ASSESSMENT OF BOTTLED WATER QUALITY IN BENIN CITY

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CERTIFICATION

We certify that this work was carried out by Faustina (MISS) in the Department of Animal and Environmental Biology, Faculty of Science University of Benin, Benin City, Nigeria.

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DEDICATION

With all privilege, this thesis is dedicated to God Almighty for his grace and wisdom and to my family for their profound support throughout this program.

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ABSTRACT

Water quality remains a critical public health concern, particularly in rapidly urbanizing regions like Benin City, Nigeria. This study assessed the physicochemical properties, essential minerals, and potential contaminants in five bottled water brands (EVA, CWAY, AQUAFINA, EIO, and ROI) to evaluate their safety and compliance with regulatory standards. Water samples were collected from different retail outlets in Benin City and analyzed for parameters such as pH, conductivity, total dissolved solids (TDS), turbidity, hardness, chloride, sulphate, nitrate, and trace metals using standard laboratory procedures.

The results showed significant variations across brands. EIO had the highest pH (7.37 ± 0.19), while ROI had the lowest (6.63 ± 0.11). Conductivity and TDS were highest in EIO (41.33 ± 1.16 µS/cm and 20.67 ± 0.58 mg/L, respectively) and lowest in ROI (12.00 ± 2.00 µS/cm and 6.00 ± 1.00 mg/L, respectively). Hardness levels were within the WHO-recommended limits, with CWAY showing the highest value (22.00 ± 2.00 mg/L). Trace metal analysis revealed that ROI had the highest levels of iron (0.12 ± 0.01 mg/L), zinc (0.27 ± 0.05 mg/L), manganese (0.48 ± 0.07 mg/L), and copper (0.52 ± 0.09 mg/L), suggesting possible contamination from natural sources or packaging materials.

While most bottled water samples met regulatory standards, ROI exhibited elevated levels of turbidity, suspended solids, and trace metals, indicating potential filtration inefficiencies. These findings emphasize the need for stricter regulatory monitoring and quality control measures to ensure the safety of bottled water in Benin City.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Water is an essential resource for human survival, serving as the cornerstone of public health and societal development. Safe and adequate water supply is crucial for drinking, sanitation, and other domestic purposes. However, access to clean and safe drinking water remains a significant challenge in many parts of the world, particularly in low- and middle-income countries like Nigeria (Ajala *et al.*, 2020; Onokogu *et al.*, 2023). In urban areas such as Benin City, these challenges are exacerbated by rapid urbanization, industrialization, and population growth, which place immense pressure on water resources and infrastructure (Foka *et al.*, 2018; Ogbeifun *et al.*, 2019).

Benin City, located in Edo State, Nigeria, relies on various water sources, including rivers, boreholes, and municipal supplies. Unfortunately, these sources are often subject to contamination. Factors such as inadequate waste management, industrial effluents, and agricultural runoff contribute to the degradation of water quality. Studies have shown that many of the boreholes in Benin City have pH levels and microbial counts that exceed the World Health Organization (WHO) permissible limits, rendering them unsafe for consumption without proper treatment (Foka *et al.*, 2018; Ogbeifun *et al.*, 2019; Ajala *et al.*, 2020). Additionally, the municipal water supply in the region is frequently unreliable, pushing residents to seek alternative sources, such as bottled and sachet water (Onokogu *et al.*, 2023).

Packaged water, particularly bottled water, has become a popular alternative in Benin City due to its perceived safety and convenience. The Nigerian bottled water industry has grown significantly in recent years, with numerous local and international brands dominating the

market. Bottled water is often marketed as a safe and high-quality alternative, free from the contamination risks associated with natural and municipal sources (Ogbeifun *et al.,* 2019). However, research has revealed several concerns about the quality of bottled water in Nigeria. Studies have identified instances of microbial contamination, high levels of dissolved solids, and inadequate labeling practices among certain brands (Foka *et al.*, 2018; Onokogun *et al.,* 2023). These issues highlight lapses in regulatory oversight and quality control, raising questions about the actual safety of bottled water.

Moreover, the reliance on bottled water as a primary source of drinking water has economic and environmental implications. Bottled water is significantly more expensive than other sources, making it inaccessible to low-income populations. Environmentally, the production and disposal of plastic bottles contribute to pollution and waste management challenges, further exacerbating the environmental strain in cities like Benin (Ogbeifun *et al.,* 2019; Onokogun *et al.*, 2023).

Public perception and awareness also play a critical role in the growing dependence on bottled water. Many consumers in Benin City believe that bottled water is superior in quality due to its packaging and branding, even in cases where the quality is comparable to or lower than that of other treated water sources (Foka *et al.*, 2018). This perception underscores the need for greater consumer education and transparency in the water industry.

In addition to bottled water, sachet water, popularly referred to as "pure water," is another widely consumed alternative in Nigeria. While sachet water is often more affordable, its quality is highly variable, with many brands failing to meet safety standards (Ogbeifun *et al.*, 2019; Ajala *et al.*, 2020). The challenges associated with both bottled and sachet water reflect broader systemic issues in water resource management, regulation, and public health.

Against this backdrop, the assessment of water quality, particularly bottled water, is critical for ensuring the health and well-being of the population in Benin City. A comprehensive understanding of the quality, safety, and regulatory status of bottled water will provide valuable insights for improving water resource management and safeguarding public health. This study aims to bridge existing knowledge gaps by evaluating the quality of bottled water relative to other water sources and examining the effectiveness of regulatory frameworks in addressing water safety challenges. By doing so, it seeks to inform policy decisions and promote sustainable water management practices in Benin City.

1.2 Justification of the Study

Benin City has experienced rapid urbanization, placing significant stress on its water resources. Despite the proliferation of bottled water brands, limited studies have assessed their compliance with national and international safety standards (Foka *et al.*, 2018; Ajala *et al.*, 2020). Understanding the quality of both natural and packaged water is essential for public health planning and consumer safety.

This study addresses critical gaps in knowledge by evaluating the quality of bottled water in Benin City compared to other water sources. It also examines consumer perceptions and regulatory frameworks, contributing to the growing discourse on water safety in Nigeria. This work will guide policy decisions and promote informed consumer choices (Ogbeifun *et al.*, 2019; Onokogun *et al.*, 2023).

1.3 Aim and Objectives

The aim of this research is to assess the quality of bottled water in Benin City.

The specific objectives were:

1. to evaluate the physicochemical properties of different bottled water brands available in Benin City.
2. to compare concentrations of essential and trace elements in different bottled water brands.
3. to identify potential contaminants and deviations from regulatory standards in bottled water samples

CHAPTER TWO

LITERATURE REVIEW

2.1 The Bottled Water Landscape: Global and Local Perspectives

The global consumption of bottled water has risen significantly due to its perceived safety, convenience, and portability. However, the bottled water industry faces scrutiny over quality, regulation, and environmental impacts. In Nigeria, the rise in bottled water consumption reflects the public's response to unreliable municipal water supplies and increasing urbanization.

Globally, bottled water is marketed as a superior alternative to tap water, attributed to advanced filtration and treatment methods. Studies like Diduch *et al.* (2013) and Akhbarizadeh *et al.* (2020) highlight the variability in bottled water quality, influenced by source water, treatment processes, and packaging. For instance, heavy metals, microplastics, and endocrine-disrupting chemicals have been detected in bottled water worldwide, raising concerns about long-term health effects.

In Nigeria, the bottled water industry serves as a critical source of drinking water, especially in urban areas where tap water is often unreliable. However, challenges persist in ensuring quality and compliance with regulatory standards. Studies such as Iliyasu *et al.* (2018) and Adekunle *et al.* (2020) reveal inconsistencies in chemical and microbiological parameters across different brands, underscoring lapses in regulatory enforcement. Factors such as poor manufacturing practices, insufficient monitoring, and weak penalties contribute to these challenges.

Moreover, the socio-economic implications of bottled water consumption are significant. While urban dwellers rely on bottled water for convenience, the cost remains prohibitive for many rural and low-income populations, exacerbating inequalities in access to safe drinking water (Vapnek & Williams, 2016). The environmental impact of plastic waste from bottled water further complicates the issue, necessitating sustainable production and disposal practices.

This review explores the current status of bottled water quality in Nigeria, drawing from global and local perspectives to understand challenges and opportunities in ensuring safe and sustainable access to potable water.

2.2 Overview of Water Quality Standards: Bottled Water in Nigeria

Access to potable water is essential for achieving Sustainable Development Goal 6 (SDG 6), which emphasizes clean water and sanitation for all. In Nigeria, water quality standards are primarily governed by the Nigerian Standards for Drinking Water Quality (NSDWQ) and the World Health Organization (WHO) guidelines, which serve as benchmarks for evaluating drinking water, including bottled and sachet water (Nwinyi *et al.*, 2020; Vapnek & Williams, 2016). These frameworks emphasize physical, chemical, and microbiological parameters to assess water safety comprehensively.

2.2.1 Key Regulatory Benchmarks

1. **Physical Parameters**:

Physical parameters such as turbidity, color, and odor are critical for aesthetic quality and consumer acceptance. NSDWQ recommends values that align with WHO thresholds for these attributes (Nwinyi *et al.*, 2020; Omokaro *et al.*, 2024). Studies across Nigeria, including in

Delta State, suggest that sachet and bottled water often meet physical quality criteria but may occasionally fail due to substandard production practices (Eyankware & Ephraim, 2021).

2. **Chemical Parameters**:

Chemical indicators, including pH, heavy metals, and dissolved solids, have been extensively assessed. For instance, bottled water in Benin City often demonstrates slightly acidic pH values, which fall outside the recommended range of 6.5–8.5 (Adams *et al.*, 2016; Ogbeifun *et al.*, 2019). Additionally, research from other regions, such as Kano (Gwamna *et al.*, 2024) and Ondo State (Adekunle *et al.*, 2020), highlights heavy metal contamination, particularly with lead, cadmium, and chromium. This contamination is often linked to industrial discharges and inadequate regulation of water source environments. Omeka *et al.* (2024) conducted a meta-analysis that further confirmed similar trends across Nigeria, emphasizing the need for stricter controls on industrial pollutants.

3. **Microbiological Parameters**:

Microbiological contamination is one of the most pressing concerns, with pathogens such as *E. coli* and total coliforms commonly detected in sachet and bottled water (Udoh *et al.*, 2021; Oyedeji *et al.*, 2009). Microbial assessments of water in Delta State, for instance, revealed occasional exceedance of WHO and NSDWQ limits for bacteria, attributable to poor hygiene during production and improper handling (Eyankware & Ephraim, 2021). Omeka *et al.* (2024) noted that rural and peri-urban areas face a higher risk due to limited regulatory oversight and quality control.

2.2.2 Challenges with Regulatory Enforcement

Despite the existence of robust frameworks, enforcement remains a significant issue. Vapnek & Williams (2016) discussed systemic regulatory weaknesses across Africa, particularly in resource-limited settings like Nigeria. These gaps contribute to variability in compliance among water producers, particularly local brands, which often lack adequate purification infrastructure (Ajala *et al.*, 2020; Nwinyi *et al.*, 2020). Omeka *et al.* (2024) further highlighted the fragmented nature of regulatory monitoring, which often focuses on urban areas while neglecting rural regions.

2.2.3 Comparative Analysis with International Standards

Comparisons with international standards reveal a need for improvements in Nigeria's water regulation and monitoring systems. Studies in countries with stringent water regulations, such as China, demonstrate significantly lower contamination rates (Cohen *et al.*, 2022). Similarly, the use of advanced assessment methods, such as chemometric modeling in developed regions, offers valuable insights that could enhance Nigeria's regulatory practices (Egbueri *et al.*, 2020; Oladipo *et al.*, 2021).

2.2.4 Future Directions

To ensure the safety of bottled water in Nigeria, several steps are necessary:

- **Adopting Advanced Technologies:** Incorporating tools such as fuzzy logic models and chemometric analyses can provide more accurate assessments of water quality (Oladipo *et al.*, 2021; Asgari *et al.*, 2021).
- **Strengthening Infrastructure:** Addressing regulatory gaps, particularly in rural and peri-urban areas, is essential. Increased government funding and collaboration with private sector stakeholders can improve the scope and consistency of quality monitoring (Omeka *et al.*, 2024; Vapnek & Williams, 2016).

- **Public Awareness Campaigns:** Educating the public on the importance of choosing quality-assured bottled water and avoiding counterfeit products is vital (Epundu *et al.*, 2017).

In conclusion, while bottled water in Nigeria generally meets physical quality standards, challenges persist regarding microbial and chemical safety. Addressing regulatory and infrastructural weaknesses can significantly enhance compliance and protect public health. Further research into innovative monitoring approaches and stronger enforcement mechanisms is essential for achieving sustainable improvements in water quality.

2.3 Physicochemical Analysis of Bottled Water

The physicochemical quality of bottled water is a critical factor in determining its suitability for human consumption. Key parameters assessed include pH, turbidity, temperature, Total Dissolved Solids (TDS), and the presence of chemical contaminants such as heavy metals. Studies conducted in various parts of Nigeria reveal significant findings about these parameters, highlighting the need for continuous monitoring to ensure compliance with water quality standards.

2.3.1 pH and Acidity

The pH of water is a crucial indicator of its acidity or alkalinity, with acceptable ranges for drinking water defined as 6.5–8.5 by the WHO and Nigerian Standards for Drinking Water Quality (NSDWQ). Several studies have reported variations in pH levels in bottled water across Nigeria. In Kano metropolis, bottled water samples were found to exhibit slightly acidic pH values, raising concerns about their potential impact on health (Iliyasu *et al.*, 2018). Similarly, bottled water exposed to sunlight in Bauchi State showed significant changes in pH, emphasizing the need for proper storage to maintain quality (Daffi & Wamyil, 2021).

2.3.2 Turbidity and Clarity

Turbidity, which measures the cloudiness of water, is an essential physical quality parameter. Low turbidity levels are generally desirable as they indicate better filtration and reduced particulate content. Bottled water studies in Abraka, Delta State, confirmed that turbidity values in most samples met regulatory limits (Otobrise *et al.*, 2021). However, improper handling and storage practices could lead to occasional increases in turbidity.

