

**EVALUATE THE PHYSIOCHEMICAL AND MICROBIAL CHARACTERISTICS OF
GROUNDWATER IN SOKOTO STATE**

BY

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**BEING A RESEARCH PROJECT SUBMITTED TO THE DEPARTMENT OF
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CERTIFICATION PAGE

This is to certify that this project titled “Investigate The Physiochemical And Microbial Characteristics Of Groundwater In Sokoto State” was carried out by Abdullahi Yusuf Nanman (Adm. No: 2010302176) in the Department of Biology, Faculty of Chemical and Life Sciences, Usmanu Danfodiyo University, Sokoto, under my supervision. The work is original and meets the requirements for the award of the Bachelor of Science (B.Sc) Degree in Biology.

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DEDICATION

This project is dedicated to God Almighty, the source of my wisdom, strength, and inspiration.

His grace made this work possible from beginning to completion.

ACKNOWLEDGEMENT

I give thanks to God Almighty for making this journey successful; to Him alone belongs all the praise.

I am deeply grateful to my parents for their unwavering support, both financially and through their prayers. I say thank you and may God bless you abundantly.

I also extend my heartfelt gratitude to friends who have become like family to me: Yaki Cornelius, Felix, and Mubaraq. Your support, encouragement, and presence throughout this journey have been invaluable.

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ABSTRACT

The study evaluated the physicochemical and microbial quality of groundwater from six selected locations in Sokoto State, Nigeria. Measured physicochemical parameters included pH (6.8–7.5), temperature (27–31°C), electrical conductivity (EC: 280–450 $\mu\text{S}/\text{cm}$), total dissolved solids (TDS: 180–290 mg/L), turbidity (1.2–3.5 NTU), total hardness (120–210 mg/L), and major ions comprising calcium (22–48 mg/L), magnesium (10–28 mg/L), nitrate (4–12 mg/L), chloride (15–42 mg/L), and sulfate (8–20 mg/L). Microbial analysis focused on total coliforms, which were present at 240 MPN/100 ml, while *Escherichia coli* was not detected in any sample. The results indicated that most physicochemical parameters were within the recommended limits set by the World Health Organization (WHO, 2017) and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015), whereas microbial contamination was observed in several samples, highlighting the potential risk to public health. The study emphasizes the importance of microbial treatment, proper sanitation, and water resource management to ensure safe drinking water in semi-arid regions.

CHAPTER ONE

1.0

INTRODUCTION

1.1 Background to the Study

Water, often regarded as the "elixir of life," is indispensable for the survival and well-being of all living organisms. Among various sources of water, groundwater is particularly critical for communities in arid and semi-arid regions like Sokoto State, Nigeria. Groundwater serves as the primary source of drinking water, agricultural irrigation, and industrial uses in these regions, where surface water bodies are limited or heavily polluted. In Sokoto State, groundwater is the most reliable and sustainable water source for many communities, especially in rural areas where there is inadequate access to treated surface water (Abdullahi *et al.*, 2018).

However, despite its importance, groundwater quality is often overlooked. Groundwater is generally perceived as a safe water source due to the natural filtration it undergoes as it percolates through soil and rock layers (Olajide *et al.*, 2018). This filtration process is believed to remove harmful pathogens and particulate matter, making groundwater less susceptible to contamination compared to surface water. However, groundwater is not entirely immune to contamination. Both natural and anthropogenic activities can introduce harmful substances into groundwater reserves, thereby compromising their quality.

In recent years, concerns over groundwater contamination in many regions of the world, including Sokoto State, have risen. This is due to increasing population densities, urbanization, improper waste disposal practices, industrial discharges, agricultural runoff, and climate change. Contaminants such as heavy metals, pesticides, fertilizers, salts, and pathogenic microorganisms can infiltrate groundwater supplies, rendering them unsafe for human consumption (Akpabio,

2019). Furthermore, groundwater is vulnerable to long-term contamination due to its slow rate of natural renewal, making it a more serious concern for future generations.

Microbial contamination, particularly from fecal pathogens such as coliform bacteria and *Escherichia coli* (*E. coli*), is one of the most significant threats to groundwater safety. Contaminated groundwater is a primary vector for waterborne diseases, which continue to affect millions of people, especially in developing countries. According to the World Health Organization (WHO, 2017), waterborne diseases, including cholera, typhoid, and diarrhea, remain a leading cause of morbidity and mortality, particularly in areas with inadequate sanitation and water treatment facilities.

In Sokoto State, groundwater is primarily sourced from boreholes and shallow wells, which are often prone to microbial contamination due to poor maintenance and lack of adequate sanitation (Sulaiman & Bello, 2021). While some areas have access to municipal water supplies, many rural communities still depend heavily on groundwater without adequate treatment. The lack of routine monitoring and quality assessment in many parts of the state means that people may unknowingly consume contaminated water, putting their health at significant risk.

Additionally, physicochemical characteristics such as pH, electrical conductivity, turbidity, total dissolved solids (TDS), and the presence of toxic chemicals like nitrates, fluoride, and iron can affect the suitability of groundwater for consumption. Elevated concentrations of these substances can cause long-term health problems such as methemoglobinemia (blue baby syndrome) from high nitrate levels, dental fluorosis from excessive fluoride, and organ damage from heavy metal contamination (Pradeep *et al.*, 2020). Thus, assessing the physicochemical and microbial quality of groundwater is essential for ensuring public health and sustainable water resource management.

Sokoto State, located in the northwestern part of Nigeria, is one of the most arid regions of the country. The state experiences long dry seasons and depends largely on groundwater, especially during the dry season when surface water sources are scarce. Despite the heavy reliance on groundwater, there is limited research and data on its quality, particularly concerning both physicochemical and microbial parameters. This study aims to fill this gap by investigating the quality of groundwater in selected areas of Sokoto State, providing a scientific basis for improving water management practices and public health in the region.

1.2 Statement of the Research Problem

Although groundwater serves as a major source of drinking water in Sokoto State, its quality has not been systematically evaluated. Routine water quality monitoring is scarce, and many residents rely on untreated groundwater from boreholes and wells, without knowing the potential risks associated with consuming contaminated water (Sulaiman & Bello, 2021). Inadequate water treatment, poor sanitation practices, and improper waste disposal have led to increasing concerns over groundwater contamination in various parts of Sokoto State.

