ASSESSMENT OF PHYSICO-CHEMICAL PROPERTIES, BACTERIAL CONTAMINATION, AND WATER QUALITY INTERRELATIONSHIPS IN LANYIRU SPRING, MERU COUNTY, KENYA

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A Thesis Submitted to the Graduate School in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science in Chemistry of Chuka University

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented for the award of diploma or conferment of degree in any other University.

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Recommendation

This thesis has been examined, passed, and submitted with our approval as University supervisors

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DEDICATION

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ABSTRACT

Reliable access to clean water is critical for public health, economic growth, and environmental sustainability. However, rural communities in Kenya continue to face water quality challenges stemming from contamination, inadequate monitoring, and fluoride pollution. Springs like Lanyiru in Meru County are commonly assumed safe based on appearance, yet the absence of regular assessments poses unrecognized health risks. This study assessed the physicochemical and microbial quality of Lanyiru Spring water to determine its suitability for domestic use. Samples were collected from four sites along Lanyiru Springs at the middle of wet and dry season (September 2025) and were analyzed through both *in situ* measurements and laboratory procedures. Physical parameters including pH, temperature, turbidity, conductivity, and total dissolved solids were measured on-site with calibrated instruments to ensure accuracy. Chemical analyses, encompassing cation and anion quantification, were conducted in the laboratory following APHA and EPA standard methods, employing techniques such as Flame Atomic Absorption Spectrometry (FAAS), Inductively Coupled Plasma–Mass Spectrometry (ICP-MS), ion chromatography, and ion-selective electrodes. Microbial contamination was assessed via the Most Probable Number (MPN) method for coliform bacteria. Data collected were analyzed using R software (version 4.3.0), with significance determined at $\alpha = 0.05$, to detect spatial variations and assess water quality relative to health standards. Significant spatial variations ($p < 0.05$) were observed in key cations, including Pb^{2+}, Fe^{2+}, Cd^{2+}, Cu^{2+}, Ca^{2+}, Mg^{2+}, and K^{+}. Notably, Pb^{2+} peaked in Sample LP1A and LP1B (0.008 mg/L), Fe^{2+} at LP4B (10.03 mg/L), and Cd^{2+} at LP3A (0.041 mg/L), exceeding recommended limits and indicating contamination risks. Cu^{2+} was highest at LP4B (0.342 mg/L), with elevated Ca^{2+} and K^{+} also recorded at LP4A. Anion analysis revealed significant differences in SO_4^{2-} , Cl^{-} , and F^{-} concentrations across sites. Sample LP4A exhibited the highest SO_4^{2-} (132.85 mg/L) and Cl^{-} (311.90 mg/L), while LP4B showed the highest fluoride level (8.40 mg/L), exceeding WHO guidelines. The Na^{+} levels showed no significant spatial variation ($p > 0.05$). Physical parameters showed no significant variation in pH (mean = 10.16), indicating overall alkalinity, but temperature varied significantly, with LP2 recording the highest at 26.87°C. Lanyiru Spring water is contaminated with heavy metals, elevated fluoride, turbidity, and microbial hazards from both natural and human activities, making it unsafe for direct consumption. To protect community health, regular water quality monitoring, pollution control, improved sanitation, household water treatment, and investment in alternative safe water sources are urgently needed.

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ACRONYMS AND ABBREVIATIONS

AAS:	Atomic Absorption Spectroscopy.
ADA:	American Oral Association
ANOVA:	Analysis of Variance
APHA:	American Public Health Association
BGLB:	Brilliant Green Lactose Bile
CME:	Chemically Modified Electrodes.
CPE:	Carbon Paste Electrodes.
EC:	Electrical Conductivity
EDTA:	Ethylenediaminetetraacetic Acid
EHEC:	Enterohemorrhagic *Escherichia coli*
EIEC:	Enter invasive Escherichia Coli
FAAS -	Flame Atomic Absorption Spectrometry
HCO_3:	Bicarbonate ion
HPLC-AFC:	High-Performance Liquid Chromatography Atomic Fluorescence Spectroscopy.
ICP-MS:	Inductively Coupled Plasma – Mass Spectrometry
ISE:	Ion Selective Electrodes
KEBS:	Kenya Bureau of Standards
LTB:	Lauryl Tryptose Broth
MCLG:	Maximum Contaminant Limit Goal
MPN:	Most Probable Number
NACOSTI:	National Commission of Science, Technology, and Innovation
NEMA:	National Environment Management Authority
PCPE:	Plain Carbon Paste Electrodes.
TDS:	Total Dissolved Solids
TH:	Total hardness
USEPA:	United States Environmental Protection Agency
WHO:	World Health Organization
Wr:	Relative weight
Wu:	Unit weight

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Access to safe and clean water is universally recognized as a fundamental human right and a cornerstone of public health, economic development, and environmental sustainability (Küfeoğlu, 2022; Sravanthi *et al.*, 2023). Despite decades of international efforts, including the Sustainable Development Goals (SDGs), approximately 2.3 billion people globally still lack access to safely managed drinking water services (Okafor *et al.*, 2024). In high-income countries, near-universal access has largely been achieved due to extensive infrastructure, centralized treatment systems, and routine monitoring (Peydayesh and Mezzenga, 2024). In contrast, low- and middle-income countries, particularly rural communities, continue to face systemic challenges in water provision and management (Okafor *et al.*, 2024; Peydayesh and Mezzenga, 2024). In these regions, reliance on unprotected water sources such as springs, rivers, and hand-dug wells exposes populations to microbial contamination, chemical leaching, and seasonal water scarcity (Tadele and Tekile, 2025).

Water quality is primarily determined by its physico-chemical and microbiological characteristics, which influence its suitability for domestic, agricultural, and industrial uses. Globally, industrial activity, land-use changes, and inadequate waste management have been shown to alter key water quality parameters, including pH, turbidity, heavy metal concentrations, and dissolved oxygen levels (Maurya *et al.*, 2021; Pant *et al.*, 2024; Navaandorj *et al.*, 2025; Hordones *et al.*, 2025). When these parameters fall outside recommended standards, they pose direct threats to human health and aquatic ecosystems. For instance, deviations in dissolved oxygen and nutrient concentrations can drive eutrophication, while elevated heavy metals and chemical pollutants can cause chronic health effects (Maurya *et al.*, 2021; Pant *et al.*, 2024).

Globally, microbial contamination is equally critical. Coliform bacteria are widely used as indicators of fecal contamination, signaling the potential presence of pathogenic microorganisms (Holcomb and Stewart, 2020). Outbreaks of waterborne diseases such as cholera, dysentery, and typhoid have been linked to unsafe drinking water, causing over 400,000 deaths annually worldwide (WHO, 2023). Even in countries with advanced water treatment systems, lapses in monitoring and treatment have occasionally resulted in contamination events, highlighting the need for comprehensive water quality management (Kunz, 2024; Matchawe *et al.,* 2022).

In Sub-Saharan Africa (SSA), access to safe and reliable drinking water remains a significant public health challenge. Approximately 319 million people in the region rely on unimproved water sources, including unprotected wells, springs, and surface water, while only about 27% of the population have access to basic sanitation facilities (WHO, 2015; WHO, 2023). Nearly half of the global population dependent on unsafe water sources resides in SSA, and 70–80% of communicable diseases in the region are associated with inadequate water quality and poor sanitation practices (Faye and Dieye, 2018). These figures illustrate the combined effect of infrastructural limitations, rapid population growth, and uneven distribution of water resources on public health outcomes.

The deterioration of freshwater sources in SSA is intensified by several interrelated factors. Rapid urbanization, agricultural expansion, and deforestation contribute to increased sedimentation, nutrient loading, and chemical runoff in water bodies. Inadequate waste disposal and limited wastewater treatment infrastructure further exacerbate contamination risks, while climate variability affects both water quantity and quality through droughts, floods, and changes in runoff patterns (Mishra, 2023). These environmental pressures increase the prevalence of microbial contamination and chemical pollutants, creating elevated risks of waterborne diseases and ecosystem disruption.

Rural communities in SSA are particularly vulnerable. Weak water governance, limited enforcement of water quality regulations, and insufficient community participation impede effective water management (Opiyo, 2023). In such contexts, reliance on untreated or minimally treated water from natural sources increases exposure to both chemical and microbiological hazards. Studies have documented high levels of coliform bacteria in water sources situated near agricultural lands or livestock activities in Ghana, Malawi, and Tanzania, often exceeding WHO standards for safe drinking water (Abdallah and Mourad, 2021; Ngowi, 2022; Malikula *et al.,* 2022).

In Kenya, access to safe drinking water and sanitation services varies widely between urban and rural areas. While urban centers have benefited from piped infrastructure and centralized water treatment, rural communities remain heavily dependent on natural water sources such as springs, rivers, and boreholes. These sources are often vulnerable to contamination from agricultural runoff, livestock intrusion, and proximity to poorly managed sanitation facilities (Weber and Kubiniok, 2022; Jung *et al.,* 2023). Weak monitoring systems, limited regulatory enforcement, and inadequate community participation further hinder effective water governance, leaving rural populations exposed to chemical and microbiological risks (Opiyo, 2023).

National policies, including Kenya Vision 2030 and the Water Act (2016), emphasize improving water access, promoting sustainable water use, and safeguarding natural water resources. However, despite these frameworks, rural springs, which serve both domestic and agricultural purposes receive limited attention in routine monitoring and water quality assessments. Springs such as Lanyiru in Meru County are often assumed safe because of their natural clarity, continuous flow, and relatively stable yield throughout the year, yet they remain directly exposed to environmental and anthropogenic pressures. Surface runoff from farmlands can introduce fertilizers, pesticides, and sediments; livestock access may contribute microbiological contamination; and proximity to sanitation facilities or unmanaged waste increases the risk of pathogenic and chemical pollutants (Weber and Kubiniok, 2022; Jung *et al.,* 2023). Unlike urban-piped systems with integrated treatment and regular testing, these rural springs lack formal protection measures.

Elevated fluoride levels in certain regions of Kenya, including parts of Meru County, have emerged as a notable public health concern (Wambu *et al.,* 2014; Demarchi *et al.,* 2022). Fluoride naturally leaches into groundwater from geological formations, and prolonged consumption at concentrations above the WHO limit of 1.5 mg/L can cause dental fluorosis, which is marked by discoloration, mottling, and pitting of teeth in children (Vasisth *et al.,* 2024). In severe cases, skeletal fluorosis may develop, leading to joint stiffness and bone deformities (Choubisa, 2024). Studies in the Rift Valley and Eastern Kenya report fluoride levels exceeding 3 mg/L in springs and boreholes, corresponding with elevated incidences of dental abnormalities (Jeptoo *et al.,* 2024; Mesfin *et al.,* 2024). These findings underscore the importance of including fluoride assessment in water quality evaluations and of identifying appropriate mitigation strategies, such as blending with low-fluoride sources, water treatment, or sourcing alternative supplies.

Physico-chemical water quality is influenced by a combination of natural and anthropogenic factors, including geology, industrial and agricultural activity, land-use change, and waste disposal practices. Parameters such as pH, turbidity, heavy metal concentrations, electrical conductivity, and dissolved oxygen levels determine water suitability for human consumption, irrigation, and domestic use (Maurya *et al.,* 2021; Pant *et al.,* 2024; Navaandorj *et al.,* 2025; Hordones *et al.,* 2025). In Kenya, research has primarily focused on urban water systems, rivers, and reservoirs, while rural springs remain under-investigated (Ontumbi, 2020; Guto *et al.*, 2025). The Lanyiru Spring, located in an agriculturally productive and ecologically sensitive area, lacks baseline data on physico-chemical quality, limiting informed decision-making regarding safe water provision.

The chemical quality of springs and wells is a crucial determinant of water safety, shaped by the interplay of geogenic processes, hydrogeological factors, and human activities. Groundwater chemistry reflects mineral dissolution from volcanic and sedimentary rocks, aquifer characteristics, and localized geological formations, while agricultural runoff, industrial effluents, and settlement patterns can introduce nutrients, heavy metals, and other contaminants (Ghilamicael *et al.*, 2017; Mather, 2020; Wekesa & Otieno, 2022; Simiyu *et al.,* 2009; Boumaza *et al.,* 2021). Chemical constituents are broadly classified into anions, such as fluoride, nitrate, and sulphate, and cations, including cadmium, copper, lead, and iron, all essential in trace amounts but potentially toxic at elevated concentrations (Kabir *et al.,* 2020; Anyanwu & Onyele, 2018).

Globally, high fluoride in springs is often geogenic, associated with volcanic rocks and arid climates (Ghilamicael *et al.,* 2017; Mukherjee & Singh, 2020), whereas heavy metal contamination commonly results from industrial and mining activities (Boumaza *et al.,* 2021; Karadeniz *et al.,* 2024). In Kenya, fluoride hotspots correspond to Rift

Valley and other volcanic regions, with studies reporting concentrations above WHO guidelines and related health effects, including dental and skeletal fluorosis (Nair *et al.,* 1984; Kirui, 2020; Kariuki & Kaham, 1997; Kiptoo, 2024). Nitrate levels are generally safe in rural springs but may rise due to local agricultural practices (Wekesa & Otieno, 2022; Simiyu *et al.,* 2009), while sulphate concentrations reflect both natural mineral sources and anthropogenic inputs (Shigut *et al.,* 2017; Boumaza *et al.,* 2021).