2.3.3 Total Dissolved Solids (TDS)

TDS measures the concentration of dissolved substances in water, influencing taste and palatability. Studies have shown that TDS levels in bottled water are generally within acceptable limits, as observed in Bauchi State (Daffi & Wamyil, 2021) and Abuja (Atiku *et al.*, 2018). However, variations in TDS can occur due to differences in the sources of water used for bottling and the purification methods employed.

2.3.4 Heavy Metals and Chemical Contaminants

The presence of heavy metals, such as lead, cadmium, and chromium, in drinking water poses significant health risks. Research across Nigeria has highlighted the prevalence of these contaminants. In Kano metropolis, Iliyasu *et al.* (2018) reported the detection of trace amounts of heavy metals in some bottled water samples, although concentrations were within regulatory limits while in Zaria, Adesakin *et al.* (2020) identified chemical contaminants in domestic water sources, underscoring the importance of robust purification systems for bottled water producers.

2.3.5 Temperature and Storage Effects

Temperature plays a significant role in maintaining the quality of bottled water. Improper storage, especially exposure to sunlight, can alter its physicochemical properties. Daffi and Wamyil (2021) demonstrated that prolonged exposure to sunlight increased the temperature of bottled water, potentially impacting its TDS and pH levels. This finding underscores the need for proper storage conditions during distribution and retail.

2.3.6 Variability in Bottled Water Quality

Despite adherence to regulatory standards, variations in bottled water quality across regions highlight disparities in production practices. Studies in Calabar Municipality (Agbo *et al.*, 2019) and Abraka (Otobrise *et al.*, 2021) noted that while many brands meet physicochemical criteria, some inconsistencies remain. These variations are often attributed to differences in source water quality and treatment processes.

2.3.7 Regulatory Implications

The findings from these studies emphasize the importance of regular monitoring and strict enforcement of standards by regulatory bodies such as NAFDAC in Nigeria. Compliance with guidelines ensures the safety and reliability of bottled water as a major drinking water source.

The physicochemical analysis of bottled water in Nigeria reveals that while most brands meet regulatory standards, occasional deviations occur due to improper storage, inadequate

treatment, or environmental factors. Continuous monitoring, public education on proper storage practices, and stricter enforcement of quality standards are essential to ensure the safety and acceptability of bottled water for consumers.

2.4 Microbial Contamination of Bottled Water

Microbial contamination in bottled water is a significant concern in Nigeria, as it poses a direct threat to public health. Contaminants, including bacteria, fungi, and protozoa, can enter bottled water through inadequate treatment processes, poor handling, or environmental factors. Various studies have explored the microbiological quality of bottled water in different regions of Nigeria, revealing notable findings.

2.4.1 Microbial Quality Assessment

Studies have consistently identified bacteria as the primary microbial contaminants in bottled water. Commonly detected organisms include *Escherichia coli*, *Staphylococcus aureus*, *Klebsiella spp.*, and *Pseudomonas spp.*, which indicate fecal contamination and poor hygiene practices. In Ile-Ife**,** a research carried out by Igbeneghu and Lamikanra (2014) reported the presence of coliform bacteria in several bottled water brands, suggesting lapses in sterilization during production. A study conducted in Awka by Samuel *et al.* (2016) found that 40% of the bottled water samples tested were contaminated with bacteria, including *E. coli*, raising concerns about the enforcement of regulatory standards in commercial water production.

2.4.2 Contamination Sources

Contamination can originate from multiple sources, including:

- **Production Process**: Inefficient purification methods or poorly maintained equipment can introduce microorganisms into bottled water (Maduka *et al.*, 2014).
- **Storage and Handling**: Environmental exposure during transportation or retail can allow microbial infiltration. Innocent *et al.* (2022) identified microbial growth in bottled water stored in unhygienic conditions at a southeastern Nigerian university.
- **Source Water Quality**: In regions where untreated surface water or poorly maintained boreholes are used as raw sources, microbial contamination is more likely (Bisiriyu *et al.*, 2020).

2.4.3 Microbial Indicators

The use of microbial indicators, such as total coliforms and fecal coliforms, is critical for assessing water safety. Studies in Imo State (Maduka *et al.*, 2014) revealed that some bottled water brands had total coliform counts exceeding WHO permissible limits, indicating possible public health risks. Similarly, research in Niger State (Bisiriyu *et al.*, 2020) found that while most bottled water brands complied with coliform thresholds, some samples showed bacterial growth upon prolonged storage, reflecting lapses in quality assurance.

2.4.4 Public Health Implications

Consumption of contaminated bottled water is associated with waterborne diseases such as diarrhea, typhoid, and cholera. Innocent *et al.* (2022) highlighted that university students consuming contaminated bottled water were at an increased risk of gastrointestinal infections. Nkiru *et al.* (2020) emphasized the broader health implications, linking poor microbial water quality to systemic health issues in rural and urban communities.

2.4.5 Regulatory Oversight

Effective regulation and monitoring are essential to mitigate microbial contamination in bottled water. The role of regulatory agencies such as NAFDAC (National Agency for Food and Drug Administration and Control) is critical in ensuring compliance with microbial safety standards. However, Samuel *et al.* (2016) noted that gaps in enforcement, especially in rural areas, allow substandard products to enter the market. Enhanced surveillance and routine inspections can help address these challenges.

To minimize microbial contamination in bottled water, the following measures are suggested:

- **Improved Treatment Processes**: Incorporating advanced filtration and sterilization technologies, such as UV disinfection or reverse osmosis, can effectively reduce microbial loads (Maduka *et al.*, 2014).
- **Hygienic Practices**: Training personnel involved in production and handling to maintain strict hygiene standards can limit contamination risks (Igbeneghu & Lamikanra, 2014).
- **Storage Guidelines**: Ensuring proper storage conditions, such as avoiding prolonged exposure to sunlight, can help maintain water quality (Innocent *et al.*, 2022).
- **Public Awareness**: Educating consumers about identifying certified bottled water brands and reporting suspicious products can enhance accountability (Bisiriyu *et al.*, 2020).

Microbial contamination remains a significant concern in the bottled water industry in Nigeria. While most brands meet regulatory standards, lapses in production and handling can lead to the presence of harmful microorganisms. Strengthening regulatory oversight, improving production processes, and raising public awareness are vital steps to ensure the safety of bottled water and protect public health.

2.5 Chemical and Emerging Contaminants in Bottled Water

Bottled water is often perceived as a safer and more reliable alternative to tap water. However, various studies have revealed that bottled water can harbor chemical contaminants and other emerging pollutants, raising concerns about its safety and long-term health implications.

2.5.1 Presence of Chemical Compounds

Chemical contaminants in bottled water can arise from natural sources, packaging materials, or production processes. Studies have identified a wide range of compounds, including heavy metals, plasticizers, and disinfection by-products:

- **Chemical Compounds**: Wątor *et al.* (2024) highlighted that substances like arsenic, lead, and nitrates are occasionally present in bottled water, depending on the source and treatment methods. These compounds, even at low levels, can pose health risks with prolonged exposure.
- **Plasticizers and Additives**: Akhbarizadeh *et al.* (2020) reviewed emerging contaminants, noting the presence of phthalates and bisphenol A (BPA), which can leach into water from plastic bottles. These chemicals are known endocrine disruptors and have been linked to reproductive and developmental issues.

2.5.2 Emerging Contaminants

Emerging contaminants, such as pharmaceuticals, personal care products, and microplastics, have become a growing concern:

- **Synthetic Polymers**: Mason *et al.* (2018) reported the presence of microplastics in bottled water from multiple global brands. These particles, often derived from

packaging materials, may accumulate in the body over time, with unknown health effects.

- **Microplastics in Nigeria**: Ibeto *et al.* (2023) documented microplastic contamination in bottled water sold in southeastern Nigeria. Their findings emphasize the need for stricter monitoring and research on the health impacts of microplastics ingestion.

2.5.3 Impact of Environmental Factors

External factors, such as storage conditions and exposure to sunlight, can exacerbate contamination levels:

- **Sunlight Exposure**: Umoafia *et al.* (2023) demonstrated that prolonged exposure to sunlight degrades plastic bottles, releasing harmful chemicals like antimony and formaldehyde into the water. This highlights the importance of proper storage to prevent deterioration.
- **Temperature Fluctuations**: Diduch *et al.* (2013) emphasized that high temperatures accelerate chemical reactions between water and plastic materials, increasing the leaching of contaminants.

2.5.4 Health Implications

Consuming bottled water contaminated with chemicals or emerging pollutants can lead to a range of adverse health outcomes:

- **Chronic Exposure Risks**: Akhbarizadeh *et al.* (2020) and Wątor *et al.* (2024) linked chronic exposure to heavy metals and plasticizers to cancers, hormonal imbalances, and cardiovascular diseases.

- **Microplastic Accumulation**: Ibeto *et al.* (2023) noted the potential for microplastics to accumulate in organs, disrupting normal physiological functions. Further research is needed to understand the full scope of these effects.
- **Carcinogenic Compounds**: Prolonged exposure to disinfection by-products and synthetic additives may increase the risk of carcinogenesis, as documented by various studies, including Mason *et al.* (2018).

2.5.5 Regulatory and Mitigation Measures

To address these challenges, stringent regulations and innovative solutions are necessary:

- **Regulatory Frameworks**: Wątor *et al.* (2024) recommended tighter control over bottled water quality through periodic testing and compliance with international standards. Regulatory agencies must enforce limits on contaminants like BPA, phthalates, and heavy metals.
- **Consumer Education**: Raising awareness about proper storage practices, such as avoiding sunlight exposure, can minimize contamination risks (Umoafia *et al.*, 2023).
- **Innovative Packaging**: Developing biodegradable or non-leaching packaging materials can significantly reduce chemical leaching and microplastic pollution (Akhbarizadeh *et al.*, 2020).

Chemical and emerging contaminants in bottled water are a significant concern, requiring coordinated efforts from regulatory bodies, manufacturers, and consumers. While bottled water remains an essential resource, particularly in regions with unreliable tap water, addressing its safety challenges is critical to safeguarding public health.

2.6 Comparative Assessment of Bottled Water and Other Water Sources

Access to clean drinking water is critical for public health, yet variations in water quality from different sources, including bottled water, sachet water, and natural sources, continue to be a significant concern. This section provides an extensive analysis of studies comparing the physicochemical and microbiological qualities of bottled water with other drinking water sources in Nigeria.

2.6.1 Bottled Water vs. Sachet Water

Bottled and sachet water are the most consumed packaged water products in Nigeria. Their quality has been a subject of numerous comparative studies:

- **Microbial Content**: Akinnibosun and Ugbawa (2017) reported that sachet water often exhibits higher microbial contamination than bottled water. This is attributed to less stringent regulatory oversight in the sachet water industry.
- **Physicochemical Properties**: Comparative analyses show that bottled water generally has better compliance with physicochemical standards, including pH, turbidity, and electrical conductivity, as noted by Agbo *et al.* (2019). However, issues like chemical leaching from plastic bottles remain a concern (Diduch *et al.*, 2013).

2.6.2 Bottled Water vs. Groundwater

Groundwater sources, such as boreholes and wells, are often compared with bottled water to evaluate the reliability of bottled water:

- **Quality Variations**: Magaji and Abimbola (2020) found that while bottled water meets drinking water standards more consistently, some boreholes demonstrated superior mineral content, which is beneficial for health.

- **Contamination Risks**: Studies such as Ogbeifun *et al.* (2019) highlight the vulnerability of groundwater to contamination from agricultural runoff and improper waste disposal, making bottled water a safer option in certain contexts.

2.6.3 Bottled Water vs. Tap Water

Tap water quality varies significantly across Nigeria due to inconsistent treatment processes and aging infrastructure:

- **Comparative Safety**: In Diobu, Port Harcourt, Aex and LB (2023) demonstrated that bottled water showed negligible microbial contamination compared to tap water, which often failed to meet microbiological safety standards.
- **Physicochemical Differences**: Bottled water had more stable physicochemical parameters, including optimal pH and lower turbidity levels, compared to tap water. However, tap water is more environmentally sustainable than bottled alternatives.

2.6.4 Urban vs. Rural Contexts

The disparity in water quality between urban and rural settings is stark, influencing reliance on bottled water:

- **Urban Advantages**: Akinnibosun and Ugbawa (2017) found that urban areas generally have better quality bottled and sachet water due to improved regulatory compliance and infrastructure.
- **Rural Challenges**: Rural populations often rely on untreated groundwater or poorly regulated sachet water, which increases the risk of waterborne diseases.

2.6.5 Health Implications of Comparative Quality

The choice of water source has significant public health implications:

- **Microbial Contamination**: Agi *et al.* (2022) emphasized that untreated sources, such as rivers and wells, pose a higher risk of waterborne diseases compared to bottled water.
- **Chemical Exposure**: Studies like Wątor *et al.* (2024) warn that while bottled water is generally safer microbiologically, it can expose consumers to harmful chemicals, particularly when stored improperly.

2.6.6 Policy and Practical Recommendations

To bridge the quality gap between different water sources, several strategies have been proposed:

- **Regulatory Enforcement**: Strengthening regulations for sachet water production and ensuring periodic monitoring of all drinking water sources can enhance safety (Oludairo and Aiyedun, 2015).
- **Public Awareness**: Educating consumers about proper storage and handling of bottled and sachet water can mitigate contamination risks (Umoafia *et al.*, 2023).
- **Infrastructure Development**: Investing in improved tap water systems and groundwater treatment can reduce reliance on bottled water and promote sustainability (Adesakin *et al.*, 2020).

Comparative studies consistently reveal that bottled water is safer and more consistent in quality than many other drinking water sources in Nigeria. However, its cost and environmental impact remain challenges. Improving the quality of tap water and sachet

water, particularly in rural areas, is essential to provide affordable and sustainable access to safe drinking water.

2.7 Challenges in Bottled Water Quality and Accessibility

Despite the increasing reliance on bottled water as a primary source of drinking water, numerous challenges persist in ensuring its quality, safety, and accessibility. These challenges span microbial contamination, chemical hazards, regulatory inconsistencies, environmental impacts, public health risks, and socioeconomic factors. This section delves into these issues, providing insights from various studies conducted in Nigeria and globally.

2.7.1 Microbial Contamination

Microbial contamination remains one of the most critical challenges in bottled water quality. Studies have revealed that some brands fail to meet acceptable microbiological standards, exposing consumers to waterborne diseases. For instance, Innocent *et al.* (2022) and Samuel *et al.* (2016) documented the presence of coliform bacteria and other pathogens in bottled water consumed in southeastern Nigeria, attributing contamination to poor manufacturing and storage practices. Similarly, Igbeneghu and Lamikanra (2014) highlighted significant microbial loads in bottled water brands in Ile-Ife, emphasizing the role of inadequate quality control.

