Journal of Neonatal Surgery
ISSN(Online): 2226-0439
Vol. 14, Issue 32s (2025)
https://www.jneonatalsurg.com
OPEN ACCESS

Multivariate Insight into Seasonal Hydrogeochemical Dynamics of the Thrissur–Ponnani Kole Wetlands, Central Kerala

Samreena Mohammed[*1], Arun kumar K. S[1], Santhosh V[2]

[*1,2]Department of PG Studies & Research in Geology, MES Ponnani College (Calicut University), South Ponnani P.O, Malappuram-679586, Kerala, India

[*]**Corresponding Author:**

Samreena Mohammed,

Department of PG Studies & Research in Geology, MES Ponnani College (Calicut University), South Ponnani P.O, Malappuram-679586, Kerala, India

Email ID: samrigeo0001@gmail.com

Cite this paper as: Samreena Mohammed, Arun kumar K. S, Santhosh V, (2025) Multivariate Insight into Seasonal Hydrogeochemical Dynamics of the Thrissur–Ponnani Kole Wetlands, Central Kerala. *Journal of Neonatal Surgery*, 14 (32s), 5220-5233.

ABSTRACT

Groundwater in Kerala's Thrissur–Ponnani Kole wetlands is increasingly threatened by seawater intrusion, agrochemical loading, and untreated effluents. To diagnose these pressures, we sampled 70 shallow wells during pre-monsoon, monsoon, and post-monsoon seasons (2022–2023) and measured 13 physico-chemical parameters. Multivariate analyses—Pearson correlation, hierarchical clustering, factor analysis, and principal component analysis—were applied to 2,730 observations. Electrical conductivity, salinity, and total dissolved solids exhibited a strong inter-correlation ($r > 0.90$), signalling chronic marine ingress. Six principal components accounted for 91.9 % of total variance: PC1 captured saline and domestic inputs, PC2 reflected carbonate weathering, and PC3 highlighted fertiliser-derived nutrients. Seasonal clustering revealed evaporative concentration and nutrient enrichment pre-monsoon, rainfall-driven dilution during monsoon, and partial salinity rebound post-monsoon. Seawater intrusion and agricultural leachate thus emerge as the dominant, seasonally modulated threats to the aquifer. We recommend a tiered monitoring framework—combining seasonal pumping controls with nutrient-management zones—to safeguard this critical coastal groundwater resource.

Keywords: *Groundwater quality, Multivariate analysis, Seasonal variation, Salinity intrusion, Kole wetlands*

1. INTRODUCTION

Groundwater is one of the most critical natural resources sustaining agriculture, ecosystems, and human well-being in coastal zones around the world (Mohammed & Arunkumar, 2025). In India, particularly in the state of Kerala, shallow aquifers are the backbone of rural water supply and paddy cultivation (Kumar et al., 2020). Among the distinctive agro-ecological regions of Kerala, the Thrissur–Ponnani Kole wetlands represent an important hydrologically sensitive landscape.

The Kole wetlands are low-lying floodplain systems located within the central coastal plain of Kerala. These wetlands support two-season paddy cultivation and act as natural flood sinks during the monsoon season (Kumar et al., 2020). However, increasing demand for freshwater resources, rapid urbanisation, and uncontrolled land-use changes are placing considerable stress on groundwater quantity and quality in the region (Das et al., 2018).

One of the major challenges facing the Kole wetlands is seawater intrusion. The region's proximity to the Arabian Sea and the extensive use of shallow wells for irrigation and domestic purposes create conditions favourable for saltwater to migrate inland, especially during the post-monsoon and dry pre-monsoon periods (Mohammed & Arunkumar, 2025). This leads to elevated salinity, total dissolved solids (TDS), and electrical conductivity (EC) in groundwater.

Another important issue is the increasing use of chemical fertilisers, pesticides, and organic waste inputs associated with high-intensity farming and aquaculture activities. These practices lead to nutrient enrichment and contamination of groundwater with nitrate (NO(_3^-)) and other agriculturally derived pollutants (VishnuRadhan et al., 2015; Priyatharsini et al., 2016). Small-scale industrial activity also contributes to localised pollution, particularly in wells near highways and peri-urban zones.

Despite the ecological and economic importance of the Kole region, most previous groundwater quality assessments have focused on limited locations and single-season datasets. They often fail to capture the temporal dynamics of aquifer chemistry across different hydro-meteorological conditions (Xu et al., 2022). A comprehensive and seasonally disaggregated study is required to better understand the primary drivers of groundwater contamination.

Multivariate statistical techniques offer powerful tools to analyse large groundwater datasets, identify correlations among physico-chemical parameters, and pinpoint natural versus anthropogenic sources of contamination (Platikanov et al., 2019; Liu et al., 2018). Principal component analysis (PCA), factor analysis (FA), and hierarchical cluster analysis (HCA) are among the most effective approaches used globally to assess hydrogeochemical processes.

Applying these methods, we aim to (i) investigate the spatial and seasonal variations in groundwater quality across the Thrissur–Ponnani Kole wetlands, (ii) identify the dominant geochemical and pollution sources influencing aquifer composition, and (iii) provide data-driven recommendations for improved groundwater resource management.

This study represents one of the first systematic applications of multivariate statistics to groundwater quality in the Kole wetlands. It provides new insight into seasonal contamination patterns, reveals the geogenic versus anthropogenic influence on water chemistry, and proposes a framework for cost-effective and targeted monitoring of groundwater resources in coastal agro-ecosystems (Mohammed & Arunkumar, 2025). natural resources sustaining agriculture, ecosystems, and human well-being in coastal zones around the world. In India, particularly in the state of Kerala, shallow aquifers are the backbone of rural water supply and paddy cultivation. Among the distinctive agro-ecological regions of Kerala, the Thrissur–Ponnani Kole wetlands represent an important hydrologically sensitive landscape.

The Kole wetlands are low-lying floodplain systems located within the central coastal plain of Kerala. These wetlands support two-season paddy cultivation and act as natural flood sinks during the monsoon season. However, increasing demand for freshwater resources, rapid urbanisation, and uncontrolled land-use changes are placing considerable stress on groundwater quantity and quality in the region.

One of the major challenges facing the Kole wetlands is seawater intrusion. The region's proximity to the Arabian Sea and the extensive use of shallow wells for irrigation and domestic purposes create conditions favourable for saltwater to migrate inland, especially during the post-monsoon and dry pre-monsoon periods. This leads to elevated salinity, total dissolved solids (TDS), and electrical conductivity (EC) in groundwater.

Another important issue is the increasing use of chemical fertilisers, pesticides, and organic waste inputs associated with high-intensity farming and aquaculture activities. These practices lead to nutrient enrichment and contamination of groundwater with nitrate (NO(_3^-)) and other agriculturally derived pollutants. Small-scale industrial activity also contributes to localised pollution, particularly in wells near highways and peri-urban zones.

Despite the ecological and economic importance of the Kole region, most previous groundwater quality assessments have focused on limited locations and single-season datasets. They often fail to capture the temporal dynamics of aquifer chemistry across different hydro-meteorological conditions. A comprehensive and seasonally disaggregated study is required to better understand the primary drivers of groundwater contamination.

Multivariate statistical techniques offer powerful tools to analyse large groundwater datasets, identify correlations among physico-chemical parameters, and pinpoint natural versus anthropogenic sources of contamination. Principal component analysis (PCA), factor analysis (FA), and hierarchical cluster analysis (HCA) are among the most effective approaches used globally to assess hydrogeochemical processes.

Applying these methods, we aim to (i) investigate the spatial and seasonal variations in groundwater quality across the Thrissur–Ponnani Kole wetlands, (ii) identify the dominant geochemical and pollution sources influencing aquifer composition, and (iii) provide data-driven recommendations for improved groundwater resource management.