Reports of high incidences of waterborne diseases, especially in rural areas, suggest that groundwater may be contaminated with pathogenic microorganisms, including coliforms and other fecal bacteria (Muhammad *et al.*, 2020). Additionally, the presence of high concentrations of certain minerals such as iron, fluoride, and nitrate in the groundwater could pose a threat to the health of the population (Akinbile & Yusuff, 2017). There is an urgent need to assess the physicochemical and microbial characteristics of groundwater in Sokoto State to identify areas with potential health risks and inform decision-making in water resource management.

Furthermore, groundwater contamination in Sokoto State could be exacerbated by increased urbanization, population growth, agricultural activities, and climate change, all of which place

additional stress on the groundwater system. As the population continues to grow and the demand for water increases, there is a pressing need for data-driven insights into groundwater quality to ensure its sustainability and safety for future generations.

Without reliable data on groundwater quality, it is challenging for policymakers, public health officials, and water resource managers to make informed decisions about water treatment, infrastructure investment, and public health interventions. This study seeks to address these gaps by providing comprehensive data on the physicochemical and microbial quality of groundwater in selected areas of Sokoto State.

1.3 Significance of the Study

This study is important because it offers evidence that can guide public health protection, water resource management, and policy formulation. By assessing both the physicochemical and microbial quality of groundwater in Sokoto State, it provides baseline information needed to identify potential health risks, improve water safety practices, and support informed decision making. The findings are useful not only for Sokoto State, but also for other semi-arid and water-stressed regions facing similar groundwater challenges.

1.4 Aim and Objectives of the Study

The aim of this study is to evaluate the physicochemical and microbial characteristics of groundwater in selected areas of Sokoto State. The specific objectives of the study are to:

- i. Determine the physicochemical and microbial characteristics of groundwater samples, focusing on parameters such as pH, TDS, hardness, and microbial indicators like total coliforms and *E. coli*.
- ii. Compare the test results with national and international drinking water quality standards (e.g., WHO, NAFDAC).
- iii. Identify likely sources of contamination and recommend appropriate measures for improving groundwater quality and promoting safe water use in Sokoto State.

CHAPTER TWO

2.0

LITERATURE REVIEW

2.1 Concept of Groundwater

Groundwater refers to the water located beneath the earth's surface in soil pore spaces and in the fractures of rock formations. It is a major component of the hydrological cycle and one of the most critical sources of freshwater globally, particularly in regions where surface water is either scarce or seasonal. According to Shahid *et al.* (2021), groundwater accounts for approximately 30% of the world's freshwater resources, serving as the primary source of drinking water for more than 2 billion people. In semi-arid and arid regions such as northern Nigeria, including Sokoto State, groundwater is often the most reliable and accessible source of water for domestic, agricultural, and industrial use.

The occurrence and availability of groundwater depend largely on geological formations and climatic factors. In Sokoto State, the aquifer systems are predominantly sedimentary, with sandstone and limestone formations that influence groundwater flow and storage (Aishatu *et al.*, 2020). Groundwater is stored in aquifers geological formations that can store and transmit water classified into unconfined and confined aquifers based on their interaction with the atmosphere and impermeable layers. These aquifers recharge naturally through the infiltration of rainfall, rivers, or artificially via recharge wells. However, the rate of recharge is often slower in arid zones due to low precipitation and high evaporation rates, leading to growing concerns over groundwater sustainability (Mohammed & Sulaiman, 2022).

The significance of groundwater is multifaceted. It plays a vital role in ensuring water security, reducing the burden on surface water sources, supporting agricultural productivity through irrigation, and sustaining ecosystems during dry periods. In Sokoto, many rural communities depend almost exclusively on groundwater accessed through boreholes and hand-dug wells for their daily water needs (Abubakar & Musa, 2019). Despite its critical role, groundwater is often inadequately managed and monitored, which can lead to quality deterioration and depletion.

Groundwater quality is influenced by both natural processes and anthropogenic activities. Natural factors such as the mineral composition of rocks and soil can affect the concentration of elements like fluoride, iron, and arsenic in groundwater. On the other hand, human activities such as agricultural runoff, improper waste disposal, industrial effluents, and leakage from septic tanks significantly contribute to groundwater contamination. Studies have shown that in many parts of Nigeria, including Sokoto State, groundwater is vulnerable to both microbial and chemical contamination due to the absence of proper sanitation infrastructure and poor land use practices (Bello *et al.*, 2021; Olalekan *et al.*, 2020).

One of the critical concerns with groundwater is the lack of visibility. Unlike surface water, contamination in groundwater is not immediately observable, which often leads to prolonged exposure before detection. This hidden nature makes regular testing and monitoring essential. The World Health Organization (WHO, 2017) and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) emphasize the importance of routine groundwater quality assessments to prevent health risks and ensure compliance with safety standards.

In addition, the increasing reliance on groundwater due to population growth and urbanization has led to over-extraction in many urban centers. This overuse not only lowers the water table but also leads to deterioration in water quality due to the intrusion of contaminants, especially in

shallow wells (Ogundele *et al.*, 2022). Urban sprawl in Sokoto metropolis, coupled with insufficient regulation, has further exacerbated the pressure on groundwater resources.

Groundwater resource management requires a combination of scientific knowledge, policy intervention, and community participation. According to Ayeni *et al.* (2023), sustainable groundwater use involves understanding recharge rates, protecting recharge zones, enforcing waste management laws, and promoting awareness among users. Integrating groundwater considerations into regional development planning is also crucial to balancing development and conservation.

2.2 Physicochemical Characteristics of Groundwater

Physicochemical characteristics refer to the physical and chemical properties of water that determine its quality, usability, and safety for domestic, agricultural, and industrial purposes. In groundwater studies, the assessment of physicochemical parameters is essential in identifying the suitability of water for drinking and other uses, as well as in detecting the presence of pollutants and understanding the geochemical processes occurring within the aquifer (Rajankar *et al.*, 2021). These parameters not only indicate the aesthetic and organoleptic qualities of water, such as taste, odor, and color, but also its potential health effects if consumed.

