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Physicochemical and Heavy Metal Analysis of Military Drinking Water in Makurdi

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ABSTRACT
Background and Objective: Safe drinking water is essential for health, hygiene, and operational readiness in military environments. However, military settings are vulnerable to water contamination, posing risks to personnel's well-being and mission effectiveness. This study assessed the physicochemical parameters and heavy metal contamination in drinking water from three military formations (A, B, and C) in Makurdi, Nigeria, to identify contamination patterns and guide corrective actions. **Materials and Methods:** Water samples were collected from 18 locations covering residential, religious, office, school, market, and control sites. Key parameters analyzed included pH, total dissolved solids (TDS), electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), hardness, Na^+, K^+, Mg^{2+}, and trace metals (nickel, zinc, chromium, cadmium, manganese), using standard APHA methods. Pearson correlation and Principal Component Analysis (PCA) were employed to evaluate relationships and classify water quality patterns. **Results:** The TDS strongly correlated with EC ($r = 0.97$), and magnesium showed significant associations with sodium and EC ($r = 0.82$-0.85), suggesting mineralization effects. PCA distinguished three site clusters: (1) low-salinity zones with elevated turbidity and BOD, indicating organic pollution; (2) office areas with high cadmium, chromium, and nickel levels, reflecting anthropogenic input; and (3) mineral-rich sites with elevated TDS (335 mg/L) and EC (667 µS/cm). Manganese and TDS levels exceeded permissible limits in select locations. **Conclusion:** The findings highlight localized contamination linked to geogenic factors, poor sanitation, and aging infrastructure. Infrastructure upgrades, improved hygiene practices, and routine water quality monitoring are recommended to ensure safe drinking water and support military operational efficiency.

KEYWORDS
Water quality, heavy metals, military formations, physicochemical parameters, multivariate analysis

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INTRODUCTION
Access to safe drinking water is fundamental to ensuring the health, operational readiness, and strategic resilience of military personnel, particularly in resource-constrained environments such as military formations. In these locations, water quality directly influences hygiene practices and disease prevention, which are critical for maintaining mission effectiveness. Inadequate access to clean water is confirmed to

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compromise hygiene, leading to increased health risks[1]. Approximately 70% of servicewomen in field training reported limited or no access to clean running water, resulting in reduced hygiene practices and higher risks of urogenital infections. Historical and contemporary evidence further highlights the threat of waterborne diseases in military contexts[2]. A Campylobacter enteritis outbreak affected 75 out of 88 conscripts in Finland due to untreated surface water consumption. Similarly[3], a leptospirosis outbreak in Okinawa, Japan, with an attack rate of 183 per 1000 among U.S. personnel exposed to contaminated water. In Nigeria[4], cholera and hepatitis E outbreaks in military training centres were linked to sewage-contaminated pipelines, while[5] *Escherichia coli* and *Vibrio cholerae* in sachet water and boreholes to confirm the compounded risks of poor sanitation and water insecurity.

Beyond health implications, water holds strategic importance in military operations. Water infrastructure is a frequent target in conflicts, disrupting access to potable water and undermining operational capabilities[6]. Centralized water systems in Ukraine are vulnerable to sabotage, worsening humanitarian and military challenges. Additionally, the intentional contamination of water supplies with biological or chemical agents poses a significant threat[7]. Heavy metal contaminants, such as lead and cadmium, further aggravate health risks by contributing to chronic conditions, including neurological and renal damage. To address these vulnerabilities[8], advocated for reliable, decentralized groundwater systems powered by renewable energy to ensure reliable water access in conflict zones. The legal and ethical dimensions of water security are equally critical. The International Humanitarian Law (IHL) prohibits the targeting of water infrastructure and actions that deny civilians access to essential water resources during conflicts. International Environmental Law (IEL) complements these protections by promoting sustainable water management. Despite these frameworks, enforcement remains challenging, as evidenced by historical tactics of water denial, such as the destruction of water towers, which weaken adversaries and civilian populations[9]. Such practices confirm the need for reliable water governance in military operations.

