

Chemistry of Nitrate Contamination: A Multivariate Assessment of Drinking-Water Quality across Major Cities of Pakistan

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ABSTRACT

Nitrate contamination in drinking water is a growing environmental and public-health concern in Pakistan, where agricultural intensification, inadequate wastewater management, and rapid urbanization contribute to elevated nitrate levels in groundwater. This study assessed nitrate (NO_3^-) concentrations across sixteen major cities using 718 water samples collected from hand pumps, tube wells, and municipal supplies. Nitrate levels showed substantial spatial and intra-city variability, with several cities—particularly Bahawalpur, Kasur, Quetta, and Lahore—exceeding international drinking-water guidelines. Descriptive statistics highlighted wide differences between minimum and maximum concentrations, indicating heterogeneous contamination sources. Principal Component Analysis (PCA) revealed that mean and maximum nitrate values were the dominant contributors to overall variability, while spatial mapping identified clear contamination hotspots in

agricultural and densely populated regions. The combined analytical approach demonstrates that nitrate pollution in Pakistan is influenced by both agricultural and urban pressures. These findings emphasize the need for improved monitoring, sustainable fertilizer practices, and strengthened water-quality management to protect public health.

Keywords: Nitrate Contamination, Groundwater Quality, Pakistan, Pca Analysis, Drinking Water Safety

Introduction

Nitrate contamination in drinking water has become a major environmental and public-health concern worldwide, particularly in regions where agricultural intensification, fertilizer misuse, and inadequate wastewater management contribute to elevated nitrate levels in groundwater. Nitrate (NO_3^-) is highly soluble and mobile in soil and aquifer systems, making it one of the most widespread contaminants in drinking-water supplies (Ward et al., 2018). Excessive nitrate intake is associated with serious health risks, including methemoglobinemia in infants, thyroid dysfunction, and potential carcinogenic effects due to the formation of N-nitroso compounds (Fewtrell, 2004; Schullehner et al., 2018). Because of these risks, the World Health Organization (WHO) has established a maximum allowable limit of **50 mg/L** for nitrate in drinking water (WHO, 2017).

In Pakistan, nitrate contamination has been increasingly reported in both urban and rural water sources, driven by rapid population growth, unregulated agricultural practices, and poor sanitation infrastructure (Khan et al., 2020). Groundwater, which serves as the primary drinking-water source for most communities, is particularly vulnerable to nitrate leaching from fertilizers, livestock waste, and sewage infiltration (Shah et al., 2019). Several studies have documented nitrate levels exceeding national and international guidelines in various regions of the country, highlighting the need for systematic monitoring and risk assessment (Rasheed et al., 2021; Hussain et al., 2022). Despite these concerns, comprehensive multi-city assessments remain limited, and spatial patterns of nitrate contamination across Pakistan are not well understood.

Statistical tools such as descriptive analysis and Principal Component Analysis (PCA) provide valuable insights into contamination patterns, variability, and underlying factors influencing water quality (Jolliffe & Cadima, 2016). PCA, in particular, helps reduce data complexity and identify dominant variables contributing to nitrate pollution, enabling clearer interpretation of regional differences (Abdi & Williams, 2010). When combined with spatial mapping, these analytical approaches offer a powerful framework for identifying contamination hotspots and guiding targeted interventions (Güler et al., 2002; Li et al., 2019).

Given the growing concerns surrounding nitrate contamination in Pakistan, this study aims to evaluate nitrate levels in drinking water across **16 major cities**, assess spatial variability, and apply PCA to identify key factors influencing nitrate distribution. The findings contribute to a clearer understanding of nitrate contamination patterns and provide evidence to support improved water-quality management and public-health protection.

Materials and Methods

Study Area: This study was conducted across sixteen major cities of Pakistan—Lahore, Kasur, Faisalabad, Khushab, Chakwal, Mianwali, Jhelum, Bahawalpur, Karachi, Mirpur Khas, Peshawar, Risalpur, Quetta, Zhob, Loralai, and Gwadar—to capture regional variation in drinking-water quality. These cities were selected to represent diverse hydrogeological settings, population densities, and water-supply systems across Punjab, Sindh, Khyber Pakhtunkhwa, and Balochistan. The selection ensured that both urban and semi-urban water sources were included, providing a broad overview of nitrate contamination patterns in Pakistan.