Trace metals such as cadmium, copper, lead, and iron are typically low in Kenyan springs but can reach concerning levels in areas affected by mining or industrial activity (Anyanwu & Onyele, 2018; Stojanović *et al.,* 2015; Karadeniz *et al.,* 2024; Ulniković & Kurilić, 2020). The spatial and hydrogeological variability of these parameters underscores the need for localized water quality assessments to ensure safe and sustainable use of spring and well water (Herms *et al.,* 2021; Ghilamicael *et al.,* 2017; Mather, 2020; Islam *et al.,* 2021; Hossain *et al.,* 2021; Solanki *et al.,* 2022).

Understanding the interrelationships among physico-chemical parameters is essential for identifying contamination sources and predicting water quality trends. Globally, multivariate approaches, such as correlation matrices, are widely used to reveal patterns and linkages between parameters (Koklu *et al.,* 2010; Muniz and Oliveira-Filho, 2023). For example, strong correlations between conductivity and total dissolved solids may indicate saline intrusion or wastewater discharge, whereas an inverse relationship between dissolved oxygen and temperature can suggest organic pollution or eutrophication (Rajwa-Kuligiewicz *et al.,* 2015; Viet *et al.,* 2016). Many rural assessments, however, focus on individual parameters, which can obscure understanding of contamination dynamics. Analysis of parameter interactions can provide actionable insights for water management and treatment strategies, particularly for spring sources that are not subject to formal monitoring.

Microbiological contamination is a further concern for rural water sources. Coliform bacteria serve as indicators of fecal contamination and the potential presence of pathogens (Holcomb and Stewart, 2020). In Africa, open defecation and poor sanitation practices contribute significantly to microbial pollution. Studies in Ghana, Malawi, and Tanzania have demonstrated that water sources near agricultural or livestock activities often exceed WHO limits for total and faecal coliforms (Abdallah and Mourad, 2021; Ngowi, 2022; Malikula *et al.,* 2022). In Kenya, elevated coliform counts have been reported in rivers, wells, and reservoirs, particularly in peri-urban areas and informal settlements (Ngonyo, 2024; Kiambi, 2024). Systematic microbial assessments of rural springs are, however, limited. Springs like Lanyiru, which serve as primary drinking water sources for local communities, are rarely tested for microbial contamination, restricting the ability to plan effective public health interventions.

This study addresses these critical knowledge gaps by evaluating the physico-chemical and microbiological quality of Lanyiru Spring. The research focuses on determining selected physico-chemical properties of the spring water, assessing correlations between these parameters, and evaluating the levels of total and faecal coliform bacteria. By situating the investigation within both national and global water quality contexts, the study generates evidence to support effective water safety management, enhance community awareness, and inform policy interventions aimed at protecting human health in rural Kenya.

1.2 Statement of the Problem

Access to safe drinking water is fundamental for public health and community well-being. While Kenya has made progress in expanding water services, many rural areas, including Maburwa in Muthara Ward, Meru County, continue to face significant challenges. Residents in this area largely depend on unprotected springs, such as Lanyiru, for both domestic and agricultural purposes. These water sources, however, are not regularly monitored, and data on their physico-chemical and microbiological quality remain limited, constraining effective water governance and public health protection. Several regions in Kenya have reported groundwater fluoride concentrations exceeding the WHO guideline of 1.5 mg/L, raising concerns about chemical contamination. In Maburwa, local observations suggest a potential link between consumption of untreated spring water and incidences of dental fluorosis. Microbial contamination, particularly from total and faecal coliform bacteria, also poses significant health risks, especially in unprotected sources vulnerable to intrusion by humans and livestock. Lanyiru Spring is further exposed to contamination from surface runoff, agricultural activities, and poor sanitation practices, yet the extent of such contamination has not been systematically evaluated to inform mitigation strategies. The lack of comprehensive data on critical physico-chemical parameters such as fluoride concentration, turbidity, dissolved oxygen, and conductivity alongside microbiological indicators, limits the ability to monitor water quality trends, identify pollution sources, and design targeted interventions. Assessing these parameters is therefore essential for safeguarding community health, ensuring safe water use, and guiding sustainable water resource management in Maburwa and surrounding areas.

1.3 Objectives of the Study

1.3.1 Broad Objectives

The broad objective of this study was to investigate the physico-chemical properties, evaluate bacterial contamination, and analyze the interrelationships among various water quality parameters in Lanyiru Spring, Meru County, Kenya.

1.3.2 Specific Objectives

The specific objectives of this study were:

i. To determine selected physico-chemical properties of water from Lanyiru Spring, Meru County, Kenya, including pH, temperature, turbidity, electrical conductivity, fluoride, calcium, magnesium, iron, lead, and dissolved oxygen.
ii. To assess the correlations among the selected physico-chemical parameters of Lanyiru Spring water, focusing on how factors such as pH, temperature, turbidity and conductivity.
iii. To evaluate the levels of total and faecal coliform bacteria in Lanyiru Spring water to establish the extent of microbial contamination and potential health risks to the local population.

1.4 Hypothesis

The null hypotheses of this study were:

$H_0 1$: There is no significant difference in the selected physico-chemical properties of water across the sampled locations of Lanyiru Spring, Meru County, Kenya.

$H_0 2$: There is no significant correlation among the selected physico-chemical parameters in the spring water across the sampled locations of Lanyiru Spring, Meru County, Kenya.

$H_0 3$: There is no significant difference in the levels of total and faecal coliform bacteria across the sampled locations of Lanyiru Spring, Meru County, Kenya.

1.5 Significance of the Study

Access to safe and clean drinking water remains a challenge for many rural communities in Kenya, including Muthara Ward, Meru County, where residents rely heavily on unprotected water sources such as Lanyiru Spring. This study is necessary because there is limited information on the quality of water from this spring, particularly regarding key physico-chemical parameters such as fluoride concentration, turbidity, and dissolved oxygen, as well as microbiological indicators including total and faecal coliform bacteria. Without reliable data, local authorities and public health practitioners are unable to assess the risks posed by untreated water or design effective mitigation measures. Prolonged consumption of contaminated water can lead to health problems such as dental fluorosis from excess fluoride and gastrointestinal diseases from microbial contamination.

The study will benefit multiple stakeholders. Local community members will gain evidence-based information about the safety of Lanyiru Spring water, enabling them to make informed decisions about water use and adopt appropriate household treatment practices. Public health officials and local government agencies will receive data to support planning and implementation of water safety interventions, including water treatment, protection of spring catchments, and monitoring programs. Policymakers will benefit from the findings by incorporating them into guidelines and regulations aimed at improving rural water safety. Additionally, researchers and development partners will gain insights into rural water quality dynamics, supporting broader initiatives in environmental health and sustainable water management.

By aligning with Sustainable Development Goal (SDG) 6, which promotes universal access to safe drinking water and sanitation, this study provides actionable evidence to reduce waterborne disease risks in rural areas. It also supports SDG 3 (Good Health and Well-being) by addressing the direct links between water quality and public health.

Overall, the research will inform practical interventions, guide policy decisions, strengthen local water governance, and enhance the well-being of vulnerable rural populations dependent on Lanyiru Spring.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview of Water Quality in Rural Areas

2.1.1 Importance of Water Quality

Water quality is a multifaceted concept encompassing physical, chemical, and biological parameters that determine its suitability for human consumption, agriculture, and ecological balance (Singh *et al.*, 2024). Key physical indicators like turbidity can signal the presence of suspended particles and microbial contaminants, while chemical factors such as pH, fluoride concentration, and dissolved oxygen influence both potability and ecosystem health (Bhardwaj *et al.*, 2023). For instance, elevated fluoride levels have been associated with dental and skeletal fluorosis, while high turbidity often correlates with harmful microorganisms including *Escherichia coli* and *Salmonella* (Choubisa, 2024; Holcomb and Stewart, 2020; Matchawe *et al.*, 2022).

Globally, over 2 billion people still lack access to safely managed drinking water, with rural populations bearing the brunt of this crisis (WHO, 2023). In Kenya, the disparity is even more acute around 70% of rural households rely on unprotected water sources such as springs, streams, and shallow wells (UNDP, 2025). These sources are highly vulnerable to contamination from human waste, agricultural runoff, and poorly managed solid waste, posing serious health risks. The World Bank reports that over 60% of illnesses in Kenya are linked to unsafe water and sanitation, costing the country nearly USD 500 million annually through lost productivity and healthcare burdens (Hutton *et al.*, 2024).

Water quality, therefore, is not only a public health concern but also a significant economic issue. In rural communities, where livelihoods are closely tied to agriculture and livestock, contaminated water can reduce crop yields, poison animals, and perpetuate poverty cycles (Rashid *et al.*, 2023; Okesanya *et al.*, 2024). Moreover, the lack of proper sanitation infrastructure in these regions exacerbates the situation, reinforcing systemic inequalities.

Addressing water quality issues is essential for achieving Sustainable Development Goal (SDG) 6, which aims to ensure availability and sustainable management of water and sanitation for all (Visseren-Hamakers, 2020). This goal is especially urgent in the context of rural landscape in Kenya, where development is often hampered by inadequate water services. As Ondieki *et al.* (2022) emphasize, improving water quality is foundational to achieving broader socio-economic objectives, including poverty reduction, food security, and public health.

Importantly, water quality challenges extend beyond health and agriculture they also affect industry and environmental sustainability. Pollutants such as pesticides, fertilizers, and heavy metals degrade soil fertility, contaminate aquatic ecosystems, and reduce agricultural productivity, further threatening food security in rural areas (Okorogbona *et al.,* 2018; Rashid *et al.,* 2023).

Despite these challenges, solutions exist. Delaire *et al.* (2017) estimate that microbial monitoring of all improved water sources across sub-Saharan Africa would cost only USD 16 million annually minuscule compared to the USD 14.8 billion needed each year to fully realize SDG 6.1. Investing in water monitoring, therefore, is not just affordable but imperative. Finally, climate change presents an escalating threat to water quality and availability. In many rural regions, seasonal water variability, floods, and prolonged droughts compound existing challenges by disrupting access to clean water and increasing reliance on contaminated sources (Abrams *et al.,* 2021). These environmental pressures highlight the urgency of resilient and sustainable water management systems that can safeguard both human health and rural livelihoods.

2.2 Variation in Physico-chemical Properties of Water

The According to Abduljabar *et al.* (2020), comprehensive data on the physical, chemical, and biological properties of water sources is essential for evaluating their suitability for domestic use. This information not only aids in understanding the water quality but also guides decisions regarding treatment and potential health impacts. Physico-chemical properties serve as critical indicators of water quality, with physical parameters playing a central role in assessing the sensory and aesthetic attributes of water. These include temperature, turbidity, colour, and electrical conductivity, which influence water usability and consumer acceptability (Dalyop *et al.,* 2024). Abduljabar *et al.* (2020), in their study of 22 spring sources in the Amadiya region of Kurdistan, Iraq, emphasized that while most physical parameters such as temperature and turbidity fell within World Health Organization limits, certain locations exhibited elevated Electrical Conductivity (EC) and total dissolved solids. The higher EC values are indicative of increased ion concentration, suggesting potential anthropogenic inputs such as domestic wastewater and agricultural runoff.

Temperature, as a fundamental physical parameter, directly affects the solubility of gases and the metabolic activities of aquatic organisms. Ghilamicael *et al.* (2017) documented significant temperature variation across five geothermal springs in Eritrea, with source temperatures ranging from 49.5°C to 100°C. Elegedi hot spring, in particular, showed significantly higher temperatures ($p < 0.05$) compared to other sites. Elevated temperatures were linked to geological settings and the depth of geothermal activity. The variation in temperature was strongly correlated with chemical properties such as sulphate, salinity, and TDS ($R^2 > 0.9$), underscoring the interconnectedness of physical and chemical parameters in hydrothermal systems.

Ngari *et al.* (2013) also highlighted the influence of geological context on physical properties in their analysis of groundwater in the Gichugu area of Kenya. The reported EC of 2.888 μS/cm suggested a moderate concentration of dissolved salts, while clarity was attributed to efficient natural filtration through surface soils. Although the water exhibited a slight fizzing effect, which they attributed to dissolved CO_2 and O_2 gases, the physical attributes remained within acceptable limits for domestic use.

Turbidity, another critical physical parameter, was generally low across most studies, indicating minimal particulate matter in suspension. However, in the Eritrean geothermal springs, particularly in Garbanabra and Gelti, high TDS and EC levels contributed to elevated salinity, influencing water taste and suitability for domestic use (Ghilamicael *et al.*, 2017). This highlights the importance of continuous monitoring, particularly in regions susceptible to seawater intrusion or volcanic activity.

Total Dissolved Solids (TDS) and Electrical Conductivity (EC) are fundamental indicators of groundwater quality, reflecting the concentration of dissolved inorganic salts, including calcium, magnesium, sodium, potassium, bicarbonates, chlorides, and sulfates (Kushwah and Singh, 2024; Valiallahi and Yazdani, 2025). While TDS quantifies the total amount of dissolved substances, EC measures the water's ability to conduct electrical current, serving as a practical proxy for estimating TDS levels. These parameters are crucial in assessing water salinity, taste, corrosiveness, and overall suitability for domestic use (Weiner, 2007).

