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ORIGINAL ARTICLE

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A Comparative Geochemical Profiling and Physicochemical Classification of Bottle Mineral Waters from Algeria and France: Implications for Consumer Health and Clinical Nutrition

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ABSTRACT

Background: As water is an indispensable physiological requirement, the bottled mineral water industry is undergoing continuous global expansion. Consequently, consumers are presented with an extensive array of commercial; thus, comparative analytical studies are crucial to ensure informed consumption and safeguard public health.

Aims: This study aimed to characterize and compare the physicochemical composition and geochemical profiles of a comprehensive selection of mineral water brands produced in Algeria and France. The objective was to enhance the characterization of hydro-geological resources in both countries and provide evidence-based guidance for consumer selection tailored to specific physiological and pathological requirements.

Material and Methods: Thirty-eight commercial mineral water brands (20 from Algeria and 18 from France) were evaluated based on standardized labelling data. The geochemical classification was performed via the Stabler diagram assessing key parameters including calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate, nitrate, nitrite, total dissolved solids (TDS), and pH. Hydro chemical facies were further elucidated using ionic balance calculations and specialized graphical representations, including Piper, Schoeller–Berkaloff, and Stiff diagrams.

Results: Analytical data revealed that Algerian mineral waters are predominantly characterized by calcium-bicarbonate profiles, with fluctuating concentrations of magnesium and sulphates. Mineralization levels varied significantly, ranging from highly mineralized brands such as *Mouzaïa* (1280 mg/L) to more balanced profiles such as *Texenna* or *Salsabil*. Conversely, French mineral waters exhibited higher ionic heterogeneity and generally superior mineralization levels, exemplified by *Vichy Célestins* (3325 mg/L), along with a more acidic pH range (5.5 – 7.6) compared to their Algerian counterparts. French waters typically manifested moderate to high concentrations of calcium, sodium, potassium, chloride, sulphate, and bicarbonate. Ionic balance assessment confirmed analytical reliability, with deviations consistently below 10%. Based on the physicochemical profiles, the 38 analyzed brands were categorized by clinical suitability: 10 were deemed appropriate for infants and patients with renal insufficiency, 9 for individuals with nephrolithiasis, 20 for those with cardiovascular disease, and 32 for the geriatric population.

Conclusions: This study establishes a robust geochemical database to assist consumers, including tourists and expatriates, in selecting mineral water brands aligned with their health status. These findings are particularly critical for vulnerable groups, such as infants, the elderly, and patients with renal or cardiovascular disorders, ensuring that water consumption supports rather than compromises therapeutic targets.

Keywords: Mineral Water; Hydrochemistry; Geochemical Profiling; Clinical Nutrition; Public Health; Algeria; France.

Article Information

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1 Introduction

Water plays a vital role in maintaining ecological equilibrium and supporting all life forms, influencing climate regulation, nutrient cycling, and the sustenance of biodiversity. Its physicochemical quality and availability are directly associated with human health; thus, sustainable water management is essential for disease prevention and the promotion of public well-being (Zhu *et al.*, 2025).

In Algeria, water resources are severely constrained and spatially unevenly distributed due to low and irregular precipitation. The national supply is derived from three primarily categories: surface water (rivers, dams, and wadis), groundwater (shallow and deep fossil aquifers), and unconventional sources such as seawater desalination and the reuse of treated wastewater (Barkat *et al.*, 2022). Within the Saharan regions, where surface flow is extremely scarce, reliance on fossil aquifers is essential. However, the governance of these resources management is increasingly challenged by aquifer over-exploitation, qualitative degradation and escalating demands from rapid urbanization, agriculture, and industrial activities (Allaoua *et al.,* 2024). To confront these pressures, Algeria has actively promoted integrated water resource management and alternative hydrological strategies tailored to future requirements (Kessar *et al.,* 2021). Consequently, the bottled water sector has experienced exponential growth, bolstered by government incentives and shifting consumer preferences. By 2024, approximately 73 bottling facilities were operational nationwide. Per capita consumption has surged from four liters in 1989 to 22 liters in 2007 reflecting a significant transition toward bottled water as a healthier and higher-quality alternative. In 2024, national bottled water consumption in Algeria reached approximately 52.5 liters per person per year (Hazzab, 2011; Labadi & Hammache, 2016).

In this context, bottled mineral water has emerged as a vital component of water supply strategies in both Algeria and France. France possesses diverse water resources encompassing both surface systems (rivers, reservoirs, and wadis) and extensive groundwater bodies including shallow alluvial and deep karst/fractured aquifers. Recent research indicates that southern France is experiencing significant declines in river discharge due to climate change, thereby threatening surface water security (Labrousse *et al.,* 2022), Furthermore, complex groundwater mapping in the Auvergne-Rhône-Alpes region underscores the complexity and management challenges of subsurface water systems. Effective governance of these varied resources therefore necessitates integrated monitoring and adaptive management strategies (Duranel *et al.,* 2021; Fleury *et al.,* 2023).

The expansion of the global bottled mineral water industry is largely driven by consumer perceptions of purity and therapeutic benefits, though it remains under scrutiny regarding its environmental footprint and long-term sustainability (Parag *et al.*, 2023). The industrial production process involves several key stages: extraction from natural springs or aquifers, filtration and treatment to eliminate impurities while preserving mineral integrity, and bottling under hygienic and pressurized conditions, packaging, and distribution to consumers (Stoots *et al.,* 2021). Each step requires strict quality control to ensure microbiological safety and compliance with mineral standards. Nonetheless, challenges related to resource depletion, plastic waste, and carbon emissions continue to prompt research into more sustainable practices (Maharjan, 2024). Natural mineral and spring waters are valued for their underground origin and purity. Mineral water maintains a stable composition and potential health benefits, while spring water, though more variable, remains microbiologically safe and potable without treatment (Chebbah & Kabour, 2023; Turhan *et al.,* 2021). Differences in the chemical composition of mineral waters are primarily governed by the geological characteristics and geochemical interactions of the aquifer systems from which they originate (Bodor *et al.,* 2021). Natural mineral water, of protected underground origin, is characterized by its stable mineral composition and inherent purity. Bottled directly at the source without disinfection, it undergoes strict quality controls. Its constant levels of minerals and trace elements provide distinctive taste and recognized therapeutic properties (Sekiou & Tamrabet, 2022). Water quality naturally varies depending on location, season, and the nature of the soil and rocks it flows through. The apparent clarity of water is not a reliable indicator of its potability. A comprehensive assessment of water safety requires the evaluation of three categories of parameters: microbiological (including bacteria, viruses, and parasites), chemical (such as minerals and metals), and physical (e.g., temperature, pH, and conductivity). Furthermore, pesticides significantly contribute to the contamination risks associated with spring water, thereby posing potential adverse effects on human health (Bodor *et al.,* 2023).