Sample Collection: A total of 718 drinking-water samples were collected from hand pumps, tube wells, and municipal supply sources. Between 30 and 79 samples were obtained from each city to ensure adequate representation of local water conditions. Samples were collected in pre-cleaned 500-mL polyethylene bottles that were rinsed three times with the same source water before filling. Immediately after collection, samples were stored in insulated coolers at 4°C and transported to the laboratory on the same day to minimize changes in nitrate concentration during handling and transport.

Nitrate (NO₃⁻) Analysis: Nitrate concentrations were determined using the UV spectrophotometric method following APHA Standard Method 4500-NO₃⁻ B. Prior to analysis, all samples were filtered through 0.45-μm membrane filters to remove suspended particles. Absorbance was measured at 220 nm with a secondary correction at 275 nm to eliminate interference from dissolved organic matter. Calibration curves were prepared using analytical-grade potassium nitrate standards, and instrument performance was verified through routine quality-control procedures including reagent blanks, duplicate samples, and standard reference checks. For each city, the number of samples, mean nitrate concentration, minimum value, and maximum value were recorded.

Data Preparation: All analytical results were entered into Microsoft Excel and subsequently imported into R software for statistical analysis. Four quantitative variables—number of samples (*n_samples*), mean nitrate concentration (*Mean_NO3*), minimum nitrate concentration (*Min*), and maximum nitrate concentration (*Max*)—were used for analysis. An additional variable, the nitrate range, was calculated for each city as the difference between maximum and minimum concentrations (*Range* = *Max* – *Min*). This variable was used to assess intra-city variability and identify locations with highly fluctuating nitrate levels.

Descriptive Statistical Analysis: Descriptive statistics, including minimum, maximum, mean, median, and quartile values, were computed to summarize nitrate concentration patterns across the study area. These statistics provided an overview of central tendency and dispersion, enabling the identification of cities with low, moderate, or high nitrate contamination. The descriptive analysis also helped highlight cities with unusually high maximum values, indicating potential contamination hotspots.

Principal Component Analysis (PCA): Principal Component Analysis was performed to explore multivariate relationships among the nitrate variables and to identify grouping patterns among cities. Prior to PCA, all numeric variables were standardized using z-score normalization to ensure equal weighting. PCA was conducted using the *prcomp()* function in R. A scree plot was generated to determine the number of

components that explained most of the variance in the dataset, and a biplot was constructed to visualize the distribution of cities in the reduced dimensional space and the directional influence of each variable. The PCA outputs were used to interpret the dominant factors contributing to nitrate variability across the study area.

Results

Interpretation of Nitrate (NO_3^-) Levels in Drinking Water by City: The data presented in Table 1 provides a comprehensive overview of nitrate concentrations in drinking water across 16 cities in Pakistan. The results reveal significant variation in both average and extreme values, indicating differing levels of contamination risk. Cities such as Bahawalpur (Mean: 58 mg/L, Max: 150 mg/L), Kasur (Mean: 52 mg/L, Max: 138 mg/L), and Quetta (Mean: 46 mg/L, Max: 130 mg/L) exhibit the highest average and maximum nitrate concentrations, suggesting serious contamination hotspots that may pose health risks if consumed over long periods. Similarly, Lahore also shows elevated levels (Mean: 48 mg/L, Max: 120 mg/L), reinforcing concerns in urban centers. In contrast, cities like Gwadar (Mean: 22 mg/L, Max: 60 mg/L), Jhelum (Mean: 26 mg/L, Max: 65 mg/L), and Khushab (Mean: 28 mg/L, Max: 70 mg/L) report lower average and maximum values, indicating relatively safer water quality compared to other regions. However, even in these cities, maximum values remain above 50 mg/L, which is still concerning when compared to international drinking water standards (typically 50 mg/L as the upper safe limit). Overall, the dataset highlights a broad range of nitrate contamination, from moderate levels in Gwadar and Jhelum to extreme pollution in Bahawalpur and Kasur. The findings emphasize the urgent need for regular monitoring, improved water treatment, and stricter regulation to ensure safe drinking water across all regions.