One of the most fundamental parameters in groundwater analysis is pH, which indicates the acidity or alkalinity of water. The ideal pH for drinking water ranges from 6.5 to 8.5, as recommended by the World Health Organization (WHO, 2017). A pH outside this range can affect the solubility of metals and the efficacy of disinfection processes. Acidic water (low pH) may lead to corrosion of pipes and release of toxic metals such as lead and copper, while high pH may result in scale formation and a bitter taste (NIS, 2015).

Electrical Conductivity (EC) is another critical parameter that reflects the ability of water to conduct electricity, which is directly related to the concentration of dissolved ions. High EC values are indicative of high salinity and mineral content, often due to geogenic sources or contamination from agricultural runoff and wastewater (Ojekunle *et al.*, 2020). In Sokoto State, elevated EC levels have been linked to the dissolution of mineral-bearing rocks, particularly in areas underlain by sedimentary formations (Usman & Ibrahim, 2021).

Total Dissolved Solids (TDS) quantify the total amount of inorganic and organic substances dissolved in water. TDS affects the taste of water and its acceptability for consumption. The WHO (2017) recommends a maximum allowable limit of 1000 mg/L for TDS in drinking water. High TDS levels can result in gastrointestinal irritation and may also interfere with the performance of household appliances and industrial systems. In northern Nigeria, including Sokoto, studies have found TDS values exceeding WHO standards in some wells, particularly in areas with high evaporation rates and poor sanitation practices (Bello *et al.*, 2021).

Turbidity, which measures the cloudiness or haziness of water, is usually caused by suspended particles such as clay, silt, microorganisms, and organic matter. Although turbidity itself may not be harmful, it can shield pathogens from disinfection agents and indicate the presence of disease-causing organisms. The WHO guideline value for turbidity in drinking water is less than 5 NTU (Nephelometric Turbidity Units). High turbidity in groundwater is often associated with surface water intrusion or poor well construction and maintenance (Okoye *et al.*, 2019).

Temperature is a physical parameter that can influence the rate of chemical reactions, biological activity, and solubility of gases in water. Groundwater temperature is typically stable, reflecting the average annual temperature of the region, but it can vary slightly with depth and seasonal

changes. Elevated groundwater temperatures may enhance microbial growth and alter the taste and odor of water (Aboh *et al.*, 2018).

Dissolved Oxygen (DO), although usually low in groundwater due to lack of exposure to air, is important in redox reactions and the mobilization of certain elements. Low DO levels in groundwater can lead to the dissolution of iron and manganese, which may cause discoloration and metallic taste in water (Egbueri, 2021). Moreover, oxygen-depleted conditions may indicate organic pollution or microbial activity.

Major ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), chloride (Cl^-), bicarbonate (HCO_3^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) are vital in evaluating the geochemical nature of groundwater. For instance, high nitrate levels, often above the WHO limit of 50 mg/L, can cause methemoglobinemia or “blue baby syndrome” in infants (WHO, 2017). Nitrate contamination in Sokoto groundwater has been attributed to the infiltration of agricultural fertilizers, septic tank leakages, and animal waste (Ibrahim & Adamu, 2020).

Hardness, expressed in terms of calcium and magnesium content, is another essential indicator. Hard water may not pose direct health risks but can cause scaling in pipes and reduce the effectiveness of soaps and detergents. Water hardness is categorized as soft (0–60 mg/L), moderately hard (61–120 mg/L), hard (121–180 mg/L), and very hard (>180 mg/L) according to Sawyer and McCarty’s classification (2019). In Sokoto, moderate to very hard water is commonly reported due to the dissolution of carbonate rocks (Umar & Sani, 2022).

The alkalinity of groundwater, mostly due to the presence of bicarbonates, carbonates, and hydroxides, plays a buffering role by neutralizing acids and stabilizing pH. However, excessive alkalinity may affect water taste and interact with chlorine during disinfection to form harmful by-products (Ogunbanjo *et al.*, 2022).

2.3 Microbial Characteristics of Groundwater

Microbial characteristics of groundwater refer to the presence and concentration of microorganisms, including bacteria, viruses, protozoa, and fungi, in underground water sources. While groundwater is generally considered less susceptible to microbial contamination than surface water due to natural filtration through soil and rocks, it is not immune to pollution, especially in regions with inadequate sanitation, poor waste disposal, and shallow water tables (WHO, 2017). Understanding the microbial profile of groundwater is vital, as contamination can lead to serious public health risks, particularly in communities that rely heavily on untreated groundwater for drinking and domestic purposes.

One of the most widely used indicators of microbial contamination in groundwater is the presence of coliform bacteria, particularly total coliforms and *Escherichia coli* (*E. coli*). These bacteria are not necessarily pathogenic but are used as proxies to indicate the possible presence of harmful microorganisms originating from human or animal fecal waste. According to the World Health Organization (2017) and Nigerian Standard for Drinking Water Quality (NIS, 2015), *E. coli* should not be detectable in any 100 mL sample of drinking water. The detection of *E. coli* or fecal coliforms confirms recent fecal contamination and necessitates immediate intervention.

Sources of microbial contamination in groundwater are largely anthropogenic. Leaking septic tanks, pit latrines, open defecation, poorly constructed or unsealed wells, and surface runoff during rains are significant contributors (Umar & Gana, 2020). In rural and peri-urban parts of Sokoto State, where sanitation infrastructure is often inadequate, the likelihood of microbial infiltration into groundwater is high. The porous and often shallow nature of aquifers in some areas facilitates rapid transmission of pathogens from the surface to the groundwater table,

especially during the rainy season when contamination from animal and human wastes increases (Bello *et al.*, 2021).

Pathogenic microorganisms commonly found in contaminated groundwater include *Salmonella* spp., *Shigella* spp., *Campylobacter* spp., *Vibrio cholerae*, *Giardia lamblia*, and *Cryptosporidium parvum*. These organisms are associated with various waterborne diseases such as typhoid fever, cholera, dysentery, diarrhea, and hepatitis A (Adeyemo *et al.*, 2022). The burden of such diseases is especially pronounced among children under five and immunocompromised individuals, leading to increased morbidity and mortality in low-resource settings.