This study evaluates the physicochemical properties and heavy metal contamination of drinking water in some military formations in Makurdi, Nigeria, to identify contamination patterns. Employing multivariate statistical techniques, the research analyzed water quality parameters and heavy metal concentrations. The study aimed to provide evidence-based information that will prompt targeted interventions and ensure safe drinking water and operational effectiveness of military personnel in Makurdi, Nigeria.

MATERIALS AND METHODS

Study area and sampling design: This study was conducted across three selected military formations in Makurdi, designated as formation A, formation B, and formation D. These formations were strategically chosen to represent varying levels of residential, administrative, and communal activities within military environments, which may influence the quality of available water resources. The formations were characterized by enclosed, regimented infrastructures with defined residential quarters, institutional buildings, and public access zones. Each formation operates as a self-contained community with its sources of potable and non-potable water, thus providing a relevant context for evaluating variations in water quality across different usage points. In each of the three formations, water samples were collected from six distinct locations representing functional land-use areas. These included residential area, worship area, office area, school area, mammy market, and control (a reference site located away from direct anthropogenic influence). A total of 18 water samples were thus collected (6 from each formation). The selection of these six sampling points per formation was guided by both ecological significance and human activity gradients to ensure that data collected reflected variations potentially arising from residential waste discharge, religious rituals, institutional effluents, school sanitation practices, commercial activities, and natural background levels. Sampling was conducted for a period of 3 months (March-May, 2024).

Measurement of water quality parameters: The analysis of trace metals in water samples was carried out[10]. Before analysis, all instruments were calibrated using certified reference standards, and appropriate quality control measures including blank samples, duplicates, and recovery checks were implemented to ensure analytical accuracy and precision. Intermediate standard solutions (100 mg/L) of nickel (Ni), cadmium (Cd), zinc (Zn), chromium (Cr), manganese (Mn), and lead (Pb) were prepared from primary stock standard solutions containing 1000 mg/L of each metal in 2N nitric acid. Working standards were obtained by serial dilution using an extraction solution and were used to construct calibration curves by plotting absorbance against known metal concentrations (mg/L). These standards were fixed into an atomic absorption spectrophotometer (Model PG-990) for analysis.

Water samples were digested with nitric acid before metal quantification. Specific detection wavelengths included 232.0 nm for Ni, 213.9 nm for Zn, 228.8 nm for Cd, and 279.5 nm for Mn. Measurements were conducted in triplicate, and blank determinations were also analysed using the same procedure to maintain quality assurance. Where sensitivity requirements necessitated, selected samples were further analysed using an ICP-OES. Hexavalent chromium (Cr^{6+}) was separately determined using the colorimetric method involving 1,5-diphenylcarbazide, with the resulting red-violet complex measured at 540 nm.

RESULTS

Descriptive statistics of physicochemical and trace metal parameters: The summary statistics of water quality parameters across the sampling points in the three military formations (A, B, and D) are presented in Table 1. Magnesium (Mg) ranged from 0.00 to 12.30 mg/L with a mean concentration of 2.77±3.20 mg/L, while sodium (Na) and potassium (K) had mean values of 2.89±2.15 and 1.41±1.12 mg/L, respectively. The pH values varied within a narrow range (6.70-7.70) with a mean of 7.19±0.24, indicating near-neutral to slightly alkaline water. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) showed wide variation, ranging from 5.10 to 335.00 mg/L (mean = 130.23±104.45 mg/L) and 25.00 to 667.00 µS/cm (mean = 273.61±195.27 µS/cm), respectively, suggesting varying levels of ionic constituents. Dissolved Oxygen (DO) concentrations ranged from 2.60 to 7.00 mg/L (mean = 3.67±1.00 mg/L), while Biochemical Oxygen Demand (BOD) remained relatively low, with a mean of 0.06±0.10 mg/L. Trace metal concentrations revealed that nickel (Ni), chromium (Cr), cadmium (Cd), and manganese (Mn) were present at varying but generally low levels. The mean concentrations of Ni, Cr, and Cd were all ≤0.01 mg/L, while zinc (Zn) and manganese (Mn) recorded higher average levels of 0.74±1.01 and 0.45±0.95 mg/L, respectively.