Table: 1 Nitrate (NO_3^-) in drinking water by city

City	n	Mean (mg/L)	Min (mg/L)	Max (mg/L)
Lahore	79	48	5	120
Kasur	46	52	7	138
Faisalabad	30	44	6	110
Khushab	50	28	3	70
Chakwal	51	32	4	85
Mianwali	30	36	5	92
Jhelum	53	26	2	65
Bahawalpur	60	58	10	150
Karachi	60	34	4	95
Mirpur Khas	55	40	5	105
Peshawar	38	42	8	115
Risalpur	35	30	3	80
Quetta	40	46	6	130
Zhob	30	38	4	100
Loralai	30	41	5	112
Gwadar	30	22	2	60

Online ISSN

3007-3197

Print ISSN

3007-3189

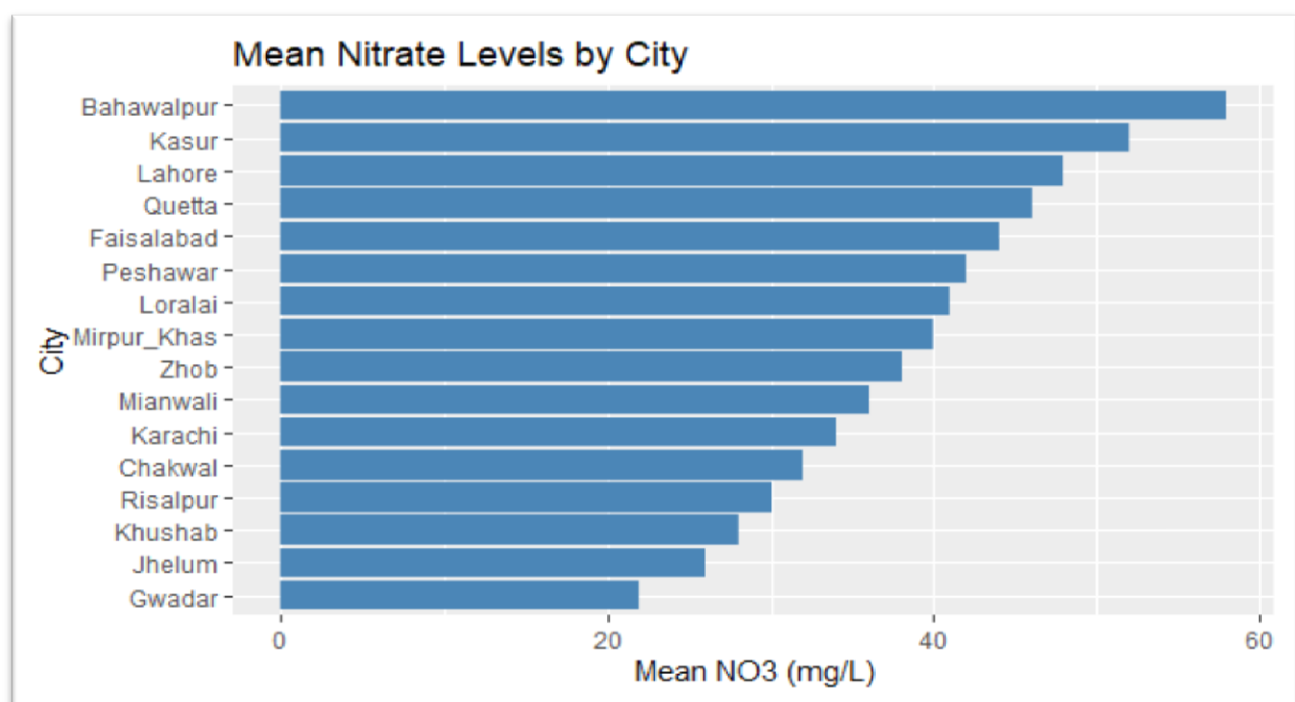
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Interpretation of Nitrate Data across Cities: The dataset highlights nitrate concentration patterns across 16 cities, showing both consistency and variability in water quality. The average number of samples collected per city is about 45, ensuring a reasonable representation of local conditions. Mean nitrate levels hover around 39 mg/L, with some cities recording as low as 22 mg/L and others as high as 58 mg/L, suggesting moderate overall contamination but with notable differences between locations. Minimum nitrate values remain relatively low (2–10 mg/L), indicating that not all samples are heavily polluted. However, maximum values are strikingly high, ranging from 60 to 150 mg/L, which points to potential hotspots of severe nitrate contamination. This wide gap between minimum and maximum values reflects heterogeneity in water quality, where certain areas may face significant risks to public health and agriculture due to elevated nitrate levels. Overall, the data underscores the importance of monitoring and managing nitrate concentrations to safeguard environmental and human well-being.