2.7.2 Chemical Contamination

Chemical hazards, including the leaching of chemicals from plastic bottles and the presence of contaminants, pose significant health risks. Bisphenol A (BPA) and phthalates, commonly leached from plastic containers, have been linked to endocrine disruption, as highlighted by

Diduch *et al.* (2013) and Akhbarizadeh *et al.* (2020). Furthermore, Ibeto *et al.* (2023) documented microplastic pollution in bottled water in southeastern Nigeria, raising concerns about long-term exposure to synthetic polymers.

2.7.3 Inadequate Regulation and Enforcement

Regulatory lapses and inconsistencies in standards contribute to the proliferation of substandard bottled water products. Many small-scale manufacturers operate without proper licensing or oversight, as noted by Vapnek and Williams (2016). Additionally, Akinnibosun and Ugbawa (2017) observed significant variability in compliance levels across urban and rural areas in Edo State, Nigeria, reflecting challenges in uniform enforcement.

2.7.4 Environmental Impact

The environmental consequences of bottled water production and disposal represent a growing challenge. The widespread use of plastic bottles contributes to pollution and waste management issues, particularly in regions with inadequate recycling infrastructure. Umoafia *et al.* (2023) and Mason *et al.* (2018) highlighted the accumulation of plastic waste in Nigeria, exacerbating environmental degradation and threatening aquatic ecosystems.

2.7.5 Storage and Distribution Issues

Improper storage and distribution practices can significantly degrade bottled water quality. Prolonged exposure to sunlight, for example, accelerates the leaching of harmful chemicals and promotes microbial growth. Daffi and Wamyil (2021) demonstrated how bottled water exposed to sunlight in Bauchi State showed marked increases in physicochemical parameters, including pH and turbidity, alongside microbial proliferation.

2.7.6 Economic and Accessibility Challenges

Bottled water is often priced beyond the reach of low-income households, limiting access to safe drinking water. In rural and underserved areas, the high cost of bottled water forces residents to rely on less safe alternatives, such as untreated groundwater and sachet water. Magaji and Abimbola (2020) underscored this disparity in Masaka, Nasarawa State, where economic constraints significantly influenced water source preferences.

2.7.7 Consumer Awareness and Misconceptions

Limited consumer awareness about the potential risks associated with bottled water consumption poses an additional challenge. Many consumers mistakenly perceive bottled water as universally safe and superior to other sources, overlooking potential contamination risks. This misconception is perpetuated by inadequate public health education and marketing strategies by water companies, as noted by Oludairo and Aiyedun (2015).

2.7.8 Health Implications

The combined challenges of microbial and chemical contamination have direct implications for public health. Waterborne diseases, such as cholera and typhoid, remain prevalent due to the consumption of contaminated water. Moreover, long-term exposure to chemical contaminants, including microplastics, poses chronic health risks, as highlighted by Wątor *et al.* (2024) and Adams *et al.* (2016).

2.7.9 Variability in Quality across Regions

Significant regional disparities in bottled water quality exist due to differences in manufacturing standards, regulatory enforcement, and environmental conditions. For example, Ezeama and Achonye (2023) observed that bottled water in south-eastern Nigeria

often contained higher levels of contaminants compared to brands in urban centers like Lagos and Abuja.

2.7.10 Impact of Climate Change

Climate change exacerbates water quality challenges by affecting groundwater recharge rates and increasing the likelihood of contamination from floods and extreme weather events. Omeka *et al.* (2024) emphasized how changing climatic conditions have intensified the need for reliable drinking water sources, further burdening the bottled water industry.

2.7.11 Limited Infrastructure for Quality Assurance

Inadequate laboratory infrastructure and technical expertise hinder effective monitoring and quality assurance of bottled water products. This limitation is particularly pronounced in rural and peri-urban areas, where resources for regular testing are scarce, as reported by Agi *et al.* (2022) and Adesakin *et al.* (2020).

The challenges associated with bottled water quality and accessibility in Nigeria are multifaceted, encompassing microbial and chemical contamination, regulatory gaps, environmental impacts, economic constraints, and public health risks. Addressing these issues requires concerted efforts from regulatory agencies, manufacturers, and consumers to ensure the safety and sustainability of bottled water as a reliable drinking water source.

2.8 Recommendations for Improving Bottled Water Quality and Accessibility

To address the challenges associated with bottled water quality in Nigeria and globally, targeted recommendations can be drawn from the literature. These strategies focus on improving regulatory frameworks, enhancing public awareness, and implementing sustainable practices.

2.8.1 Strengthening Regulatory Frameworks and Enforcement

The need for robust regulation is paramount. Vapnek and Williams (2016) highlighted gaps in the enforcement of water quality standards across Africa, including Nigeria. Strengthening these frameworks requires revising existing regulations to align with international benchmarks like those set by the World Health Organization (WHO). Agencies such as the National Agency for Food and Drug Administration and Control (NAFDAC) should increase surveillance and conduct routine inspections of bottled water production facilities to ensure compliance. Collaboration between regulatory bodies and independent researchers, as suggested by Omeka *et al.* (2024), could enhance data transparency and accountability.

2.8.2 Improving Storage and Distribution Practices

Proper storage and transportation practices are critical to maintaining bottled water quality. Studies by Daffi and Wamyil (2021) and Umoafia *et al.* (2023) emphasized the risks of prolonged exposure to sunlight. Manufacturers and distributors should adopt storage guidelines that minimize chemical leaching and microbial growth, such as using UV-resistant packaging materials and climate-controlled warehouses. Public awareness campaigns can also educate retailers and consumers about the importance of proper storage.

2.8.3 Enhancing Quality Monitoring and Testing

Quality monitoring requires state-of-the-art laboratories and trained personnel. Adesakin *et al.* (2020) advocated for equipping regulatory agencies with advanced analytical tools to detect contaminants like microplastics and heavy metals. Partnerships with academic institutions and international organizations could facilitate the transfer of technical expertise and resources, as suggested by Akhbarizadeh *et al.* (2020). Regular publication of test results in public forums could also promote accountability.

2.8.4 Promoting Consumer Awareness and Education

Consumer education is essential for improving water safety practices. Igbeneghu and Lamikanra (2014) emphasized that public health campaigns can dispel misconceptions about bottled water safety and encourage informed decision-making. Educational programs should focus on recognizing certified brands, understanding water labels, and reporting suspected substandard products.

2.8.5 Encouraging Innovation in Packaging

The environmental impact of bottled water can be mitigated by promoting biodegradable and reusable packaging. Mason *et al.* (2018) and Umoafia *et al.* (2023) proposed adopting sustainable alternatives to single-use plastics, such as glass or biodegradable materials. Government incentives, such as tax breaks for companies investing in eco-friendly packaging, could accelerate this transition.

2.8.6 Expanding Accessibility in Rural and Low-Income Areas

Addressing the economic barriers to bottled water requires policies that subsidize production costs or provide incentives for distribution in underserved areas. Magaji and Abimbola (2020) suggested that public-private partnerships could facilitate the delivery of affordable

bottled water in rural communities. Additionally, local governments could establish water purification and bottling facilities to reduce dependency on external sources.

2.8.7 Conducting Long-Term Research

Long-term studies on bottled water quality, as recommended by Innocent *et al.* (2022), can help track trends in contamination and evaluate the effectiveness of interventions. Research priorities should include emerging contaminants, the impact of climate change on water sources, and advancements in purification technologies.

2.8.8 Incentivizing Recycling and Waste Management

Addressing plastic waste requires a multi-pronged approach. Ibeto *et al.* (2023) recommended implementing extended producer responsibility programs, where manufacturers take part in the recycling of used bottles. Governments should also invest in community-based recycling initiatives and public awareness campaigns to promote proper waste disposal practices.

2.8.9 Leveraging Technology for Traceability

Digital solutions such as blockchain technology can enhance supply chain transparency. Consumers and regulators could access real-time data on the origin, processing, and distribution of bottled water products, reducing the prevalence of counterfeit or substandard brands (Omeka *et al.*, 2024).

2.8.10 Regional Collaboration

Regional collaboration among West African nations could harmonize standards and practices for bottled water quality. Joint efforts in research, monitoring, and policy development would

streamline resource allocation and improve regulatory efficiency, as suggested by Vapnek and Williams (2016).

By implementing these strategies, stakeholders can address the multifaceted challenges associated with bottled water quality and accessibility, ultimately safeguarding public health and promoting sustainability.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Benin City, Edo State. This city serves as an urban hub with multiple sources of drinking water including municipal supplies, boreholes, sachet water and bottled water. Bottled water brands were sampled from various outlets to ensure diversity and represent a wide range of production processes.

3.2 Sample Collection

Ten (10) samples of bottled water were collected, two (2) from each of five different water-producing factories operating in Benin City. Samples were transported to the laboratory within 6 hours of purchase to preserve integrity.

3.3 Physico-Chemical Analysis

The conventional parameters used in assessing the quality and portability of water for drinking are level of Suspended Solids, Total Dissolved Solid, Appearance, Hardness, Conductivity, pH, Colour, Odour, etc. (APHA-AWWA, 1998; Okorafor *et al.*, 2012).

3.3.1 Conductivity

Conductivity Meter (Model: Hanna Instrument H18733) was used. The conductivity meter probe was rinsed with distilled water and inserted into the sample in a beaker, conductivity reading was displayed (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

3.3.2 pH

The pH was determined with a pH meter (Model: Mettler Toledo Mp 220). The pH meter probe was inserted into the water sample in a beaker, the READ key was pressed and the pH reading was taken (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

3.3.3 Turbidity

A turbidity meter was used. (Model: Hanna Instrument H193703). The sample was placed in the turbidimeter bottle and the bottle wiped clean with a cloth to erase any finger print that may affect the reading. The bottle was then placed on the turbidometer and the read key pressed, the turbidity reading was displayed (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

3.3.4 Colour

The colour was determined using Lovibond Comparator. The test kit was assembled and the water sample was poured into a tube and place in the right hand of the comparator. The disc was place on the comparator and noted as the colour value (Agbo *et al.,* 2019).

3.3.5 Total Dissolved Solids (TDS)

This was determined by multiplying through the conductivity value. The conductivity of the sample was determined and the value multiplied by 0.6 to get the TDS (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

TDS = Conductivity x 0.6.

3.3.6 Total Hardness

1 mL of the sample was placed in a reaction cell and 1 mL of total hardness reagent H-1k added with a pipette. Three minutes reaction time was allowed before total hardness was determined in spectrophotometer at a wavelength of 450 nm (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

3.3.7 Major Ions

Calcium: 0.1 mL of the sample was placed in a test tube using pipette and 0.5 mL of calcium reagent Ca-1 was added and mixed. 0.4 mL each of calcium reagent Ca-2 and Ca-3 were also added to the test tube and mixed. The sample was allowed to stand for 8 minutes to elicit full colour development and then filled into a reaction cell, placed in spectrophotometer where the calcium concentration was displayed (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

Magnesium: 1 mL of the sample was placed in a reaction cell and mixed and 1 mL of magnesium reagent Mg-1k added to it. This was allowed to stand for 3 minutes and thereafter, 0.3 mL of magnesium reagent Mg-2k added, mixed and placed in spectrophotometer. Magnesium concentration was read at a wavelength of 568 nm (Okorafor *et al.,* 2012; Brooks *et al.,* 2017; Iyakndue *et al.,* 2017).

3.4 Chloride Determination (Argentometric Method)

Chloride concentration in the bottled water samples was determined using the argentometric titration method, a standard approach for chloride analysis in water. 50 mL of each water sample was measured into a conical flask. A few drops of potassium chromate (K_2CrO_4) indicator were added to the sample. The sample was titrated with a 0.0141 M silver nitrate

($AgNO_3$) solution until a reddish-brown endpoint appeared, indicating the formation of silver chromate. The chloride concentration (mg/L) was calculated using the formula:

$$Chloride\ (mg/l) = \frac{VA\ x\ NA\ x\ 35.45\ x\ 1000}{Vs}$$

Where V_A = Volume of $AgNO_3$ used (mL)

N_A = Normality of $AgNO_3$

35.45 = Atomic weight of chloride

V_S = Sample volume (mL)

(Adams *et al.*, 2016).

3.5 Sulphate Determination (Turbidimetric Method)

Sulphate concentration was measured using the turbidimetric method, which relies on the formation of barium sulphate precipitate in a sample. A 5% barium chloride ($BaCl_2$) solution was prepared. 50 mL of each water sample was placed in a beaker, and buffer solution (to maintain pH 4–5) and a measured amount of $BaCl_2$ were added. The solution was stirred and allowed to develop turbidity. The absorbance was measured at 420 nm using a spectrophotometer. Sulphate concentration was determined using a calibration curve generated from standard sulphate solutions (Adekunle *et al.*, 2020).

3.6 Nitrate Determination (UV Spectrophotometric Method)

The concentration of nitrates in the bottled water samples was determined using the UV spectrophotometric method, which measures nitrate absorption at 220 nm. Each sample was filtered to remove particulates. 10 mL of the water sample was transferred into a cuvette, and absorbance was measured at 220 nm using a UV-visible spectrophotometer. To eliminate

interference from dissolved organic matter, a second reading was taken at 275 nm, and the corrected nitrate concentration was determined using the formula:

$$Nitrate\ (mg/L) = (\mathrm{A220} - 2\ x\ A275)\ x\ conversion\ factor$$

Where A_{220} and A_{275} are absorbance values at their respective wavelengths (Adesakin *et al.,* 2020).

3.7 Heavy Metals Analysis

The heavy metals (Cu, Mn, Cd, Zn, Pb,and Fe) of the water samples were determined with atomic absorption spectrophotometer (Model AA500) following the procedure described by Chinedu *et al*. (2011).

3.8 Statistical Analysis

Descriptive statistics (mean, ranges and standard deviations) were computed. Data were recorded as mean ± standard deviation. All calculations and statistical tests were carried out using Microsoft Office Suite 2016 Excel sheets and IBM SPSS Statistics 2021.