Elevated TDS and EC values in groundwater typically result from natural processes such as mineral dissolution, rock-water interactions, and, in some cases, anthropogenic factors like agricultural runoff and urban effluents. For instance, Abduljabar *et al.* (2020) documented TDS values ranging from 290 to 731 mg/L in spring waters of the Amediye district, Kurdistan, with a mean of 389.86 mg/L, remaining within WHO acceptable limits (1000 mg/L). However, in geothermal springs of Eritrea, Ghilamicael *et al.* (2017) reported significantly higher concentrations of sodium (3,800 mg/L), calcium (1,653 mg/L), and chloride (5,946 mg/L), attributed to seawater mixing and geothermal activity. While informative, such geothermal-influenced data may not be directly comparable to typical fresh water springs like Lanyiru Spring.

In Jordan, Al-Khashman *et al.* (2017) observed EC values ranging from 510 to 1,215 µS/cm across various springs, with corresponding TDS values between 323 and 728 mg/L. Notably, TDS concentrations displayed seasonal fluctuations, often peaking during dry periods due to reduced dilution from surface recharge. This seasonal dynamic is particularly relevant for regions dependent on spring water, where water availability and quality fluctuate with rainfall patterns. In the Kenyan context, studies on groundwater quality in volcanic and sedimentary regions have reported variable TDS and EC levels, often influenced by underlying geology and land use. For example, groundwater sources in Meru and surrounding counties have been shown to exhibit elevated EC values due to prolonged water-rock interactions in volcanic terrains (Mungai *et al.*, 2014). However, localized assessments, such as for Lanyiru Spring, remain scarce despite their critical importance for rural water supply. Assessing TDS and EC levels in Lanyiru Spring is therefore essential to understand salinity levels, potential scaling issues, and overall water quality suitability for domestic consumption. Furthermore, monitoring seasonal variations can inform management strategies to ensure year-round water safety and usability for the local community.

Water temperature plays a critical role in determining the solubility of gases, the precipitation of salts, and the stability of chemical equilibria in natural water bodies (Weiner, 2007). Temperature fluctuations can also affect microbial activity and the safety of water for consumption, as higher temperatures may promote the growth of pathogenic microorganisms (Mugwanya *et al.,* 2022). Additionally, temperature influences the chemical reactions that control nutrient availability and pollutant removal, which is particularly relevant for assessing the water quality of groundwater sources like Lanyiru Spring.

In Kurdistan, Abduljabar *et al.* (2020) observed groundwater temperatures ranging from 11.8°C to 24.1°C, with some values exceeding typical acceptable ranges for drinking water, which can impact both chemical processes and biological contamination. Similarly, Al-Khashman *et al.* (2017) recorded temperatures in Jordanian springs varying from 16.31°C ± 1.73°C to 24.30°C ± 3.28°C. These variations were largely influenced by the elevation at spring emergence points, with higher elevations generally corresponding to cooler temperatures. In the context of Meru County, Kenya, temperature variations at Lanyiru Spring are expected to be influenced by both the region's tropical climate and its volcanic geological formations. Given that Meru County lies at an average elevation of approximately 1,500 meters above sea level (Gichaba *et al.*, 2020), spring water temperatures may range from 18°C to 25°C, depending on seasonal rainfall patterns, groundwater depth, and local topography. Seasonal temperature fluctuations can also affect the overall water quality. During the dry season, reduced rainfall and increased evaporation may lead to higher water temperatures, potentially promoting the growth of bacteria and affecting dissolved oxygen levels. During the wet season, cooler temperatures and increased water flow may reduce the temperature and improve oxygen solubility, benefiting both aquatic life and water quality.

2.2.2 Chemical Parameters

Chemical parameters are essential for assessing the potability, corrosiveness, and ecological impact of water sources (Baloïtcha *et al.,* 2022). These include pH, total hardness, concentrations of major cations and anions (such as calcium, magnesium, sodium, chloride, sulphate, and nitrate), as well as trace elements and heavy metals (Gwira *et al.*, 2024). Across the studies reviewed, chemical properties exhibited greater spatial variability compared to physical parameters, largely due to geological differences and anthropogenic influences.

2.2.2.1 Calcium, Magnesium, and the Role of Hardness in Water Quality

Water hardness, predominantly determined by the concentrations of dissolved calcium and magnesium ions, is a critical parameter in groundwater quality assessment (Ingin *et al.*, 2024). In rural settings, where groundwater sources like springs serve as primary domestic water supplies, hardness directly impacts both household usage and public health. Elevated hardness contributes to scaling in pipes and household appliances, increased soap consumption, and can influence the aesthetic quality of water (taste and feel) (Akram and Rehman, 2018). From a health perspective, prolonged consumption of very hard water has been associated with kidney stone formation and potential cardiovascular effects, although scientific consensus on these links remains debated (Zhang *et al.*, 2025). In low-resource settings, such as rural Kenya, these risks are compounded by limited access to water treatment technologies, necessitating localized assessments.

Globally, hardness variations are largely controlled by the dissolution of carbonate and bicarbonate minerals in aquifers. For example, Abduljabar *et al.* (2020) reported high groundwater hardness in the Kurdistan region of Iraq, with values ranging from 346 to 574 mg/L (mean: 394 mg/L), significantly exceeding the WHO recommended limit of 300 mg/L (Mohammad *et al.*, 2024). Correspondingly, calcium concentrations ranged between 260–485 mg/L, and magnesium between 75–120 mg/L, both surpassing the respective WHO guideline values of 150 mg/L and 50 mg/L (Mohammad *et al.*, 2024). These elevated concentrations were attributed to the region's carbonate-rich lithology, illustrating the profound influence of local geology on groundwater quality (Mohammad *et al.*, 2024).

In Kenya, Ngari *et al.* (2013) documented groundwater hardness levels of 126.1 mg/L as $CaCO_3$ in Gichugu, Kirinyaga County, which were within WHO acceptable limits. However, even at these moderate hardness levels, the study reported elevated iron (>0.3 mg/L) and manganese (>0.1 mg/L) concentrations, highlighting the multifaceted nature of groundwater contamination. This underscores the necessity of comprehensive water quality assessments that consider both primary parameters like hardness and associated trace metals. For Meru County, where Lanyiru Spring is located, specific data on groundwater hardness, calcium, and magnesium concentrations are scarce. The region's diverse geology, characterized by volcanic rocks, basaltic formations, and sedimentary deposits (Gevera and Onyari, 2024), suggests that mineral dissolution processes influencing hardness in other Kenyan regions are likely to be relevant here as well. Consequently, assessing these parameters is crucial for determining the suitability of Lanyiru Spring water for domestic use, while also providing insight into potential infrastructural and health implications for the local population.

2.2.2.2 Chemical Parameters in Springs and Wells

The chemical quality of springs and wells is a critical determinant of water safety and suitability for human consumption. Groundwater chemistry is influenced by a combination of geogenic processes, including the dissolution of minerals from volcanic and sedimentary rocks, and hydrogeological factors such as aquifer type, residence time, and local geological formations (Ghilamicael *et al.*, 2017; Mather, 2020). Additionally, anthropogenic activities, including agricultural runoff, industrial discharges, and settlement patterns, significantly affect water composition by introducing nutrients, heavy metals, and other pollutants (Wekesa & Otieno, 2022; Simiyu *et al.*, 2009; Boumaza *et al.*, 2021). Understanding the concentration, distribution, and dynamics of chemical parameters is essential for evaluating potential health risks, guiding water treatment, and designing sustainable water management strategies (Islam *et al.*, 2021; Hossain *et al.*, 2021; Solanki *et al.*, 2022).

Groundwater chemical constituents are broadly classified into anions (such as fluoride, nitrate, and sulphate) and cations (including cadmium, copper, lead, and iron), encompassing elements that are essential in trace amounts but potentially toxic at elevated concentrations (Kabir *et al.*, 2020; Wekesa & Otieno, 2022; Anyanwu & Onyele, 2018).

At a global level, studies have shown that the chemical quality of springs and wells varies widely depending on local geology, climatic conditions, and human interventions. For example, high fluoride levels in springs are frequently linked to volcanic formations and arid climates (Ghilamicael *et al.*, 2017; Mukherjee & Singh, 2020), whereas heavy metal contamination is often associated with industrial and mining activities (Boumaza *et al.,* 2021; Karadeniz *et al*., 2024).

In the Kenyan context, fluoride hotspots generally coincide with the Rift Valley and other volcanic regions, with studies reporting both safe and elevated concentrations in groundwater (Nair *et al.,* 1984; Kirui, 2020; Kariuki & Kaham, 1997; Kiptoo, 2024). Similarly, nitrate levels in rural springs have largely been within safe limits, although localized agricultural and anthropogenic influences can increase contamination risk (Wekesa & Otieno, 2022; Simiyu *et al.,* 2009). Trace metals such as cadmium, lead, and copper in Kenyan springs and wells are typically low but require monitoring due to potential geogenic contributions and human activity (Anyanwu & Onyele, 2018; Stojanović *et al.,* 2015; Karadeniz *et al.,* 2024).

Fluoride is a naturally occurring anion in groundwater, primarily released through the weathering and dissolution of fluoride-bearing minerals such as fluorite, biotite, and apatite. Its concentration in water depends on local geology, climatic conditions, and human influences, including industrial and agricultural activities. At low to moderate concentrations (0.5–1.5 mg/L), fluoride is beneficial, helping to prevent dental caries and aiding in the mineralization of bones and teeth (Kabir *et al.,* 2020; Weiner, 2007; Zhou *et al.,* 2023). However, excessive fluoride concentrations, typically above 1.5 mg/L, are associated with dental fluorosis, skeletal fluorosis, weakened bones, joint deformities, and arthritis-like conditions, which can have profound impacts on community health.

Globally, high fluoride levels have been reported in both springs and wells, predominantly due to geogenic processes. In Eritrea, for instance, Ghilamicael *et al.* (2017) documented fluoride concentrations ranging from 6.48 to 8.20 mg/L in Akwar and Maiwooi springs. These elevated levels were linked to volcanic rock formations and geothermal CO_2 interactions, demonstrating the influence of hydrothermal activity on groundwater chemistry. Similarly, Mukherjee and Singh (2020) noted that arid climates exacerbate fluoride accumulation in groundwater due to high evaporation rates and limited recharge, further highlighting the interaction between geochemistry and climate. Anthropogenic sources, such as the use of fluoride-containing fertilizers and industrial effluents, can also increase fluoride loads in water systems (Zuhra *et al.*, 2024).

In the Kenyan context, high fluoride concentrations are often reported in regions dominated by volcanic formations, particularly within the Rift Valley, Nairobi, Central, and Eastern provinces. Nair *et al.* (1984) conducted a comprehensive survey and found elevated fluoride levels that increased with borehole depth, reflecting the geogenic origin of contamination. Kirui (2020) further reported skeletal deformities in communities around Lake Baringo, attributing these to long-term consumption of fluoride-rich groundwater. Similarly, Kariuki and Kaham (1997) identified fluorosis in children around Lake Elementaita, with exposure arising from both drinking water and the consumption of locally grown crops irrigated with contaminated water. More recently, Kiptoo (2024) documented spatial variability in fluoride concentrations in the upper River Njoro catchment, Nakuru County, with some springs and river water sites exceeding the WHO guideline of 1.5 mg/L. These studies highlight that fluoride contamination is both geographically and hydrogeologically specific, necessitating localized monitoring and interventions.

In Meru County, the Lanyiru Spring and other springs in Muthara Division are suspected fluoride hotspots. The geological formations, comprising both volcanic and sedimentary rocks, provide a natural source for fluoride leaching into groundwater. Slow-replenishing water sources, such as springs and boreholes, are particularly vulnerable to fluoride accumulation. Elevated fluoride levels in these water sources pose significant health risks to communities reliant on them for drinking water. Therefore, continuous monitoring and potential defluoridation measures are essential to safeguard public health.

Nitrate is another crucial anion in water quality assessment, commonly used as an indicator of agricultural runoff, sewage contamination, and other anthropogenic activities. Ingestion of water with high nitrate levels, typically above 50 mg/L, is associated with health risks such as methemoglobinemia (“blue baby syndrome”), particularly in infants, and potential long-term risks for cancer. In Kenya, Wekesa and Otieno (2022) reported nitrate concentrations within safe limits in springs from Manga

Subcounty, Nyamira County, contributing to a favorable water quality index rated as "excellent" to "good" for domestic use. Similarly, Simiyu *et al.* (2009) observed low nitrate levels in rural springs within the Nzoia River catchment, Tongaren Division, though microbial contamination remained a pressing concern. These findings underscore the complex interplay between chemical and biological water quality parameters, highlighting that low nitrate levels do not necessarily imply overall water safety, as microbial contamination can independently pose significant health risks. Globally, nitrate contamination varies widely, with elevated concentrations frequently observed near agricultural regions or densely populated settlements. The occurrence and mobility of nitrate in groundwater are influenced by soil type, permeability, rainfall, and land use practices. Seasonal variations and rainfall patterns often modulate nitrate concentrations in springs and wells, highlighting the importance of long-term monitoring to accurately assess risks associated with nitrate contamination.