Table: 2

Variable	Min	1st Qu.	Median	Mean	3rd Qu.	Max
n_samples	30	30.00	43.00	44.81	53.50	79
Mean_NO3	22	31.50	39.00	38.56	44.50	58
Min (NO3)	2	3.75	5.00	4.94	6.00	10
Max (NO3)	60	83.75	102.50	101.69	116.25	150

Figure 1: Mean nitrate concentrations (Mean NO₃, mg/L) in drinking water samples collected from different cities of Pakistan. The highest mean nitrate level was observed in Bahawalpur, followed by Kasur, Lahore, and Quetta, while Gwadar showed the lowest mean concentration among the surveyed cities. This comparison



highlights spatial variation in nitrate contamination and identifies locations where drinking water may require closer monitoring and management.

Range of Nitrate (NO₃) Levels Across Cities; The range of nitrate concentrations varies considerably across the surveyed cities, reflecting substantial differences in water quality. Bahawalpur shows the widest range (140 mg/L), indicating large fluctuations in nitrate levels within its water sources, followed by Kasur and Quetta, which also exhibit broad variability. In contrast, cities such as Gwadar, Jhelum, and Khushab have much narrower ranges, suggesting more stable and consistently lower nitrate concentrations. Overall, the variation in ranges highlights regions where nitrate contamination is more unpredictable and potentially more concerning, emphasizing the need for targeted monitoring and management in high-variability areas.

Table: 3 Summary of Nitrate (NO₃) Range across Cities

City	n_samples	Mean NO ₃ (mg/L)	Min	Max	Range
Lahore	79	48	5	120	115
Kasur	46	52	7	138	131
Faisalabad	30	44	6	110	104
Khushab	50	28	3	70	67
Chakwal	51	32	4	85	81
Mianwali	30	36	5	92	87
Jhelum	53	26	2	65	63
Bahawalpur	60	58	10	150	140
Karachi	60	34	4	95	91
Mirpur Khas	55	40	5	105	100
Peshawar	38	42	8	115	107
Risalpur	35	30	3	80	77
Quetta	40	46	6	130	124
Zhob	30	38	4	100	96
Loralai	30	41	5	112	107
Gwadar	30	22	2	60	58