The physicochemical quality of water is determined by key parameters such as pH, conductivity, turbidity, and major ion content. These indicators reflect dissolved salts, suspended particles, and potential health risks such as nitrate contamination. Continuous monitoring ensures water safety, stability, and compliance with drinking standards (Ketrouci *et al.,* 2023). Spring waters exhibit variable, generally low to moderate mineralization influenced by local geology and hydrology, while natural mineral waters display stable compositions and defined mineralization classes. Classified by dissolved salt content and dominant ions, mineral waters possess specific physicochemical properties. This classification underpins their regulation, utilization, and therapeutic utilization (AFSSA, 2008). While both spring and natural mineral waters provide essential micronutrients—such as calcium, magnesium, sodium, and bicarbonates—natural mineral water is valued for its consistent nutritional profile, which supports musculoskeletal and metabolic health (Tamrabet *et al.,* 2024).

This comparative study investigates the physicochemical similarities and discrepancies between bottled mineral waters marketed in Algeria and France. The selection of these two nations is based on several criteria: the similarity of water quality regulation, linguistic and labeling similarities, and the high volume of human mobility between the two regions, —including tourists and the diaspora— facilitated by deep historical and cultural ties.

Ultimately, this research seeks to enhance consumer awareness regarding the quality and safety of bottled waters while promoting their distinctive health-related properties. By elucidating the influence of climatic and geological factors on the physicochemical composition of these resources, this study aims to guide consumers towards informed choices and contribute to a more profound understanding of sustainable water resource management in a Mediterranean context

2 METHODS

This cross-sectional observational study was conducted to evaluate a comprehensive range of bottled mineral water brands available within the Algerian and French markets. The investigation took place over a three-month period, from March to May 2025. The physicochemical composition of each brand was recorded based on the mandatory nutritional labeling provided on the packaging. The collected data were then subjected to hydro-geochemical comparative analysis and visualized through graphical representation to identify regional ionic trends.

2.1 Selection of Algerian Mineral Water Brands

Following an exhaustive survey of the Algerian market, twenty prominent mineral water brands were identified. Each brand was categorized by its source of origin and the respective province (Wilaya) of production. The sampled brands included: *Saïda* (Saïda), *Lalla Khedidja* (Béjaïa), *Guedila* (Biskra), *Ifri* (Béjaïa), *Youkous* (Tébessa), *Mouzaïa* (Blida), *Messerghine* (Oran), *Texenna* (Jijel), *El Goléo* (Ghardaïa), *Manbaa* (Biskra), *Toudja* (Béjaïa), *Sfid* (Saïda), *Mansourah* (Tlemcen), *Batna* (Batna), *N'Gaous* (Biskra), *Salsabil* (Ghardaïa), *Sidi Okba* (Biskra), *Milok* (Laghouat), *Baniane* (Biskra), and *Thevest* (Tébessa).

2.2 Selection of French Mineral Water Brands

Similarly, eighteen established French mineral water brands were selected for analysis. These brands were documented alongside their specific production regions and natural springs: *La Salvetat* (Hérault), *Mont Roucous* (Haut-Languedoc), *Perrier* (Occitanie), *Contrex* (Vosges), *Rozana* (Auvergne), *Wattwiller* (Alsace), *Vittel* (Vosges), *Volvic* (Dôme), *Saint Amand* (Saint-Amand), *Alpes* (Alpes), *Neuve* (Occitanie), *Saint Diéry* (Saint Diéry), *Vichy Célestins* (Auvergne), *Evian* (Alpes), *Sainte Marguerite* (Puy-de-Dôme), *Hépar* (Vittel), *Magnésienne* (Tarn-et-Garonne), and *Badoit* (Loire).

2.3 Data Acquisition and Documentation Protocol

Primary data collection regarding the bottled water brands and their physicochemical specifications was performed through field surveys of diverse retail and wholesale food outlets selling food products, located in different wilayas and cities across Algeria and France, this approach aimed to obtain precise information on their composition, origin, producer, and specific labeling details. It enabled the development of a reliable visual database, thereby facilitating the comparative analysis of the selected water samples.

2.4 Ionic Balance (IB)

To ensure the analytical consistency and reliability of the documented mineral compositions, each brand was subjected to a preliminary validation through the calculation of the ionic balance expressed as a percentage. The IB was determined employing the following formula:

$$\text{Ionic balance (\%)} = \frac{(\sum \text{cations} - \sum \text{anions})}{(\sum \text{cations} + \sum \text{anions})} \times 100$$

Note: Ensure all concentrations are converted to milliequivalents per liter (meq/L) prior to the calculation. (APHA, 2005).

$$[\text{mEq/L}] = \frac{[\text{ mg/L}]}{\text{Molar mass A}} \times \text{valence N}$$

For the analytical results to be deemed valid for further interpretation, the difference between the sum of cations and anions must remain within the range of ±10%. This margin represents an acceptable error threshold for classification-based studies, ensuring that the physicochemical profiles are sufficiently reliable (Sekiou & Kellil, 2014). Any deviation exceeding these parameters was interpreted as potential analytical bias. Specifically, the reliability of the IB was categorized according to established criteria: -1% < IB < 1% indicates excellent reliability; -5% < IB < 5% denotes acceptable reliability; -10% < IB < 10% suggests poor reliability. IB < -10% or IB > 10% were considered non-compliant and excluded from further analysis (Labadi & Hammache, 2016).

The clinical selection criteria utilized in this study were derived from regulatory standards and mineralization thresholds established by the World Health Organization (WHO) for vulnerable populations. For infant consumption, the thresholds included: Total Dissolved Solids (TDS) < 500 mg/L, NO3-< 10 mg/L, Na^+ < 20 mg/L, Ca^{2+} < 100 mg/L, Cl^- < 250 mg/L, Mg^{2+} < 50 mg/L, SO_4^{-2} < 140 mg/L. Criteria for patients with renal impairment were defined as: TDS < 500 mg/L, Na^+< 20 mg/L, pH ≥ 7, while for nephrolithiasis (kidney stones), the limits were < 500 mg/L, Na^+< 20 mg/L, Ca^{2+} < 150 mg/L, Cl^- < 50 mg/L. Furthermore, a sodium restriction of: Na^+< 20 mg/L was applied for individuals with cardiovascular diseases. For the geriatric population, sulfate concentrations were restricted to SO_4^{-2} < 250 mg/L to prevent the risk of dehydration associated with potential laxative effects (WHO, 2017).

