁻¹** to **138.80 mg L⁻¹**, and sulphate was detected in **12 of the 18 villages** during the monsoon compared with only **6 villages** in the pre-monsoon period.

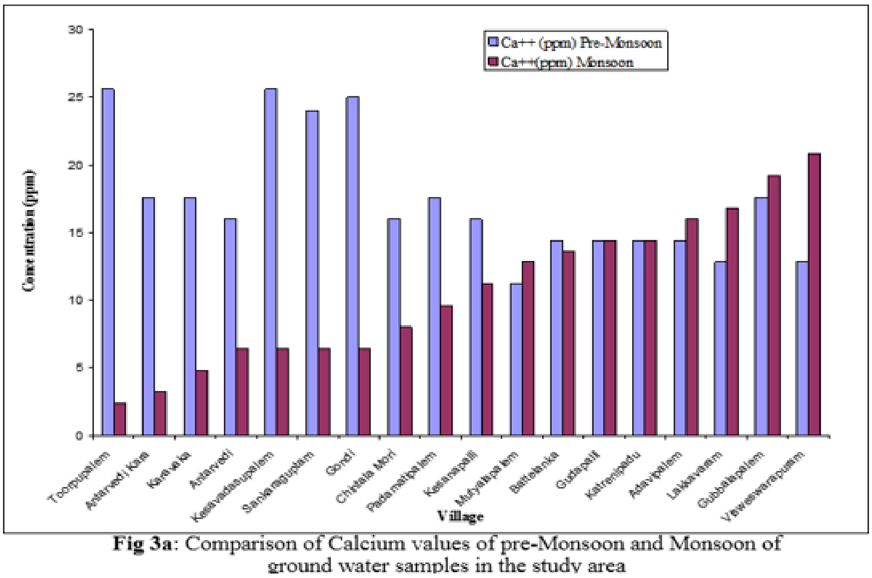

Fig 3a: Comparison of Calcium values of pre-Monsoon and Monsoon of ground water samples in the study area

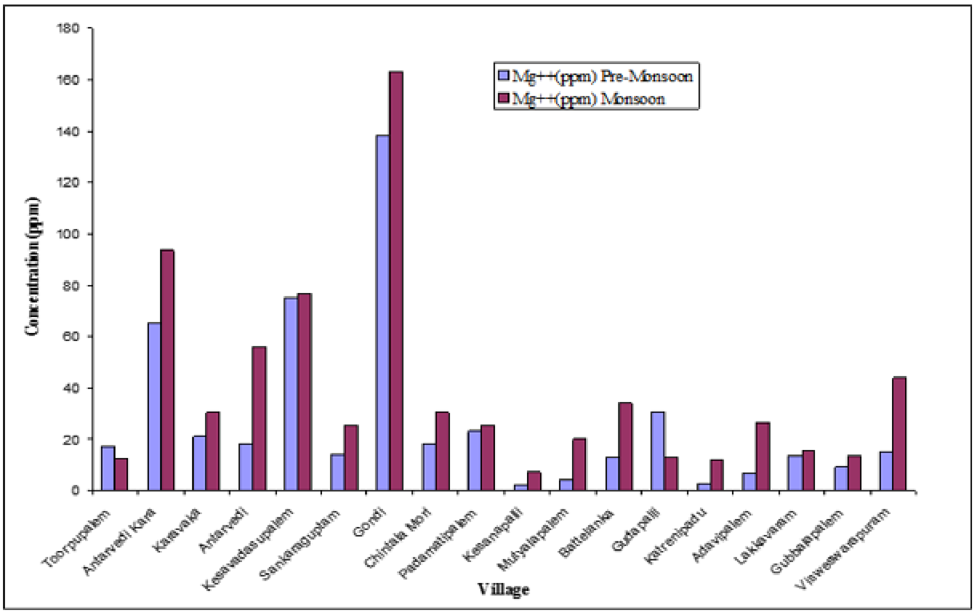

Fig 3b: Comparison of Magnesium values of pre-Monsoon and Monsoon of ground water samples in the study area

Groundwater **alkalinity** also increased slightly, with the average value rising from **435.31 mg L^{-1}** in the pre-monsoon season to **450.22 mg L^{-1}** during the monsoon. Alkalinity exceeded **500 mg L^{-1}** in five villages and surpassed **1000 mg L^{-1}** in two villages, indicating enrichment of bicarbonate and carbonate ions, mainly associated with sodium and magnesium. This increase is likely related to seawater intrusion and enhanced mineral dissolution.

In contrast, **calcium (Ca^{2+})** concentrations declined from an average of **16.60 mg L^{-1}** to **10.71 mg L^{-1}**, with values falling below **10 mg L^{-1}** in nearly **50% of the villages** during the monsoon season. This decline suggests dilution of calcium-rich groundwater by rainwater recharge. Similarly, **total dissolved solids (TDS)** decreased from **2160 mg L^{-1}** to **1561 mg L^{-1}**, while **salinity** declined from **1.56 ppt** to **1.28 ppt**. Significant reductions were also observed in **chloride** (631 to 378 mg L^{-1}) and **nitrate** (33.47 to 16.91 mg L^{-1}) concentrations, indicating dilution of groundwater through monsoonal rainfall and recharge.

The concentration of **sodium** increased from **185.61 mg L^{-1}** to **232.94 mg L^{-1}**, further supporting the influence of saline water intrusion. Overall, the seasonal hydrochemical variations suggest that groundwater quality is controlled by the combined effects of **seawater intrusion**, which increases magnesium, sodium, sulphate, hardness, and alkalinity, and **rainwater infiltration**, which dilutes calcium, potassium, chloride, nitrate, TDS, and salinity. These findings demonstrate the complex interaction between natural hydrogeochemical processes and aquaculture activities in shaping groundwater quality in coastal regions.

6. Conclusion

Groundwater quality in aquaculture-intensive coastal regions is strongly influenced by both natural hydrogeochemical processes and aquaculture activities. This review indicates that **alkalinity and hardness** are key indicators of groundwater suitability, as they regulate pH stability, nutrient cycling, and the health of aquatic organisms.

Elevated alkalinity and hardness are mainly associated with carbonate weathering, seawater intrusion, and the accumulation of dissolved salts from aquaculture operations. Seasonal variations further demonstrate that monsoon recharge dilutes several dissolved constituents, while seawater intrusion increases magnesium, sodium, sulphate, hardness, and alkalinity. The predominance of high alkalinity over hardness in most locations reflects bicarbonate enrichment of groundwater, whereas localized non-carbonate hardness indicates the influence of saline water and anthropogenic inputs. Continuous monitoring of groundwater hydrochemistry, coupled with sustainable aquaculture management practices, is therefore essential to protect freshwater resources, maintain aquaculture productivity, and ensure long-term environmental sustainability.

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