This study represents one of the first systematic applications of multivariate statistics to groundwater quality in the Kole wetlands. It provides new insight into seasonal contamination patterns, reveals the geogenic versus anthropogenic influence on water chemistry, and proposes a framework for cost-effective and targeted monitoring of groundwater resources in coastal agro-ecosystems.. In particular, the Thrissur–Ponnani Kole wetlands, a unique low-lying agro-ecosystem, rely heavily on shallow aquifers to sustain seasonal rice cultivation and freshwater demands. However, population growth, land-use change, and over-extraction are increasingly compromising groundwater quality in this region.

Seawater intrusion, particularly during the post-monsoon season when hydraulic gradients reverse, introduces salinity and elevated ion concentrations. Simultaneously, excessive use of fertilisers and untreated discharge from small-scale industries contribute nutrient pollutants and organic loads into the aquifer system. These stressors collectively deteriorate water quality, posing significant risks to public health and the region's ecological stability.

Although several hydrochemical investigations have previously been undertaken in coastal Kerala, most studies have focused on limited spatial or temporal datasets, preventing a comprehensive understanding of seasonal dynamics. There is an urgent need for integrative methodologies that can analyse complex multivariate datasets to reveal the key factors influencing groundwater composition.

Multivariate statistical techniques such as principal component analysis (PCA), factor analysis (FA), and hierarchical cluster analysis (HCA) have proven effective in deciphering pollutant sources and classifying groundwater samples according to their hydrogeochemical characteristics. These tools reduce data dimensionality, uncover latent correlations, and facilitate strategic monitoring.

Accordingly, this study aims to: (i) characterise groundwater quality across three seasonal phases (pre-monsoon, monsoon, post-monsoon) in the Thrissur–Ponnani Kole tract; (ii) identify dominant geogenic and anthropogenic processes using PCA, FA and HCA; and (iii) propose tailored management recommendations that enhance monitoring efficiency and mitigate contamination risks in the region.

Groundwater sustains Kerala's coastal agriculture, domestic supply and emerging industries. In the reclaimed Kole wetlands, abstraction already exceeds safe yields and quality deterioration—via saline intrusion and diffuse pollution—jeopardises food security and public health [1]. Prior hydrochemical surveys remain fragmentary, often single-season and limited in analytical scope [2, 3]. Multivariate statistics provide a cost-efficient pathway to interrogate large datasets, reveal latent pollution sources and support data-driven management [4–6]. This study (i) characterises seasonal groundwater chemistry in the Thrissur–Ponnani Kole tract, (ii) identifies natural and anthropogenic drivers using HCA, FA and PCA, and (iii) recommends evidence-based mitigation actions.

2. STUDY AREA

The Thrissur–Ponnani Kole wetlands, a Ramsar-recognised ecosystem, lie in the central coastal region of Kerala between latitudes 10°20′–10°45′ N and longitudes 75°55′–76°15′ E. These wetlands extend over approximately 1,100 km² and are situated within the districts of Thrissur and Malappuram. The area is characterised by low-lying paddy fields reclaimed from backwaters and subjected to seasonal flooding. Figure 1 illustrates the spatial distribution of the sampling locations used in this study.

Geologically, the region consists of Quaternary alluvium overlying Neogene laterites and Precambrian charnockites, which serve as the basement rocks. These geological formations influence the hydrogeochemical characteristics of groundwater by contributing weathering-derived ions such as calcium, magnesium, and bicarbonates (Kumar et al., 2020). The soil in the Kole wetlands is primarily clayey, with poor permeability, which affects both groundwater recharge and contaminant transport.

The climate is humid tropical, with an average annual rainfall of approximately 3,200 mm, mostly received during the southwest monsoon (June–September). The hydrological year is typically divided into three seasons: pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–February). These seasonal shifts cause significant variations in groundwater recharge, salinity levels, and contaminant dispersion, making temporal water quality analysis essential (Das et al., 2018).

Land use in the region is dominated by two-season paddy farming, shrimp aquaculture, and scattered peri-urban industrial clusters. Paddy cultivation is highly dependent on groundwater, particularly during the pre-monsoon dry season. The shallow phreatic aquifers in the area (generally <20 m depth) serve as the primary water source for drinking and irrigation. However, these aquifers are vulnerable to contamination from agricultural runoff, saline intrusion, and untreated effluents (Mohammed & Arunkumar, 2025).

The proximity of the Kole wetlands to the Arabian Sea further exacerbates the risk of salinity ingress. During the dry season and in post-monsoon months, the lowering of hydraulic heads often facilitates inland movement of seawater, resulting in elevated levels of total dissolved solids (TDS), electrical conductivity (EC), and sodium chloride in groundwater samples. Saline water ingress has been reported in multiple studies conducted in adjacent riverine and coastal aquifers (VishnuRadhan et al., 2015).

Additionally, human activities such as excessive use of fertilisers and pesticides, improper waste disposal, and effluent discharge from food processing units concentrated near highways (such as the Kunnamkulam Highway) compound the contamination risks. These activities contribute to elevated nitrate, sulphate, and potassium concentrations in the groundwater (Priyatharsini et al., 2016).

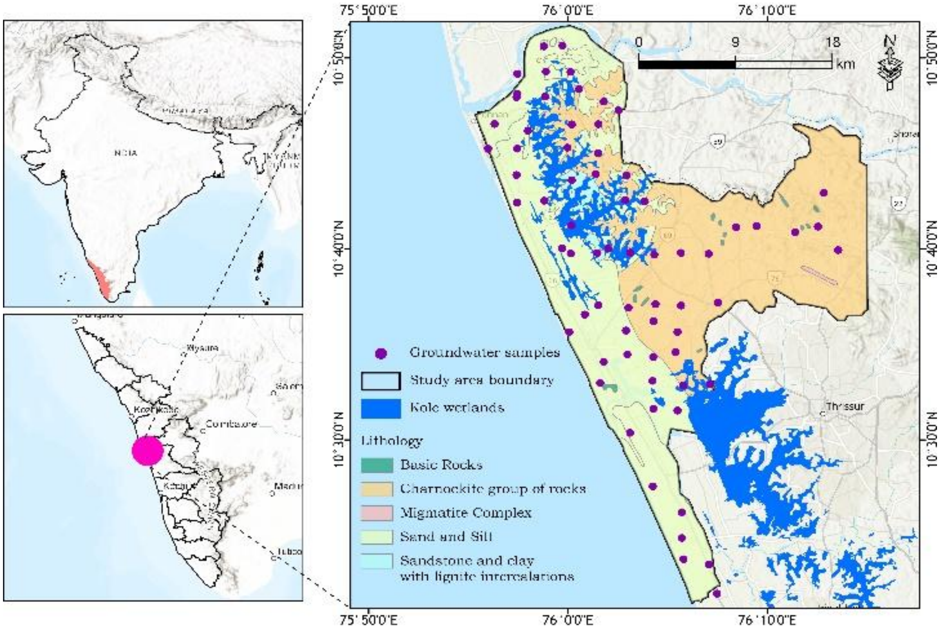

Figure 1. Map showing the study area and sampling locations in the Thrissur–Ponnani Kole wetlands.

Given the geological heterogeneity, climatic variability, and anthropogenic pressures, the Thrissur–Ponnani Kole wetlands present a complex but highly relevant setting for studying spatio-temporal trends in groundwater quality. The application of multivariate statistical techniques to this dataset allows for better understanding of contamination patterns, source apportionment, and the development of adaptive water quality management strategies.