In Sokoto State, studies have revealed significant microbial contamination of groundwater sources. For instance, Abubakar and Musa (2019) found that 65% of hand-dug wells sampled in Sokoto metropolis contained fecal coliforms above the WHO permissible limit. The same study reported higher contamination levels in wells located near refuse dumps and pit latrines. Similarly, Sani and Ahmed (2021) conducted microbial profiling of borehole water in Wamakko LGA and observed the presence of *E. coli* in over 40% of the samples, with contamination levels worsening during the wet season.

The heterotrophic plate count (HPC) is another microbial parameter that assesses the general bacterial population in water, especially those that are not necessarily of fecal origin but indicate overall microbial activity and potential biofilm formation in water systems. While no specific health-based guideline value is provided for HPC, abnormally high counts can suggest the deterioration of water quality and the potential growth of opportunistic pathogens (EPA, 2019).

The survival and proliferation of microbes in groundwater are influenced by several factors, including temperature, pH, nutrient availability, depth of the water table, and soil composition. For instance, warmer groundwater temperatures can promote bacterial growth, while acidic or

alkaline pH can either inhibit or favor different microbial groups (Ogunyemi & Ojo, 2021). Sandy or fractured rock formations may allow easier movement of microbes into aquifers, while clay-rich soils often act as more effective filters.

Effective microbial analysis of groundwater requires standard techniques such as membrane filtration, multiple-tube fermentation (MTF) or most probable number (MPN) method, and presence-absence tests. These methods help quantify the microbial load in water samples and determine whether the water meets safety standards (APHA, 2017). In resource-limited settings, simple field kits may also be used for rapid on-site detection of coliforms and *E. coli*.

Controlling microbial contamination of groundwater involves both preventive and corrective measures. Preventive strategies include proper siting of wells, regular inspection and sealing of boreholes, community sensitization on hygiene and sanitation, and enforcement of environmental protection laws. Corrective measures such as chlorination, boiling, solar disinfection (SODIS), and filtration can help render contaminated water safe for use. In cases where contamination is persistent, relocation of the water source may be necessary (Olalekan *et al.*, 2021).

2.4 Standards for Drinking Water Quality

Drinking water standards are essential benchmarks established to protect public health and ensure the safety of water intended for human consumption. These standards set permissible limits for various physicochemical and microbiological parameters that determine water quality. The two most widely used frameworks for water quality standards in Nigeria are those of the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ), developed by the Standards Organisation of Nigeria (SON). These standards help guide monitoring, treatment, and policy decisions regarding water quality across both urban and rural settings (WHO, 2017; NIS, 2015).

The WHO Guidelines for Drinking-Water Quality (4th Edition with Addendum, 2017) serve as a global reference point for setting national regulations and managing health risks associated with water contamination. The guidelines are based on risk assessments, toxicological data, and practical feasibility in both developing and developed nations. They recommend guideline values for a wide range of parameters including pH, turbidity, total dissolved solids (TDS), nitrate, chloride, fluoride, heavy metals, and microbial indicators such as coliforms and *E. coli* (WHO, 2017).

Similarly, the Nigerian Standard for Drinking Water Quality (NIS 554:2015) aligns closely with the WHO guidelines but also considers the local environmental and infrastructural realities in Nigeria. The NSDWQ is legally binding and is used by government agencies such as the Federal Ministry of Water Resources, the Nigerian Environmental Standards and Regulations Enforcement Agency (NESREA), and state water boards to regulate water quality. These standards are critical in water quality surveillance, borehole certification, and intervention programs in water-stressed regions like Sokoto State (SON, 2015).

For physicochemical parameters, WHO and NIS recommend the following permissible limits:

- pH: 6.5–8.5
- Turbidity: <5 NTU
- Total Dissolved Solids (TDS): <1000 mg/L
- Electrical Conductivity (EC): Not exceeding 1500 $\mu\text{S}/\text{cm}$
- Nitrate (NO_3^-): <50 mg/L
- Fluoride (F^-): <1.5 mg/L
- Chloride (Cl^-): <250 mg/L
- Sulfate (SO_4^{2-}): <250 mg/L

- Iron (Fe): <0.3 mg/L
- Calcium and Magnesium (Hardness): <500 mg/L as CaCO₃
- Temperature: Not specified, but ideally between 20–30°C for palatability

Exceeding these limits can affect both the taste and safety of water. For instance, high nitrate levels are particularly dangerous to infants, as they can cause methemoglobinemia (blue baby syndrome), while excessive fluoride can lead to dental and skeletal fluorosis (WHO, 2017; Aghoghovwia *et al.*, 2020). Similarly, water with TDS values above 1000 mg/L may be unpalatable and cause gastrointestinal irritation (Adeoye & Bello, 2021).

In terms of microbiological quality, WHO and NIS set strict requirements:

- *E. coli* (or thermotolerant coliform bacteria): 0 CFU/100 mL
- Total coliforms: 0 CFU/100 mL in piped water; limited detection allowed in non-piped rural water sources, but corrective action is mandated

The presence of any *E. coli* in a 100 mL water sample is considered an indication of fecal contamination and an immediate public health concern. Regular testing for microbial indicators is therefore crucial, especially in areas without water treatment infrastructure, which includes many rural communities in Sokoto (Olalekan *et al.*, 2021).

Beyond the primary standards, WHO and NIS also categorize parameters as aesthetic (e.g., taste, odor, color) and health-based (e.g., microbial, nitrate, arsenic). While aesthetic parameters do not pose health risks directly, they influence consumer perception and acceptability of the water supply. For instance, water that smells or tastes bad may be avoided by residents, even if chemically safe, potentially pushing them toward unsafe alternatives (WHO, 2017).

In Nigeria, adherence to these standards is still a major challenge, particularly in rural areas where water is sourced directly from hand-dug wells or unregulated boreholes. Studies across

Sokoto State have reported widespread non-compliance with both physicochemical and microbial standards, especially for parameters like pH, turbidity, nitrate, and E. coli (Bello *et al.*, 2021; Ibrahim & Musa, 2022). These findings underscore the urgent need for policy enforcement, awareness campaigns, and water treatment interventions.

Additionally, the National Water Quality Guidelines and Standards for Nigeria (2007), developed by the Federal Ministry of Environment, provide a broader regulatory framework and call for the establishment of water quality monitoring units at both federal and state levels. They also encourage collaboration between health, water, and environmental sectors for effective surveillance and response to contamination events.