Correlation analysis of water quality parameters: Pearson correlation analysis (Table 2) revealed significant relationships among the measured variables. Strong positive correlations were observed between magnesium and sodium (r = 0.82), magnesium and EC (r = 0.85), and TDS and EC (r = 0.97), indicating that these parameters may be influenced by similar geochemical processes or sources of ionic input. Notably, TDS also showed a significant inverse relationship with pH (r = -0.68). A negative correlation was observed between potassium and DO (r = -0.39), implying a potential link between elevated potassium levels and oxygen depletion. Turbidity correlated positively with BOD (r = 0.58), highlighting the role of suspended organic matter in oxygen demand. Furthermore, hardness was positively associated with TDS (r = 0.69) and EC (r = 0.73), supporting the assumption that the dissolved ionic load contributes to total hardness. Among the trace metals, nickel showed significant positive correlations with both chromium and cadmium (r = 0.80 each), suggesting co-occurrence and possibly similar sources, such as corrosion or military-related contaminants.

Table 1: Summary statistics of water quality and trace metals in the three military formations in Makurdi, Nigeria

Variable	Minimum	Maximum	Mean	Std. Dev
Mg	0.00	12.30	2.77	3.20
Na	0.00	8.80	2.89	2.15
K	0.00	4.30	1.41	1.12
pH	6.70	7.70	7.19	0.24
TDS	5.10	335.00	130.23	104.45
DO	2.60	7.00	3.67	1.00
Temp	26.00	28.10	26.63	0.60
EC	25.00	667.00	273.61	195.27
Turb	0.00	109.00	6.31	25.65
BOD	0.00	0.30	0.06	0.10
Hard	0.00	14.20	2.72	4.71
Ni	0.00	0.02	0.00	0.01
Zn	0.00	3.01	0.74	1.01
Cr	0.00	0.01	0.00	0.00
Cd	0.00	0.02	0.00	0.01
Mn	0.00	3.02	0.45	0.95

Mg: Magnesium (mg/L), Na: Sodium (mg/L), K: Potassium (mg/L), pH: Potential of hydrogen (unitless), TDS: Total dissolved solids (mg/L), DO: Dissolved oxygen (mg/L), Temp: Temperature (°C), EC: Electrical conductivity (µS/cm), Turb: Turbidity (NTU), BOD: Biochemical oxygen demand (mg/L), Hard: Total hardness (mg/L as CaCO), Ni: Nickel (mg/L), Zn: Zinc (mg/L), Cr: Chromium (mg/L), Cd: Cadmium (mg/L) and Mn: Manganese (mg/L)

Table 2: Correlations of water quality and trace metals in the three military formations in Makurdi, Nigeria