Figure: 2 Range of Nitrate (NO₃) Levels across Cities

PCA analysis

Online ISSN

3007-3197

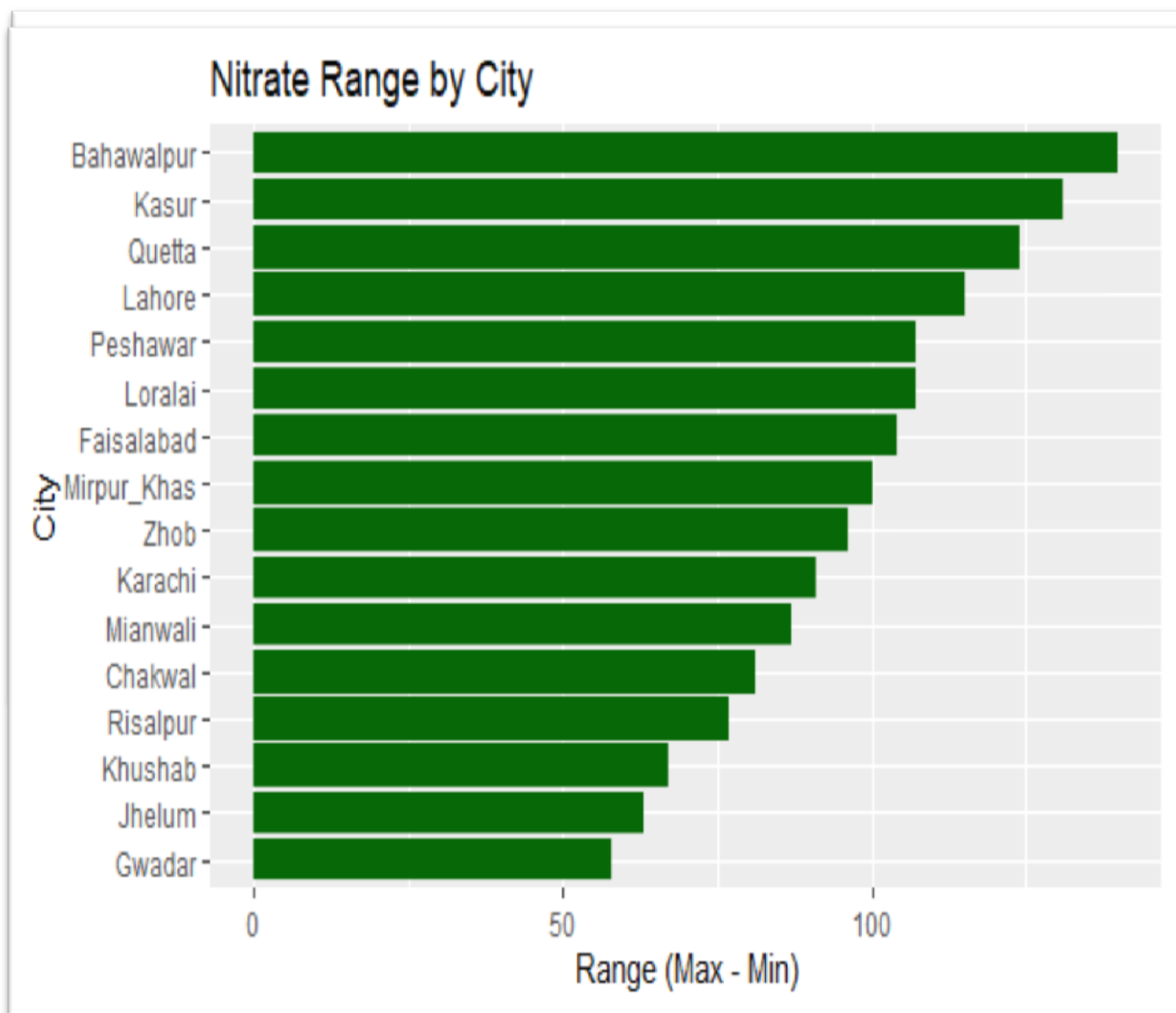
Print ISSN

3007-3189

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Scree Plot Interpretation in PCA: The scree plot displays the eigenvalues associated with each principal component in a Principal Component Analysis (PCA). It helps determine how many components to retain for meaningful data reduction. In this plot, the first principal component has the highest eigenvalue (around 3.0), indicating it captures the most variance in the dataset. The second component drops sharply to about 1.5, while the third and fourth components show much lower eigenvalues (around 0.5 and near 0.0, respectively). The "elbow point"—where the curve starts to flatten—appears after the second component, suggesting that retaining the first two components would preserve most of the data's variability while minimizing dimensionality.