2.5 Statistical Analysis and Geohydrochemical Modeling

Quantitative data processing was performed employing SPSS Statistics (version 20). Histograms were generated for TDS (mg/L) and pH to visualize the distribution and concentration gradients across the sampled brands, with waters categorized in ascending order of mineral content.

Geohydrochemical modeling and graphical representations were executed utilizing the R statistical software (version 4.5.0). The following diagrams were utilized to characterize the hydrochemical profiles:

- **Stabler diagram**: Utilized to represent the milliequivalent concentrations of major ions, including Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{-2}, HCO_3^{-}, and NO_3^{-}.
- **Piper diagram:** Employed to identify hydrochemical facies and classify the water samples according to their dominant ionic species (Gao, 2019),
- **Schoeller-Berkaloff Diagram**: Employed to compare ionic concentrations on a semi-logarithmic scale, facilitating the visualization of geochemical signatures and the identification of distinct water types
- **Stiff diagram**: Provided a polygonal graphical representation of the relative proportions of major cations (Ca^{2+}, Mg^{2+}, Na^{+} + K^{+}) and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}, sometimes NO_3^{-}) (Hegui, 2020).

3 Results

3.1 Regulatory Compliance of Physicochemical Composition

In accordance with the prevailing Algerian legislative framework, specifically the Inter-ministerial Order of January 22, 2006—which defines the permissible concentrations of elements in natural mineral and spring waters, as well as authorized treatments—all analyzed samples demonstrated full compliance. Concentrations were found to be strictly within the statutory limits (OJAR, 2006). Similarly, all French mineral water samples aligned with the quality criteria stipulated in the Order of January 10, 2023, which amends the March 14, 2007, decree regarding labeling and specific treatments for packaged waters (OJFR, 2023).

3.2 Comparative Analysis of Nitrite (NO^{2-}) Content

Nitrite concentrations in both Algerian and French mineral waters is generally very low, ranging from 0 and 0.06 mg/L, indicating high quality and a lack of significant nitrogenous pollution. Nitrites, as intermediate compounds in the nitrogen cycle, typically indicate anthropogenic contamination or bacterial reduction of nitrates; their absence confirms the integrity of the aquifers. Analyses demonstrated that Algerian concentrations remained well below the WHO thresholds of 0.3 mg/L (Yousefi & Douna, 2023). French mineral waters demonstrated a similar degree of purity, confirming the absence of significant agricultural or industrial runoff. Maintaining these low levels is clinically essential, as nitrites are toxic and pose a particular risk of methemoglobinemia in pediatric population (Scippo *et al.,* 2025).

3.3 Total Dissolved Solids (TDS) and pH Profiles

As illustrated in Figure 1, Algerian mineral waters exhibit substantial variability in TDS. Brands such as *Mouzaïa* represent moderately mineralized profiles (500 – 1500 mg/L) with a peak of 1280 mg/L, whereas others such as *Texenna* (152 mg/L), are classified as low-mineralization waters. In contrast, the French market displays a broader spectrum of dry residues. Several brands are classified as highly mineralized (> 1500 mg/L) including *Contrex, Rozana, Saint Diéry, Vichy, Hépar,* and *Magnésienne*, Vichy Célestins reaching a maximum of 3325 mg/L. Conversely, other waters are middle mineralized (500 – 1500 mg/L) such as *Vittel, Saint Amand, Sainte Marguerite, La Salvetat,* and *Badoit. Mont Roucous* represents the ultra-low mineralization category (< 50 mg/L) at 30 mg/L. TDS serves as a global indicator of the mineralization of a water, representing the total quantity of dissolved mineral salts after evaporation at 180°C. TDS depends strongly on the geological strata traversed and the residence time of water within the aquifer (EU Directive, 2009).

Regarding pH, as displayed in Figure 1, Algerian mineral waters display values generally fall within a range of 6.5 to 7.69, indicating that the water is generally neutral to slightly alkaline pH reflects a mineralization dominated by carbonate and bicarbonate ions. These waters, often derived from limestone or dolomitic formations, benefit from a natural buffering effect that stabilizes the pH in a neutral to basic range, as highlighted by several hydro chemical studies (Bouteldjaoui & Taupin, 2024). This pH range is consistent with Algerian and international standards, which recommend a pH between 6.5 and 8.5 for drinking water. Conversely, French mineral waters possess lower pH values (5.5 – 7.6), with some waters being moderately acidic. This reflects a more pronounced acidity in some French waters such as *Sainte Marguerite* and *Perrier*, with a pH of 5.5. This relative acidity is explained by the predominance of granitic, volcanic or low-carbonate terrains, as well as by capture in less buffered geological areas (Beauger *et al.,* 2023). This geological diversity results in a lower buffering capacity, which leads to naturally more acidic waters, without however compromising their health quality. This relative acidity is compatible with European standards which accept a pH between 4.5 and 9.5 for bottled waters (Directive 98/83/EC). The pH of water influences its taste, chemical stability, and interaction with pipes. An acidic pH (< 6.5) may indicate potential aggression