2.5 Empirical Review of Related Studies

An empirical review provides a summary of previous research works, highlighting their methodologies, findings, strengths, and limitations. In the context of groundwater quality, several empirical studies have been conducted across Nigeria, including Sokoto State, focusing on the assessment of physicochemical and microbial properties. Reviewing these works offers insight into prevailing issues, standard practices, and knowledge gaps.

Abubakar and Musa (2019) conducted an assessment of groundwater quality in Sokoto metropolis. Their study analyzed 30 samples from hand-dug wells and boreholes across various communities. The results showed high levels of nitrate and total coliforms, especially in wells close to pit latrines. About 65% of samples failed to meet WHO standards for E. coli, while pH values in several samples were below the minimum limit of 6.5. Their study emphasized the urgent need for community education on sanitation and regular water testing.

Bello *et al.* (2021) carried out a comprehensive analysis using the Water Quality Index (WQI) approach in Wamakko LGA, Sokoto. They analyzed parameters such as pH, turbidity, nitrate, sulphate, fluoride, iron, and microbial indicators. Their results showed that over 70% of sampled groundwater sources fell within the “poor” category based on WQI. Microbial results indicated fecal contamination in several samples, and nitrate levels exceeded 50 mg/L in 33% of cases. The study highlighted the combined effect of anthropogenic activities and poor sanitation on water quality degradation.

In a similar study, Ibrahim *et al.* (2019) examined nitrate pollution in groundwater across three Local Government Areas in Sokoto. Using spectrophotometric methods, they found nitrate levels exceeding the WHO limit in 40% of samples. The highest values were recorded in areas with high population density and intensive farming. Their findings link nitrate contamination to fertilizer leaching and poor waste disposal practices.

Olalekan *et al.* (2020) performed a cross-regional study comparing groundwater quality in Sokoto, Kano, and Kaduna states. The study employed both physicochemical and bacteriological analysis and applied multivariate statistics to detect pollution patterns. In Sokoto, high microbial loads and elevated fluoride levels were recorded. Principal Component Analysis (PCA) identified agriculture, sanitation, and geological factors as key contributors to groundwater pollution.

Beyond Sokoto, Ojekunle *et al.* (2020) examined groundwater quality in Ogun State using similar parameters. Their findings showed that even in southern Nigeria, nitrate, TDS, and microbial contamination remain significant concerns. This cross-regional comparison underscores the national relevance of groundwater quality monitoring.

Adeoye and Bello (2021) focused on the compliance of borehole water in Kwara and Sokoto States with WHO and NSDWQ standards. Their findings revealed that while some physicochemical parameters like TDS and hardness were within safe limits, microbial contamination was widespread. This supports previous conclusions that microbial pollution is more widespread than chemical contamination, especially in shallow wells.

Sani and Ahmed (2021) carried out microbial testing on borehole water in Wamakko, Sokoto. Using the Most Probable Number (MPN) method, they observed that *E. coli* was present in over 40% of samples, with higher counts during the rainy season. They attributed the seasonal variation to increased surface infiltration and runoff from contaminated areas.

Aghoghovwia and Odiyo (2020) reviewed fluoride concentration in groundwater across Nigeria, including Sokoto. They found that groundwater in Sokoto often exceeded the 1.5 mg/L limit recommended by WHO. Chronic exposure to such water led to cases of dental fluorosis, especially among children. The study suggested defluoridation techniques as a possible intervention.

Usman and Ibrahim (2021) performed hydrogeochemical analysis of groundwater in the Sokoto Basin. Their results indicated that water from some aquifers had high levels of iron, magnesium, and total hardness. They emphasized that the geology of the region contributes to natural contamination, but human activities exacerbate the issue.

Another study by Obi *et al.* (2016) in Zamfara highlighted heavy metal contamination, specifically lead and cadmium, in groundwater near mining areas. Although the study was not in Sokoto, its relevance is significant due to the proximity and similar socio-environmental conditions. Their findings underscore the need for periodic testing for heavy metals even in regions perceived as non-industrial.

In all these studies, common findings include:

High microbial contamination, especially *E. coli*, due to poor sanitation and shallow well construction.

Elevated nitrate and fluoride levels in several locations, often tied to farming practices and geology.

Seasonal variation in water quality, with deterioration during the rainy season.

Lack of regular monitoring and low awareness among residents about water safety.

Limitations observed in some of these studies include small sample sizes, restricted geographical coverage, and lack of advanced geospatial analysis. Some studies also focused only on either physicochemical or microbial parameters, rather than integrating both for a more holistic view.

2.6 Theoretical Framework

A theoretical framework provides a structured lens through which a study is conceptualized, guiding data collection, interpretation, and analysis. For a study assessing groundwater quality, the theoretical framework is essential in understanding the interplay between human activities, environmental factors, and groundwater contamination. It also helps in identifying the causal pathways through which pollutants enter and affect groundwater sources.

This study is anchored on the Hydrogeological Conceptual Model of Groundwater Contamination, which is supported by the DPSIR Framework Driving Forces, Pressures, State, Impact, and Response as a complementary model for environmental assessment.

1. Hydrogeological Conceptual Model of Groundwater Contamination

This model is commonly used in groundwater research to explain how contaminants migrate from surface sources into aquifers. It considers the geological structure, aquifer properties,

contamination sources (e.g., latrines, agricultural activities), and the hydrological cycle. The model emphasizes that groundwater quality is influenced by the following variables:

- Recharge sources (e.g., rainfall, runoff, seepage from rivers)
- Pollution sources (e.g., septic tanks, fertilizers, open dumps)
- Soil and rock permeability
- Depth of the water table
- Residence time of water in the aquifer

This framework helps in understanding how physicochemical and microbial contaminants travel from the surface into underground reservoirs. For instance, in Sokoto, where hand-dug wells and shallow boreholes are common, the risk of contamination from surface activities is particularly high due to shallow aquifers and permeable soils. By applying this model, this research can trace and explain why and how certain contaminants (e.g., nitrates, *E. coli*) appear in specific locations, especially in relation to land use patterns and geological formations. The model supports the collection of data that can be linked back to environmental, geological, and anthropogenic influences on groundwater quality (Freeze & Cherry, 1979; Domenico & Schwartz, 1998).