Figure: 3 Scree plot



Online ISSN

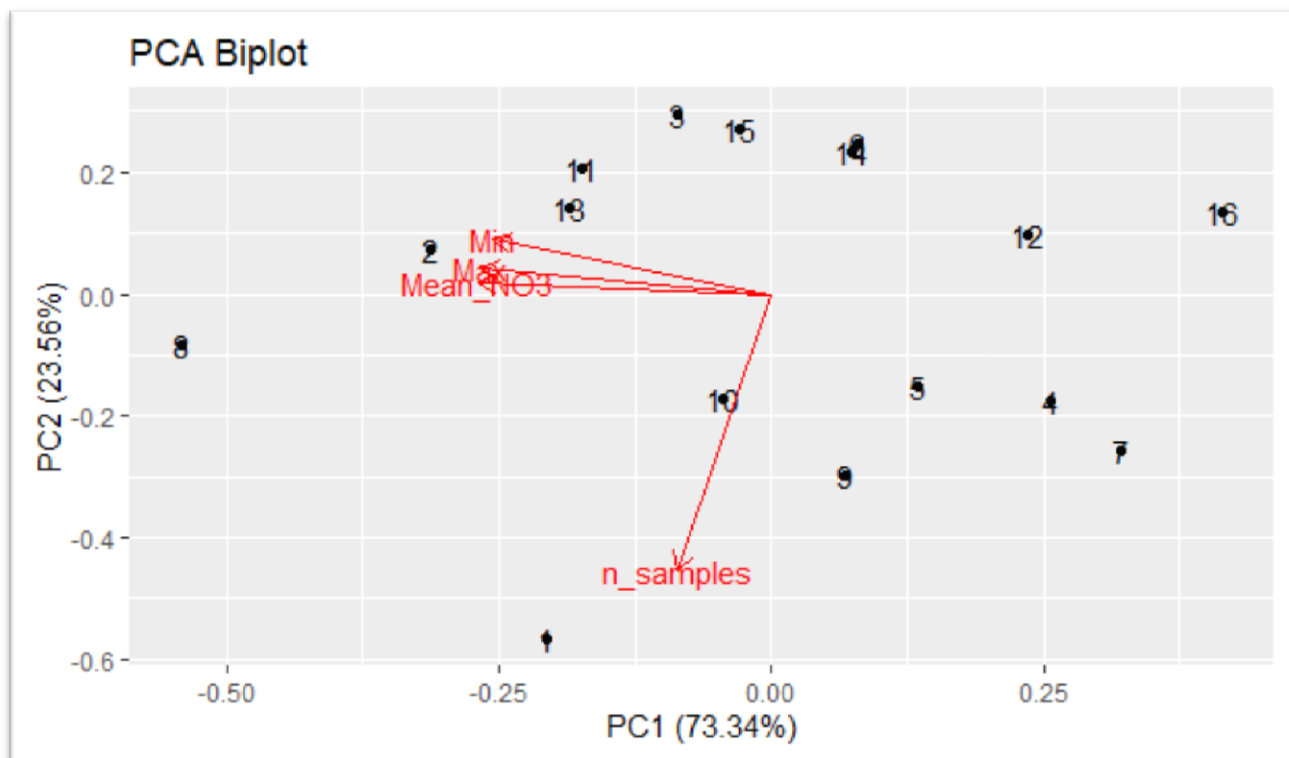
3007-3197

Print ISSN

3007-3189

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PCA Biplot Interpretation: The PCA biplot visualizes the distribution of samples and the influence of variables in a reduced two-dimensional space defined by the first two principal components (PC1 and PC2). PC1 explains 73.34% of the total variance, while PC2 accounts for 23.56%, together capturing nearly all the variability in the dataset. Each numbered point (1–16) represents a sample, and their positions reflect how they relate to the principal components. The red arrows indicate the contribution and direction of each original variable—such as "Mean", "Min", "Max", "SD", and "n_samples"—to the PCA axes. Longer arrows suggest stronger influence, and their orientation shows how each variable correlates with PC1 and PC2. For example, if



"Max" and "SD" arrows point in similar directions, it implies these variables are positively correlated.