CHAPTER FOUR

RESULTS

The physicochemical properties of five bottled water brands (EVA, CWAY, AQUAFINA, EIO, ROI) were analyzed and shown in Table 4.1. For the pH, the highest was seen in EIO samples (7.37 ± 0.19), while the lowest was in ROI samples (6.63 ± 0.11). The highest Conductivity (µS/cm) was observed in EIO samples (41.33 ± 1.16), ROI samples (12.00 ± 2.00) had the least. The highest Total Dissolved Solids (TDS, mg/L) was observed in EIO samples (20.67 ± 0.58) while the lowest, in ROI samples (6.00 ± 1.00). The Suspended Solids (mg/L) was seen in only ROI samples (1.33 ± 0.58). It was absent in other brands. Turbidity (NTU) values were highest in CWAY samples (0.67 ± 0.58) but was absent in EVA and AQUAFINA samples. Colour (Pt.Co.) was detected only in ROI samples (0.67 ± 0.58). Hardness (mg/L) values were highest in CWAY samples (22.00 ± 2.00), lowest in AQUAFINA samples (17.33 ± 1.16). The highest Chloride (mg/L) values was observed in EVA, CWAY, and EIO samples (14.12 ± 0.00), AQUAFINA samples (7.06 ± 0.00) had the lowest. Sulphate (mg/L) values were highest in ROI samples (2.33 ± 1.53) and lowest in AQUAFINA samples (1.00 ± 0.00). Nitrate (mg/L) was highest in CWAY samples (0.21 ± 0.00) and lowest in ROI samples (0.03 ± 0.003). Calcium (mg/L) were observed to be highest in CWAY samples (7.21 ± 0.81), and lowest in ROI samples (4.81 ± 2.78). Magnesium (mg/L) had the highest value in ROI samples (1.62 ± 1.13) but was lowest in CWAY and AQUAFINA samples (0.97 ± 0.49 and 0.97 ± 0.00, respectively). Iron (mg/L): was highest in ROI samples (0.12 ± 0.01), lowest in EVA (0.02 ± 0.00, range: 0.017–0.025). ROI samples has the highest amount of Zinc (mg/L) (0.27 ± 0.05), while Eva samples recorded the lowest (0.04 ± 0.01). ROI samples also recorded the highest Manganese (mg/L) (0.48 ± 0.07), Eva recording the lowest (0.25 ± 0.004). Copper (mg/L) was highest in ROI samples (0.52 ±

0.09), with the lowest seen in AQUAFINA (0.28 ± 0.22). Lead and Cadmium were not detected in any of the samples.

Figure 4.1 showed the mean pH of bottled water samples. It ranged from 6.63 ± 0.11 (ROI) to 7.37 ± 0.19 (EIO). The highest mean pH was recorded in EIO, making it slightly more alkaline, while ROI had the lowest pH, making it the most acidic among the samples. The pH values of all brands were within the WHO-recommended range of 6.5–8.5 for drinking water.

Figure 4.2 showed the mean conductivity of bottled water samples. The highest mean conductivity was observed in EIO (41.33 ± 1.16 µS/cm), while the lowest was in ROI (12.00 ± 2.00 µS/cm). A higher conductivity suggests a greater concentration of dissolved minerals, while lower conductivity indicates fewer dissolved solids.

The mean total dissolved solids (TDS) of bottled water samples was shown in Figure 4.3. TDS values followed a similar trend as conductivity, with EIO recording the highest mean value of 20.67 ± 0.58 mg/L and ROI having the lowest at 6.00 ± 1.00 mg/L. TDS represents the total concentration of dissolved substances in the water, and all samples fell within the acceptable limit for drinking water (<500 mg/L).

The mean suspended solids of bottled water samples are recorded in Figure 4.4. Suspended solids were absent in all samples except for ROI, which had a mean value of 1.33 ± 0.58 mg/L. This suggests that ROI contained small amounts of undissolved particles, possibly due to poor filtration or contamination.

Table 4.1. Physicochemical properties of bottled water samples

PARAMETERS	**EVA Mean ± Standard deviation**	**CWAY Mean ± Standard deviation**	**AQUAFINA Mean ± Standard deviation**	**EIO Mean ± Standard deviation**	**ROI Mean ± Standard deviation**	**Range**
pH	6.67 ± 0.03	6.78 ± 0.03	7.15 ± 0.05	7.37 ± 0.19	6.63 ± 0.11	6.63-7.37
Conductivity (µS/cm)	32.00 ± 2.00	38.67 ± 1.16	40.67 ± 1.15	41.33 ± 1.16	12.00 ± 2.00	12-41.33
TDS (mg/l)	14.33 ± 2.08	19.33 ± 0.58	20.33 ± 0.57	20.67 ± 0.58	6.00 ± 1.00	6.00-20.67
Suspended Solid	0	0	0	0	1.33 ± 0.58	0.00-1.33
Turbidity (NTU)	0	0.67 ± 0.58	0	0.33 ± 0.58	0.33 ± 0.58	0.00-0.67
Colour (Pt.Co.)	0	0	0	0	0.67 ± 0.58	0.00-0.67
Hardness (mg/l)	20.67 ± 1.16	22.00 ± 2.00	17.33 ± 1.16	20.67 ± 1.16	20.67 ± 1.16	17.33-22.00
Chloride (mg/l)	14.12 ± 0.00	14.12 ± 0.00	7.06 ± 0.00	14.12 ± 0.00	9.41 ± 4.08	7.06-14.12
Sulphate (mg/l)	1.33 ± 0.58	1.33 ± 0.58	1.00 ± 0.00	2.00 ± 1.00	2.33 ± 1.53	1.00-2.33
Nitrate (mg/l)	0.13 ± 0.00	0.21 ± 0.00	0.12 ± 0.00	0.12 ± 0.00	0.03 ± 0.003	0.03-0.21
Calcium (mg/l)	6.14 ± 0.46	7.21 ± 0.81	5.34 ± 0.46	6.41 ± 0.00	4.81 ± 2.78	4.81-7.21
Magnesium (mg/l)	1.30 ± 0.57	0.97 ± 0.49	0.97 ± 0.00	1.13 ± 0.28	1.62 ± 1.13	0.97-1.62
Iron (mg/l)	0.02 ± 0.00	0.04 ± 0.004	0.05 ± 0.005	0.05 ± 0.01	0.12 ± 0.01	0.02-0.12
Zinc (mg/l)	0.04 ± 0.01	0.05 ± 0.01	0.05 ± 0.009	0.05 ± 0.01	0.27 ± 0.05	0.04-0.27
Lead (mg/l)	ND	ND	ND	ND	ND	ND
Manganese (mg/l)	0.25 ± 0.004	0.28 ± 0.002	0.29 ± 0.001	0.28 ± 0.001	0.48 ± 0.07	0.25-0.48
Copper (mg/l)	0.56 ± 0.01	0.51 ± 0.003	0.28 ± 0.22	0.49 ± 0.06	0.52 ± 0.09	0.28-0.56
Cadmium (mg/l)	ND	ND	ND	ND	ND	ND