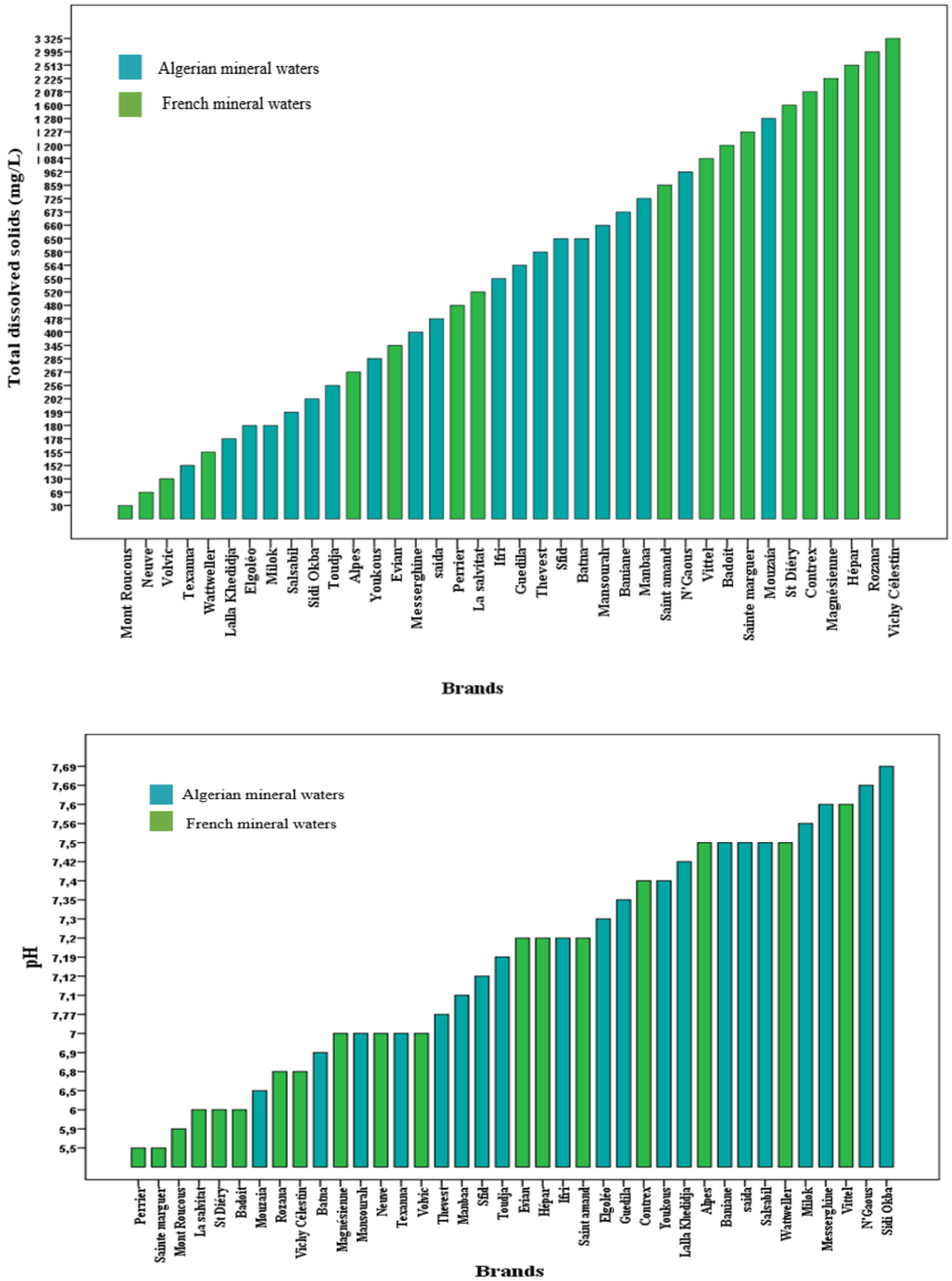

Figure 1. Classification of Algerian and French Mineral Waters Based on their Total Dissolved Solids (TDS) and pH Values

towards metallic materials (corrosion) and higher dissolution of certain heavy metals (lead, copper).

3.4 Comparison of Mineral Waters with Stabler Diagram

Figure 2 provides a comprehensive summary of ionic distributions.

- **Calcium (Ca^{2+}):** Algerian samples ranged from 22.4 mg/L (*Salsabil*) to 143 mg/L (N'Gaous). French waters exhibit a polarized distribution: while several were moderate, *Hépar* (549 mg/L) and *Magnésienne* (541 mg/L) exhibited exceptionally high concentrations.
- **Magnesium (Mg^{2+}):** While most Algerian samples exhibited low to moderate levels, *Mouzaia* (75 mg/L) was a notable exception. French brands were

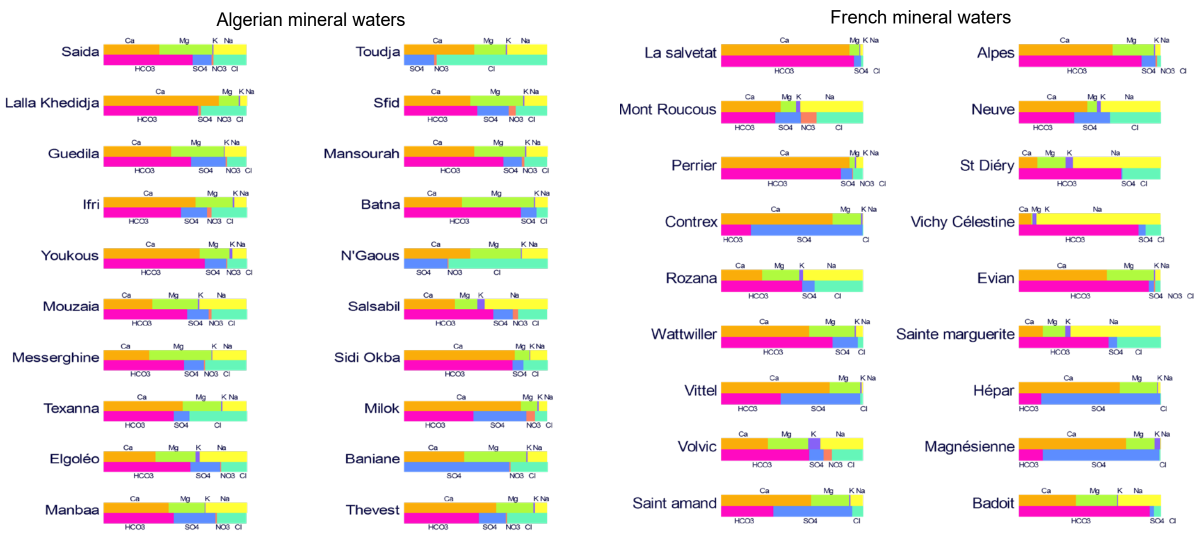

Figure 2. Stabler Diagram of Algerian and French Bottle Mineral Waters

distinguished by relatively higher magnesium content, with *Rozana* peaking at 160 mg/L.