Variables	Mg	Na	K	pH	TDS	DO	Temp	EC	Turb	BOD	Hard	Ni	Zn	Cr	Cd	Mn
Mg	1.00	0.82	0.38	-0.49	0.80	-0.13	-0.05	0.85	-0.22	0.00	0.38	0.40	-0.05	0.31	0.31	0.47
Na	0.82	1.00	0.26	-0.21	0.56	-0.07	0.19	0.61	-0.23	-0.02	0.12	0.20	-0.26	0.12	0.12	0.43
K	0.38	0.26	1.00	-0.38	0.33	-0.39	-0.20	0.43	-0.02	0.10	0.35	-0.13	0.04	0.06	0.07	-0.10
pH	-0.49	-0.21	-0.38	1.00	-0.68	0.13	-0.08	-0.73	0.53	0.33	-0.68	-0.29	-0.09	-0.29	-0.29	0.01
TDS	0.80	0.56	0.33	-0.68	1.00	-0.10	0.06	0.97	-0.28	-0.24	0.69	0.37	-0.11	0.29	0.29	0.35
DO	-0.13	-0.07	-0.39	0.13	-0.10	1.00	0.08	-0.14	0.09	-0.05	-0.29	0.03	-0.30	0.10	0.10	0.04
Temp	-0.05	0.19	-0.20	-0.08	0.06	0.08	1.00	0.09	-0.19	0.18	0.23	-0.15	-0.09	-0.35	-0.35	0.06
EC	0.85	0.61	0.43	-0.73	0.97	-0.14	0.09	1.00	-0.32	-0.15	0.73	0.34	-0.02	0.28	0.28	0.32
Turb	-0.22	-0.23	-0.02	0.53	-0.28	0.09	-0.19	-0.32	1.00	0.58	-0.15	-0.14	0.03	-0.06	-0.06	-0.12
BOD	0.00	-0.02	0.10	0.33	-0.24	-0.05	0.18	-0.15	0.58	1.00	0.13	0.05	-0.01	0.16	0.16	-0.18
Hard	0.38	0.12	0.35	-0.68	0.69	-0.29	0.23	0.73	-0.15	0.13	1.00	0.29	0.01	0.29	0.29	-0.07
Ni	0.40	0.20	-0.13	-0.29	0.37	0.03	-0.15	0.34	-0.14	0.05	0.29	1.00	-0.02	0.80	0.80	0.46
Zn	-0.05	-0.26	0.04	-0.09	-0.11	-0.30	-0.09	-0.02	0.03	-0.01	0.01	-0.02	1.00	-0.27	-0.27	0.21
Cr	0.31	0.12	0.06	-0.29	0.29	0.10	-0.35	0.28	-0.06	0.16	0.29	0.80	-0.27	1.00	1.00	-0.03
Cd	0.31	0.12	0.07	-0.29	0.29	0.10	-0.35	0.28	-0.06	0.16	0.29	0.80	-0.27	1.00	1.00	-0.03
Mn	0.47	0.43	-0.10	0.01	0.35	0.04	0.06	0.32	-0.12	-0.18	-0.07	0.46	0.21	-0.03	-0.03	1.00

Values in bold are different from 0 with a significance level alpha = 0.95, Mg: Magnesium (mg/L), Na: Sodium (mg/L), K: Potassium (mg/L), pH: Potential of hydrogen (unitless), TDS: Total dissolved solids (mg/L), DO: Dissolved oxygen (mg/L), Temp: Temperature (°C), EC: Electrical conductivity (µS/cm), Turb: Turbidity (NTU), BOD: Biochemical oxygen demand (mg/L), Hard: Total hardness (mg/L as $CaCO_3$), Ni: Nickel (mg/L), Zn: Zinc (mg/L), Cr: Chromium (mg/L), Cd: Cadmium (mg/L) and Mn: Manganese (mg/L)

Principal component analysis (PCA): Principal Component Analysis (PCA) was used to reduce the dimensionality of the data and classify water sampling locations based on similarities in physicochemical and trace metal parameters. The eigenvalue decomposition showed the first three principal components (PCs) had eigenvalues greater than 1, accounting for a significant portion of the total variance. While the first principal component (F1) had an eigenvalue of 5.93, explaining 32.98% of the total variance, the second principal component (F2) had an eigenvalue of 2.91, contributing 16.15% of the variance, resulting in a combined effect of 49.13% of the total variability in the data (Fig. 1).

The first principal component (F1) explained 32.98% of the total variance, while the second component (F2) accounted for an additional 16.15% as shown in Fig. 2. Variables with the highest positive loadings on F1 included electrical conductivity (EC = 0.93), total dissolved solids (TDS = 0.91), magnesium (Mg = 0.86), hardness (0.68), and sodium (Na = 0.62), suggesting F1 to represent a mineralization gradient influenced by dissolved ionic constituents. Conversely, F2 was positively correlated with cadmium (Cd = 0.81), chromium (Cr = 0.81), nickel (Ni = 0.61), and biochemical oxygen demand (BOD = 0.34), indicating F2 captures variability associated with trace metal contamination and organic pollution.