Key: TDS – Total Dissolved Solids

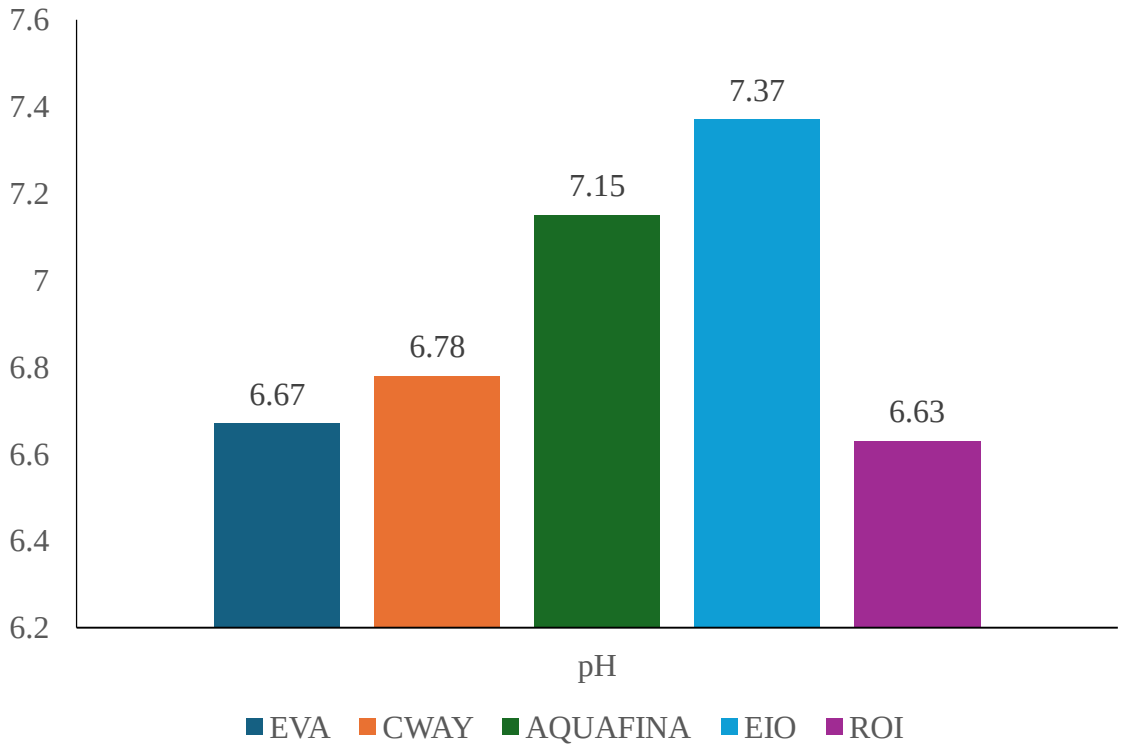

Figure 4.1. Mean pH of Bottled water samples

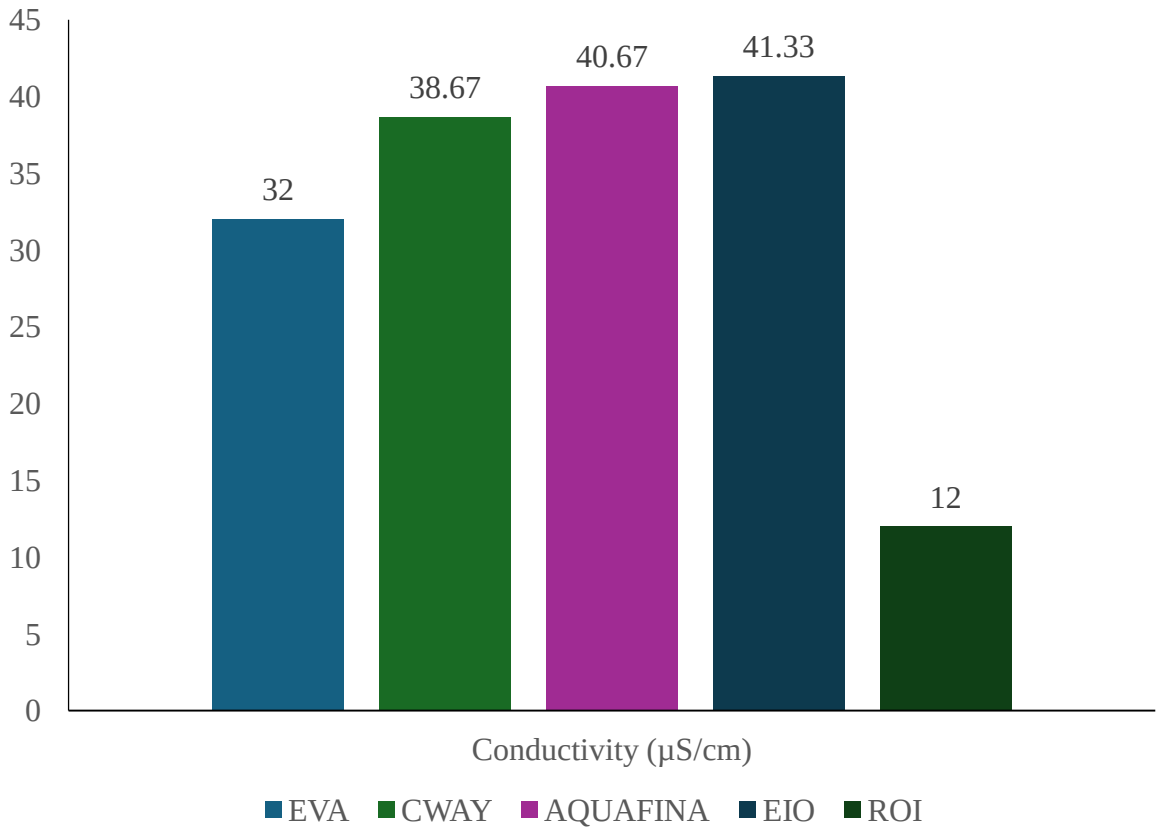

Figure 4.2. Mean Conductivity of Bottled water samples

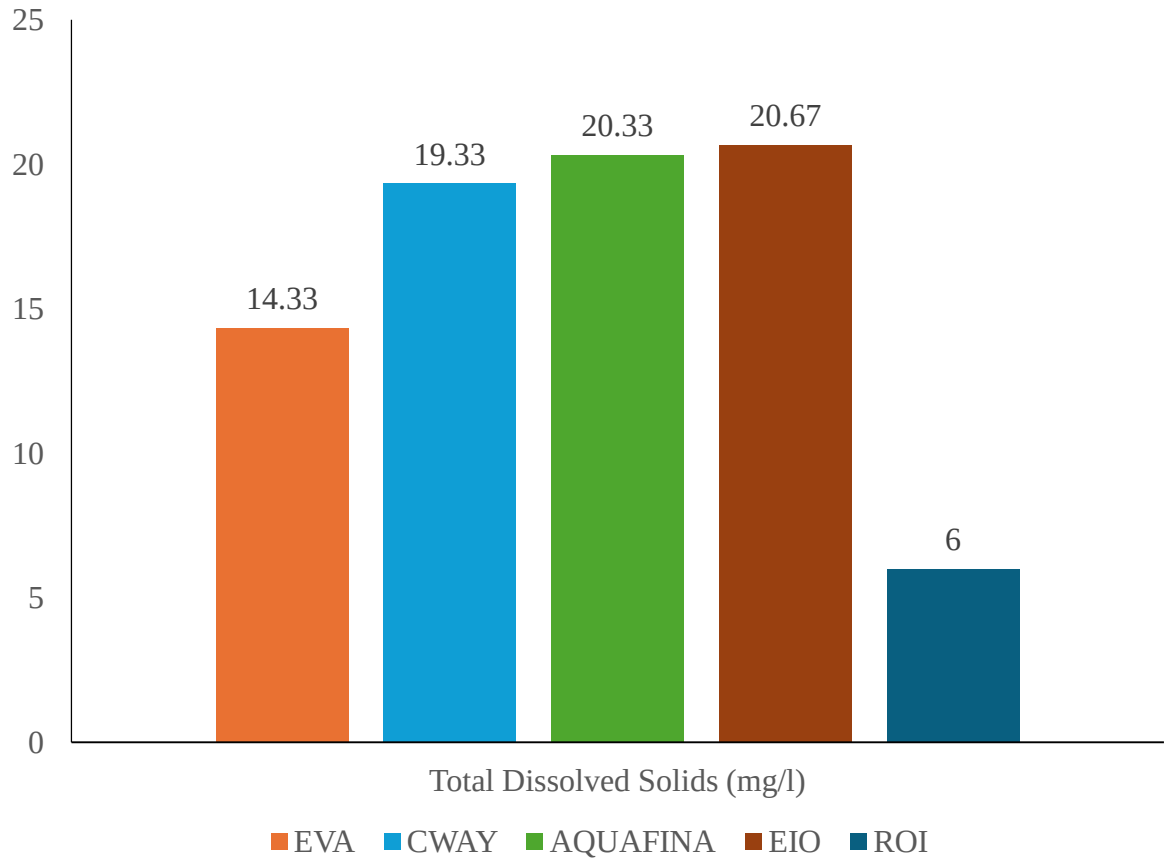

Figure 4.3. Mean Total Dissolved Solids of Bottled water samples

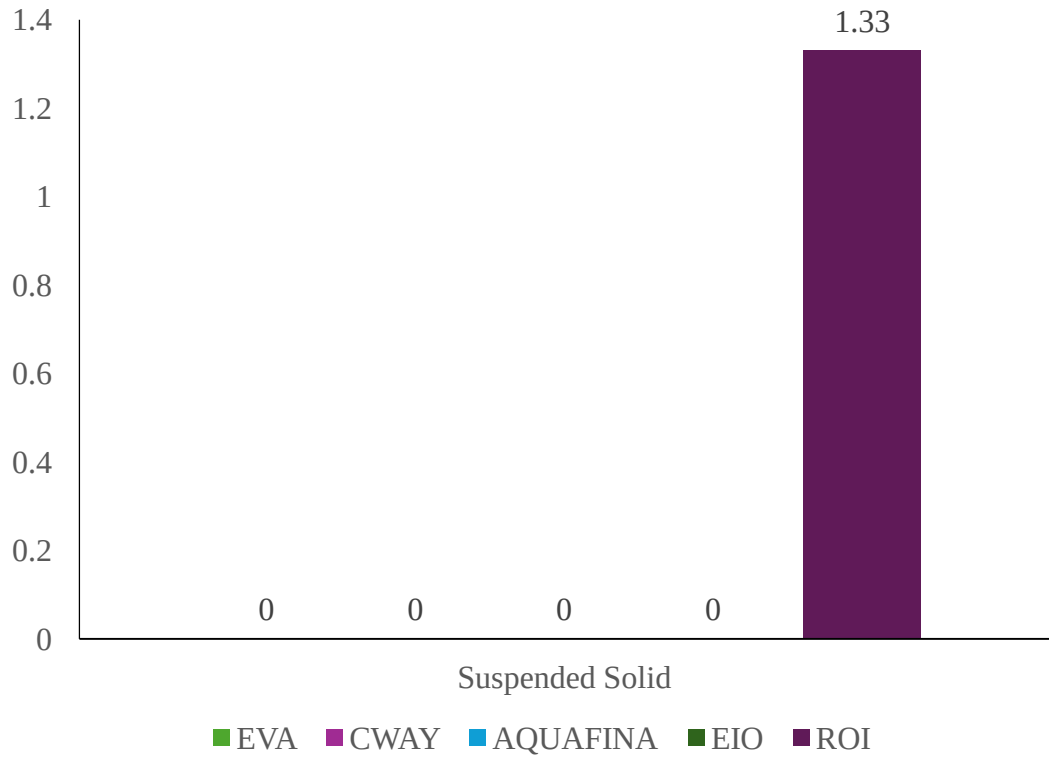

Figure 4.4. Mean Suspended Solids of Bottled water samples

In Figure 4.5, the mean turbidity of bottled water samples was revealed. Turbidity, which measures water clarity, was lowest (0 NTU) in EVA and AQUAFINA but present in CWAY (0.67 ± 0.58 NTU), EIO (0.33 ± 0.58 NTU), and ROI (0.33 ± 0.58 NTU). Higher turbidity can indicate the presence of suspended particles, which may affect water quality.

Figure 4.6 showed the mean colour of bottled water samples Colour was only detected in ROI (0.67 ± 0.58 Pt.Co.), while all other samples had 0 Pt.Co.

The mean hardness of bottled water samples (Figure 4.7) revealed Water hardness, which results from dissolved calcium and magnesium, was highest in CWAY (22.00 ± 2.00 mg/L) and lowest in AQUAFINA (17.33 ± 1.16 mg/L). Hardness affects the taste of water and its reaction with soap, but all samples were within the WHO-recommended limit.

Figure 4.8 showed the mean chloride of bottled water samples. Chloride concentrations were highest in EVA, CWAY, and EIO (14.12 ± 0.00 mg/L) and lowest in AQUAFINA (7.06 ± 0.00 mg/L). Chloride in drinking water comes from natural sources, industrial waste, or agricultural runoff, but all values were within safe drinking limits.

The mean sulphate of bottled water samples is shown in Figure 4.9. Sulphate content varied among the samples, with ROI having the highest mean value (2.33 ± 1.53 mg/L) and AQUAFINA having the lowest (1.00 ± 0.00 mg/L). Sulphate contributes to the taste of water and may cause a laxative effect at high concentrations, but all values were within acceptable limits.

Figure 4.10 (the mean nitrate of bottled water samples) revealed that Nitrate levels were highest in CWAY (0.21 ± 0.00 mg/L) and lowest in ROI (0.03 ± 0.003 mg/L). High nitrate levels in drinking water can pose health risks, particularly to infants, but the recorded values were well below the WHO limit of 50 mg/L.

Figure 4.11 (the mean calcium of bottled water samples) revealed that Calcium content was highest in CWAY (7.21 ± 0.81 mg/L) and lowest in ROI (4.81 ± 2.78 mg/L). Calcium contributes to water hardness and is essential for human health.

Figure 4.12 Mean magnesium of bottled water samples. Showed that the highest magnesium concentration was found in ROI (1.62 ± 1.13 mg/L), while the lowest was in CWAY and AQUAFINA (0.97 mg/L each). Magnesium is important for bone health and muscle function.

Figure 4.13: Mean Iron of Bottled Water Samples. Iron concentration was highest in ROI (0.12 ± 0.01 mg/L) and lowest in EVA (0.02 ± 0.00 mg/L). Excess iron can cause an unpleasant metallic taste and discoloration, but all values were within acceptable limits.

The mean zinc of bottled water samples (Figure 4.14) revealed that zinc levels were highest in ROI (0.27 ± 0.05 mg/L) and lowest in EVA (0.04 ± 0.01 mg/L). Zinc is an essential trace element but may affect water taste if present in high concentrations.

The mean manganese of bottled water samples (Figure 4.15) showed that Manganese was highest in ROI (0.48 ± 0.07 mg/L) and lowest in EVA (0.25 ± 0.004 mg/L). Manganese can cause discoloration in water and stains in plumbing fixtures if present in high amounts.

Figure 4.16 showed the mean copper of bottled water samples. Copper was highest in ROI (0.52 ± 0.09 mg/L) and lowest in AQUAFINA (0.28 ± 0.22 mg/L). Copper is an essential micronutrient, but excessive levels can cause gastrointestinal issues.