Sulphate is a naturally occurring anion derived from the oxidation of sulphide minerals, rock weathering, and dissolution of sulphate-rich deposits. Its concentration in water is influenced by both geological formations and anthropogenic inputs, including industrial effluents. In Ethiopia, Shigut *et al.* (2017) reported sulphate concentrations in springs within WHO permissible limits, suggesting minimal human impact and predominance of natural sources. Conversely, Boumaza *et al.* (2021) observed elevated sulphate levels in Algerian springs located in phosphate mining areas, attributing the increased concentrations to industrial discharges. High sulphate concentrations can affect the taste of water, cause gastrointestinal irritation, and, in combination with other ions, contribute to scaling in water distribution systems. In Kenya, sulphate concentrations in groundwater are generally within safe limits but can vary locally depending on rock mineralogy, agricultural activities, and land use patterns. Springs in volcanic regions may have naturally higher sulphate levels due to mineral dissolution, while areas with intensive fertilizer application may experience elevated anthropogenic sulphate inputs.

Cadmium is a highly toxic heavy metal that poses serious health risks even at trace concentrations. It is introduced into groundwater via natural leaching from mineralized rocks, industrial activities, and phosphate-based fertilizers. Chronic exposure to cadmium can lead to renal dysfunction, bone demineralization, and increased risk of cancer. In Nigeria, Anyanwu and Onyele (2018) reported cadmium concentrations in rural springs exceeding permissible limits, posing long-term health risks. Similarly, Karadeniz *et al.* (2024) documented Cd levels up to 0.76 µg/L in Turkish springs, reflecting both geogenic and anthropogenic contributions. Boumaza *et al.* (2021) found cadmium contamination associated with phosphate mining effluents in Algeria, demonstrating the site-specific nature of Cd contamination.

Copper is an essential micronutrient required for enzyme function and iron metabolism. However, excessive levels can cause gastrointestinal distress, liver and kidney damage, and, in rare cases, neurological disorders. Stojanović *et al.* (2015) found copper levels in Serbian springs reaching 14.9 µg/L, while Karadeniz *et al.* (2024) reported mean concentrations of 9.79 µg/L in Turkish springs, generally below WHO standards. In Nigeria, Anyanwu and Onyele (2018) observed that seasonal variations influenced Cu concentrations in springs, emphasizing the role of hydrological cycles in modulating trace metal levels. In Kenya, copper concentrations in springs are typically safe for human consumption, though localized variations may occur in areas with mining or industrial activities.

Lead is a neurotoxic metal with no safe exposure threshold, particularly harmful to children and pregnant women. Chronic exposure can impair cognitive development, damage kidneys, and cause cardiovascular disorders. Ulniković and Kurilić (2020) reported lead concentrations approaching regulatory limits in springs in Belgrade, Serbia. In Nigeria and Algeria, elevated Pb levels were associated with geogenic sources and phosphate mining activities (Anyanwu & Onyele, 2018; Boumaza *et al.*, 2021). Lead contamination is often site-specific, influenced by local geology, industrial activities, and water flow dynamics. In Kenya, while Pb contamination is generally low, areas near mining operations or industrial centers may experience elevated concentrations, warranting monitoring.

Iron is abundant in most groundwater systems, derived from mineral dissolution, rock weathering, and anthropogenic inputs. While essential for human health, high iron levels can impart undesirable taste, odor, and color to water and cause infrastructure problems such as pipe corrosion. Stojanović *et al.* (2015) documented Fe concentrations up to 168.3 µg/L in Serbian springs, while Shigut *et al.* (2017) and Boumaza *et al.* (2021) reported elevated iron in Ethiopian and Algerian springs, respectively. In Kenyan springs, iron levels are typically moderate, but localized geogenic sources, particularly in volcanic terrains, can contribute to higher concentrations.

2.2.2.3 pH Variability

The pH is a critical parameter for assessing water quality, as it directly influences the solubility and toxicity of various chemical substances, including metals, nutrients, and other contaminants (Soltan *et al.*, 2019). Water pH also plays a significant role in determining the corrosiveness of water, which can affect infrastructure and water treatment processes (Weiner, 2007). Neutral pH levels, within the range of 6.5 to 8.5, are generally considered ideal for drinking water and are less likely to cause adverse health effects. In the Amediye district, Kurdistan, Abduljabar *et al.* (2020) reported a neutral pH with an average of 6.81, falling well within the World Health Organization's (WHO) recommended range of 6.5–8.5. Similarly, Al-Khashman *et al.* (2017) found pH values ranging from 6.69 to 8.23 across Jordanian springs, with a median of 7.73 ± 0.35, suggesting a generally neutral to slightly alkaline range. Variations in pH were often attributed to factors such as bicarbonate concentrations, organic pollution, and domestic wastewater discharge.

In Kenya, Ngari *et al.* (2013) documented slightly acidic groundwater (pH 6.48) in Gichugu, Kirinyaga County. The acidic nature of the water in this case was attributed to local geological conditions and anthropogenic factors, such as land use practices and pollution from agricultural runoff. These findings show the importance of considering both natural and human-induced factors when interpreting pH values in groundwater. For Lanyiru Spring in Meru County, although specific pH data are currently unavailable, it is important to consider the region's volcanic geology, which often contributes to the natural buffering of water, potentially resulting in slightly alkaline to neutral pH values. The presence of mineral-rich volcanic soils, along with seasonal variations in water flow and infiltration, can also influence pH. Furthermore, local agricultural practices and nearby human settlements may introduce acidic or alkaline pollutants, which could further impact pH levels (Akhtar *et al.*, 2021). Assessing pH variability at Lanyiru Spring is crucial for understanding the suitability of the water for domestic consumption, as well as its potential effects on local infrastructure and public health. The pH levels outside the ideal range can lead to corrosion of pipes, reduced effectiveness of water treatment, and health risks from increased solubility of toxic metals like lead (Soltan *et al.,* 2019).

2.2.2.4 Spatial and Hydrogeological Variability

The chemical composition of spring waters exhibits significant spatial and hydrogeological variability, governed by rock type, mineral content, groundwater flow patterns, and human activities. Herms *et al.* (2021) emphasized that both natural and anthropogenic factors interplay to create distinct water chemistry profiles across hydrogeological zones. In Eritrea, Ghilamicael *et al.* (2017) employed non-metric multidimensional scaling (NMDS) to reveal distinct chemical clustering among springs in different zones, illustrating the role of local geology in influencing water chemistry.

In Meru County, the presence of volcanic and sedimentary rocks influences mineral content, including calcium, magnesium, fluoride, and trace metals, thereby shaping the overall water quality (Mather, 2020). Agricultural runoff and human settlement further modify groundwater chemistry by introducing nitrates, phosphates, and other contaminants. This combination of geogenic and anthropogenic influences underscores the necessity for site-specific water quality assessments, particularly in fluoride-endemic areas or regions with high mining or industrial activity (Islam *et al.,* 2021; Hossain *et al.,* 2021; Solanki *et al.,* 2022).

2.3 Correlation between Physico-Chemical Parameters in Water

Correlation analysis is a fundamental statistical tool used to explore the relationships between various physico-chemical parameters in water (Memon *et al.,* 2023). It helps in identifying common sources of contaminants, understanding geochemical processes, and providing insights into the factors influencing water quality. This approach is particularly useful for rural springs such as Lanyiru, where water quality is affected by both natural processes and anthropogenic activities. Kothari *et al.* (2021) conducted a comprehensive correlation analysis of water quality parameters in Uttarakhand, India. They reported strong positive correlations between Total Dissolved Solids, fluoride, total hardness (TH), magnesium, and chloride, indicating these parameters likely originate from common sources such as soil leaching, mineral dissolution, or domestic wastewater infiltration. Electrical Conductivity (EC) also showed high correlation with TDS, chloride, and hardness, suggesting that EC can serve as a reliable indicator of overall ionic content in groundwater and spring water systems.

In a similar study, Mrazovac and Vojinović-Miloradov (2011) observed significant correlations among sodium, chloride, calcium, and sulfate ions in groundwater, which were attributed to geochemical processes such as ion exchange and mineral weathering. Their findings underscore the importance of understanding the geological context of a water source, as these processes can heavily influence water chemistry, a factor relevant to the assessment of Lanyiru Spring. Panda *et al.* (2018) analyzed water samples from River Salandi, India, and reported strong positive correlations between TDS and hardness, sulfates, nitrates, and chlorides. These relationships pointed to cumulative effects of agricultural runoff, leachates, and effluents impacting water quality. Interestingly, negative correlations between pH and several other parameters highlighted the buffering capacity of water and potential pollutant interactions considerations that are critical when evaluating spring water used for domestic purposes.

Furthermore, Abbasnia *et al.* (2019) evaluated groundwater in Sistan and Baluchistan, Iran, and found strong positive correlations (above 0.8) among calcium, hardness, sulfate, TDS, sodium, and chloride. These relationships highlighted the combined influence of natural geochemical processes such as rock-water interactions, mineral weathering, and ion exchange alongside anthropogenic factors like agricultural runoff and wastewater discharge. Such findings are critical for understanding water chemistry in groundwater-fed springs, where multiple sources contribute to water quality variations. This is particularly relevant for springs like Lanyiru, which are vulnerable to similar influences.

In a related study within the East African context, Kipto *et al.* (2024) conducted a correlation analysis on spring water sources in Njoro, Nakuru, Kenya. Their research revealed that fluoride concentrations were negatively correlated with pH, but positively correlated with Total Dissolved Solids (TDS) and Electrical Conductivity (EC). This suggests that higher fluoride levels are often associated with increased ionic content in water, indicative of mineral dissolution, soil leaching, and prolonged water-rock interaction within the aquifer systems. The negative correlation with pH implies that slightly acidic conditions may enhance fluoride solubility and mobility, increasing its presence in groundwater and spring water. Such geochemical dynamics are essential considerations when assessing the quality of rural spring water used for domestic consumption.

Additionally, Ambiga and Annadurai (2015) investigated the interrelationships among various water quality parameters in groundwater and surface water sources. Their study consistently found strong positive correlations between TDS, EC, calcium, magnesium, total hardness, and chloride, confirming their common geogenic origins. Conversely, weaker or negative correlations were observed for parameters like nitrate, chromium, and iron, reflecting their different sources, mobility mechanisms, and possible anthropogenic influences. These findings underscore the value of correlation analysis as a diagnostic tool to identify the dominant processes and potential pollution sources affecting water chemistry. Collectively, these studies demonstrate that correlation analysis not only reveals interdependencies among physico-chemical parameters but also helps in tracing contamination sources, understanding hydrogeochemical processes, and informing water management strategies. For springs like Lanyiru, such insights are crucial for designing effective interventions to safeguard water quality.

2.4 Total and Faecal Coliform Bacteria: Biological Contaminants

Waterborne diseases, caused by microbial contamination, continue to pose a major public health challenge globally, particularly in developing countries where water treatment and sanitation infrastructure are limited (Shayo *et al.,* 2023). Contaminated water is a leading cause of diarrhea, affecting over a billion children under five years of age and contributing substantially to childhood morbidity and mortality in these regions (Manetu *et al.,* 2021). Beyond diarrhea, exposure to pathogenic microorganisms in drinking water can lead to a range of other gastrointestinal illnesses, including dysentery, typhoid, and cholera, which impose significant economic and social burdens on affected communities. Human sewage, agricultural runoff, and animal waste are primary sources of microbial contamination in water, introducing pathogenic bacteria, viruses, and protozoa into both surface and groundwater resources (Aleruchi *et al.*, 2025).

Among the bacterial pathogens, *Escherichia coli* strains, particularly Enterohemorrhagic (EHEC) and Enteroinvasive (EIEC), are of notable concern. Although EHEC strains are not typically abundant in drinking water, they can persist for extended periods—months, in some cases—in manure, sediments, and water-trough environments. Their presence in water systems can result in outbreaks associated with severe gastrointestinal disease (Dhakal, 2023). EIEC strains, meanwhile, are recognized for causing gastroenteritis, enterocolitis, and dysentery, with clinical manifestations including abdominal cramps, diarrhea, fever, chills, and bloody stools. These strains highlight the potential for serious health outcomes arising from microbial contamination in both rural and urban water sources.

Groundwater microbial communities are often diverse, including environmental bacteria such as *Pseudomonads* and *Helicobacter pylori*, which are naturally found in soil, aquifers, and other aquatic environments (Custodio *et al.*, 2025). In addition to bacteria, protozoan species such as *Bodomorpha minimum*, *Vahlkampfia*, *Naegleria gruberi*, and *Acanthamoeba astronyxis* are frequently detected in water samples. While many of these protozoans are not pathogenic, their presence indicates broader microbial ecosystems and potential environmental contamination (Cabral, 2010). Yeasts, particularly *Candida* spp., contribute to the microbial diversity and may influence water chemistry and nutrient cycling (Caicedo-Bejarano *et al.*, 2023). Molds, when present in water or beverages, can pose additional health risks through the production of allergens, mycotoxins, and enzymes that alter flavor or degrade food quality (Gholami-Shabani *et al.*, 2023).