- **Sodium (Na^+) Potassium (K^+)**: As illustrated in Figure 2, Algerian waters generally maintained moderate sodium levels such as *Mouzaïa* (145 mg/L) which displayed relative elevation, while others exhibited lower concentrations (*Lalla Khedidja*: 3.5 mg/L). French brands indicated extreme variability in sodium such the case of *Vichy Célestins* with 1172 mg/L is, and the lowest is *Wattwiller* with a content of 3 mg/L.
- **Potassium (K^+):** For Algerian mineral waters, the content is generally low, ranging from approximately 0.4 mg/L (*Lalla Khedidja*) to 4 mg/L (*Manbaa*) with the highest level 11.5 (*Messagrine*). These levels remain below the Algerian regulatory value of 20 mg/L. Conversely, French brands contain slightly higher potassium levels, with high levels of 66 mg/L for *Vichy Célestins*, and very low levels of 0.4 mg/L for *Mont Roucous* (Figure 2).
- **Anions (Cl^-, SO_4^{2-}, HCO_3^- NO_3^-):** For Algerian mineral waters, chloride levels vary considerably, ranging from low concentrations around 7 mg/L (*Lalla Khedidja*) to high values close to 150 mg/L (*Mouzaia*). These values, however, remain lower than the Algerian standards, which set a maximum between 200 and 500 mg/L. French mineral waters exhibit varying chloride concentrations, but tend to be more moderate. The highest concentration was recorded for *Rozana* (649 mg/L), and the lowest (3.2 mg/L) for *Mont Roucous* (Figure 2). Regarding Sulfate levels, considerable variations were observed. Some Algerian brands possess relatively high concentrations, *Baniane* (158 mg/L), and *Lalla Khedidja* (3 mg/L). However, French mineral waters displayed a wide variety of sulfate levels. Some brands, such as *Hépar* or *Contrex*, recognized for their high sulfate concentrations; *Hépar* (1530 mg/L). Other brands, such as *Evian* or *Volvic* possess significant reduced values (< 50 mg/L), and *Mont Roucous* (2.4 mg/L). Concerning bicarbonate (HCO_3^-) concentrations, some Algerian brands exceed 400 mg/L such as *Mouzaïa* (600 mg/L), while others with approximately 200 mg/L or less, such as *Texenna* (60 mg/L). The French mineral waters present a wide range of bicarbonate. Some brands, such as *Vichy Célestins*, are particularly rich in bicarbonate (2989 mg/L), while others are much less concentrated, less than 300 mg/L, the lowest concentration was recorded for *Mont Roucous* (6.3 mg/L). For nitrate (NO_3^-), Algerian mineral waters vary considerably from one brand to another, ranging from 0 to 30 mg/L. *Batna* and *Texenna* present the lowest values 0 mg/L, while others display higher levels, such as *Sfid* (28 mg/L). On the other hand, French mineral waters indicate a general tendency towards more moderate and homogeneous nitrate contents, ranging between 0 and 8 mg/L.

3.5 Ionic Balance (IB) Assessment

The IB for all Algerian and French brands remained within the ±10% threshold, confirming the analytical validity and internal consistency of the data (Figure 3). Several brands, including *Lalla Khedidja* (0.2%), *Milok* (0.19%), *Mansourah* (-0.15%), *Contrex* (-0.14%), *Perrier* (-0.21%), and *Saint amand* (-0.11%) exhibited balances near zero, reflecting high analytical precision.

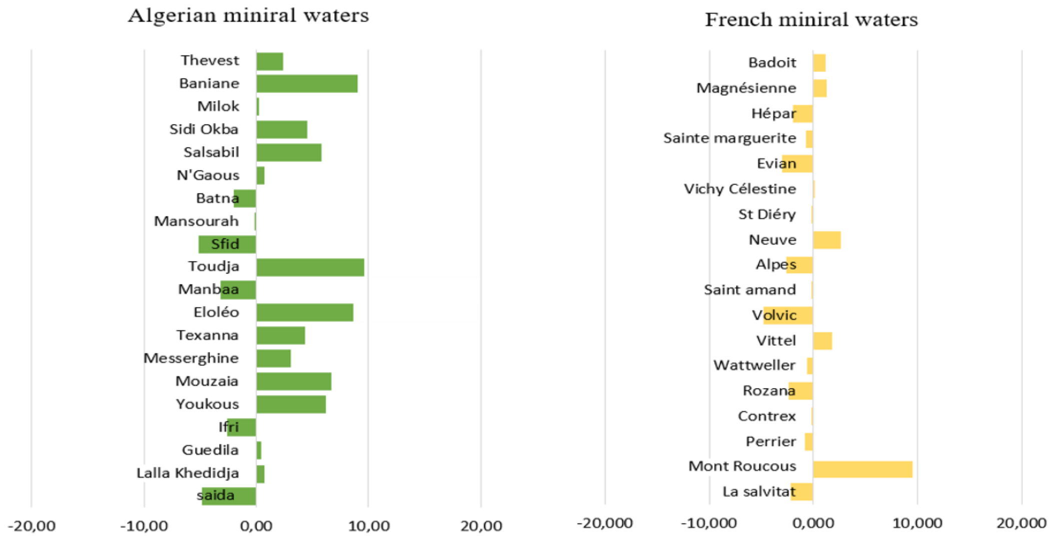

Figure 3. Ionic Balance of Algerian and French Mineral Waters

3.6 Hydrochemical Facies via Piper Diagram

The Piper diagram (Figure 4) reveals that the majority of Algerian samples cluster within the chloride-calcium (*Guedila*) and sulfate-calcium (*Youkous*) zones. This suggests a geological origin dominated by evaporitic (halite, gypsum) and carbonate formations. In contrast, French waters exhibit greater chemical heterogeneity. Although some waters are also of the calcium type, others are calcium- bicarbonate (*Vichy Célestins*) and calcium-sulfate (*Contrex*), and others are magnesium-sulfate (*Magnesian, Saint amand, and Vittel*). This diversity could be attributed to the geological variety of the French subsoil (granites, limestones, volcanic rocks) and the diversity of the aquifers exploited. Ionic exchanges in clays or the alteration of feldspars can in particular favor the presence of sodium ions. The type of water is typical of shallow aquifers in carbonate formations. Moderate mineralization and stable chemical composition suggest relatively rapid circulation of water in shallow systems, subject to homogeneous geological influence. This reflects a greater heterogeneity of the French subsoil, but also a possible variation in the depth of the catchments or in the length of time the groundwater remains (Bodor *et al.,* 2021; Bodor *et al.,* 2023).