The Kole wetlands (≈1,100 km²) occupy the central coastal plain of Kerala between 10°20′–10°45′ N and 75°55′–76°15′ E. Quaternary alluvium overlies Neogene laterites and Archaean charnockites. The climate is humid-tropical (mean rainfall ≈3,200 mm y^{-1}) with distinct pre-monsoon (March–May), southwest monsoon (June–September) and post-monsoon (October–February) periods. Intensive paddy farming and shrimp aquaculture dominate land use; small-scale food-processing units cluster along the Kunnamkulam highway. Shallow phreatic aquifers (depth <20 m) are the main potable source.

3. MATERIALS AND METHODS

To comprehensively evaluate groundwater quality across the Thrissur–Ponnani Kole wetlands, a robust and systematic methodology was adopted. The study was designed to capture spatial and temporal variability through a three-seasonal sampling strategy: pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–February). A total of 70 groundwater samples were collected from spatially distributed shallow wells across the study region, ensuring representative coverage of different land use categories including agricultural zones, residential belts, and peri-urban areas near industrial facilities. The wells were geo-referenced and mapped using GPS (see Fig. 1).

Water samples were collected following standard protocols recommended by the American Public Health Association (APHA, 2017). In-situ measurements for pH and electrical conductivity (EC) were recorded using calibrated portable multiparameter meters. Samples for laboratory analysis were stored in pre-cleaned polyethylene bottles and transported in ice boxes to maintain sample integrity. Analytical procedures were carried out to determine major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), anions (Cl^{-}, SO_4^{2-}, NO_3^{-}), and physico-chemical indices including total hardness (TH), total alkalinity (TA), and total dissolved solids (TDS). Ca^{2+}, Mg^{2+}, TH, and TA were quantified through titrimetric methods; Na^{+} and K^{+} were determined using flame photometry; and Cl^{-}, SO_4^{2-}, and NO_3^{-} were analysed using ion chromatography (Mohammed & Arunkumar, 2025; Xu et al., 2022).

To ensure data quality and precision, stringent quality assurance and quality control (QA/QC) measures were implemented. These included the use of field blanks, analytical duplicates (5 % of total samples), and maintenance of ionic balance within ±5 %. Calibration of instruments was performed daily, and reagent blanks were used to monitor background contamination. The accuracy of analytical results was cross-validated using ionic balance errors and comparison with standard reference materials when available (Das et al., 2018).

For data interpretation, multivariate statistical analyses were conducted using R software version 4.3. All parameters were first tested for normality and subsequently log-transformed and z-standardised to minimise skewness and scale discrepancies.

Pearson correlation matrices were used to explore pairwise relationships among variables. Hierarchical cluster analysis (HCA) was performed using Ward's linkage and Euclidean distance to classify the sampling sites based on water quality similarities. Principal component analysis (PCA) and factor analysis (FA) with varimax rotation were applied to reduce dimensionality and to identify latent factors influencing groundwater chemistry. Suitability for PCA and FA was confirmed by Kaiser–Meyer–Olkin (KMO) test (>0.80) and Bartlett's test of sphericity ($p < 0.001$) (Liu et al., 2018; Platikanov et al., 2019).

3.1 Sampling and analysis

Seventy wells (Fig. 1) were sampled thrice (July 2022, November 2022, March 2023). In-situ parameters (pH, EC) were recorded with calibrated probes; major ions were analysed by titrimetry (Ca^{2+}, Mg^{2+}, TH, TA), ion chromatography (Cl^-, SO_4^{2-}, NO_3^-) and flame photometry (Na^+, K^+). QA/QC included field blanks, duplicates (5 %) and ionic balance <±5 %.

3.2 Statistical procedures

Variables were log-normalised and z-scaled. Pearson correlation, HCA (Ward linkage, Euclidean distance), FA (varimax rotation) and PCA were performed in R 4.3. The Kaiser–Meyer–Olkin (KMO = 0.85) and Bartlett tests confirmed dataset suitability.

4. RESULTS AND DISCUSSION

The application of multivariate statistical analysis enabled a thorough interpretation of groundwater quality variations across pre-monsoon, monsoon, and post-monsoon seasons. Each method—correlation matrix, PCA, FA, and HCA—revealed distinct hydrochemical patterns and dominant influencing factors. These findings provide a comprehensive understanding of the temporal shifts in groundwater composition and pollution sources.

4.1 Seasonal Correlation Matrix Analysis

The correlation matrix revealed strong seasonal dependencies between various water quality parameters. In the pre-monsoon season, high correlations ($r > 0.90$) among EC, TDS, and salinity suggested a dominant influence of saline water ingress, likely intensified by high evaporation and reduced recharge. This pattern was further supported by strong associations with Na^+ and Cl^-, indicative of halite dissolution and anthropogenic inputs (Priyatharsini et al., 2016).

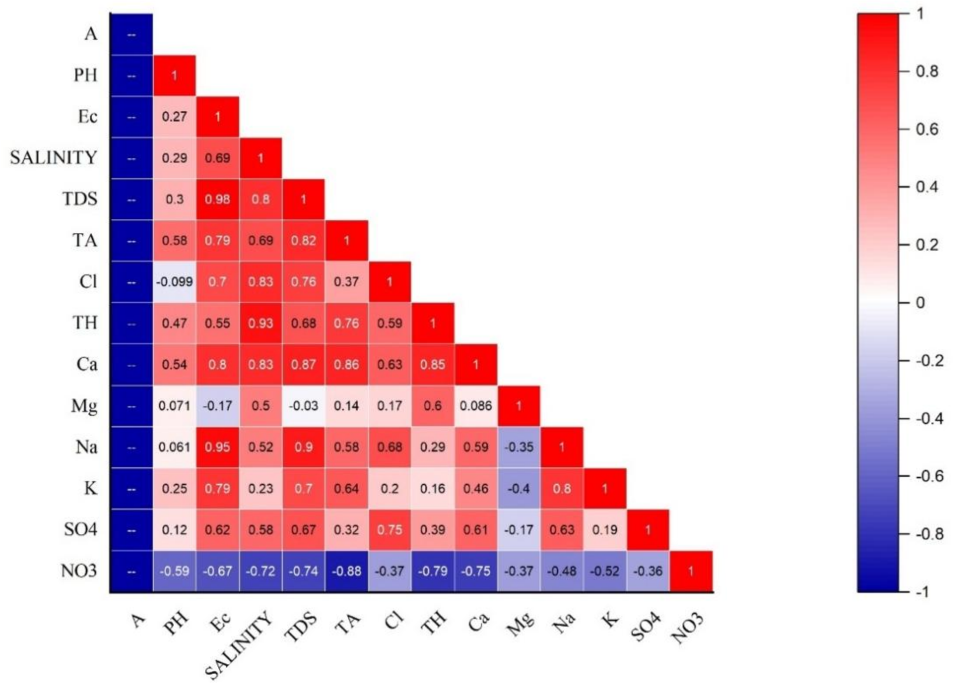

Figure 2. Pearson correlation matrix for pre-monsoon groundwater quality parameters

During the monsoon season, dilution by heavy rainfall weakened these correlations. However, EC and TDS retained moderate positive correlations, pointing to continuous ionic influx from agricultural runoff. The correlation between nitrate and other variables diminished significantly, suggesting that nutrient input was diluted or redistributed by rainfall events (Sarkar et al., 2021).