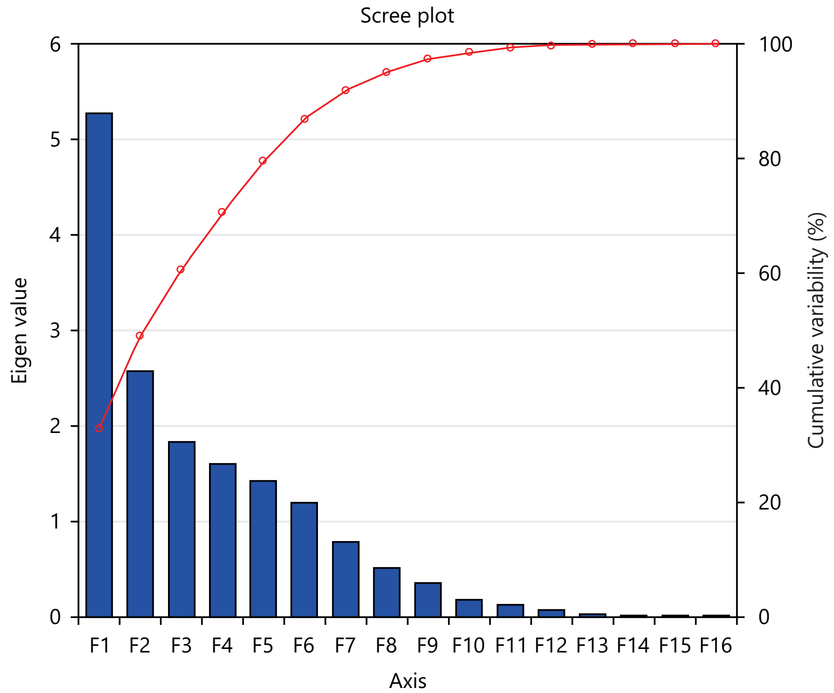

Fig. 1: PCA Scree plot of water quality and trace metals in the three military formations in Makurdi, Nigeria