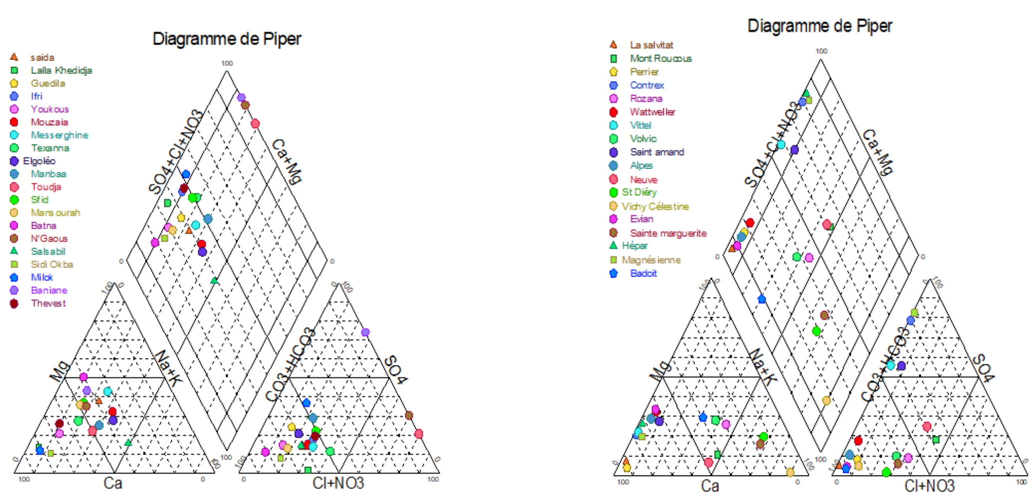

Figure 4. Piper diagram of Algerian and French mineral waters

3.7 Comparative Profiling: Schoeller-Berkaloff and Stiff Diagrams

Schoeller-Berkaloff profiles (Figure 5) for Algerian waters indicate high contents of Ca^{2+}, HCO_3^-, occasionally associated with Cl^- and SO_4^{2-}. This profile typically corresponds to a calcic bicarbonate calcic facies in *Saïda* and *Ifri* or chlorinated in *Thevest*, characteristic of limestone or evaporite systems (Labadi & Hammache, 2016). French profiles demonstrate a broader range, including sodium-bicarbonate types, such as *Contrex* and *Hépar, Saint-Diéry* and *Saint-Marguerite*. Low-mineral waters are represented by *Mont Roucous*. These differences illustrate the geological diversity of the French territory, which directly influences the chemical composition of bottled waters (Bertoldi *et al.,* 2011; Bodor *et al.,* 2023).

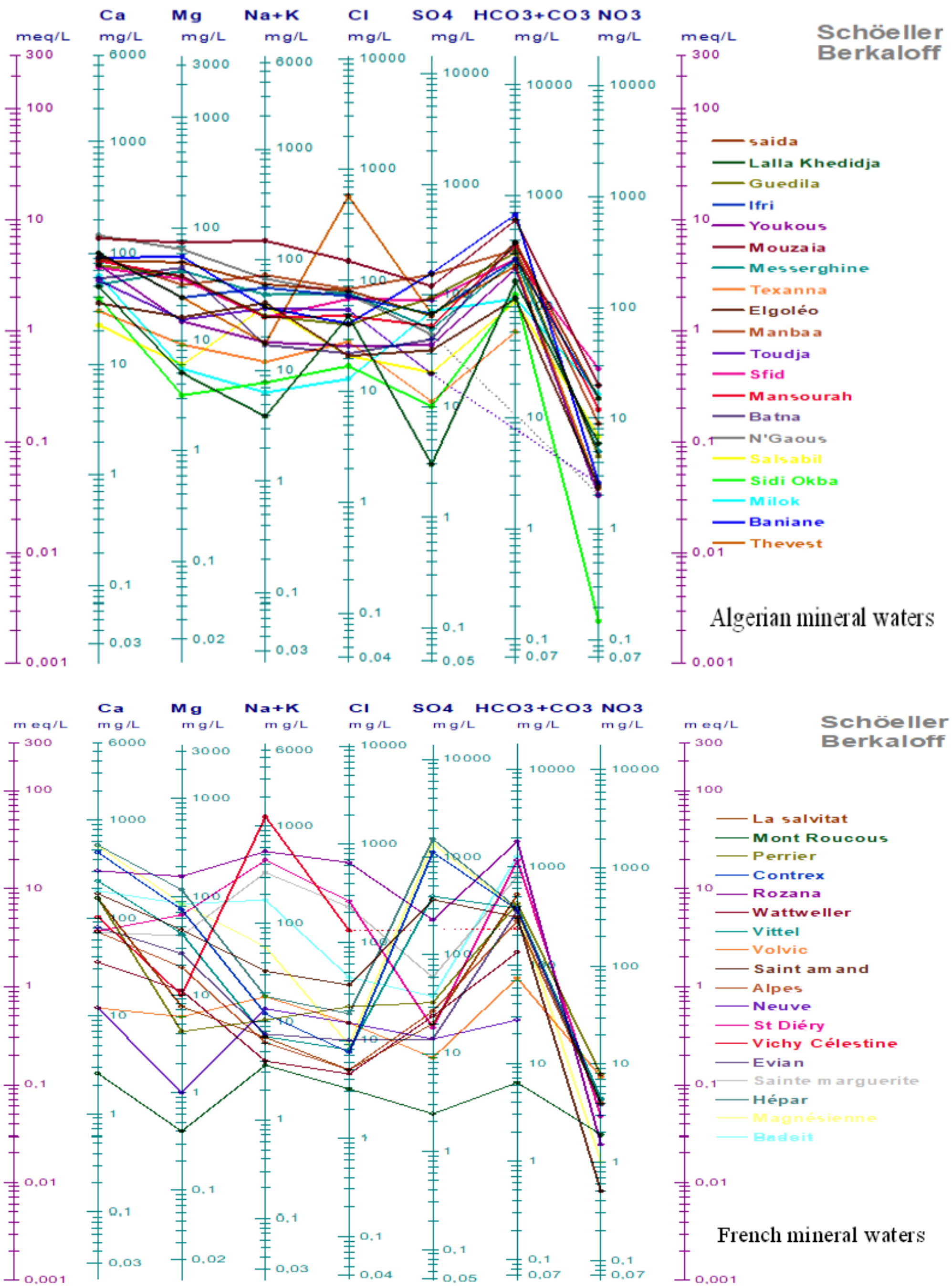

Figure 5. Schoeller-Berkaloff Diagram of Algerian and French Mineral Waters

The Stiff polygon (Figure 6) for Algerian waters typically emphasizes the Ca^{2+} and HCO_3^- axis, followed by Mg^{2+} and SO_4^{2-}. The shape of the polygon indicates a calcium/magnesium bicarbonate facies, the most mineralized is *Mouzaïa*, and some brands are homogeneous, such as *Texenna*, *Salsabil* and *Sidi Okba*, typical of waters from carbonate terrains. The French mineral waters present a more regular, symmetrical and wider shape, reflecting a more balanced ionic composition. We also observed a dominance of Ca^{2+} and HCO_3^-, but with Mg^{2+}, Na^+ and Cl^- contents generally lower than in the Algerian samples. The French waters are therefore highly mineralized, some brands indicate low mineralization such as *Wattwiller*, *Volvic* and *Neuve*, when *Mont Roucous* it is the brand with the lowest mineralization.