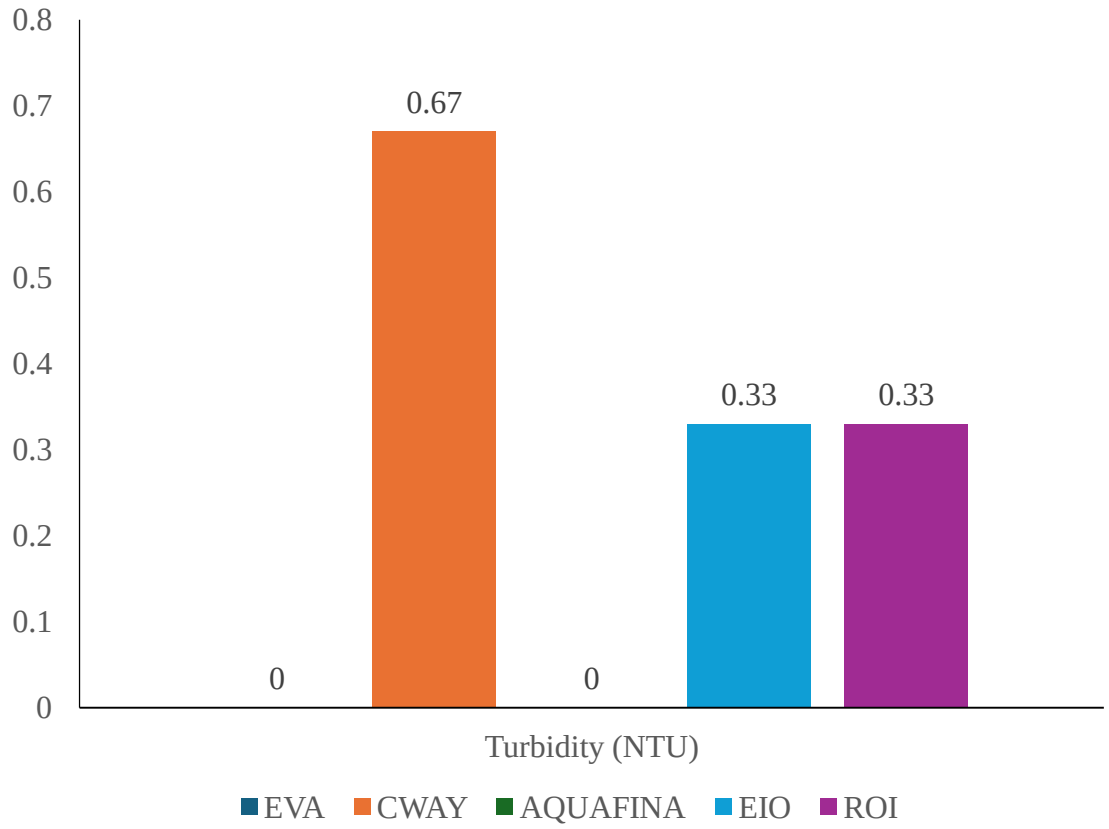

Figure 4.5. Mean Turbidity of Bottled water samples

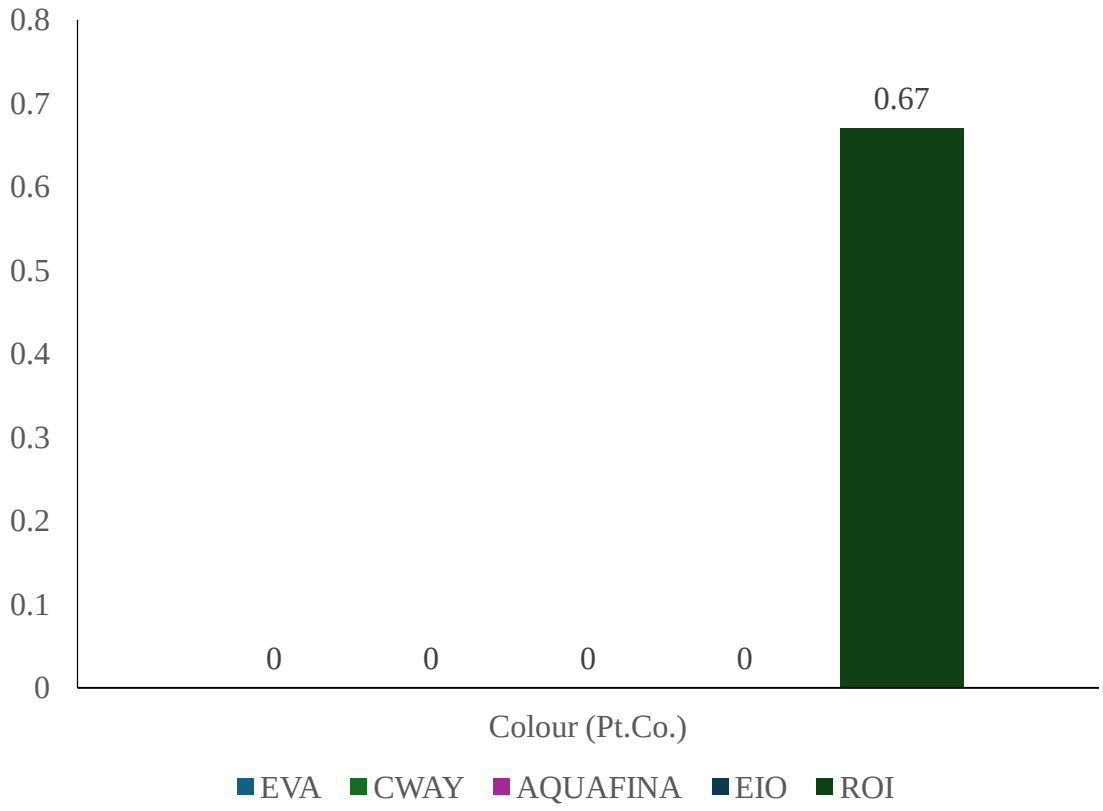

Figure 4.6. Mean Colour of Bottled water samples

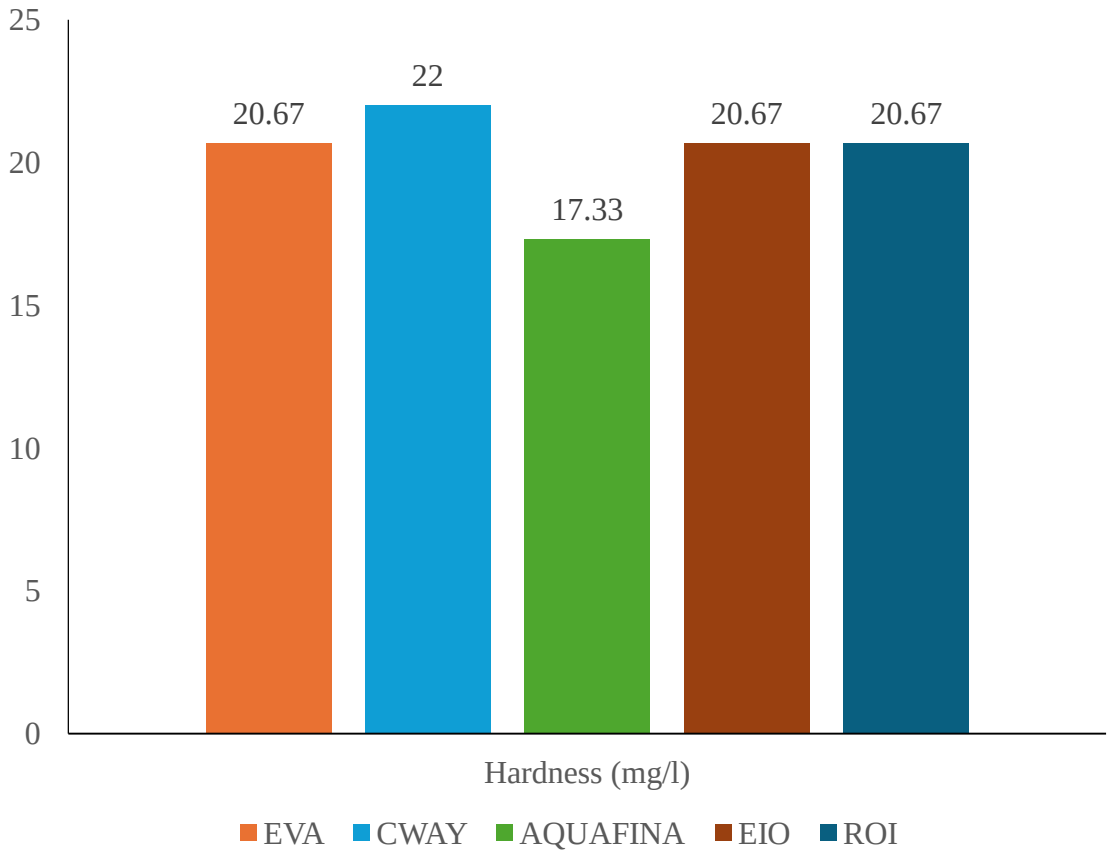

Figure 4.7. Mean Hardness of Bottled water samples

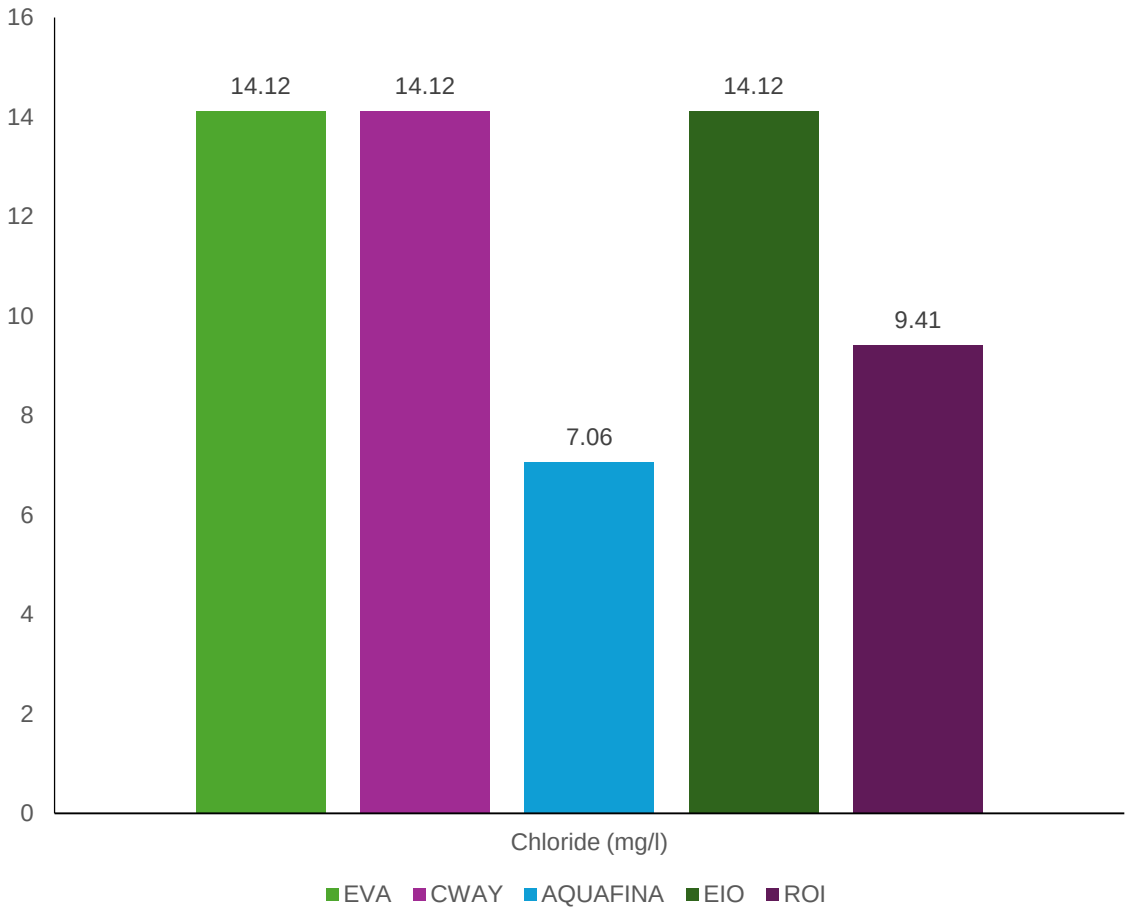

Figure 4.8. Mean Chloride of Bottled water samples

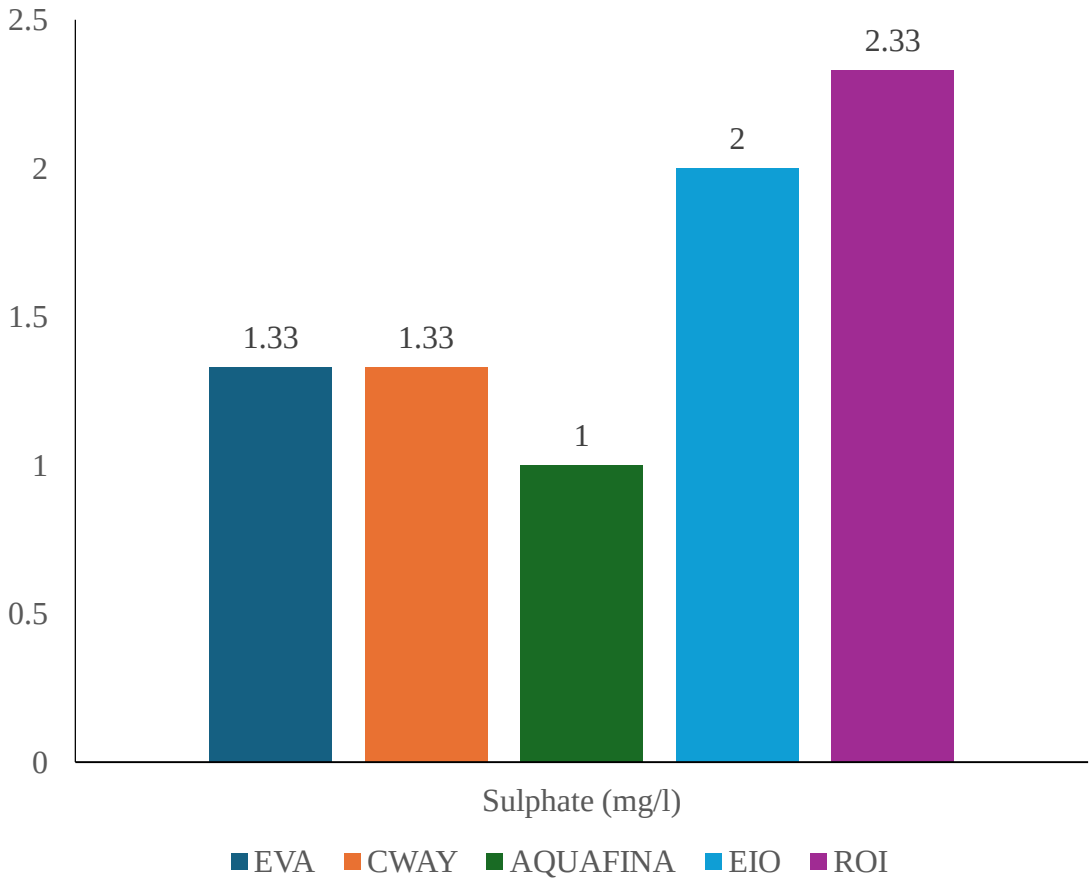

Figure 4.9. Mean Sulphate of Bottled water samples

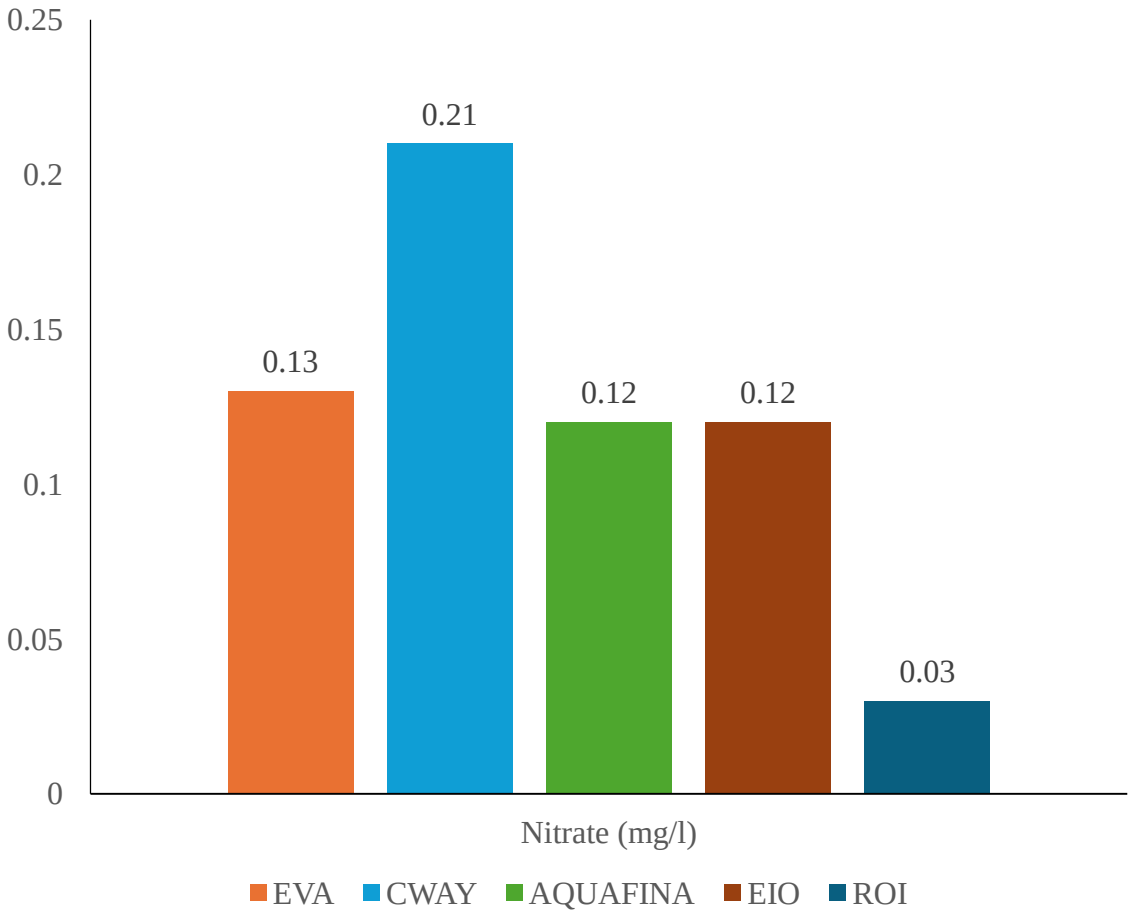

Figure 4.10. Mean Nitrate of Bottled water samples

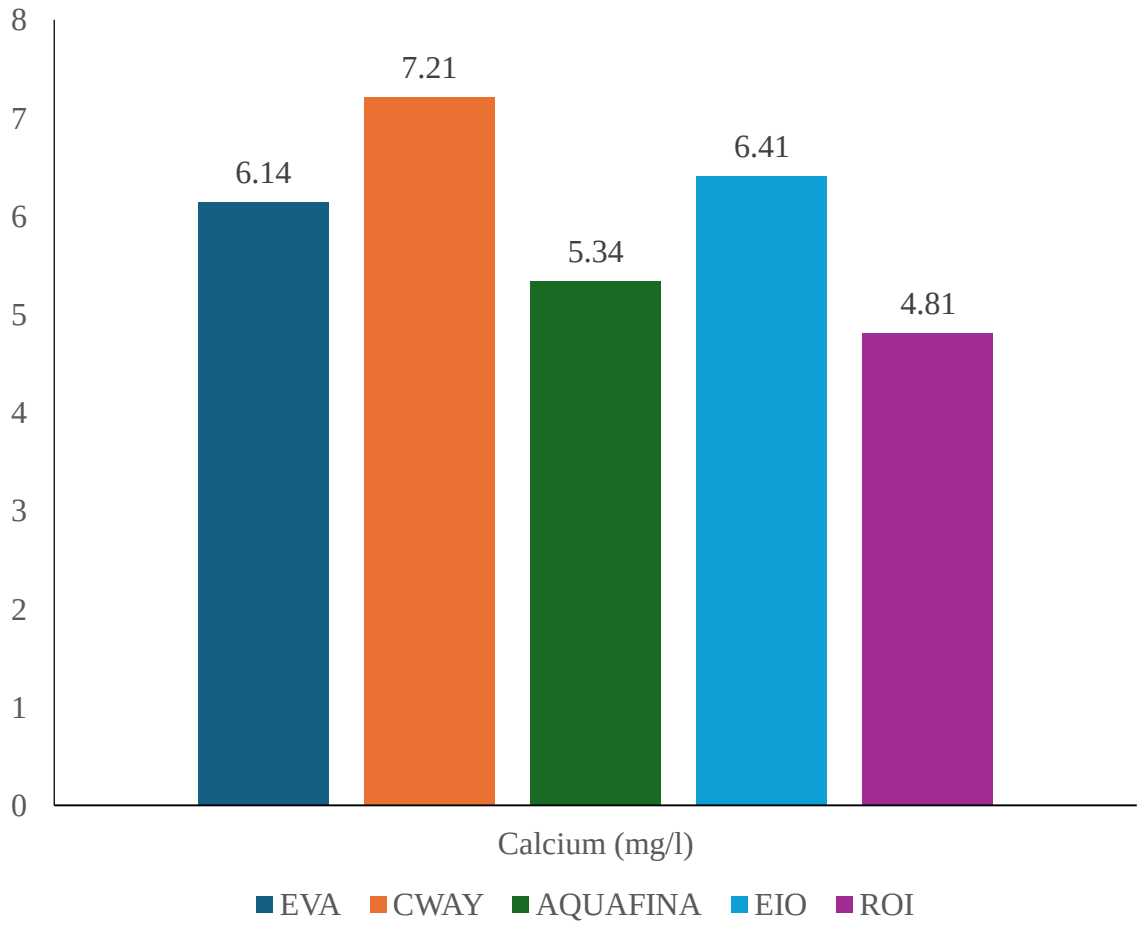

Figure 4.11. Mean Calcium of Bottled water samples

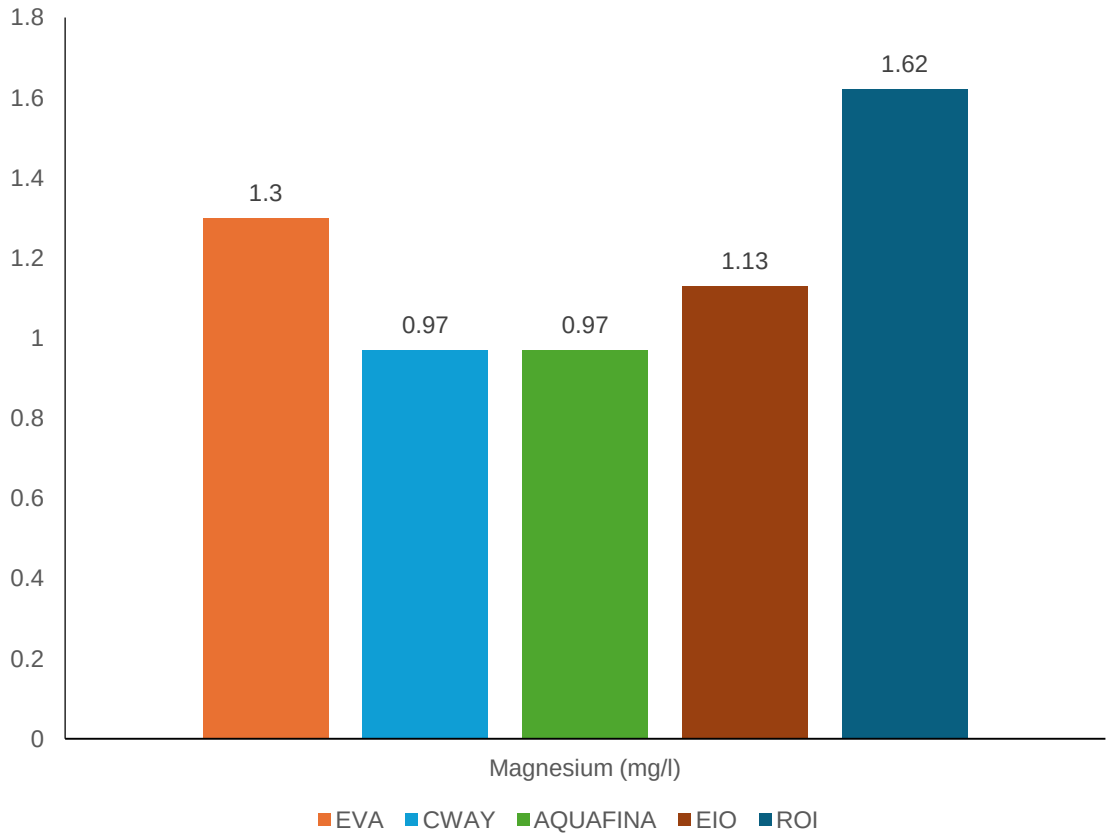

Figure 4.12. Mean Magnesium of Bottled water samples

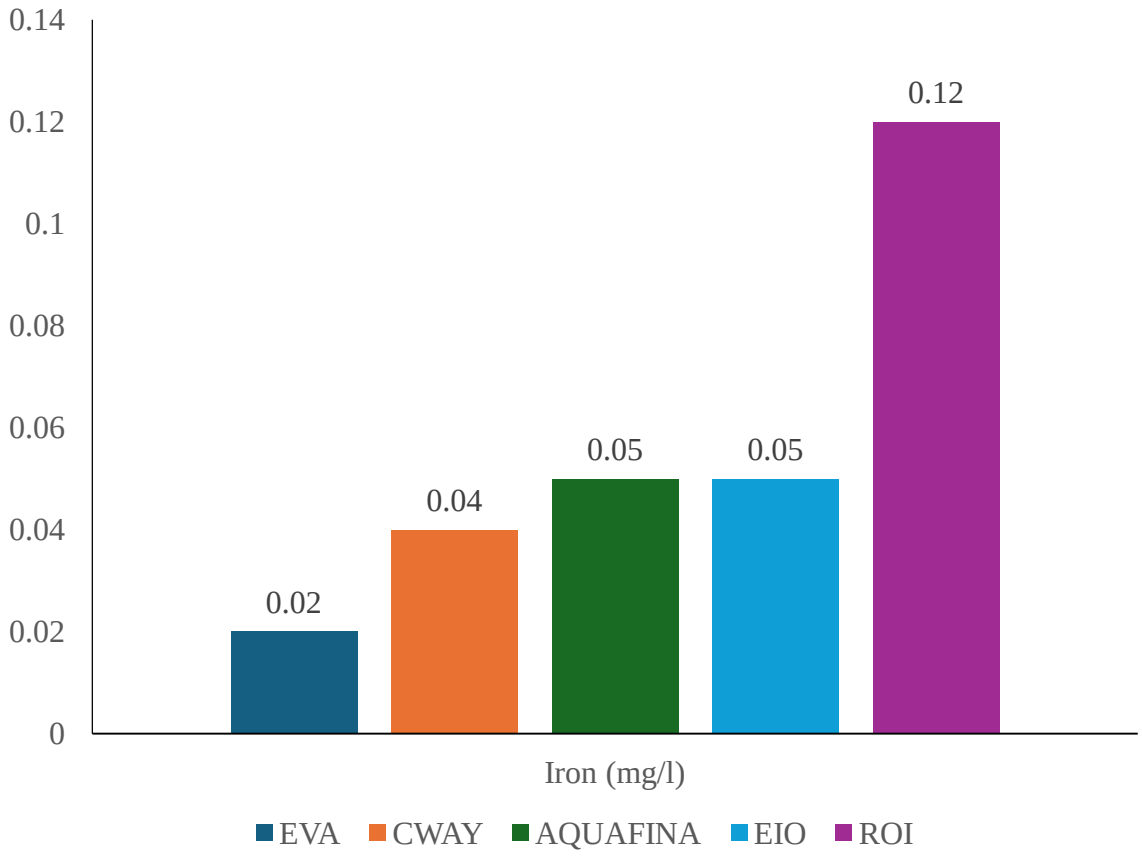

Figure 4.13. Mean Iron of Bottled water samples

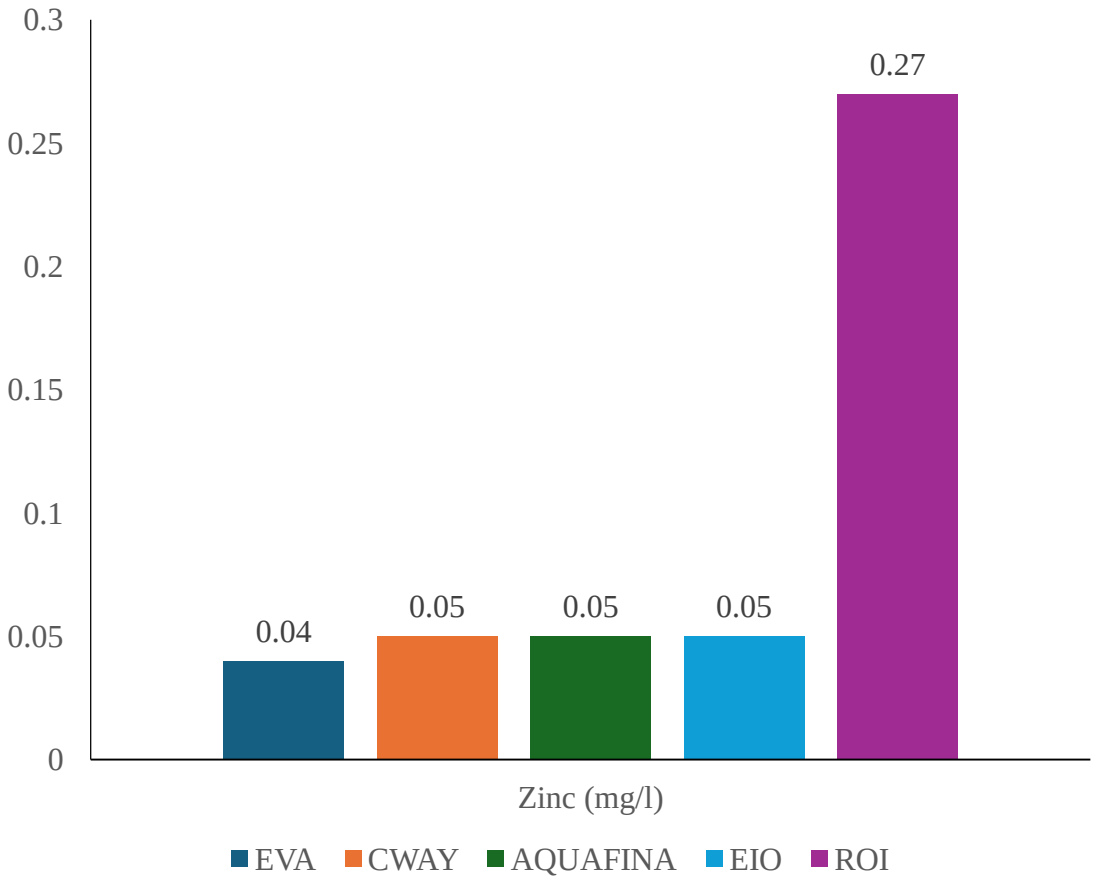

Figure 4.14. Mean Zinc of Bottled water samples

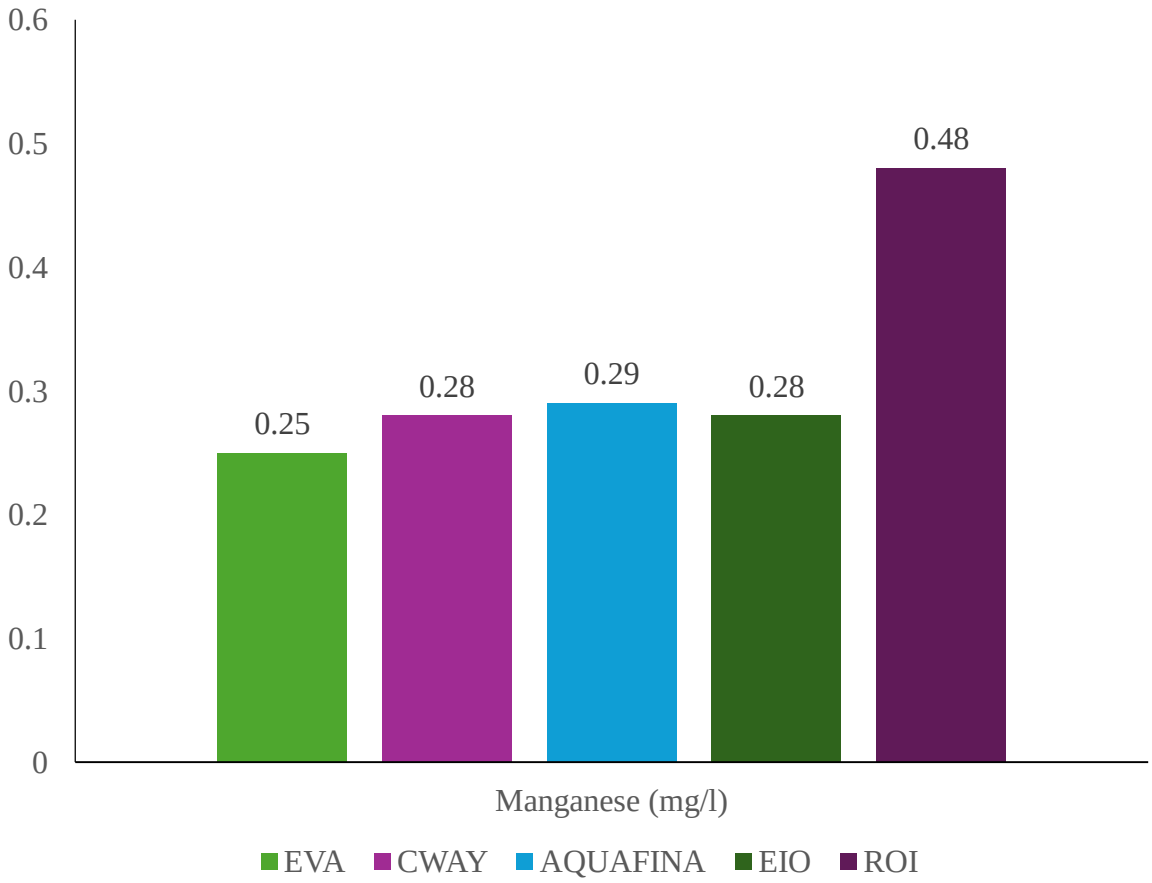

Figure 4.15. Mean Manganese of Bottled water samples

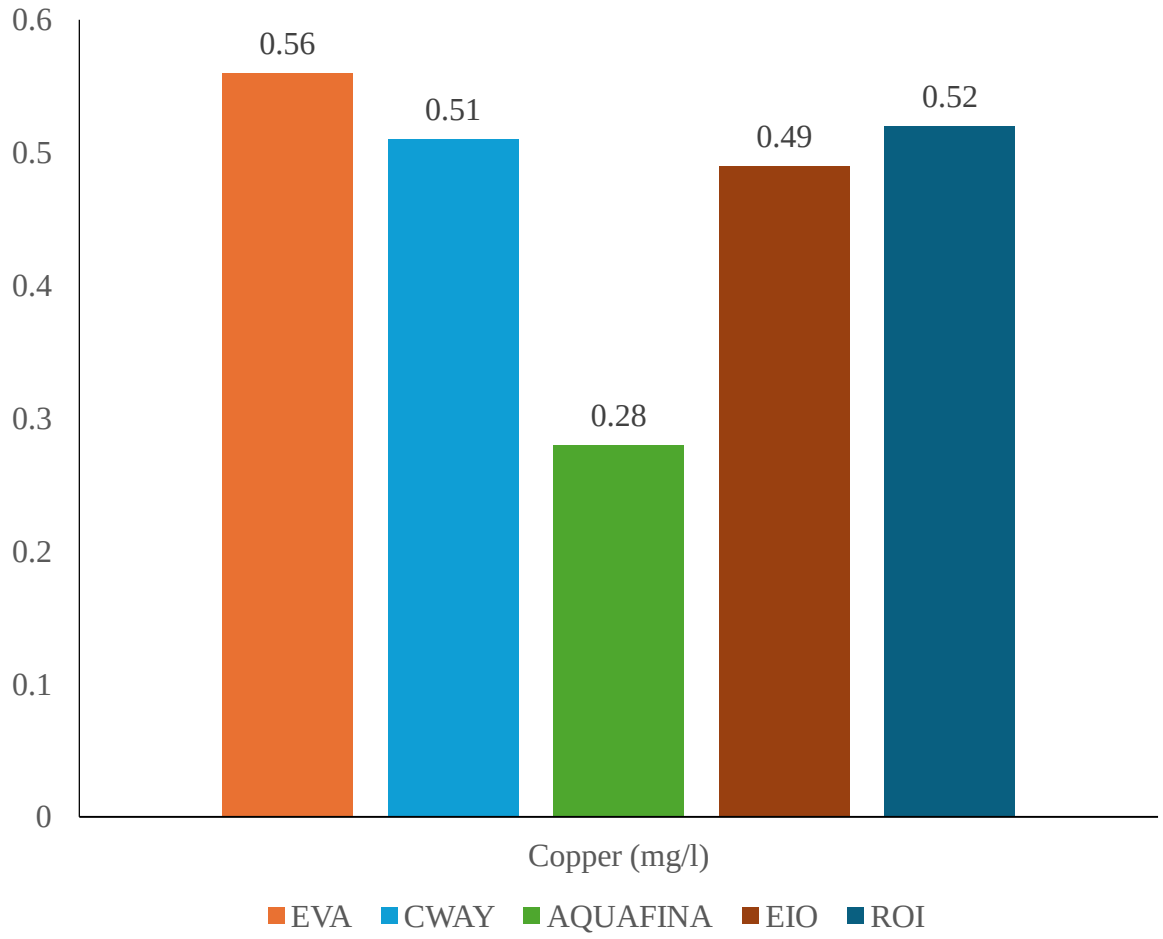

Figure 4.16. Mean Copper of Bottled water samples

CHAPTER FIVE

DISCUSSION

The assessment of the physicochemical properties of bottled water is crucial in determining its quality and safety for consumption. Physicochemical parameters such as pH, conductivity, total dissolved solids (TDS), turbidity, colour, hardness, and chloride content provide insights into the purity, mineral composition, and potential contamination of drinking water. In this study, five different bottled water brands were analyzed, and significant variations in their physicochemical properties were observed.

The pH of the water samples ranged from 6.63 ± 0.11 (ROI) to 7.37 ± 0.19 (EIO), indicating that all samples fell within the WHO-recommended range of 6.5–8.5 for drinking water. The slightly acidic nature of ROI suggests possible differences in water sources or treatment processes, as noted by Adekunle *et al.* (2020), who reported similar pH variations in bottled water samples from Ondo State. pH plays a vital role in the palatability of drinking water and influences the solubility of minerals and potential contaminants. Water with a pH below 6.5 can be corrosive, potentially leaching metals from pipes, while excessively high pH can affect taste. Conductivity and TDS levels, which measure the concentration of dissolved ions, showed marked differences among the brands. EIO had the highest conductivity (41.33 ± 1.16 µS/cm) and TDS (20.67 ± 0.58 mg/L), whereas ROI had the lowest (12.00 ± 2.00 µS/cm and 6.00 ± 1.00 mg/L, respectively). These findings align with those of Aex and LB (2023), who reported that variations in conductivity and TDS often result from differences in the mineral content of source water and purification methods. Higher TDS and conductivity values typically indicate the presence of dissolved salts, minerals, and trace elements, which can influence the taste and health benefits of the water.

Turbidity, colour, and suspended solids are critical indicators of water clarity and purity. In this study, turbidity was detected in CWAY (0.67 ± 0.58 NTU), EIO (0.33 ± 0.58 NTU), and ROI (0.33 ± 0.58 NTU), while EVA and AQUAFINA had 0 NTU. Similarly, suspended solids were absent in all samples except ROI (1.33 ± 0.58 mg/L), which also exhibited slight coloration (0.67 ± 0.58 Pt.Co.). These findings suggest that ROI may contain undissolved particulates, potentially from inadequate filtration or contamination, as previously observed by Agbo *et al.* (2019) in drinking water sources in Calabar Municipality. Suspended solids and turbidity in bottled water may arise from organic or inorganic matter, indicating poor processing or storage conditions. Water hardness, which is primarily determined by calcium and magnesium levels, was found to be highest in CWAY (22.00 ± 2.00 mg/L) and lowest in AQUAFINA (17.33 ± 1.16 mg/L). Hardness affects the taste of water and its interaction with soap, with higher hardness linked to increased mineral content. Angnunavuri *et al.* (2022) reported similar variations in bottled water hardness in Accra, Ghana, where differences were attributed to the geological characteristics of water sources.

Chloride content, an indicator of salinity and possible contamination, was highest in EVA, CWAY, and EIO (14.12 mg/L) and lowest in AQUAFINA (7.06 mg/L). Elevated chloride levels may indicate contamination from industrial discharge or agricultural runoff, as noted by Adams *et al.* (2016) in their study on water quality in Benin City. While all recorded chloride levels were within acceptable limits, variations suggest differences in water sources and treatment methods. Overall, the physicochemical analysis revealed significant differences among bottled water brands, emphasizing the need for continuous monitoring to ensure compliance with safety standards.