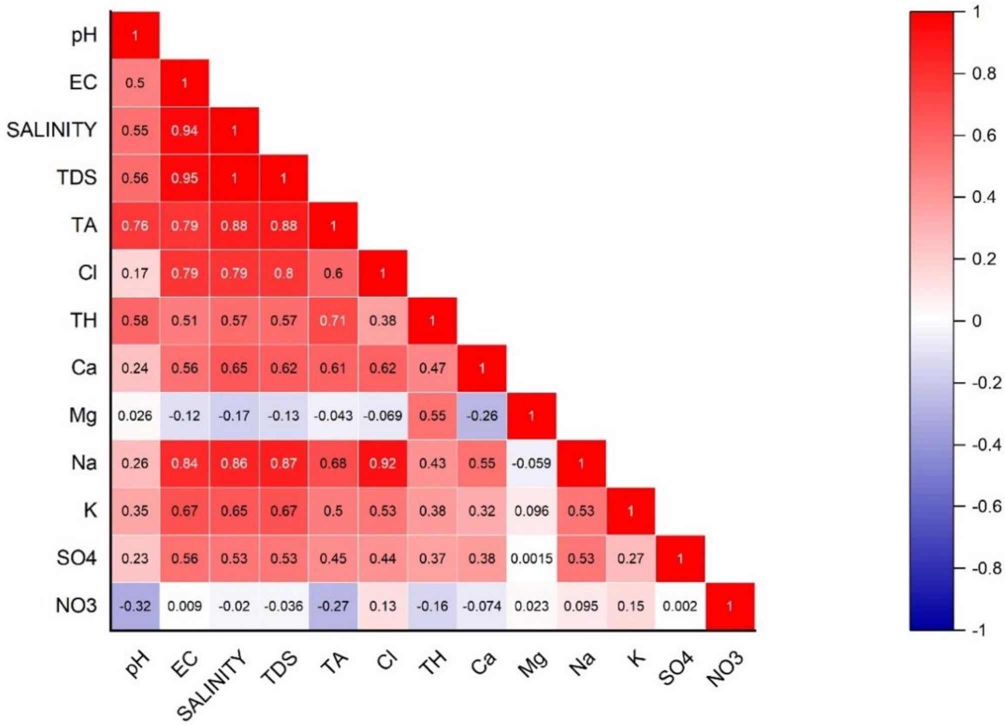

Figure 3. Pearson correlation matrix for monsoon groundwater quality parameters.

Post-monsoon matrices showed a resurgence in ionic correlation, though weaker than in the pre-monsoon period. This reflects partial aquifer recharge and a re-concentration of dissolved ions. Salinity, EC, and TDS correlations persisted, reinforcing the cyclical nature of saline ingress and evaporation-dominated processes (VishnuRadhan et al., 2015).

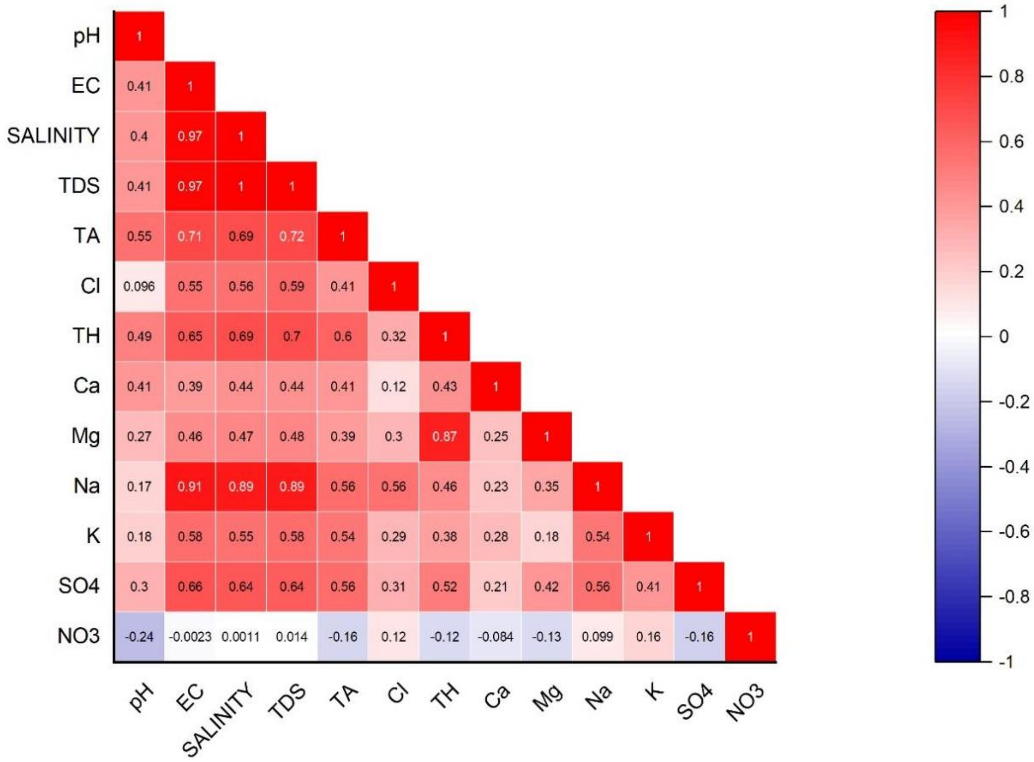

Figure 4. Pearson correlation matrix for post-monsoon groundwater quality parameters.

4.2 Principal Component Analysis (PCA)

PCA effectively reduced the dataset into six principal components explaining 91.9% of the total variance. PC1 (29.8%) was dominant across all seasons and associated with EC, TDS, salinity, Na^+, and Cl^-, reflecting salinisation and domestic effluent discharge. PC2 (17.1%) captured variations in hardness and alkalinity parameters (Ca^{2+}, Mg^{2+}, TH, TA), attributable to geogenic carbonate weathering (Liu et al., 2018).

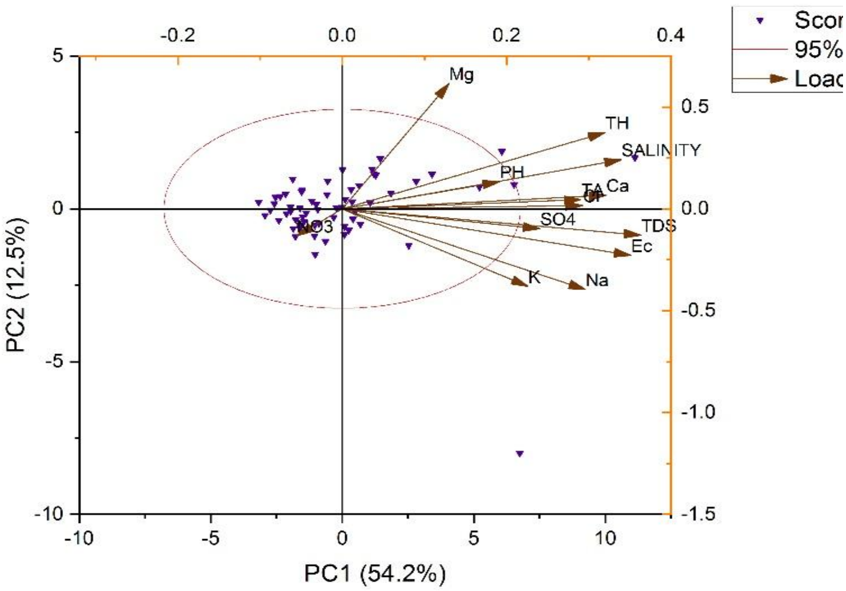

Figure 5. PCA biplot of pre-monsoon samples indicating principal component loadings and groundwater sample scores.

PC3 (13.3%) was driven by NO_3^-, SO_4^{2-}, and K^+, linking it to agricultural leachate and possible pyrite oxidation under reducing conditions. The seasonal PCA plots (Figures 5–7) illustrate the spread of groundwater samples with varying geochemical signatures. Notably, samples such as Site 19 showed high PC1 loadings, pointing to site-specific saline or industrial contamination.