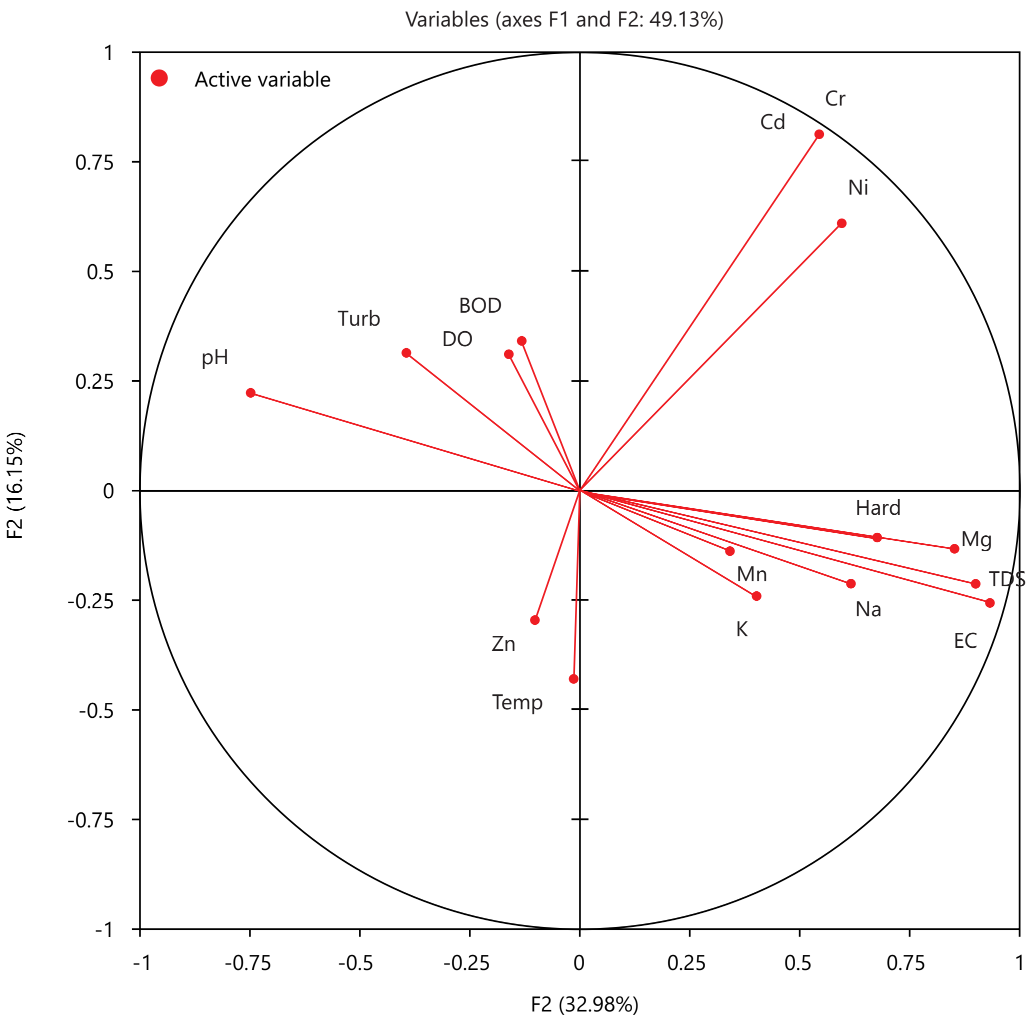

Fig. 2: Factor loading of water quality and trace metals in the three military formations in Makurdi, Nigeria