The comparison of essential and trace elements in bottled water samples is critical in assessing their nutritional value and potential health risks. Essential minerals such as calcium

and magnesium are beneficial for human health, while trace metals like iron, zinc, manganese, and copper must be present in controlled amounts to prevent adverse effects. The results of this study revealed significant variations in the concentrations of these elements across different bottled water brands, indicating differences in water sources and purification processes.

Calcium and magnesium are key contributors to water hardness and play vital roles in bone health, muscle function, and cardiovascular regulation. In this study, CWAY had the highest calcium concentration (7.21 ± 0.81 mg/L), while ROI had the lowest (4.81 ± 2.78 mg/L). Magnesium levels were also highest in ROI (1.62 ± 1.13 mg/L) and lowest in CWAY and AQUAFINA (0.97 mg/L each). These findings align with those of Asgari *et al.* (2021), who reported that variations in calcium and magnesium concentrations in bottled water could be attributed to differences in geological formations of the water source and treatment methods. Although calcium and magnesium levels in all samples were within the WHO-recommended limits, the lower concentrations in some brands may reduce their potential health benefits.

Iron is an essential trace element, but excessive amounts can cause undesirable taste, staining, and potential health risks. The highest iron concentration was found in ROI (0.12 ± 0.01 mg/L), while EVA had the lowest (0.02 ± 0.00 mg/L). These values fall within permissible limits, but the elevated iron levels in ROI suggest possible contamination from underground water sources or iron-containing pipes, as noted by Adams *et al.* (2016) in their study on heavy metals in water sources in Benin City. High iron content in drinking water has been linked to oxidative stress and gastrointestinal issues when consumed in excess. Zinc, another essential trace element, was present in varying concentrations across the samples. ROI had the highest zinc content (0.27 ± 0.05 mg/L), while EVA had the lowest (0.04 ± 0.01 mg/L). Zinc is necessary for immune function and enzyme activity, but excessive levels can impart a

metallic taste to water. Ibeto *et al.* (2023) reported similar variations in bottled water brands in southeastern Nigeria, attributing differences in zinc content to possible leaching from packaging materials or varying purification methods.

Manganese was also detected in all samples, with the highest concentration found in ROI (0.48 ± 0.07 mg/L) and the lowest in EVA (0.25 ± 0.004 mg/L). Manganese, while essential in trace amounts, can cause neurological issues if consumed in excess over a prolonged period. The higher levels in ROI raise concerns about water treatment efficiency, as similar findings were reported by Chinedu *et al.* (2011), where variations in manganese concentrations were linked to inadequate filtration. Copper was another trace metal found in all samples, with the highest concentration in ROI (0.52 ± 0.09 mg/L) and the lowest in AQUAFINA (0.28 ± 0.22 mg/L). While copper is necessary for red blood cell formation and connective tissue health, excessive amounts can lead to gastrointestinal discomfort. Adekunle *et al.* (2020) noted that high copper levels in bottled water could result from corrosion of copper pipes used in water distribution.

Overall, the comparison of essential and trace elements revealed that ROI consistently had the highest concentrations of iron, zinc, manganese, and copper, suggesting possible contamination from natural sources or packaging materials. While most values were within regulatory limits, variations among brands highlight the need for stricter monitoring of bottled water composition to ensure both safety and nutritional benefits.

The identification of potential contaminants and deviations from regulatory standards in bottled water samples is essential for assessing their safety and suitability for consumption. Contaminants such as suspended solids, turbidity, colour, and trace metals can indicate poor filtration, contamination from water sources, or leaching from packaging materials. The