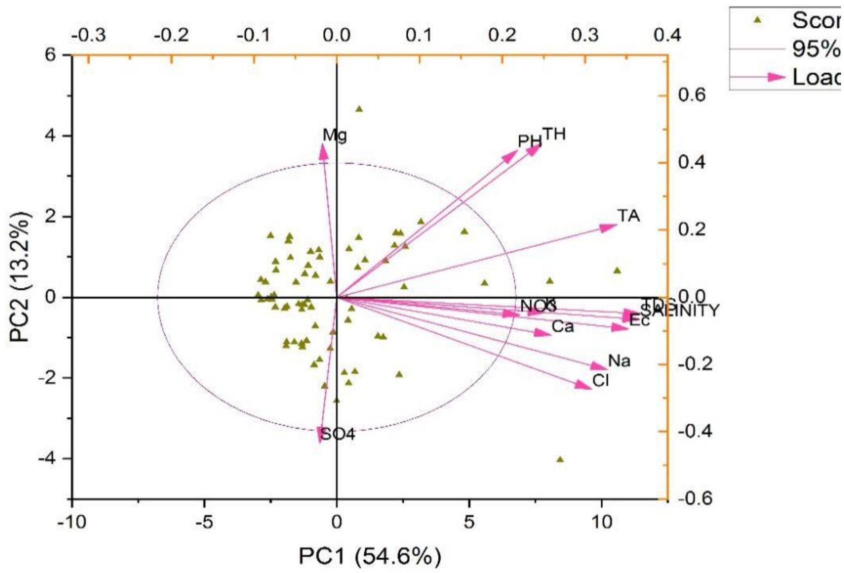

Figure 6. PCA biplot of monsoon samples showing variation in water quality parameters.

Pre-monsoon PCA biplots demonstrated clustering near high EC and TDS loadings, indicating strong evaporation and salt concentration. Monsoon plots showed a more dispersed pattern, consistent with dilution. Post-monsoon samples realigned towards PC1 and PC2, highlighting a blend of recharge and contaminant concentration (Xu et al., 2022).

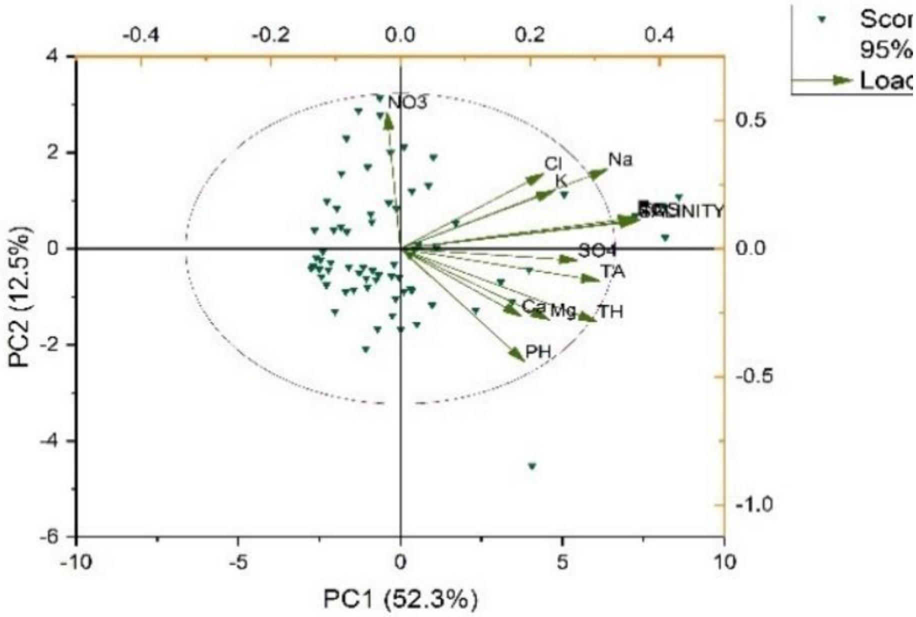

Figure 7. PCA biplot of post-monsoon samples highlighting geogenic and anthropogenic sources.

4.3 Cluster and Factor Analysis of Seasonal Groundwater Quality

The application of multivariate statistical techniques such as cluster and factor analysis provided valuable insights into the temporal variability and governing processes affecting groundwater quality across the Thrissur-Ponnani Kole region of central Kerala. These methods allowed for a nuanced understanding of how anthropogenic influences and natural geochemical processes interact across three seasonal cycles—pre-monsoon, monsoon, and post-monsoon.

4.3.1 Pre-Monsoon Season

Hierarchical Cluster Analysis (HCA) classified groundwater quality parameters into two primary clusters (Figure 8). The first cluster included sulfate (SO_4^{2-}), nitrate (NO_3^-), pH, and chloride (Cl^-), suggesting influences from surface contamination, potentially due to agricultural runoff and residential effluents. The second cluster, comprising salinity, total dissolved solids (TDS), and electrical conductivity (EC), reflects mineral dissolution and saline intrusion (Liu et al., 2018). A third subset, including Ca^{2+}, Mg^{2+}, total alkalinity (TA), and total hardness (TH), indicated geogenic influences such as carbonate weathering (Xu et al., 2022).

Factor Analysis revealed two dominant factors explaining 66.7% of the total variance (Figure 9). Factor 1 accounted for 54.2% and was loaded positively with TDS, EC, sodium (Na^+), and potassium (K^+), signifying mineralization and anthropogenic inputs. Factor 2, contributing 12.5%, was associated with Mg^{2+} and pH, representing buffering processes and natural variability (Arıman et al., 2024).

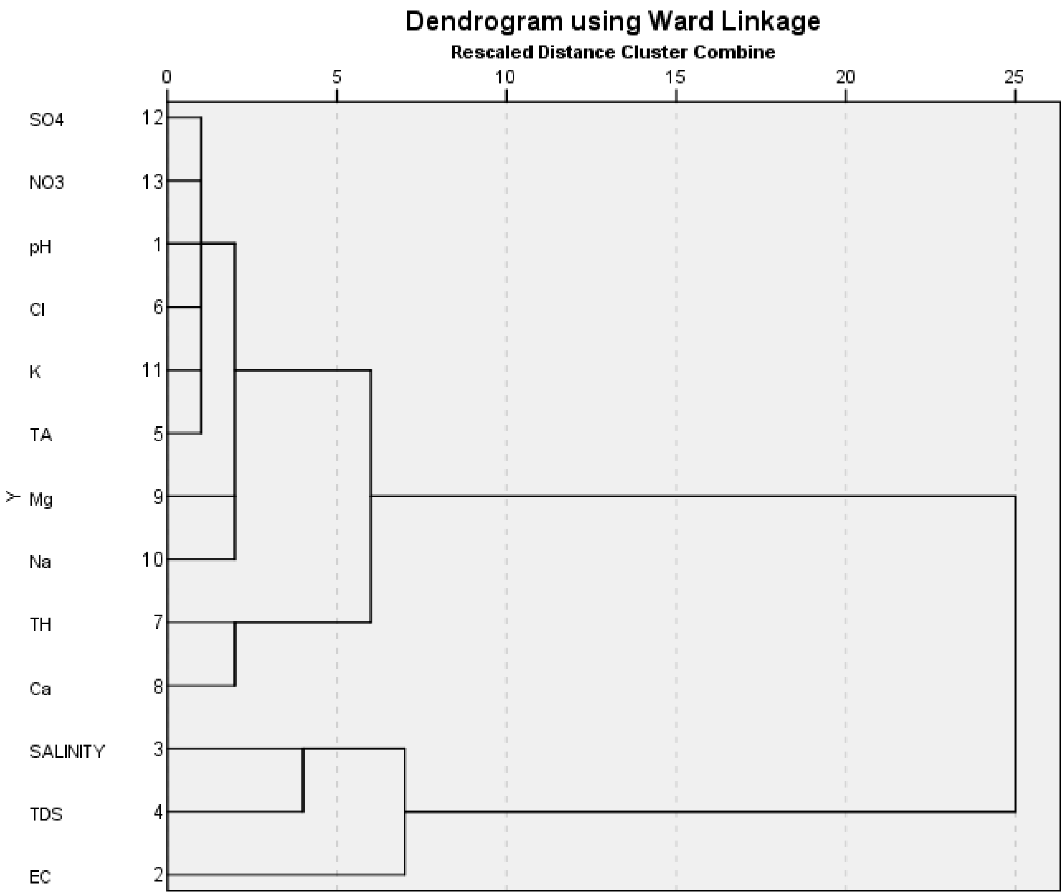

Figure 8. Pre-monsoon cluster dendrogram grouping ions by salinity, nutrients, and carbonate weathering.