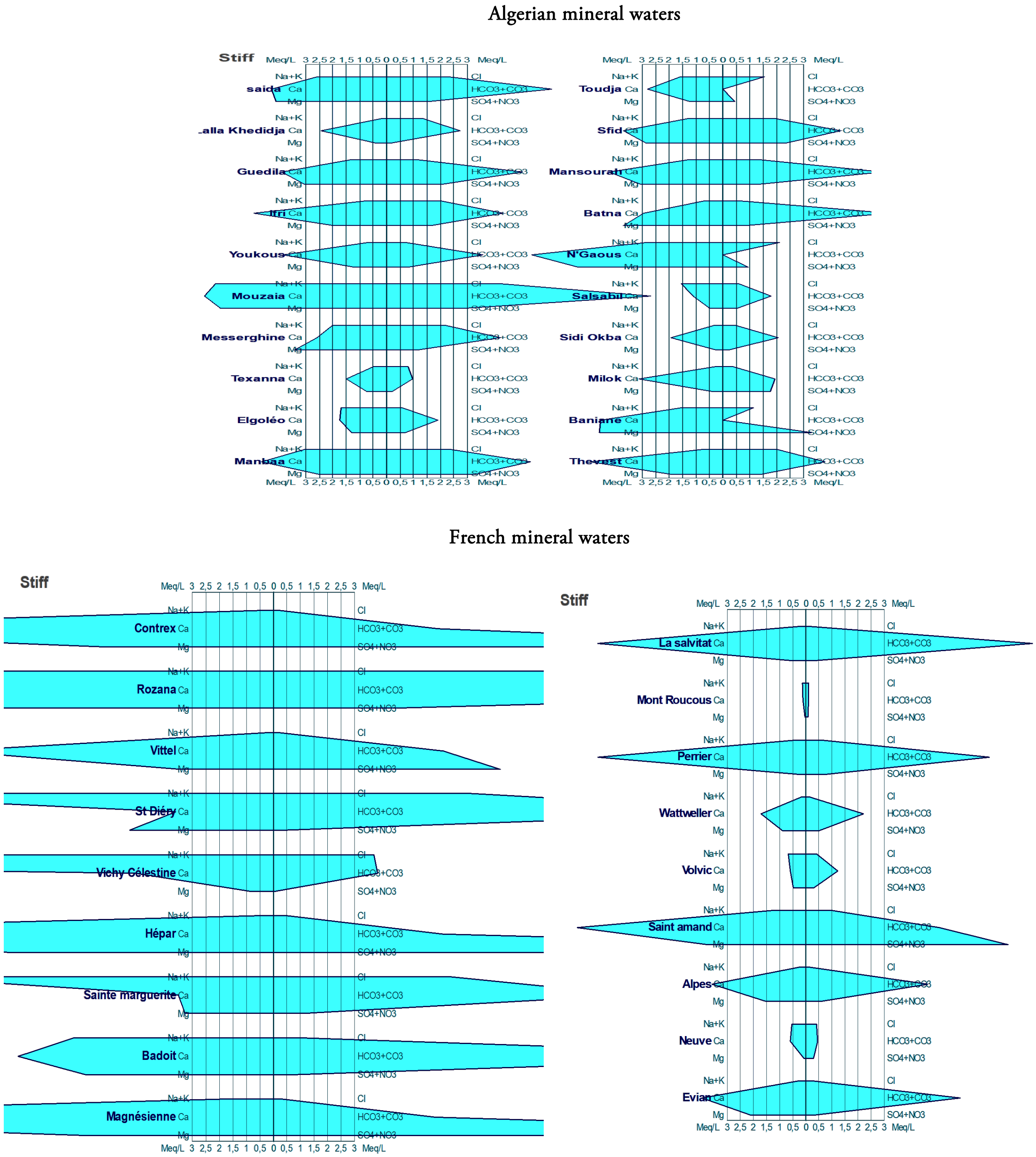

Figure 6. Stiff Diagram of Algerian and French Mineral Waters

Summary of Findings

Algerian waters are characterized by higher overall-mineralization and a marked dominance of calcium and bicarbonates due to the local geology. French waters, while including highly mineralized therapeutic brands, also offer a wider selection of low-mineralization and slightly acidic waters. This reflects both different geological conditions and rigorous resource management, limiting ion input (Bodor *et al.,* 2023).

4 Discussion

The pronounced variability in calcium concentrations observed in Algerian waters is reflective of the complex geological architecture of the Algerian subsoil. This finding aligns with established literature emphasizing that geological diversity within catchment areas directly influences water hardness— a critical parameter for both potability and long-term health outcomes (Hamid *et al.,* 2020). High mineralization in these waters may serve as a significant nutritional asset, contributing to the recommended daily intake of calcium, which is vital for skeletal integrity (Hubert *et al.,* 2002). Identical correlations between geological context and mineral signature have been documented in France by Maréchal & Rouillard (2020) and Atega *et al.* (2022). The differentiation in French mineral profiles often stems from the exploitation of aquifers with lower limestone content or through more stringently controlled mineralization processes.

The heterogeneity of magnesium content in Algerian samples is primarily attributed to the country's diverse mineralogical landscape, characterized by the coexistence of limestone, dolomitic, and volcanic formations. This mineralogical heterogeneity directly influences the composition of the exploited groundwater. Furthermore, the absence of strict standards in the choice of sources accentuates this irregularity observed on the market, these findings are consistent with previous work by Sekiou & Tamrabet (2022) and Bouteldjaoui & Taupin (2024), which respectively highlight the low average mineralization of bottled waters in Algeria and the lack of nutritional valorization, particularly in magnesium, in the national industry. The diversity of mineral compositions in French waters, often with low mineral content, results from the exploitation of aquifers with moderate mineralization and a commercial strategy favoring waters adapted to the specific needs of certain populations, such as infants or people with kidney problems.