The persistence, proliferation, and distribution of these microorganisms in water are influenced by multiple factors, including the availability of nutrients, organic matter, temperature, pH, and the inherent characteristics of the water source such as flow rate and turbidity. Furthermore, human activities that range from wastewater disposal to agricultural practices, can exacerbate microbial contamination, creating environments conducive to the growth and survival of pathogenic organisms. Understanding the composition and dynamics of microbial communities in water sources is therefore essential for developing effective water quality management strategies, mitigating health risks, and ensuring safe water supply, particularly in resource-limited settings.

2.4.1 Spatial Patterns of Nitrate-Microbial Associations

The spatial distribution of nitrate concentrations in groundwater is closely linked to microbial contamination, reflecting the combined influence of natural hydrogeological processes and human activities. Nitrate, a key nutrient for microbial growth, can originate from both geogenic sources and anthropogenic inputs, including agricultural fertilizers, manure, and domestic waste. Vasudevan *et al.* (2021) identified three distinct zones A, B and C, exhibiting different patterns of nitrate levels and microbial contamination, highlighting the heterogeneity of groundwater quality even within relatively small geographic areas.

Zone A is characterized by relatively low nitrate concentrations but elevated Total Viable Count (TVC) activity. This suggests that organic-rich clay sediments act as nutrient reservoirs, supporting microbial proliferation even in regions with minimal fertilizer application (Keesari *et al.,* 2016). The high microbial activity in these areas underscores the importance of natural organic matter as a driver of microbial dynamics in groundwater.

Zone B shows higher nitrate concentrations, largely attributed to agricultural runoff, and is accompanied by increased microbial activity. This zone demonstrates how human-modified landscapes, including the presence of wetlands, rivers, and agricultural fields, create favorable conditions for microbial growth. The positive relationship between nitrate levels and microbial counts in this zone illustrates the synergistic effect of nutrient enrichment and water movement in promoting microbial proliferation. In contrast, Zone C exhibits comparatively high nitrate concentrations but lower microbial activity. This pattern suggests that while agricultural runoff significantly contributes to chemical contamination, it does not necessarily correspond to proportional microbial proliferation. Factors such as hydrological flow, dilution, and soil type may limit microbial growth despite elevated nutrient levels.

2.4.2 Role of Nitrate as a Nutrient for Microbes

Nitrate acts as a critical nutrient for microbial growth and metabolism, particularly in water bodies enriched with organic matter. It serves as a primary source of nitrogen, which is essential for microbial protein synthesis, nucleic acids, and other cellular components. Agricultural fertilizers and manures are significant contributors to nitrate contamination, and microorganisms readily utilize these nitrates to support their growth and metabolic activities (Oskay & Yalçın, 2013; Munsuz & Unver, 1995). In regions with intensive agricultural activity, elevated nitrate concentrations are often accompanied by increased microbial populations, including total and fecal coliforms. This relationship illustrates how anthropogenic nutrient inputs can enhance microbial proliferation, potentially exacerbating public health risks when water sources are used for drinking or domestic purposes. In Vasudevan et al.'s (2021) study, Zone B exemplifies this pattern, where higher nitrate levels coincide with heightened microbial activity, highlighting the synergistic effect of nitrate enrichment and favorable environmental conditions such as the presence of wetlands and proximity to rivers.

Furthermore, organic nitrogen and free ammonia from sewage, livestock waste, and fertilizers provide additional nutrients, further stimulating microbial growth and contributing to the persistence of pathogenic bacteria in groundwater (UNEP/WHO, 1996; BIS, 2012). These findings underscore nitrate's dual role in groundwater systems: it acts not only as a chemical pollutant impacting water quality but also as a nutrient that supports microbial proliferation. Recognizing this dual function is essential for developing targeted strategies to monitor, manage, and mitigate microbial contamination in nitrate-impacted water sources.

2.4.3 Hydro Chemical-Microbial Correlations

Understanding the relationships between hydrochemical parameters and microbial contamination is crucial for assessing groundwater quality. Vasudevan *et al.* (2021) employed correlation matrices to identify significant associations between chemical and microbial indicators. Positive correlations were observed between nitrate concentrations and total and fecal coliforms, reflecting contributions from human and animal waste. Specifically, agricultural zones with high nitrate levels (Zone B) also exhibited increased microbial contamination, emphasizing the impact of fertilizer runoff on both chemical and biological water quality. Similarly, fecal streptococci correlated positively with calcium ions (Ca^{2+}), highlighting the influence of domestic and livestock waste on pathogenic bacterial populations. Chloride (Cl^-), often associated with sewage disposal and wastewater infiltration, also correlated significantly with fecal coliforms, further confirming anthropogenic contributions to microbial contamination (Kazmi & Khan, 2005; Vignesh *et al.*, 2013). These hydrochemical-microbial correlations demonstrate the interdependent effects of chemical pollutants and microbial growth, reinforcing the importance of integrated monitoring and management strategies.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Muthara Ward, which is part of Tigania East Constituency in Meru County, Kenya, home to approximately 72,549 people [Figure 1(County Government of Meru (Gok), 2023). The focus was on three Lanyiru springs water sources that are essential for local domestic use. The area lies beneath the Nyambene Ranges near Nyambene Hills, which produce seasonal and perennial springs and streams supporting agriculture and households. It is located between 0°7'5" S to 0°28'7" N latitude and 37°0'0" W to 37°57'0" E longitude, with elevations from 624 to 4540 meters above sea level. The geology is mainly volcanic and metamorphic rocks, such as basalts and phonolites, weathered into fertile Andosols and Ferralsols soils that support farming and affect groundwater quality. The climate is tropical highland with two rainy seasons, from March to May and October to December, receiving 800–1200 mm of rainfall annually. Temperatures range from 15°C to 28°C depending on altitude (County Government of Meru (Gok), 2023).

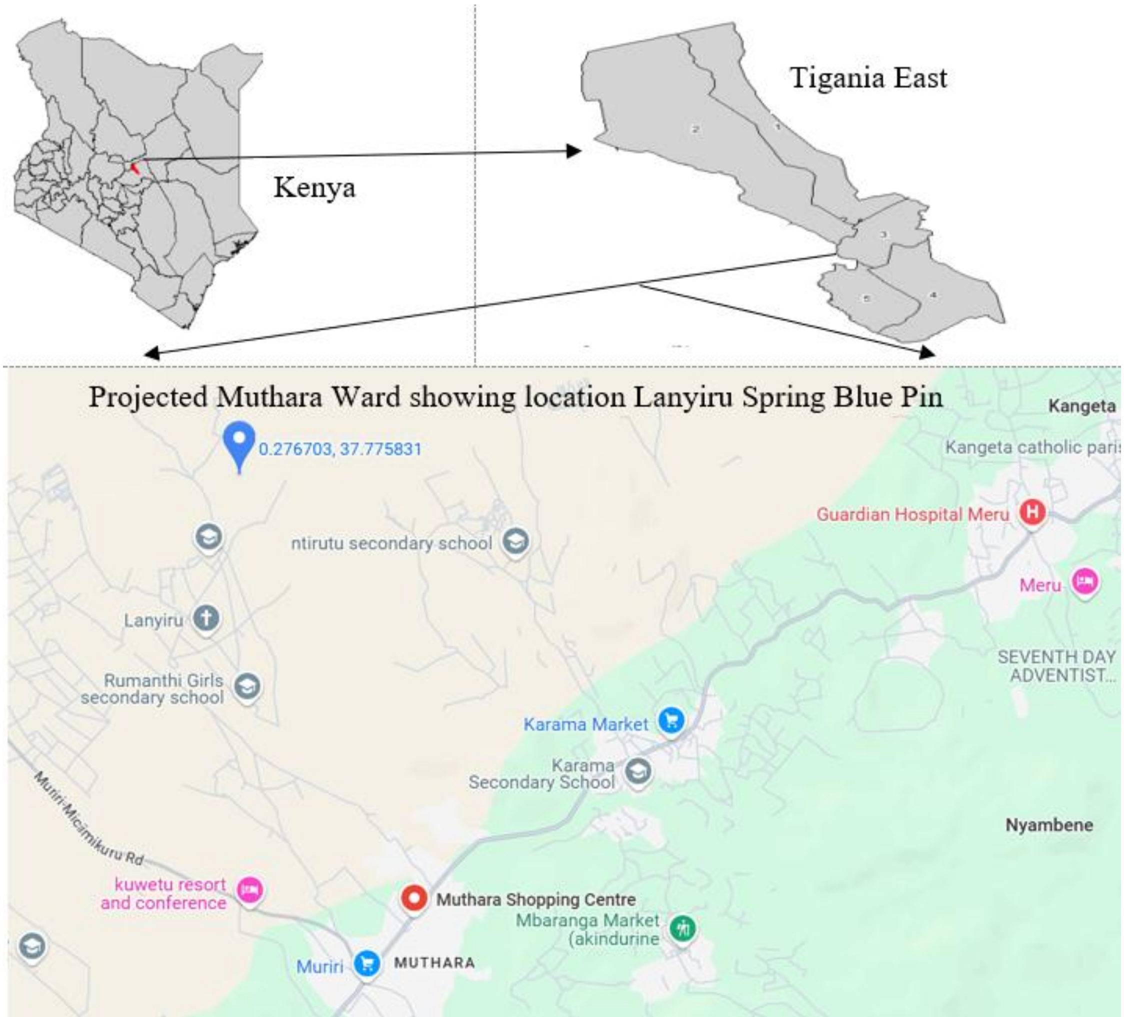

Figure 1: Map showing the location of Lanyiru Spring in Meru County

The hilly terrain influences water runoff and groundwater recharge, resulting in many springs. The largely rural population relies on these springs for water, with increasing demand and land use changes affecting water availability and quality.

Muthara Ward was identified as a suitable study area due to its intensive agricultural activity and heavy reliance on natural water sources. Farming formed the main livelihood for the residents, and both traditional and modern farming techniques were commonly practiced. Notably, the application of agrochemical inputs such as fertilizers, herbicides, and pesticides are widespread as farmers attempted to improve agricultural productivity, secure food supply, and combat the adverse effects of climate variability and change. The Lanyiru springs were chosen as sampling sites because they represented the primary water sources for most households, raising concerns over potential contamination from nearby agricultural practices. Sampling are were marked using GPS (Table 1).

Table 1: Coordinates of water sampling points with the Location along the Lanyiru Spring.

Sample	Latitude	Longitude
LP1	0.271	37.779
LP1A	0.271	37.778
LP1B	0.272	37.778
LP2	0.273	37.778
LP2A	0.274	37.778
LP2B	0.277	37.776
LP3	0.279	37.776
LP3A	0.28	37.776
LP3B	0.281	37.777
LP4	0.384	37.777
LP4A	0.287	37.777
LP4B	0.289	37.777

Where; The sample codes represent accession numbers assigned to water samples collected from different locations along the Lanyiru Spring.

Table 1 presents the geographical coordinates of the water sampling points along the Lanyiru Spring. The table lists each sample by its unique code (LP1, LP1A, LP1B, etc.), along with the corresponding latitude and longitude. These codes serve as accession numbers assigned to water samples collected from various locations along the spring, allowing for precise identification and spatial reference of each sampling site. The coordinates indicate the specific position of each sample along the course of Lanyiru Spring, providing a basis for subsequent spatial analysis of water quality.

3.2 Study Design

The study adopted a cross-sectional descriptive design, aimed at assessing the water quality of the Lanyiru Springs in Muthara Ward, Meru County. A cross-sectional approach was chosen because it allowed for the collection of water samples and relevant environmental data at a single point in time across multiple locations along the spring. This design facilitated the evaluation of spatial variation in water quality and the potential influence of agricultural practices on the springs. The study involved systematic sampling of water from selected points along the Lanyiru Springs (Table 1). The design enabled the measurement of physicochemical and microbiological parameters of water, which were analyzed to determine contamination levels and assess compliance with water quality standards. Data collected were analyzed to identify patterns, relationships, and potential risks associated with water use by the local population. This design was appropriate because it provided a snapshot of water quality conditions, allowed for the comparison of multiple sampling sites simultaneously, and supported subsequent recommendations for water resource management in the area.

3.3 Chemicals and Analytical Instruments

The study utilized high-purity analytical-grade chemicals and reagents to ensure accuracy and reproducibility in all experimental procedures. A formazin primary standard suspension was used specifically for turbidity calibration. Other chemicals employed included ethylenediaminetetraacetic acid (EDTA, 99% purity) for metal ion complexation, hydrochloric acid (HCl, 37%) for sample acidification, nitrous oxide for relevant analytical procedures, and potassium hydroxide (KOH, 99% purity) for pH adjustments. All chemicals were procured from Merck, a recognized supplier of laboratory-grade reagents. Additionally, a standard potassium chloride (KCl) solution (99.99% purity) was obtained from Sigma-Aldrich for calibration of electrical conductivity meters. Ultra-pure water, used for sample dilution, reagent preparation, and cleaning of laboratory apparatus, was sourced from the Chuka University Laboratory to minimize contamination and maintain the integrity of analytical results.