results of this study revealed variations in these parameters across different bottled water brands, with ROI consistently showing higher levels of impurities compared to other samples.

Turbidity, a measure of water clarity, was detected in CWAY (0.67 ± 0.58 NTU), EIO (0.33 ± 0.58 NTU), and ROI (0.33 ± 0.58 NTU), while EVA and AQUAFINA had 0 NTU. The presence of turbidity suggests that these brands contained suspended particles, which could be organic matter, microorganisms, or fine sediments. Agbo *et al.* (2019) reported similar findings in drinking water sources in Calabar Municipality, where elevated turbidity levels were associated with inadequate filtration. High turbidity can affect consumer perception of water quality and may also indicate the presence of harmful pathogens. Suspended solids were present only in ROI (1.33 ± 0.58 mg/L), while all other brands had no detectable levels. The presence of suspended particles in bottled water is unusual and may result from inadequate filtration or post-production contamination. Ezeama and Achonye (2023) found that some bottled and borehole water samples in Anambra State contained suspended solids due to improper handling and poor storage conditions. The presence of these particles can affect water clarity and taste, potentially indicating microbial contamination.

Water colour was detected only in ROI (0.67 ± 0.58 Pt.Co.), while all other brands had 0 Pt.Co. Colour in drinking water can result from dissolved organic compounds, metals, or residual disinfectants. Daffi and Wamyil (2021) found that bottled water exposed to sunlight exhibited changes in colour and other physicochemical properties, likely due to the breakdown of plastic packaging materials or microbial growth. The presence of colour in ROI suggests possible contamination from natural organic matter or leaching of compounds from the bottle material. Iron and manganese, two trace metals commonly associated with contamination, were found in higher concentrations in ROI (0.12 ± 0.01 mg/L for iron and 0.48 ± 0.07 mg/L for manganese). Chinedu *et al.* (2011) highlighted that elevated iron levels

in drinking water could lead to an unpleasant metallic taste, staining of plumbing fixtures, and potential health risks if consumed regularly. Manganese, when present in excess, can cause neurological problems, particularly in infants. The relatively high levels of these metals in ROI suggest contamination from underground water sources or insufficient removal during treatment.

The presence of heavy metals such as zinc (0.27 ± 0.05 mg/L) and copper (0.52 ± 0.09 mg/L) in ROI raises concerns about potential leaching from packaging materials. Ibeto *et al.* (2023) noted that microplastics and heavy metals could leach from plastic bottled water packaging, particularly when exposed to heat. While the values recorded in this study were within acceptable limits, continued exposure to elevated levels of these metals could have long-term health implications. Overall, the findings indicate that ROI exhibited the highest levels of potential contaminants, including suspended solids, turbidity, colour, iron, manganese, zinc, and copper. While most values remained within regulatory limits, the presence of these contaminants suggests possible filtration inefficiencies, contamination during bottling, or chemical interactions with packaging materials. These results align with studies such as Adams *et al.* (2016) and Adekunle *et al.* (2020), which found similar contamination issues in bottled water samples across Nigeria. Continuous monitoring and stricter quality control measures are necessary to ensure that bottled water meets safety standards and remains free from harmful impurities.

5.1 Conclusion

This study assessed the physicochemical properties, essential minerals, and potential contaminants in five bottled water brands. The results revealed significant variations across samples, with ROI consistently exhibiting higher levels of impurities, including turbidity, suspended solids, colour, and elevated concentrations of iron, manganese, zinc, and copper.

While all brands met regulatory limits for pH, conductivity, and TDS, differences in calcium and magnesium levels suggest varying nutritional benefits. The presence of trace metals in some samples highlights potential contamination from natural sources, filtration inefficiencies, or leaching from packaging materials. These findings align with previous studies on bottled water quality in Nigeria, emphasizing the need for stricter regulatory monitoring to ensure consumer safety and maintain high drinking water standards.

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