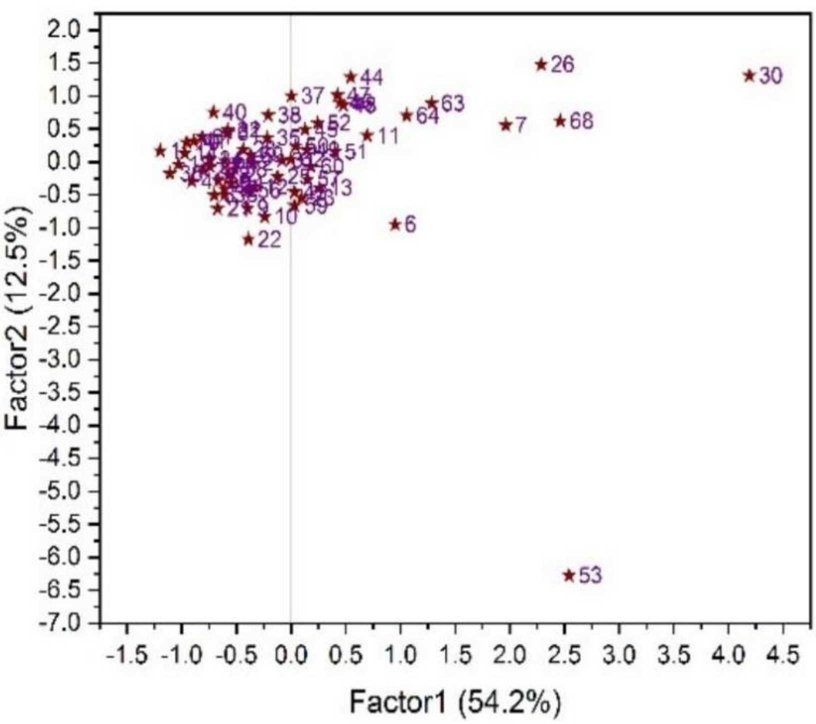

Figure 9. Pre-monsoon factor plot showing saline and anthropogenic influence (Factor 1) and geogenic buffering (Factor 2).

4.3.2 Monsoon Season

During the monsoon, increased precipitation introduced dilution effects and mobilized contaminants, altering groundwater chemistry. Cluster Analysis (Figure 10) again identified two principal clusters. Cluster I comprised NO_3^-, K^+, SO_4^{2-}, TA, and pH—parameters associated with agricultural runoff and wastewater. Cluster II included Ca^{2+}, Mg^{2+}, TH, TDS, and EC, indicative of enhanced mineral weathering and leaching due to rainwater infiltration (Sahoo et al., 2024).

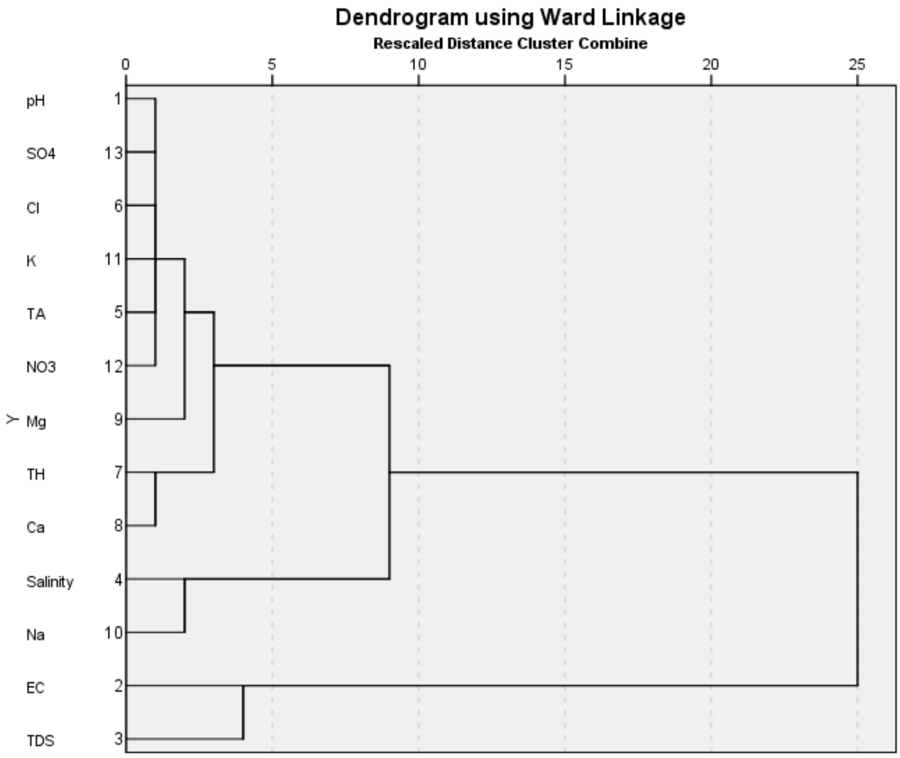

Figure 10. Monsoon cluster dendrogram reflecting dilution and mixed sources.

Factor Analysis for this season (Figure 11) emphasized the increasing influence of anthropogenic pollution. Factor 1, explaining 54.6% of the variance, was dominated by salinity-related ions (Na^+, Cl^-, TDS, EC), while Factor 2 (13.2%) reflected pH and carbonate-buffering chemistry. This pattern aligns with similar findings in monsoon-dominated aquifer systems (Luoma et al., 2015, https://doi.org/10.5194/hess-19-1353-2015).

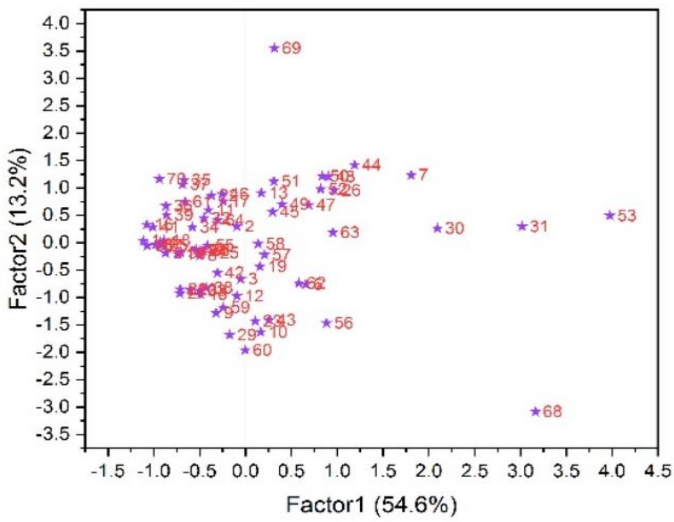

Figure 11. Monsoon factor plot highlighting dilution-driven grouping of salinity and pH-related parameters.

4.3.3 Post-Monsoon Season

The post-monsoon period revealed stabilized hydrochemical signatures. Cluster Analysis (Figure 12) grouped parameters similarly to pre-monsoon, but with less pronounced correlations, suggesting reduced dilution and consistent geogenic control. Notably, nitrate and pH formed a separate sub-cluster, indicating localized anthropogenic influence.