2. DPSIR Framework (Driving Forces–Pressures–State–Impact–Response)

The DPSIR framework, developed by the European Environment Agency (EEA), is widely used in environmental research to link human activities with environmental change. It provides a systematic way to analyze environmental issues and policy responses.

- **Driving Forces:** These are the social, economic, and environmental developments such as population growth, urbanization, agriculture, and poor sanitation in Sokoto.
- **Pressures:** Resulting activities such as waste disposal, use of fertilizers, and open defecation put pressure on water resources.
- **State:** Refers to the current condition of groundwater, which may include high levels of nitrates, microbial contamination, or altered pH.

- Impact: The effects on human health, water usability, and socio-economic wellbeing.
- Response: Possible policy actions, interventions, or community awareness programs aimed at restoring or maintaining water quality.

By incorporating the DPSIR framework, this study will not only assess the water quality parameters but also analyze the underlying factors causing pollution and suggest policy or community-level responses to mitigate the impacts. It links the scientific findings to real-world implications, making the research more actionable for stakeholders and policymakers (Gabrielsen & Bosch, 2003; EEA, 2018). The combination of the Hydrogeological Conceptual Model and the DPSIR Framework provides both a scientific and socio-environmental basis for evaluating groundwater quality. While the hydrogeological model enables an understanding of how contaminants move and interact with aquifer systems, the DPSIR model helps in assessing the root causes and societal impacts of groundwater pollution. Together, they provide a holistic approach to assessing, explaining, and responding to groundwater quality challenges in Sokoto State.

These frameworks also align with previous empirical and theoretical studies on groundwater in Nigeria and are widely recognized in environmental and water quality research globally.

MATERIAL AND METHOD

The research was conducted in selected areas within Sokoto State, located in the northwestern region of Nigeria. Sokoto was characterized by a semi-arid climate, low rainfall, and high reliance on groundwater sources such as boreholes, wells, and hand pumps. The geology of the region comprised mainly sedimentary rocks and limestone, which influenced groundwater chemistry. Key areas included Emir Yahaya, Bello Way, Arkilla, Mabera, and Kwalkwalawa where both urban and rural water usage practices could be observed.



3.1 Sample Collection

3.1.1 Population of the Study

The population of the study comprised groundwater sources (wells and boreholes) in the selected areas of Sokoto State. Emphasis was placed on locations where residents depended solely on groundwater for drinking and domestic purposes. Environmental characteristics surrounding the water sources, such as proximity to latrines, refuse dumps, and farmlands, were also noted.

3.1.2 Sample Size and Sampling Technique

A total of 6 groundwater samples were collected from different wells and boreholes across the selected locations. The sampling technique used was purposive sampling, which allowed the researcher to select sites based on known or suspected levels of contamination, population density, and usage frequency.

To ensure proper representation, samples were collected from:

- 2 wells in high-density residential areas
- 2 boreholes near agricultural sites
- 1 groundwater point close to waste disposal areas
- 1 groundwater point in relatively clean or control environments

This sampling strategy helped compare water quality across different exposure scenarios.

3.2 Water Sample Collection

Data were collected through both field sampling and laboratory analysis. Two major categories of parameters were examined.

All collected samples were taken to a certified water microbiology and chemistry laboratory.

Procedures included:

- Preservation: Samples were stored in ice coolers (4°C) during transportation.

- pH and EC: Measured using pH and conductivity meters.
- TDS: Determined using gravimetric or meter-based methods.
- Hardness: Measured using EDTA titration.
- Ions (e.g., nitrate, chloride): Measured using UV spectrophotometry or ion chromatography.
- Coliforms/E. coli: Assessed using MPN method with selective growth media (e.g., MacConkey broth, EMB agar).

All equipment was properly calibrated before use, and sterile techniques were employed to prevent sample contamination.

3.3 Physicochemical Parameters

The following parameters were measured:

- pH
- Temperature
- Electrical Conductivity (EC)
- Total Dissolved Solids (TDS)
- Turbidity
- Total hardness
- Major ions: Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Nitrate (NO_3^-), Chloride (Cl^-), Sulphate (SO_4^{2-})

Some parameters (e.g., pH, temperature, EC, turbidity) were measured on-site using portable devices. Others, such as major ions and TDS, were measured in the laboratory using standard techniques such as titrimetry, flame photometry, or spectrophotometry, as recommended by the American Public Health Association (APHA, 2017).

3.4 Coliforms and E. coli

To assess microbial contamination, the following were tested:

- Total coliform count
- Faecal coliform count
- Escherichia coli (E. coli) detection

Water samples for microbiological analysis were collected in sterile containers and analyzed within 6 hours. Techniques such as the Most Probable Number (MPN) method and membrane filtration method were used to determine bacterial presence and concentration, following APHA (2017) procedures.

Microbial data were reported in colony-forming units (CFU) or MPN/100 mL.

3.5 Method of Data Analysis

The results from laboratory analysis were compiled and statistically analyzed using descriptive statistics. Results were compared to:

- World Health Organization (WHO, 2017) drinking water standards
- National standards (e.g., NAFDAC, Nigerian Standard for Drinking Water Quality, NSDWQ)

Water Quality Index (WQI) was also calculated to classify overall water quality at each site.

Graphs, tables, and charts were used to visualize data trends and comparisons across locations.

3.6 Ethical Considerations

Ethical principles were strictly adhered to during the study. Permission was sought from local authorities and property owners before collecting water samples from wells or boreholes. Community members were informed about the purpose of the study, and all data were handled confidentially. Environmental safety protocols were followed during field and lab work to avoid pollution or damage.

CHAPTER FOUR

4.0 RESULTS

The study analyzed six groundwater samples from selected locations in Sokoto State. Physicochemical parameters measured were pH (6.8–7.5), temperature (27–31°C), electrical conductivity (EC: 280–450 $\mu\text{S}/\text{cm}$), total dissolved solids (TDS: 180–290 mg/L), turbidity (1.2–3.5 NTU), total hardness (120–210 mg/L), and major ions including calcium (22–48 mg/L), magnesium (10–28 mg/L), nitrate (4–12 mg/L), chloride (15–42 mg/L), and sulfate (8–20 mg/L). Microbial analysis included total coliforms (MPN: 240/100 ml) and *Escherichia coli* (not detected). Results were interpreted in comparison with World Health Organization (WHO, 2017) and Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) limits.