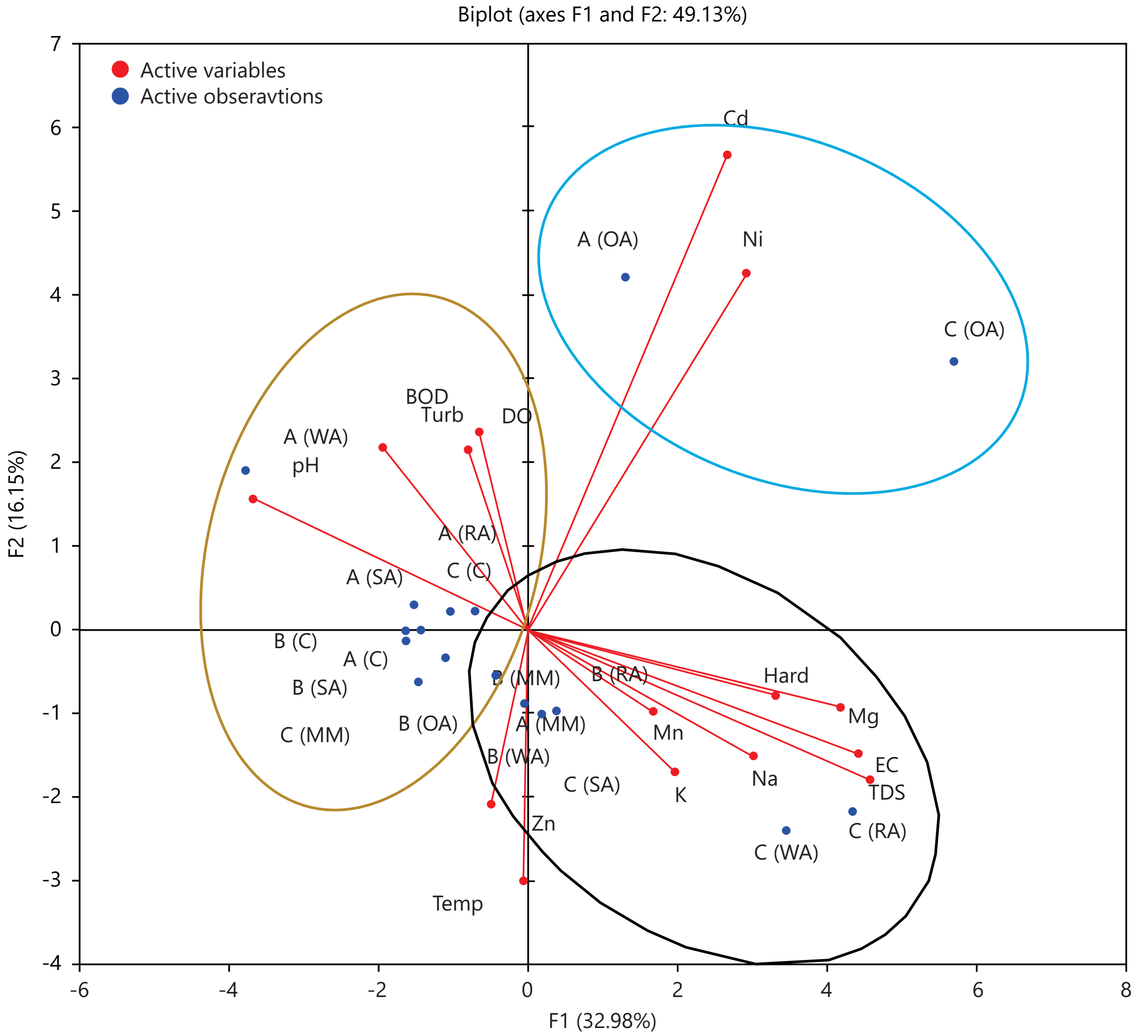

Fig. 3: PCA biplot showing three water quality clusters: Low-salinity/organic-polluted sites, trace metal impacted office areas, and mineral-rich locations

Three major clusters were visually evident on the PCA biplot (Fig. 3), each reflecting distinct water quality characteristics. The first cluster comprised sampling sites such as A (Worship Area), A (School Area), A (Residential Area), and C (Control). These locations were characterized by low F1 scores (ranging from -1.0 to -3.7) and moderate-to-high F2 scores (ranging from 0.2 to 1.9), indicating low salinity but higher turbidity, BOD, and DO. These parameters had vector contributions of BOD (0.70), turbidity (0.61), and DO (0.31) to F2, suggesting susceptibility to organic pollution likely arising from household wastewater or unregulated runoff. The second cluster included A (Office Area) and C (Office Area). These two sites showed high F2 values (A [OA] = 4.21, C [OA] = 3.20) and moderate-to-high F1 values (A [OA] = 1.31, C [OA] = 5.71), positioning them close to the cadmium (0.81), nickel (0.61), and chromium (0.81) vectors. This indicates that these office areas are uniquely burdened with trace metals, possibly due to building materials, corroded plumbing, or administrative waste discharge. These metals, though low in mean concentration contributed significantly to the compositional separation of these zones, warranting further investigation and targeted mitigation. The third and largest cluster included sites such as B (Residential Area), B (Mammy Market), B (Office Area), C (Residential Area), and C (School Area). These points had high F1 scores (ranging from 3.5 to 5.7) and low F2 scores (ranging from -2.4 to -0.6), strongly aligning with mineral-related vectors such as EC, TDS, Mg, Na, and hardness. C (Residential Area) had an F1 score of 4.36 and an F2 of –2.17, indicating high mineral content but minimal organic or trace metal influence. This group corresponds to sampling points with the highest recorded EC (up to 667 μS/cm), TDS (up to 335 mg/L), and hardness (up to 14.2 mg/L), reflective of groundwater mineralization or aging infrastructure. The directional vectors and angles further revealed associations among parameters. Strong collinearity among EC, TDS, Na, and Mg confirms shared sources and behaviour. Similarly, Cd, Ni, and Cr clustered together, reinforcing the likelihood of a shared anthropogenic source.

DISCUSSION

The analysis revealed considerable spatial variation in the chemical characteristics of drinking water across the military formations studied. The first principal component (PC1), which accounted for the largest proportion of variance in the dataset, was dominantly influenced by high concentrations of dissolved ions, particularly magnesium, sodium, and parameters related to water hardness. The pattern observed in Formations B and C strongly suggests that mineral enrichment in these locations is the result of sustained interaction between groundwater and the underlying geologic formations. Processes such as the weathering of silicate and carbonate-bearing rocks, coupled with the leaching of elements from subsurface minerals, were probably the driving forces of the observed mineralization[11]. Weathering processes are fundamental in releasing both essential and toxic elements from parent materials, which then enter aquatic systems. A similar study by Masters *et al.*[12] confirmed that the mineral composition of parent materials in loess and other soil types significantly affects water chemistry. A study by Mukhopadhyay[13] provided further support, noting that the mineralogical composition of granite and gneiss in Ore, Nigeria, had direct implications on the chemical evolution of resulting water chemistry. The influence of such geogenic processes is often intensified by climatic and edaphic conditions, which govern the rate and extent of mineral breakdown. Corrosive interactions have been noted to release ionic constituents into the supply network's water ages within metallic pipelines[14]. Older pipelines increase water corrosivity and promote metal leaching. This has been confirmed to increase salinity and alter the ionic profile of the water. The need for timely infrastructure management to maintain acceptable water quality in municipal systems has been emphasized by many researchers.