Magnesium content varies primarily according to local geology, with higher concentrations in waters from dolomitic or dolomitic limestone formations. Studies confirm that regular consumption of French waters rich in magnesium helps prevent frequent deficiencies in vulnerable groups such as adolescents, the elderly, and pregnant women (Bertoldi *et al.,* 2011). Regarding sodium concentrations, the variability in Algerian waters suggests significant geological shifts and perhaps a lack of standardized selection criteria for water sources. High sodium levels in certain brands may necessitate consumption restrictions for individuals with cardiovascular diseases, a concern echoed by Tamrabet *et al.* (2024), who identified high sodium concentrations in semi-arid Algerian regions due to intense evaporation and rock-water interactions. In France, although therapeutic waters such as *Vichy* are sodium-rich, the majority of the market favors low-sodium options (Stoots *et al.,* 2021; Bodor *et al.,* 2023). Water containing Na^{2+} < 20 mg/L is considered low in sodium and aligns with WHO recommendations to prevent hypertension and arterial stiffness (WHO, 2012).

Potassium levels in Algerian waters are influenced by the presence of evaporite or siliceous zones, leading to a non-standardized distribution (Hammadi *et al.,* 2022). Public health guidelines recommend maintaining controlled potassium intake (2.0 – 2.4 g/day) to support cardiovascular health (D'Elia, 2024). Furthermore, chloride levels in Northern Algeria remain generally low to moderate. This trend could be attributed to the geological nature of the aquifers, generally poor in soluble salts, or due to the dry climate limiting rock leaching. These results are consistent with the findings of Lakhdari *et al.,* (2025) and Tamrabet *et al.* (2024) who reported a low chloride concentration in the majority of waters in northern Algeria, except in semi-arid zones where salinity increases. In contrast, French waters, particularly from volcanic or thermal regions exhibit higher chloride and sulfate concentrations such as *Vichy* (> 300 mg/L), offering them a pronounced salty taste (Beauger *et al.,* 2023). The presence of high sulfate concentration in such waters as *Hépar* or *Contrex*, is correlated with the crossing of gypsum terrain or to secondary mineralization associated with local geology. Some waters from volcanic or granitic regions could present low rates in sulfates which are recognize to contribute to the mineral balance. However, their excess can cause a laxative effect, particularly in sensitive individuals or young children. European regulations set a maximum limit of 250 mg/L of sulfates for drinking water to avoid laxative effects at high concentrations such as diarrhea (Bear *et al.,* 2024; Duranel *et al.,* 2021).

The diversity of bicarbonate content is particularly evident in French thermal and volcanic springs (*Vichy Célestins*), where CO_2 degassing and carbonate dissolution are intense (Bertoldi *et al.,* 2011; Bodor *et al.,* 2023).

Bicarbonates are essential for maintaining acid-base balance and neutralizing gastric acidity, making such waters beneficial for digestive health (Sekiou & Kellil, 2014). These observations highlight significant regional disparities in water quality, possibly linked to geological, agricultural and regulatory factors. The presence of nitrates in water is a key indicator of pollution from agricultural or urban sources, and the higher levels detected in some Algerian waters (*Lejdar, Safid, Arwa*) suggest the need for increased monitoring to prevent health risks (Scippo *et al.*, 2025).

Clinically, the physicochemical characterization of the 38 brands facilitated the identification of products suitable for specific medical needs. Based on low TDS and reduced ionic loads NO_3^-, Na^+, Ca2+, Cl^-, Mg2+, and SO_4^{-2}, 10 brands — four Algerian (e.g., *Lalla Khedidja*, *Youkous, Texenna, and Sidi Okba*) and six French (e.g., *Mont Roucous, Wattwiller, Volvic, Alpes, Neuve,* and *Evian*) — were identified as optimal for infants and patients with renal failure. Low mineralization is critical for infants due to renal immaturity, preventing dehydration from solute overload (WHO, 2017). Similarly, nine brands; four Algerian brands (*Lalla Khedidja*, *Youkous, Texenna*, and *Sidi Okba*) and five French brands (*Wattwiller, Volvic, Alpes, Neuve*, and *Evian*) were categorized as suitable for nephrolithiasis management by ensuring maximum urinary dilution to inhibit stone formation. Concerning cardiovascular health, twenty brands; eight Algerian (*Lalla Khedidja, Ifri, Youkous, Texenna, Batna, Sidi Okba, Milok,* and *Thevest*) and 12 French (*La Salvetat, Mont Roucous, Perrier, Contrex, Wattwiller, Vittel, Volvic, Alpes, Neuve, Evian, Hépar,* and *Magnésienne*) with sodium content (< 20 mg/L), were identified. It is well established in the literature that low-sodium intake is vital to manage blood volume and protect myocardial function. Finally, thirty-two brands; 20 Algerian brands and 18 French brands except *Contrex, Rozana, Vittel, Saint Amand, Hépar*, and *Magnésienne* were deemed appropriate for the elderly, as they respect the sulfate threshold (< 250 mg/L), thereby preventing electrolyte imbalances caused by osmotic laxative effects (WHO, 2017).

The findings of the present study provide Algerian and French consumers with a comprehensive database regarding the physicochemical and nutritional quality of all mineral water brands available on the market, thereby facilitating informed choices for vulnerable consumer groups. Nevertheless, this study presents several limitations, including the possibility that not all brands present on the Algerian and French markets were identified. Furthermore, the mineral content analyzed herein is based on the information declared on product packaging, which should be corroborated by laboratory analyses.

5 CONCLUSIONS

This comparative investigation reveals a high degree of heterogeneity in the hydro chemical composition of mineral waters from Algeria and France. The majority of the sampled waters exhibit a calcium/magnesium bicarbonate facies, characteristic of circulation within carbonate terrains. Algerian waters are generally characterized by a neutral to slightly alkaline pH (6.5 – 7.69) and a dominance of Ca^{2+} and HCO_3^-, followed by Mg^{2+} and SO_4^{2-}, with *Mouzaïa* and some brands such as *Texenna, Salsabil* and *Sidi Okba* are more homogeneous. In contrast, French waters display a more balanced yet diverse ionic composition, ranging from the ultra-low mineralization of *Mont Roucous* to the highly mineralized therapeutic profiles of *Vichy Célestins* (3325 mg/L), regularly presenting a more acidic pH (5.5 – 7.6).

Verification of the ionic balance confirmed the reliability and internal consistency of the data, with deviations consistently under 10%. Despite regional variability driven by geological and environmental conditions, all analyzed brands complied with their respective national and international safety standards. Furthermore, the current study identified ten brands suitable for infants and patients with renal impairment, nine for nephrolithiasis prevention, twenty for individuals with cardiovascular disease, and thirty-two for geriatric consumption. These findings provide a robust, evidence-based database for consumers and healthcare professionals in both countries, facilitating the appropriate selection of bottled waters tailored to specific physiological and pathological requirements.

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