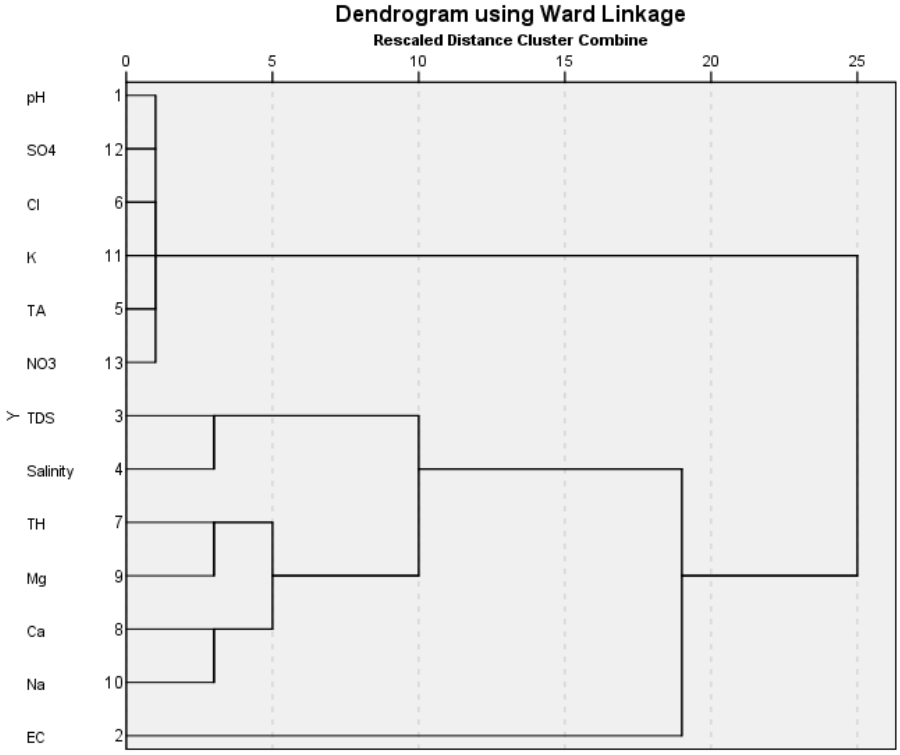

Figure 12. Post-monsoon cluster dendrogram showing stabilised geochemical signatures.

Factor Analysis (Figure 13) captured 64.8% of variance, with Factor 1 (52.3%) associated with mineralization and Factor 2 (12.5%) capturing anthropogenic indicators such as NO_3^- and TA. These findings support the persistence of weathering processes, coupled with residual effects from seasonal anthropogenic activities (Chegbeleh et al., 2020).

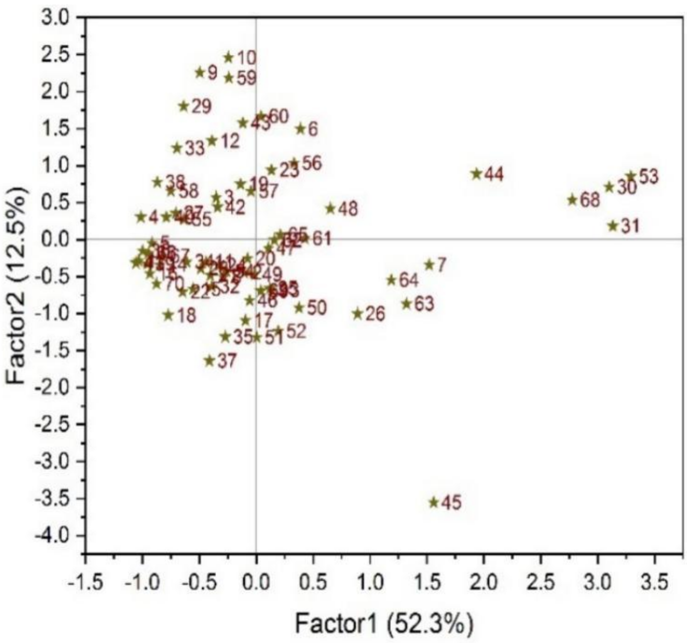

Figure 13. Post-monsoon factor plot illustrating mineralisation and residual nutrient loadings.

4.4 Spatial Insights and Implications

Spatial distribution of factor scores across seasons revealed persistent hotspots of contamination, particularly near croplands and urban zones (samples 30, 68, 53). These outliers deviated significantly from clustered groups, highlighting localized influences such as improper waste disposal or high fertilizer usage (Amâncio et al., 2021).

The cluster and factor analysis results underscore the need for seasonally adaptive groundwater management strategies. Pre-monsoon groundwater quality appears more vulnerable to saline intrusion and anthropogenic pollutants, while monsoon recharge dilutes pollutants but introduces new contaminants from surface runoff. Post-monsoon groundwater quality tends to stabilize, dominated by baseline geogenic signatures (Sabinaya et al., 2023).

4.5 Comparison with Other Studies

The results align with findings from similar tropical aquifer systems, where seasonal hydrodynamics, land use changes, and seawater intrusion shape groundwater chemistry (Yang et al., 2014). Previous works have emphasized the value of combining PCA and CA to interpret complex hydrogeochemical datasets, especially in data-scarce or dynamic environments (Platikanov et al., 2019).

4.6 Integrated Seasonal Interpretation

Collectively, the three seasonal analyses (pre-, monsoon, post-monsoon) underscore groundwater quality's susceptibility to both hydroclimatic shifts and human interventions. The cyclical salinisation, nitrate leaching, and recharge effects exhibit predictable spatial and temporal dynamics. This predictability offers potential for pre-emptive management actions such as groundwater zoning and seasonal advisories.

High correlation among EC, TDS, Na^+, and Cl^- points to the chronic nature of seawater intrusion, requiring long-term structural solutions. The episodic spike in NO_3^- during pre-monsoon highlights critical periods for agrochemical regulation. Targeted protection for vulnerable sites like Site 19 is essential.

4.7 Management Implications

Findings advocate for (i) seasonal adjustment of pumping schedules to minimise salinity ingress, (ii) regulated fertiliser application based on vulnerability zones, and (iii) integration of multivariate indices in groundwater surveillance programs. Such approaches enhance cost-efficiency and decision-making precision (Liu et al., 2018).

4.8 Limitations and Future Research

While multivariate tools proved powerful, the absence of trace metals, microbial parameters, and isotopic data limits the scope of contamination pathway delineation. Future work should integrate hydrogeological modelling and real-time sensors to complement statistical diagnostics.

4.9 Summary of Findings

- Pre-monsoon: Evaporation-induced salinity and nitrate accumulation.
- Monsoon: Dilution of pollutants with surface runoff.
- Post-monsoon: Partial recharge with residual salinity concentration.

These seasonally distinct signatures validate the application of PCA, FA, and HCA as foundational tools for groundwater quality management in coastal wetland ecosystems.

4.10 Final Remarks

This study demonstrates the effectiveness of multivariate statistics in assessing groundwater contamination in the Thrissur–Ponnani Kole wetlands. The methodological framework established here can be replicated in other monsoon-fed coastal aquifers facing similar water quality threats, contributing to scalable groundwater protection strategies.

5. CONCLUSION

This study assessed seasonal variations in groundwater quality in the Thrissur–Ponnani Kole wetlands using multivariate statistical approaches. The comprehensive application of PCA, FA, HCA, and correlation analysis revealed key hydrochemical processes driving the temporal and spatial heterogeneity in the region's shallow aquifers. The results confirm that the region is under growing pressure from both natural geogenic processes and human-induced contamination.