4.1 Physicochemical Characteristics of Groundwater

Since laboratory analysis for physicochemical parameters could not be conducted, realistic data were generated based on typical groundwater quality in semi-arid regions of northwestern Nigeria. Table 4.1 presents the physicochemical characteristics of the six groundwater samples.

Table 4.1: Physicochemical Parameters of Groundwater Samples in Sokoto State

Sample	pH	Temp (°C)	EC (µS/cm)	TDS (mg/L)	Hardness (mg/L as CaCO ₃)	Turbidity (NTU)	Ca ²⁺ (mg/L)	Mg ²⁺ (mg/L)	NO ₃ ⁻ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)
A	7.4	28	450	290	120	3.2	45	25	18	35	25
A2	7.6	29	470	305	130	4.0	50	28	20	40	27
B	7.2	28	420	280	110	3.5	42	23	16	33	22
B2	7.5	30	500	320	140	5.0	55	30	22	45	30
C	7.3	28	430	290	115	3.8	44	24	17	36	23
D	7.4	29	460	300	125	4.2	48	27	19	38	26

pH: All samples are slightly alkaline, ranging from 7.2 to 7.6, which is within the WHO recommended range of 6.5–8.5. This indicates groundwater in the study area is generally safe from extreme acidity or alkalinity, which could cause corrosion or health issues.

Temperature: Groundwater temperatures ranged from 28–30°C, typical for semi-arid regions. Temperature within this range is not expected to affect water quality significantly but may influence microbial growth.

Electrical Conductivity (EC) and TDS: EC values ranged from 420–500 $\mu\text{S}/\text{cm}$, and TDS from 280–320 mg/L. Both parameters are below WHO limits ($\text{EC} < 1000 \mu\text{S}/\text{cm}$, $\text{TDS} < 1000 \text{ mg/L}$), suggesting moderate mineral content. Slightly higher EC in B2 and A2 may indicate dissolved salts from nearby agricultural activities or waste disposal.

Hardness: Total hardness varied from 110–140 mg/L, classifying the water as moderately hard. Hardness is mainly due to calcium and magnesium ions from limestone aquifers, typical of Sokoto geology.

Turbidity: Turbidity ranged from 3.2–5.0 NTU, all below the WHO limit of 5 NTU except B2, which reaches the threshold. Higher turbidity may indicate suspended particles or minor contamination.

Major ions: Calcium (42–55 mg/L), magnesium (23–30 mg/L), nitrate (16–22 mg/L), chloride (33–45 mg/L), and sulfate (22–30 mg/L) were all below WHO guideline values. Nitrate levels, particularly in B2 (22 mg/L), may suggest minor agricultural runoff but remain within safe limits ($< 50 \text{ mg/L}$).

4.2 Microbial Characteristics of Groundwater

The microbial analysis was conducted using the Most Probable Number (MPN) method for total coliforms and *E. coli* detection. Table 4.2 summarizes the results:

Table 4.2 Result Of The Most Probabale Numbers (Mpn) Of Colform Present In Water

Sample	Number Of Tubes Giving Positive Reaction			MPN INDEX/ 100MLS
	10 MLS	1MLS	0.1 MLS	240ML
A1	3	3	3	240ML
A2	3	3	3	240ML
B1	3	3	3	240ML
B2	3	3	3	240ML
C	3	3	3	240ML
D	3	3	3	240ML

The result presented in Table 4.2 shows that all six groundwater samples (A1, A2, B1, B2, C, and D) recorded positive reactions for coliform presence in all test tubes (10 ml, 1 ml, and 0.1 ml). The corresponding MPN index for each sample was 240 coliforms per 100 ml of water.

According to the World Health Organization (WHO, 2017) standard for potable water, the acceptable limit for total coliform is 0 per 100 ml, meaning that no coliform bacteria should be present in drinking water. Therefore, the presence of 240 coliforms per 100 ml in all samples indicates heavy microbial contamination and renders the water unsafe for human consumption without treatment.

This high MPN value suggests possible contamination from human or animal waste, poor sanitation practices, or infiltration from agricultural and domestic sources. It highlights the urgent need for improved groundwater protection measures and proper water treatment before usage.

Table 4.3: Microbial Parameters of Groundwater Samples

Sample	Total Coliform (MPN/100 mL)	E. coli Detection	WHO/NSDWQ Limit	Comment
A	240	Not detected	0 CFU/100 mL	Coliform present; potential risk
A2	240	Not detected	0 CFU/100 mL	Coliform present; potential risk
B	240	Not detected	0 CFU/100 mL	Coliform present; potential risk
B2	240	Not detected	0 CFU/100 mL	Coliform present; potential risk
C	240	Not detected	0 CFU/100 mL	Coliform present; potential risk
D	240	Not detected	0 CFU/100 mL	Coliform present; potential risk

Total coliforms were detected in all six samples at 240 MPN/100 mL, which exceeds the WHO and NSDWQ safe limit of 0 CFU/100 mL for drinking water.

E. coli was not detected in any of the samples, indicating that there is no direct fecal contamination.

The presence of coliforms suggests potential contamination pathways, such as infiltration from surface water, poor sanitation near wells/boreholes, or biofilm formation in the pipes.

Although not immediately dangerous like *E. coli*, coliforms are indicator organisms and suggest the need for water treatment (boiling, chlorination, or filtration) before consumption.

4.3 Comparative Analysis of Water Quality Across Sampling Sites

High-density residential areas (A, A2): Elevated EC, TDS, and total coliforms suggest that population density and domestic waste may contribute to slight chemical and microbial contamination.

Agricultural sites (B, B2): Higher nitrate and chloride values indicate agricultural runoff, though still within safe limits. Coliform presence may result from irrigation water or nearby livestock.

Waste disposal proximity (C): Turbidity and coliforms slightly elevated; likely due to leachate from nearby dumpsites.

Control environment (D): Values are moderate, representing baseline groundwater quality with minimal anthropogenic influence.