A combination of field and laboratory instruments was employed to determine the physical, chemical, and microbiological characteristics of the spring water samples. Field measurements of temperature, pH, and electrical conductivity were performed using a Hanna Combo H198129 waterproof tester. Laboratory cross-checks of pH and conductivity were conducted using a Corning pH meter model 430 and a DDS 307 conductivity meter. For precise determination of pH and ion concentrations, a Metrohm 692 pH/Ion meter was employed. Anions, including fluoride, nitrate, sulfate, and carbonate, were quantified using Ion Chromatography (Thermo Scientific Dionex Aquion IC system) and/or Ion-Selective Electrode (ISE) methods, ensuring accurate measurement of water chemical composition. Cations, such as sodium (Na^{+}), potassium (K^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), as well as trace metals (Cd, Cu, Pb, Fe), were analyzed using a Flame Atomic Absorption Spectrometer (FAAS), providing sensitive and reliable quantification.

3.4. Validity, Reliability of Instruments and Sample Collection

3.4.1 Validity Test

Validity in this study refers to the extent to which the instruments and procedures accurately measured the intended water quality parameters. Instruments were selected based on their established performance in water quality analyses, supported by peer-reviewed literature, standard operating procedures, and expert recommendations. Before field deployment, all instruments were calibrated according to manufacturer specifications to reduce measurement bias.

The research methodology, including instrument selection, sampling techniques, and analytical procedures, was reviewed by academic and technical experts at Chuka University. Their feedback guided adjustments to equipment usage and sample collection protocols. Operator competence was considered, as experience with field and laboratory instruments affects measurement accuracy. Errors were minimized by following procedural guidelines, performing instrument calibrations, and handling samples consistently. Multiple readings were obtained for each parameter, and values were recorded only when they fell within the expected range. Any inconsistent readings were verified through recalibration and repeated measurement. These procedures ensured that the collected data accurately represented water quality at the sampling sites.

3.4.2 Reliability Test

Reliability refers to the consistency and repeatability of measurements obtained from the instruments and procedures. In the field, duplicate readings were taken for each parameter during sampling, and any discrepancies were resolved by recalibrating instruments and repeating measurements. In the laboratory, analyses were repeated for selected samples, and consistent results were obtained to confirm reproducibility. Laboratory protocols, including the standardized use of reagents, instruments, and calibration standards, were strictly followed to minimize procedural variation. These steps ensured that measurements were consistent, precise, and replicable across both field and laboratory analyses.

3.4.3 Sample Collection

Water samples (12) were collected once from four designated Lanyiru spring sources in September 2025 for the analysis of physicochemical and microbiological water quality parameters. Sampling procedures followed established environmental and water quality monitoring protocols. At each spring, samples were collected directly from the flowing water at the spring outlet to ensure that they were representative of the spring water at the time of sampling. Samples were collected in one-litre high-density polyethylene (HDPE) containers. Prior to sampling, all containers were thoroughly cleaned with laboratory-grade detergent, rinsed with distilled water, and then rinsed twice with water from the respective spring to eliminate the risk of cross-contamination between samples. Dry season samples were subdivided into half-litre HDPE containers for transport and labeled with the sample ID, date, and sampling location. Wet season samples were transported in a portable ice box maintained at 4–6°C to preserve both physico-chemical parameters and microbial integrity during transit.

Upon arrival at the Chuka University Laboratory, all samples were transferred to opaque containers and stored at ambient room temperature (approximately 22–25°C) to minimize microbial growth and prevent alterations in sensitive parameters, including dissolved oxygen, turbidity, and microbial composition. Containers remained sealed until analysis. All sampling, transport, and handling procedures followed strict aseptic techniques, including the use of disposable gloves, sterilized equipment, and sanitized surfaces, to ensure that the collected samples accurately reflected the water quality of the springs during both seasonal periods.

3.5 Data Collection

Water quality data were collected to determine the physical, chemical, and biological characteristics of the Lanyiru spring water samples. Analyses were conducted using a combination of in situ measurements at the sampling site and laboratory analyses to ensure accuracy and preserve sample integrity. All instruments were calibrated before use, and standardized procedures were followed for all measurements.

3.5.1. Determination of Physiochemical Properties

3.5.1.1 Determination of Physical Properties

The TDS was measured directly at the spring outlet using a Hanna Combo H198129 waterproof tester, which measures the total concentration of dissolved inorganic salts and ions in water. Before each measurement session, the instrument was calibrated using the manufacturer-specified procedure with the appropriate standard solutions. Calibration ensures the accuracy and reproducibility of measurements. At each sampling point, the instrument was immersed directly in the flowing water at the spring outlet to avoid interference from stagnant water, surface debris, or container effects. Measurements were recorded once the readings stabilized, typically within 30–60 seconds. The TDS value obtained reflects the ionic composition of the water at the time of sampling and is crucial for estimating the water's suitability for domestic, irrigation, or industrial use.

Turbidity was determined in situ using the nephelometric method, which quantifies the scattering of light by suspended particles. The instrument was calibrated immediately before each measurement using a formazin primary standard suspension, following standard laboratory and manufacturer protocols to ensure accurate readings. Water samples were measured directly at the spring outlet without transferring to containers to prevent sedimentation or particle loss. Readings were taken in triplicate at each point, and the average value was recorded. Turbidity provides a direct measure of particulate matter, including silt, organic debris, and microbial aggregates, which can affect water clarity, aesthetic quality, and suitability for treatment processes.

The pH of each spring water sample was measured directly at the spring outlet using a Corning pH meter model 430. Prior to measurements, the meter was calibrated using standard buffer solutions at pH 4.00, 7.00, and 10.00, prepared and verified according to manufacturer guidelines. Calibration ensured measurement accuracy across the expected pH range of the spring water. Readings were recorded once the meter stabilized, typically within 30–60 seconds, to avoid errors due to temperature fluctuations or atmospheric CO_2 exposure. Measurements were taken immediately at the spring outlet to reflect in situ conditions.

The electrical conductivity (EC) was measured in situ using a DDS 307 conductivity meter, calibrated prior to sampling with standard conductivity solutions as per the manufacturer's instructions. Measurements were performed directly at the spring outlet to capture the natural ionic composition of the water. To estimate total dissolved solids (TDS), EC readings were multiplied by a conversion factor of 0.67 as done by Stigter *et al.* (2013), based on the ionic characteristics of the local groundwater:

Conductivity (S/cm) x 0.67) = TDS (ppm).

This factor aligns with values used in previous hydrochemical studies of similar water sources. Each EC measurement was recorded after the reading stabilized, and duplicate readings were taken to ensure precision.

Water temperature at each sampling site was recorded using a calibrated mercury-in-glass thermometer. Calibration was performed prior to fieldwork to ensure accurate readings. Readings were taken immediately, and the thermometer was allowed to equilibrate with the water for consistent measurement.

3.5.1.2 Determination of Cations

Major cations (Na^+, Ca^{2+}, Mg^{2+}) were determined as the dissolved fraction by Flame Atomic Absorption Spectrometry (FAAS), and trace metals (Cd, Cu, Pb, Fe reported as total Fe) were determined as total-recoverable concentrations by Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) following microwave-assisted acid digestion. Immediately on receipt, each sample was split into two aliquots in the laboratory: one aliquot was filtered through a 0.45 µm cellulose nitrate membrane filter using a sterile syringe/filter assembly to obtain the dissolved fraction for FAAS, and a second unfiltered aliquot was set aside for total-recoverable analysis. The dissolved-fraction aliquots were acidified to pH < 2 by adding ultrapure concentrated nitric acid (trace-metal grade, 69–70% HNO_3) at approximately 1 mL per 100 mL of sample (volume added adjusted as required to attain pH < 2), the final pH was verified, and samples were stored at 4 ± 2 °C until analysis. The unfiltered aliquots for total-recoverable metals were preserved with the same acidification procedure prior to digestion.

For FAAS determination of Na^+, Ca^{2+} and Mg^{2+}, filtered and acidified aliquots were analyzed on a calibrated flame atomic absorption spectrometer. Instrument settings (lamp current, burner height, slit width) were optimized for each element according to the manufacturer's instructions; an air–acetylene flame was used for the three cations. Calibration was performed daily using certified single-element standard solutions prepared at a minimum of five concentration points spanning the expected sample range; calibration curves were accepted only if correlation coefficients (R^2) were $\geq$ 0.995. Laboratory procedural blanks, method blanks, and a quality control standard were analyzed with each batch. Each sample was run in duplicate; if duplicate results differed by more than 5% relative, the sample was re-analyzed. Concentrations were calculated from the calibration curves and reported in mg/L.

For total-recoverable Cd, Cu, Pb and total Fe, unfiltered aliquots were subjected to microwave-assisted acid digestion prior to ICP-MS analysis. For each digestion, 50 mL of unfiltered sample was placed into a Teflon microwave vessel and 5 mL of ultrapure concentrated nitric acid (69–70% HNO_3) was added. Vessels were sealed and digested in a microwave system using a program that ramped to ~180 °C and held for 10 minutes (program and exact ramp/hold times followed the microwave manufacturer's recommended protocol for aqueous samples). After cooling to room temperature, digestates were quantitatively transferred to 50 mL volumetric flasks and brought to volume with ultrapure water. Digestates were filtered through 0.45 µm membrane filters if particulates remained, and aliquots were further diluted as necessary to bring concentrations within calibration ranges.

The ICP-MS analysis was performed on the digested, diluted samples using an instrument tuned and optimized the same day as the analyses. Multi-element calibration standards (at least five levels) prepared from certified reference materials were used to construct calibration curves; internal standardization (e.g., indium or rhodium at a fixed concentration added to all standards and samples) was employed to correct for matrix effects and instrument drift. Method blanks, laboratory control spikes (matrix spikes), and a certified reference material (CRM) were included with each analytical batch. Duplicate analyses were performed for at least 10% of samples. Acceptance criteria for QC samples were set at recoveries between 80–120% for spikes and CRM agreement within the certified range; batches failing QC were reprocessed. Limits of detection (LOD) and limits of quantification (LOQ) were determined from repeated analysis of blanks and low-level standards and are reported with the results. Final trace metal concentrations are reported as mg/L (or µg/L where appropriate) for each element. All reagents and standards were trace-metal grade, all glassware and digestion vessels were acid-washed and rinsed with ultrapure water, and procedural blanks accompanied every batch to check for contamination. Results from FAAS and ICP-MS were blank-corrected, checked against QC criteria, and only accepted when all quality control checks passed.

3.5.1.3 Determination of Anions

The concentrations of nitrate (NO_3^-), sulphate (SO_4^{2-}), and carbonate (CO_3^{2-}) in the spring water samples were determined using ion chromatography (IC) in accordance with APHA (2017) and EPA (1993) guidelines. Analyses were carried out on a Thermo Scientific Dionex Aquion IC system fitted with an AS-DV Autosampler, an IonPac AS14 analytical column (4 × 250 mm), an IonPac AG14 guard column (4 × 50 mm), and a suppressed conductivity detector. Immediately after collection, water samples were transported to the laboratory in sealed HDPE containers and stored at room temperature until analysis. Prior to measurement, each sample was brought to ambient temperature and filtered through a 0.45 µm cellulose nitrate membrane filter to remove suspended particulates, after which 10 mL of the filtrate was transferred into pre-cleaned, labeled polypropylene vials.

Calibration of the IC system was performed using certified multi-ion standards of nitrate, sulphate, and carbonate prepared at 1, 5, 10, 25, and 50 mg/L, and calibration curves with $R^2 \geq 0.995$ were accepted. The eluent used was 3.5 mM sodium carbonate/1.0 mM sodium bicarbonate prepared in ultrapure water, degassed before use, and pumped at a flow rate of 1.2 mL/min, while the injection volume was set at 25 µL for all samples and standards. Each water sample was injected in duplicate, and the separated ions were detected by suppressed conductivity, with peak areas quantified against the calibration standards. To check for contamination or carryover, ultrapure water blanks were run after every three samples, and after every ten injections, one calibration standard was re-analyzed to verify instrument stability. Quality assurance was further ensured by including a laboratory control sample and a duplicate field sample in each analytical batch, and results were accepted only when quality control recoveries were within ±10% of expected values. The final concentrations of nitrate, sulphate, and carbonate were calculated in mg/L, and only values falling within the established calibration range were reported.

Fluoride concentration in the spring water samples was determined using an Ion-Selective Electrode (ISE) method in accordance with APHA (2017) protocols. A Metrohm 692 pH/Ion Meter fitted with a Metrohm fluoride ion-selective electrode and a Metrohm Ag/AgCl reference electrode was used for the measurements. Prior to analysis, the electrode system was conditioned according to the manufacturer's instructions. Calibration was carried out by preparing a series of standard fluoride solutions with known concentrations (0.1–10 mg/L). The standards were measured to generate a calibration curve, and electrode slope and response were verified to fall within the acceptable range of –54 to –60 mV per decade change in concentration.

For each sample, 10 mL of the water sample was placed in a clean plastic beaker, and an equal volume of Total Ionic Strength Adjustment Buffer (TISAB III) was added to control pH, eliminate potential interferences from polyvalent ions, and maintain constant ionic strength. The solution was stirred gently with a magnetic stirrer to ensure homogeneity.