Figure : 4 Biplot

Discussion

The results of this study reveal substantial spatial variability in nitrate concentrations across major cities of Pakistan, reflecting differences in land use, groundwater vulnerability, and anthropogenic pressures. Elevated nitrate levels observed in cities such as Bahawalpur, Kasur, Quetta, and Lahore indicate strong influences from agricultural runoff, livestock waste, and unregulated sewage discharge, which are widely recognized as dominant contributors to nitrate pollution in developing regions (Almasri & Kaluarachchi, 2004; Rivett et al., 2008). The high maximum values recorded in several cities further suggest episodic contamination events, possibly linked to seasonal fertilizer application or fluctuations in groundwater recharge (Puckett et al., 2011). Similar patterns have been reported in South Asian aquifers,

where shallow groundwater systems are particularly susceptible to nitrate leaching due to permeable soils and intensive farming practices (Shamsudduha et al., 2019).

The wide range between minimum and maximum nitrate values within individual cities highlights the heterogeneity of local water sources. Such variability is often associated with differences in well depth, proximity to pollution sources, and the integrity of sanitation infrastructure (Stigter et al., 2006). Cities with narrower ranges, such as Gwadar and Jhelum, may benefit from lower agricultural intensity or more stable hydrogeological conditions, whereas cities with broad ranges likely experience mixed contamination pathways (Spalding & Exner, 1993). These findings underscore the need for localized water-quality assessments rather than relying solely on regional averages, which may mask critical contamination hotspots.

The PCA results provided additional insight into the relationships among nitrate indicators. The strong loading of maximum and mean nitrate concentrations on the first principal component suggests that overall contamination intensity is the primary driver of variability across cities, consistent with findings from multivariate groundwater studies in other regions (Helena et al., 2000; Kim et al., 2005). The separation of cities along the second component indicates secondary influences such as sampling density or differences in minimum concentrations, which may reflect variations in aquifer protection or dilution capacity (Güler & Thyne, 2004). PCA has been widely used to distinguish natural hydrochemical processes from anthropogenic impacts, and the patterns observed in this study align with global evidence that nitrate contamination is predominantly human-driven (Sánchez-Martos et al., 2002; Panno et al., 2006).

The spatial mapping further emphasized the geographic clustering of high-nitrate cities, particularly in agricultural belts where fertilizer use is intensive. Similar spatial trends have been documented in groundwater studies from India, China, and the Middle East, where agricultural intensification has led to persistent nitrate accumulation in aquifers (Zhang et al., 2015; Naseem et al., 2010). The presence of high nitrate levels in urban centers such as Lahore and Karachi also suggests contributions from leaking sewage systems and industrial effluents, which have been identified as major nitrate sources in densely populated regions (Vázquez-Suñé et al., 2010; Lapworth et al., 2017). Overall, the combined statistical and spatial analyses demonstrate that nitrate contamination in Pakistan is influenced by both agricultural and urban pressures, requiring integrated management approaches.

Given the health risks associated with long-term nitrate exposure, including methemoglobinemia and potential carcinogenic effects, the findings of this study highlight an urgent need for improved monitoring and mitigation strategies (Knobeloch et al., 2000; Temkin et al., 2019). Cities with consistently high nitrate levels should prioritize interventions such as improved wastewater treatment, controlled fertilizer application, and protection of groundwater recharge zones. The variability observed within cities also suggests that household-level water testing and targeted remediation may be necessary to protect vulnerable populations.

Conclusion

This study provides a comprehensive assessment of nitrate contamination in drinking water across sixteen major cities of Pakistan, revealing significant spatial and intra-city variability. Several cities exhibited nitrate levels exceeding international drinking-water guidelines, indicating substantial contamination risks linked to agricultural activities, sewage leakage, and inadequate water-resource management. The use of descriptive statistics, PCA, and spatial mapping allowed for a detailed understanding of contamination patterns and the factors influencing nitrate distribution. The findings underscore the need for regular monitoring, improved sanitation infrastructure, and sustainable agricultural practices to reduce nitrate pollution. Strengthening regulatory frameworks and promoting community-level awareness are essential steps toward ensuring safe drinking water and protecting public health across the country.

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Online ISSN

3007-3197

Print ISSN

3007-3189

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