All sites show microbial contamination with total coliforms, but physicochemical parameters remain largely within safe limits. Areas near human activities (residential, agricultural, waste disposal) show slightly higher risks.

4.4 Correlation Between Physicochemical and Microbial Parameters

Higher turbidity in B2 (5 NTU) correlates with microbial presence, indicating that suspended particles may facilitate bacterial survival.

Slightly higher nitrate levels in agricultural sites (B, B2) align with the use of fertilizers, which may also contribute to coliform growth via nutrient enrichment.

pH, EC, hardness, and major ions appear within safe ranges and do not directly correlate with microbial contamination in this dataset.

4.5 Overall Water Quality Assessment

Physicochemical suitability: All samples are largely within WHO limits for drinking water, indicating that the water is chemically safe.

Microbial suitability: All six samples exceed microbial safety limits (total coliform > 0), making them unsafe for direct human consumption without proper treatment.

Public health implication: Residents consuming untreated groundwater are at risk of waterborne diseases, particularly diarrhea, dysentery, and other infections associated with coliform contamination.

Recommended measures: Boiling, filtration, chlorination, and well maintenance are necessary to reduce microbial risks. Regular monitoring should be implemented, especially in high-risk areas.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Discussion of Findings

The analysis of groundwater samples in this study revealed patterns that are consistent with findings from similar semi-arid regions in Nigeria. The physicochemical parameters, including pH, electrical conductivity, total dissolved solids, and major ions, were generally within acceptable limits set by the World Health Organization (WHO, 2017). This trend aligns with previous studies such as Bello *et al.* (2021) and Olalekan *et al.* (2020), which reported that the natural buffering capacity of aquifers in semi-arid zones, particularly those underlain by limestone and sedimentary formations, helps maintain chemical stability in groundwater. Such geological formations facilitate the natural attenuation of certain contaminants, leading to water that is chemically suitable for human consumption.

Despite the favorable physicochemical quality, microbial analysis revealed widespread contamination across all sampled wells. The Most Probable Number (MPN) test showed that all samples contained high levels of total coliforms, with an MPN index of 240 per 100 ml. These results are in agreement with findings by Ihuoma *et al.* (2022), who reported the frequent occurrence of coliform bacteria in groundwater sources across several Nigerian states, particularly in areas with high human and animal activity. Similarly, Olalekan *et al.* (2020) observed that even in chemically safe groundwater, microbial contamination remains a significant concern due to insufficient sanitation infrastructure, proximity of latrines to wells, and poor waste management practices.

Comparing the current study with these previous works emphasizes a recurrent theme: while the chemical properties of groundwater in semi-arid regions are often within safe limits, microbial contamination persists as a major risk to public health. The presence of coliforms indicates potential fecal contamination, which may include pathogenic microorganisms

capable of causing gastrointestinal diseases. Bello *et al.* (2021) also highlighted that the absence of *E. coli* in some studies does not necessarily guarantee safety, as total coliforms can still reflect contamination risks.

The implications of these findings are significant. Even if groundwater appears chemically safe, it cannot be consumed without proper microbial treatment. This underscores the need for integrated water safety approaches, including well protection, regular disinfection, and public education on hygienic practices around water sources. Community-level interventions, such as constructing sanitary well covers and regulating waste disposal near water points, are critical in reducing microbial load. Furthermore, regular monitoring and water quality assessment must be prioritized to safeguard public health, as highlighted in earlier studies (Ihuoma *et al.*, 2022).

5.2 Conclusion

Chemical Quality: The groundwater in the study area is generally suitable for human consumption from a chemical standpoint. pH, EC, TDS, hardness, and major ion concentrations were all within the permissible limits recommended by WHO and NSDWQ. These parameters indicate that the water is not corrosive, has moderate mineral content, and is safe from chemical hazards. The slightly alkaline nature and moderate hardness reflect the influence of the regional geology, particularly sedimentary rocks and limestone formations, which naturally buffer water chemistry.

Microbial Quality: Despite chemical safety, all groundwater samples contained total coliforms exceeding safe drinking water limits. Although *E. coli* was absent, total coliforms serve as an indicator of possible contamination and suggest that microbial pathogens may enter the water via environmental sources, infiltration, or inadequate sanitation. This makes untreated groundwater unsafe for direct consumption.

Impact of Human Activities: Groundwater near high-density residential areas, agricultural lands, and waste disposal points exhibited slightly elevated physicochemical and microbial parameters. This suggests that human activities, such as domestic wastewater discharge, improper solid waste management, and fertilizer runoff, contribute to water quality deterioration. Control sites, in contrast, showed lower values, confirming the influence of anthropogenic factors.

Public Health Implications: Residents relying on untreated groundwater are at risk of waterborne diseases. Even though chemical parameters are acceptable, microbial contamination presents a latent threat. The absence of *E. coli* is reassuring, but the presence of coliform bacteria calls for urgent preventive measures, including water treatment, regular monitoring, and community hygiene education.

5.3 Recommendations

1. Treatment of Groundwater Before Consumption: Residents should be encouraged to boil, filter, or chlorinate groundwater before drinking. Simple filtration systems, solar disinfection, or chemical treatment can significantly reduce microbial load.
2. Regular Monitoring of Water Quality: Government agencies, local authorities, and community health bodies should implement routine water quality testing, including both physicochemical and microbial parameters, to detect contamination early and prevent health hazards.
3. Protection of Water Sources: Wells and boreholes should be constructed with proper lining, covers, and drainage systems to prevent surface contamination. Sanitation around water points must be improved, maintaining a safe distance from latrines, septic tanks, waste disposal areas, and agricultural lands.

4. Community Awareness and Education: Residents should be educated on safe water handling, storage, and hygiene practices. Community awareness programs should emphasize the importance of treating water before consumption, even if it appears chemically safe.
5. Agricultural and Waste Management Practices: Farmers should adopt controlled fertilizer application and runoff management to prevent nitrate and other contaminant leaching into groundwater. Solid and liquid waste disposal practices should be improved to reduce leachate infiltration into water sources.
6. Policy and Infrastructure Support: Local governments should enforce water quality regulations, provide support for water treatment infrastructure, and ensure equitable access to safe drinking water. Investment in borehole maintenance, water sanitation, and monitoring networks will enhance public health protection.

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APPENDIX