The fluoride ISE was then immersed in the prepared sample solution, and readings were recorded once the electrode potential stabilized (typically within 2–3 minutes). Each sample was analyzed in duplicate to confirm repeatability, and results were interpolated directly from the calibration curve. Between analyses, the electrode was rinsed thoroughly with distilled water and gently blotted dry to prevent cross-contamination. All measurements were carried out at the Chuka University Laboratory under controlled conditions. Quality control was maintained by reanalyzing one calibration standard after every five samples to check for electrode drift. Any drift exceeding ±5% prompted recalibration of the instrument before proceeding with further analyses.

3.5.2 Coliform Bacteria Analysis using Most Probable Number Method

Coliform bacteria in the spring water samples were analyzed using the Most Probable Number (MPN) method in accordance with APHA (2017) standard procedures. Analysis for coliform bacteria was carried out a day after the samples were received in the laboratory and maintained at 4 ± 2 °C in a portable icebox until inoculation. Lauryl tryptose broth (LTB) with inverted Durham tubes was prepared in both double-strength (for 10 mL inocula) and single-strength (for 1.0 mL and 0.1 mL inocula), and all media and glassware, including Durham tubes, were sterilized by autoclaving at 121 °C for 15 minutes before use. For each sample, fifteen sterile tubes were arranged in three sets of five tubes: Set A contained 10.0 mL double-strength LTB, Set B contained 10.0 mL single-strength LTB, and Set C contained 10.0 mL single-strength LTB. Using sterile calibrated pipettes, 10.0 mL of sample was inoculated into each tube of Set A, 1.0 mL into each tube of Set B, and 0.1 mL (100 µL) into each tube of Set C, after which tubes were gently inverted to mix.

A sterile control tube containing media with sterile distilled water and a positive control tube inoculated with a known coliform strain were included in each batch. The inoculated tubes were incubated upright at 35.0 ± 0.5 °C for 24–48 hours and examined at both 24 and 48 hours for gas in the Durham tubes and turbidity; tubes showing either were recorded as presumptive positive. The number of positive tubes in the three sets was recorded as a triplet (5-3-1) and compared to the 5-tube MPN index table to estimate the number of coliform organisms per 100 mL, with values exceeding table limits reported as greater than the maximum index. To confirm total coliforms, 1.0 mL from each presumptive positive tube was transferred into 10.0 mL of Brilliant Green Lactose Bile (BGLB) broth and incubated at 35.0 ± 0.5 °C for 48 hours, with gas production confirming coliform presence.

For fecal (thermotolerant) coliforms, 1.0 mL aliquots from presumptive positive tubes were inoculated into 10.0 mL of EC broth and incubated at 44.5 ± 0.2 °C for 24 hours, with gas in the Durham tubes recorded as positive. Each analytical batch included sterility controls (media + sterile water), positive controls (reference coliform culture), duplicate field samples, and reagent blanks, and any batch failing control criteria was invalidated and repeated. Final results were expressed as MPN of total and fecal coliforms per 100 mL of sample with 95% confidence limits based on the MPN table. All contaminated materials were autoclaved at 121 °C for 15 minutes prior to disposal, and work areas and pipettes were disinfected with 70% ethanol after each batch.

3.5 Data Analysis

The dataset consisted of quantitative measurements of physicochemical parameters (major cations, trace metals, anions, temperature, pH, turbidity, and electrical conductivity) and microbiological parameters (total coliforms and fecal coliforms) collected from spring water sources across different sampling sites. All data were analyzed using R Studio version 2.4.3. Data cleaning and analysis were performed with the tidyverse package, statistical tests with car, regression diagnostics with lmtest and MASS, and visualizations with ggplot2. Descriptive statistics (mean, median, standard deviation, minimum, maximum) were first computed for each parameter across sites to provide a summary of the data. Boxplots, histograms, and Q-Q plots were used to visually assess distributional properties of the variables.

To compare concentrations of cations, anions, and physical parameters across spring sites, one-way Analysis of Variance (ANOVA) was applied. This is a parametric test that assumes normally distributed residuals and homogeneity of variances. Normality of residuals was checked using the Shapiro–Wilk test and Q-Q plots, while homogeneity of variance was assessed with Levene’s test. Where assumptions were met, ANOVA was applied with sampling site as the categorical independent variable and the individual parameter concentration as the dependent variable. For significant ANOVA results ($p < 0.05$), pairwise mean comparisons were conducted using the Least Significant Difference (LSD) test with Bonferroni correction to control for Type I error inflation.

For variables that did not meet ANOVA assumptions even after log or square-root transformation, Kruskal–Wallis tests were applied. This is a non-parametric test that compares medians across groups without assuming normality. To explore associations between continuous variables (between cations and anions, or between physicochemical and physical properties), Spearman’s rank correlation was used. This is a non-parametric correlation method chosen because many of the parameters did not follow a normal distribution and because relationships among water quality parameters are not strictly linear.

Microbiological data (total and fecal coliform counts) were analyzed using the Kruskal–Wallis test because bacterial are discrete, skewed, and non-normally distributed, violating ANOVA assumptions. Where significant differences were found, post-hoc pairwise comparisons were carried out using Dunn's test with Bonferroni adjustment. In addition, Spearman correlations were computed between coliform counts and physicochemical parameters to evaluate possible associations between microbial contamination and chemical conditions. To examine the combined influence of chemical parameters on microbial contamination, a multiple linear regression model was constructed with total coliform count as the dependent variable. Independent variables included selected heavy metals (Cd, Cu, Pb) and physicochemical parameters (turbidity, pH, conductivity). Because coliform counts are non-normally distributed, counts were log-transformed prior to regression to approximate normality.

Regression assumptions (linearity, independence of errors, normality of residuals, and homoscedasticity) were checked using residual plots, the Shapiro–Wilk test, and the Breusch–Pagan test. Models were refined using the MASS stepwise regression function, and multicollinearity was assessed using variance inflation factors (VIF). All statistical analyses were performed at a significance level of $\alpha = 0.05$. Results were reported with corresponding effect sizes and 95% confidence intervals where applicable. Final outputs were presented using visualizations including boxplots (for group comparisons), scatterplots with regression lines (for correlations and models), and bar graphs (for site-wise summaries).

3.6 Ethical Consideration

Ethical approval for the study was formally sought and obtained from the Chuka University Ethics Committee (Appendix I & II), ensuring that the research met the institutional requirements for conducting studies involving environmental sampling. In addition, external research authorization was granted by the National Commission for Science, Technology, and Innovation (NACOSTI) (Appendix III), in accordance with national regulations governing scientific research in Kenya. Permission to collect water samples from the spring under investigation was also sought from the relevant departments of the Meru County Government, including environmental and public health offices, to ensure compliance with local governance structures and environmental protection laws. Throughout the sample collection, handling, and laboratory analysis, strict ethical standards were upheld. This included the responsible and safe handling of chemicals and reagents, with proper disposal in line with laboratory safety protocols to prevent environmental contamination or harm to personnel. Academic integrity was maintained by ensuring that all secondary information, data sources, and references used in the study were accurately cited. Proper referencing formats were adhered to in order to avoid any form of plagiarism and to give due credit to original authors and researchers whose work informed this study.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physicochemical Properties of the Lanyiru Spring Waters in Meru County in Kenya

4.1.1 Chemical Properties (Cations)

Analysis of cations in Lanyiru spring water revealed pronounced spatial variations across sampling sites (Table 2). Overall, sodium (Na^{+}) and calcium (Ca^{2+}) dominated the cation profile, while trace metals such as lead (Pb^{2+}) and cadmium (Cd^{2+}) were present in comparatively low concentrations. Lead (Pb^{2+}) levels were consistently low, ranging between 0.005 and 0.008 mg/L. Despite the narrow range, ANOVA results indicated statistically significant site differences, $F(11, 24) = 4.84 \times 10^{28}$, $p < 0.001$, driven mainly by elevated values at LP1A and LP1B relative to other sites. Iron (Fe) exhibited much greater variability, from 0.652 mg/L at LP1B to 10.029 mg/L at LP4B, with ANOVA confirming significant heterogeneity, $F(11, 24) = 21.38$, $p < 0.001$. Cadmium (Cd^{2+}), though generally at trace levels, showed the widest relative differences, ranging from 0.0011 mg/L at LP1B to 0.041 mg/L at LP3A. The effect of site was highly significant, $F(11, 24) = 64, 264$, $p < 0.001$.

Table 2: Levels of Cations in Lanyiru spring water in Meru County in Kenya

Sample ID	Pb^{2+}	Fe^{2+}	Cd^{2+}	K^{+}	Na^{+}	Cu^{2+}	Ca^{2+}	Mg^{2+}	$CaCO_3$
LP1A	0.0076^{a}	2.211^{g}	0.022^{cde}	10.668^{k}	230.213^{f}	0.034^{fg}	11.973^{cd}	7.935^{a}	10.333^{a}
LP1B	0.0076^{a}	0.652^{h}	0.0011^{f}	11.835^{e}	258.752^{e}	0.014^{ij}	11.428^{cd}	2.645^{bc}	10.200^{ab}
LP1	0.0050^{b}	0.659^{h}	0.019^{cde}	10.765^{k}	173.136^{j}	0.061^{e}	8.163^{d}	4.959^{abc}	9.800^{c}
LP2	0.0050^{b}	2.796^{ef}	0.018^{cde}	17.574^{c}	407.154^{b}	0.090^{c}	10.340^{cd}	1.653^{bc}	9.967^{bc}
LP2A	0.0050^{b}	2.614^{fg}	0.014^{ef}	16.147^{d}	431.887^{a}	0.026^{gh}	13.061^{cd}	1.322^{c}	$9.967b^{c}$
LP2B	0.0050^{b}	2.884^{ef}	0.026^{cde}	12.322^{h}	197.869^{h}	0.073^{d}	14.694^{c}	5.951^{ab}	10.267^{a}
LP3	0.0050^{b}	5.299^{d}	0.015^{de}	12.127^{i}	175.038^{j}	0.023^{hi}	11.428^{cd}	1.984^{bc}	10.467^{a}
LP3A	0.0050^{b}	3.095^{e}	0.041^{a}	12.808^{g}	186.454^{i}	0.024^{h}	8.163^{d}	1.984^{bc}	10.367^{a}
LP3B	0.0050^{b}	3.214^{e}	0.039^{ab}	13.067^{f}	258.752^{e}	0.011^{j}	9.796^{cd}	1.322^{c}	10.467^{a}
LP4	0.0050^{b}	7.199^{c}	0.028^{abc}	15.305^{e}	213.089^{g}	0.041^{f}	14.693^{c}	0.992^{c}	10.400^{a}
LP4A	0.0050^{b}	8.781^{b}	0.028^{bcd}	36.900^{a}	283.486^{d}	0.106^{b}	37.551^{a}	7.935^{a}	10.400^{a}
LP4B	0.0050^{b}	10.029^{a}	0.022^{cde}	33.819^{b}	294.901^{c}	0.342^{a}	29.932^{b}	2.314^{bc}	10.300^{a}
Mean	0.005	4.119	0.023	16.945	259.228	0.070	15.102	2.893	331.778
WHO limits	0.01	0.3	<300	12	<60	1.3	150	400-420	100-300
Lsd (α=0.05)	0.0026	0.440	0.013	0.191	10.375	0.009	5.935	4.416	15.424
Cv (%)	1.512	5.963	17.920	0.358	1.271	4.347	12.483	48.487	1.477

Means followed with same letters in columns are not statistically significantly different at α = 0.05.

Among the major cations, sodium (Na^+) recorded the highest concentrations, spanning 173.136 mg/L at LP1 to 431.887 mg/L at LP2A, with ANOVA indicating strong site differences, $F(11, 24) = 2641$, $p < 0.001$. Potassium (K^+) concentrations were comparatively lower, ranging from 10.668 mg/L at LP1A to 36.900 mg/L at LP4A, but still showed pronounced variation across sites, $F(11, 24) = 1068$, $p < 0.001$. Copper (Cu^{2+}) was present in low to moderate amounts (0.011 mg/L at LP3B to 0.342 mg/L at LP4B), with statistically significant differences confirmed by ANOVA, $F(11, 24) = 211.6$, $p < 0.001$. Calcium (Ca^{2+}) concentrations varied substantially, from 8.163 mg/L at LP1 and LP3A to 37.551 mg/L at LP4A, with ANOVA showing significant site effects, $F(11, 24) = 12.8$, $p < 0.001$. Magnesium (Mg^{2+}) was lowest at LP4 (0.992 mg/L) and highest at LP1A and LP4A [(7.935 mg/L) Table 2], again with significant variation among sites, $F(11, 24) = 7.31$, $p < 0.001$.

There was significant spatial variation in the concentrations of sodium, potassium, copper, calcium, magnesium, iron, and cadmium across the sampling sites, and therefore the null hypothesis that there are no statistically significant differences in these cations is rejected. Measured concentrations of these ions were generally within the permissible limits set by WHO and the Kenya Bureau of Standards (KEBS) for drinking water, except for cadmium at LP3A, which exceeded the recommended maximum of 0.003 mg/L (WHO, 2017; KEBS, 2014), indicating a potential health concern. Lead concentrations, while slightly variable across sites, remained below both WHO (0.01 mg/L) and KEBS limits and showed minimal differences; therefore, the null hypothesis for lead cannot be entirely rejected.