Salinity intrusion, driven by over-abstraction and proximity to the Arabian Sea, was found to be a persistent influence across all seasons. High correlations among EC, TDS, salinity, and Na^+/Cl^- suggest that seawater ingress is a chronic stressor, particularly in pre- and post-monsoon periods when groundwater levels drop due to reduced recharge (VishnuRadhan et al., 2015). The PCA biplots demonstrated this pattern vividly, with several wells showing high PC1 loadings attributable to salinisation.

Agricultural intensification contributed significantly to groundwater pollution, with high nitrate and sulphate levels reflecting leaching of fertilisers and pesticides. These impacts were especially prominent during the pre-monsoon season, when lower recharge enhances pollutant concentrations. The third principal component (PC3) and associated factors in FA captured these effects, validating earlier findings in monsoon-driven agro-ecosystems (Priyatharsini et al., 2016).

Cluster analysis revealed clear seasonal groupings of sampling locations, reflecting the strong role of hydrometeorological variability. Monsoon samples showed dilution-driven clustering, while post-monsoon samples displayed recovery trends with residual contaminant concentrations. This temporal dimension highlights the need for seasonally dynamic water management strategies (Liu et al., 2018).

Spatially, vulnerable zones such as sites near highways and industrial belts—e.g., Site 19—emerged as outliers in the FA and PCA plots. These areas exhibited combined signatures of saline intrusion and organic or chemical effluent loadings. Such patterns emphasise the importance of integrating land use regulation into groundwater management planning (Mohammed & Arunkumar, 2025).

The strength of the multivariate statistical framework lies in its ability to reduce analytical redundancy while retaining diagnostic power. Six principal components explained over 90% of the dataset variance, enabling streamlined interpretation without compromising scientific depth. These tools are therefore well suited for long-term monitoring and water quality modeling initiatives in data-limited regions (Platikanov et al., 2019).

From a policy standpoint, the study underscores the importance of groundwater zoning, seasonal abstraction control, and nutrient load management. The adoption of preventive and adaptive strategies, tailored to seasonal and spatial vulnerabilities, is critical for safeguarding groundwater in the Thrissur–Ponnani Kole wetlands and similar coastal plains. By combining hydrochemical insight with robust statistical modeling, this work lays a replicable foundation for sustainable groundwater resource management.

Future studies should integrate hydrogeological modeling, isotopic tracing, and real-time monitoring technologies to enhance diagnostic capacity. Nonetheless, the findings presented here represent a major step forward in diagnosing complex groundwater quality issues using low-cost, high-impact analytical frameworks in vulnerable wetland ecosystems. quality in the Kole wetlands is shaped by the interplay of seawater intrusion, carbonate weathering and diffuse agro-industrial loadings. Multivariate tools distilled complex chemistry into actionable signatures, pinpointing both regional drivers and site-specific anomalies. Policymakers should focus on salinity management and nutrient reduction to safeguard this critical resource.

Acknowledgements

We thank MES Ponnani College for laboratory facilities and field support.

Declarations

Conflicts of Interest: None.

CRediT Author Statement: *Samreena Mohammed*—Conceptualisation, Methodology, Investigation, Writing-original draft. *K.S. Arunkumar*—Supervision, Writing-review & editing. *Santhosh V*—Review & editing.

REFERENCES

[1] Amâncio, R., Tavares, M. A., Farias, C. A., & Monteiro, M. (2021). Spatial variation of hydrochemical parameters and water quality index in the Jatobá dam, Paraíba, Brazil. *Revista Virtual de Química, 13*(4), 1077–1091. https://doi.org/10.6008/cbpc2179-6858.2021.004.0010

[2] Arıman, S., Düzgün, H. S. B., & Yetiş, Ü. (2024). Multivariate statistical evaluation of groundwater quality in a semi-arid region of Turkey. *Water, 16*(11570), 1–15. https://doi.org/10.3390/w16111570

[3] Chegbeleh, L. P., Kuma, J. S., Adjei, K. A., & Dogbey, K. T. (2020). Hydrogeochemical and statistical approach to groundwater quality assessment in parts of the Voltaian Basin of Ghana. *Journal of Water Resource and Protection, 12*(7), 607–628. https://doi.org/10.4236/jwarp.2020.127036

[4] Das, S., Sharma, P., Ghosh, S., & Dutta, R. (2018). Assessment of groundwater quality by water quality indices for irrigation and drinking in South-West Delhi, India. *Data Brief, 18*, 2019–2028. https://doi.org/10.1016/j.dib.2018.04.120

[5] Kumar, P. J. S., Joseph, B., & Thomas, M. (2020). Nutrient chemistry and seasonal variation in groundwater of a riverine island on the west coast of Kerala, India. *Environmental Earth Sciences, 79*(10), 1–11. https://doi.org/10.1007/s12665-020-08999-7

[6] Liu, S., Zhang, L., Zhang, Y., & Wang, X. (2018). Characterisation of spatial variability in water quality using multivariate statistics. *Marine Pollution Bulletin, 137*, 137–151. https://doi.org/10.1016/j.marpolbul.2018.10.026

[7] Luoma, S. N., Rainbow, P. S., Wang, W. X., & Ackerman, J. T. (2015). Seasonal shifts in metal bioaccumulation in estuarine food webs. *Hydrology and Earth System Sciences, 19*, 1353–1370. https://doi.org/10.5194/hess-19-1353-2015

[8] Mohammed, S., & Arunkumar, K. S. (2025). Groundwater hydrochemistry in central Kerala: Implications for aquifer infrastructure and environmental water management. *Indonesian Journal of Sustainable Agriculture and Environmental Science, 1*, 1–14. [DOI Pending]

[9] Platikanov, S., Rodríguez, M. A., & Tauler, R. (2019). Chemometric analysis for river water quality assessment. *Science of the Total Environment, 667*, 552–562. https://doi.org/10.1016/j.scitotenv.2019.02.405

[10] Priyatharsini, P., Kumar, M., & Subramanian, V. (2016). Water quality characteristics of Vembanoor wetland. *International Journal of Current Microbiology and Applied Sciences, 5*, 852–860. https://doi.org/10.20546/ijcmas.2016.505.088

[11] Sabinaya, S., Sivakumar, S., & Nithya, N. (2023). Groundwater vulnerability assessment using hybrid multivariate and GIS methods in the Neyveli aquifer. *Research Square Preprint*. https://doi.org/10.21203/rs.3.rs-2526556/v1

[12] Sahoo, S., Kar, D., & Sarkar, D. (2024). Seasonal variability in groundwater quality in a coastal aquifer: Multivariate and spatial modeling approach. *Research Square Preprint*. https://doi.org/10.21203/rs.3.rs-4204728/v1

[13] Sarkar, D., Sahoo, S., & Kar, D. (2021). Seasonal changes in groundwater chemistry and its hydrogeochemical evolution in a coastal aquifer. *Environmental Monitoring and Assessment, 193*, 1–19. https://doi.org/10.1007/s10661-021-08882-0

[14] VishnuRadhan, R., Srinivas, Y., & Srinivasan, P. (2015). Southwest monsoon influences on Mandovi estuary water quality. *Chemistry and Ecology, 31*, 217–230. https://doi.org/10.1080/02757540.2015.1024081

[15] Xu, K., Liu, Y., Wang, F., & Zhang, L. (2022). Hydrogeochemical characteristics of a multilayer groundwater system in a coal-mine area. *Water, 14*(3146), 1–19. https://doi.org/10.3390/w14193146

[16] Yang, Y., Wang, Y., Fu, Q., & Liu, C. (2014). Evaluation of groundwater chemistry and water quality in shallow aquifer of Western Liaohe River Plain, Northeast China. *Polish Journal of Environmental Studies, 23*(4), 1441–1448. https://doi.org/10.15244/pjoes/30263