In contrast to the geochemical drivers captured by PC1, the second principal component (PC2) was defined by the presence of trace metals, particularly cadmium, chromium, and nickel. This trend was especially prominent in the office areas within Formations A and C. The compositional pattern is indicative of anthropogenic factors. These influences may probably originate from corroded plumbing fixtures, metallic storage units, or residues from administrative and military operations[15]. Cadmium emissions predominantly occurred through non-ferrous metal smelting and fossil fuel combustion[16]. On the other hand, identified coal-based stationary sources as major contributors to atmospheric chromium. Although the concentrations recorded remained below permissible limits, the long-term presence of these metals in potable water raises significant public health concerns. Chronic exposure has been associated with nephrotoxicity and carcinogenic effects, as documented in previous toxicological studies. Another study by Gleick *et al.*[17] stressed the health risks associated with low-dose exposure to trace metals in water sources, particularly where regulatory oversight is limited.

The study delineated three distinct water quality typologies. The first cluster exhibited water with low mineral content and high turbidity and biochemical oxygen demand. This suggests the influence of organic pollution, likely introduced through sanitation practices, informal greywater discharge, and leaking septic tanks[18]. Poorly managed septic systems contribute significantly to nutrient pollution and microbial infiltration of shallow aquifers. A study by Tuholske *et al.*[19] confirmed that septic systems account for 5% of nitrogen loading in underground waters. Furthermore, a report[20] proved that greywater discharges undermine ecological water quality, particularly in densely inhabited areas. These findings underline the need for enhanced sanitation infrastructure and community-level water management. A second group of sites presented underlying chemistry primarily affected by the concentration of dissolved minerals. This condition could be as a result of extended contact between water and mineral-rich geological substrata or insufficient water treatment before delivery. The persistently high ion levels suggest natural geogenic input and an absence of effective treatment mechanisms. This pattern indicates an influx of degradable organic materials, which, if unaddressed, may create anaerobic environments that are conducive to microbial proliferation. Even though average values for most measured parameters remained within acceptable limits established by both international and national guidelines, several sampling points were high, particularly for Manganese and TDS[21]. These anomalies are likely the result of specific local influences, such as mineral-rich lithological formations or the accumulation of dissolved constituents in storage infrastructure. These site-specific deviations pose regulatory concerns, especially when prolonged exposure.

CONCLUSION

The geogenic factors, such as mineral-rich groundwater, increased the levels of magnesium, sodium, and TDS in formations B and C where geological interactions and aging infrastructure were prominent. The anthropogenic sources may have contributed to the trace metal contamination (cadmium, chromium, nickel) in office areas of formations A and C. On the other hand, organic pollution from poor sanitation and greywater discharge probably led to the increased turbidity and BOD at specific sites. Although most parameters were within regulatory standards, the high level of manganese and TDS indicates site-specific risks. Targeted interventions, including infrastructure upgrades, improved sanitation, and regular monitoring, are therefore suggested to ensure safe drinking water and support operational readiness in military formations.

SIGNIFICANCE STATEMENT

Safe drinking water is critical for military health and readiness, but contamination risks in Makurdi, Nigeria, threaten personnel and operations. Analysis of water from three military formations revealed manganese and TDS exceeding limits, with organic pollution, trace metals in office areas, and mineral enrichment from geogenic sources and aging infrastructure. These results pinpoint contamination sources, guiding targeted interventions like infrastructure upgrades to ensure safe water and operational efficiency. The study supports military readiness and informs water management in resource-constrained settings, enhancing resilience against contamination.

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