The concentration of lead (Pb^{2+}) in the spring waters of Lanyiru revealed location-specific variability. LP1A and LP1B recorded the highest concentrations at 0.008 mg/L, whereas other sampling points consistently measured 0.005 mg/L. These values are below the WHO permissible limit of 0.01 mg/L for drinking water. However, the detection of lead remains concerning due to its cumulative toxicity. In contrast, a study by Lajçi *et al.* (2017) in the Rugova region of Kosovo found no detectable levels of lead in spring waters, suggesting either a more pristine geological formation or minimal anthropogenic influence in that region. The presence of lead in Lanyiru spring waters may be attributed to local geology, particularly lead-bearing minerals such as galena and cerussite, or to anthropogenic factors such as deteriorating plumbing, vehicle emissions, or informal waste disposal.

Lead is a non-essential and highly toxic metal, and even low-level exposure has been linked to serious health effects. It can mimic calcium and disrupt enzymatic processes, leading to neurological, reproductive, renal, and cognitive impairments, especially in children. Chronic exposure results in accumulation within bones and organs, compounding long-term risks (Gudadhe *et al.*, 2024). Thus, although measured concentrations were within WHO limits, no level of lead exposure is considered completely safe, underscoring the need for regular monitoring and preventive interventions.

Iron (Fe) concentrations varied substantially across the study sites, ranging from 0.652 mg/L at LP1B to 10.029 mg/L at LP4B. These values exceed the WHO's aesthetic guideline of 0.3 mg/L, suggesting that although the water remains safe for consumption, elevated iron may affect taste, color, and household usability. The wide variability in Fe levels reflects local geological differences and groundwater-rock interactions, which strongly influence iron content in spring waters. Comparable findings have been reported globally. Siepak *et al.* (2022) documented high Fe levels in Polish springs in both urban and forested regions, while Shigut *et al.* (2017) observed elevated Fe in Ethiopian springs linked to deep aquifer mineralogy and rock structures. These parallels confirm that Fe variability is primarily geologically controlled. Although not directly toxic at low levels, excessive Fe can cause aesthetic issues, encourage iron bacteria growth, and complicate household water storage and distribution systems. Regular monitoring is therefore necessary to safeguard both consumer satisfaction and infrastructure longevity.

Cadmium (Cd^{2+}) concentrations ranged from 0.0011 mg/L at LP1B to 0.041 mg/L at LP3A. The highest value exceeds the WHO guideline of 0.003 mg/L by more than tenfold, indicating potential health hazards. Unlike the current findings, Lajçi *et al.* (2017) reported no detectable Cd in Kosovo spring waters, highlighting the atypical and alarming presence in Lanyiru. Cadmium is often linked to agricultural runoff, yet in areas without intensive agriculture, its occurrence may be geogenic, derived from cadmium-containing rocks or natural leaching from soils. Cadmium is a toxic non-essential element associated with kidney damage, bone demineralization, hypertension, and carcinogenic effects (Bibi *et al.*, 2023). It also competes with zinc in biological systems, disrupting essential enzymatic pathways (Brzóska & Moniuszko-Jakoniuk, 2001). These findings raise a public health concern, particularly at LP3A, where direct human consumption should be restricted and remediation strategies, such as reverse osmosis or activated carbon filtration, explored.

Potassium (K^+) concentrations ranged from 10.668 mg/L at LP1A to 36.900 mg/L at LP4A. These values are significantly higher than those reported by Lajçi *et al.* (2017) in Kosovo (0.542–0.912 mg/L), indicating substantial local variability likely due to geological or hydrochemical processes. Potassium is an essential nutrient, but very high concentrations in natural waters are rare. While agricultural fertilizer runoff can elevate K levels, the absence of intensive farming in the study area suggests a predominantly geogenic origin. Although measured values do not exceed established health guidelines, individuals with kidney disease may be vulnerable due to impaired excretion of excess potassium. Continued water quality surveillance and tailored public health advisories may therefore be warranted.

Sodium (Na^+) concentrations ranged between 173.136 mg/L at LP1 and 431.887 mg/L at LP2A, making it the dominant cation across all sites. Elevated sodium levels in drinking water can pose risks for individuals with hypertension or other cardiovascular conditions, even when within general safety thresholds (Spahia *et al.*, 2024). The high variability observed across sites likely reflects the influence of aquifer mineralogy and local hydrogeological dynamics rather than anthropogenic inputs. Compared to values reported in spring waters from other regions, the sodium levels in Meru are relatively elevated, emphasizing the need for long-term monitoring to ensure the safety of vulnerable populations.

Calcium (Ca^{2+}) concentrations showed substantial variation, ranging from 8.163 mg/L at LP1 and LP3A to 37.551 mg/L at LP4A. Magnesium (Mg^{2+}) levels were lowest at LP4 (0.992 mg/L) and highest at LP1A and LP4A (7.935 mg/L). Together, Ca^{2+} and Mg^{2+} contribute to moderate water hardness in the study area. Hardness influences water palatability, scaling in household appliances, and suitability for industrial use. According to Kozisek (2020), hardness is primarily controlled by dissolution of carbonate rocks such as limestone and dolomite, consistent with the likely geological context of Meru County.

Compared with other regions, the observed Ca^{2+} and Mg^{2+} levels are higher than those reported in Ethiopian springs (Shigut *et al.*, 2017) but lower than in Libya and Nepal (Tyeb *et al.*, 2022; Pokhrel *et al.*, 2025). This highlights the role of local geology and aquifer interactions in shaping mineral content. The moderate hardness detected suggests the water is suitable for human consumption, with minimal risks of scaling or kidney stone formation sometimes associated with excessively hard water.

From a management standpoint, these results are encouraging. Moderate hardness reduces the need for costly softening treatment, which can be impractical in resource-limited settings. It also underscores the importance of routine monitoring, as shifts in groundwater chemistry due to natural or anthropogenic drivers could alter mineral balance over time. Although magnesium levels were relatively low compared to other regions, they still contribute positively to dietary intake. For communities heavily reliant on spring water, however, the low Mg^{2+} content highlights the need for integrated water quality and nutritional surveillance to ensure adequate mineral consumption.

4.1.2 Properties of Anions in Lanyiru Spring Water

Sulfate (SO_4^{2-}) concentrations varied notably across sites, ranging from a low of 29.975 mg/L at LP1 to a high of 132.853 mg/L at LP4A, with an overall mean of 68.030 mg/L. ANOVA results confirmed statistically significant differences among sampling sites, $F(11, 24) = 1068$, $p < 0.001$.

Table 3: Levels of anions in Lanyiru spring water in Meru County in Kenya

Sample ID	SO_4^{2-} (mg/L)	Cl^- (mg/L)	F^- (mg/L)
LP1A	53.870^{g}	251.922^{g}	2.467^{g}
LP1B	39.087^{h}	281.913^{b}	3.400^{f}
LP1	29.975^{i}	259.919^{ef}	2.767^{g}
LP2	97.225^{c}	271.916^{cd}	7.567^{b}
LP2A	35.643^{h}	261.252^{ef}	4.133^{e}
LP2B	67.033^{e}	263.918^{e}	2.600^{g}
LP3	59.133^{f}	277.914^{b}	4.067^{e}
LP3A	59.940^{f}	269.916^{d}	3.333^{f}
LP3B	61.360^{f}	261.917^{ef}	3.833^{e}
LP4	75.740^{d}	276.581^{bc}	4.867^{d}
LP4A	132.853^{a}	311.903^{a}	6.667^{c}
LP4B	104.500^{b}	257.920^{f}	8.400^{a}
Means	68.0301	270.5826	4.5083
Lsd (α=0.05)	5.0744	5.9343	0.3747
Cv (%)	2.3692	0.6966	2.6401

Means followed with same letters in columns are not statistically significantly different at $\alpha = 0.05$.

On the other hand, Chloride (Cl^-) levels were generally higher and more consistent compared to sulfate, spanning from 251.922 mg/L at LP1A to 311.903 mg/L at LP4A, with a mean of 270.583 mg/L. ANOVA indicated statistically significant variability among the springs, $F(11, 24) = 211.6$, $p < 0.001$. Lastly, Fluoride (F^-) concentrations were comparatively lower than chloride but displayed wider variability than sulfate, ranging from 2.467 mg/L at LP1A to 8.400 mg/L at LP4B, with an average of 4.508 mg/L. ANOVA results showed statistically significant differences across sites, $F(11, 24) = 838$, $p < 0.001$ (Table 3).

4.1.3 Physical Properties of Lanyiru Spring

Water was generally alkaline, ranging from 8.9 at LP1 to 10.467 at LP3 and LP3B, with a mean of 10.156 (Table 4). ANOVA results indicated statistically significant differences across sampling sites, $F(11, 24) = 78.65$, $p < 0.001$. Water temperature varied moderately across sampling sites, from 23.833 °C at LP3 to 26.867 °C at LP2, with an overall mean of 25.264 °C. ANOVA results confirmed statistically significant differences among sites, $F(11, 24) = 56.38$, $p < 0.001$. Conductivity varied from 739.333 µS/cm at LP3A to 867.667 µS/cm at LP4A, averaging 775.722 µS/cm. ANOVA results indicated statistically significant differences among sampling sites, $F(11, 24) = 1373$, $p < 0.001$. Turbidity showed the greatest variability, ranging from

7.137 NTU at LP1B to 1000.000 NTU at LP4B, with a mean of 138.137 NTU. ANOVA results confirmed statistically significant differences among sampling sites, $F(11, 24) = 7.241$, $p < 0.001$ (Table 4).

Table 4: Levels of physical parameters in Lanyiru spring Water in Meru County in Kenya

Sample ID	pH	Temp (°C)	Conductivity (µS/cm)	Turbidity (NTU)
LP1A	10.333 [a]	25.233 [cd]	746.667 [b]	8.650 [d]
LP1B	10.2 [ab]	24.367 [e]	749.333 [b]	7.137 [d]
LP1	8.9 [d]	26.500 [ab]	768.000 [b]	7.273 [d]
LP2	9.8 [c]	26.867 [a]	758.333 [b]	25.500 [cd]
LP2A	9.967 [bc]	26.800 [a]	755.333 [b]	25.547 [cd]
LP2B	10.27 [a]	26.200 [ab]	758.667 [b]	19.500 [cd]
LP3	10.47 [a]	23.833 [e]	750.667 [b]	20.990 [cd]
LP3A	10.37 [a]	25.933 [bc]	739.333 [b]	8.137 [d]
LP3B	10.47 [a]	24.100 [e]	750.667 [b]	17.310 [cd]
LP4	10.4 [a]	24.633 [de]	805.667 [ab]	60.933 [c]
LP4A	10.4 [a]	24.267 [e]	867.667 [a]	456.667 [b]
LP4B	10.3 [a]	24.433 [de]	858.333 [a]	1000.000 [a]
Means	10.156	25.264	775.722	138.137
Lsd (α=0.05)	0.273	0.821	66.823	44.056
Cv (%)	0.853	1.036	2.736	10.129

Means followed with same letters in columns are not statistically significantly different at α = 0.05.

The physical parameters of Lanyiru spring waters exhibited clear spatial variability, leading to the rejection of the null hypothesis that these characteristics are uniform across sampling sites. The pH values across the Lanyiru springs were consistently high, with both the lowest and highest readings exceeding the WHO recommended range of 6.5–8.5 for potable water. These values exceed those reported in Ethiopia (Shigut *et al.*, 2017), Nepal (Pokhrel *et al.*, 2025), Iraq (Abduljabar *et al.*, 2020), India (Singh *et al.*, 2014; Vardhan *et al.*, 2015), Pakistan (Kanwal *et al.*, 2017) and Libya (Tyeb *et al.*, 2022), where spring water pH generally remained closer to neutral or moderately alkaline. The elevated pH likely results from geochemical processes, such as the weathering of feldspathic and carbonate minerals releasing sodium and calcium (Venkatramanan *et al.*, 2013). Localized anthropogenic contributions, including detergent use, wastewater discharge, and agricultural runoff, may also influence pH. High pH can reduce the formation of hypochlorous acid during water disinfection and, over prolonged exposure, may irritate mucous membranes or disrupt digestion. While not indicative of immediate acute toxicity, these levels highlight the need for continued monitoring to ensure safe water quality.

Temperature varied across the Lanyiru springs, with the lowest values observed at shaded or less exposed sites and the highest at springs receiving greater solar exposure. Compared with other regions, Lanyiru spring temperatures are relatively elevated. Groundwater temperatures in Iraq ranged from 11.8°C to 24.1°C (Abduljabar *et al.,* 2020), in India between 20.69°C and 21.5°C (Singh *et al.,* 2014), and in Pakistan from 13°C to 22°C (Kanwal *et al.,* 2017). The higher temperatures at Lanyiru springs may result from local climatic conditions, reduced canopy cover, direct sunlight, and shallow aquifer characteristics. Elevated temperatures can influence microbial activity and mineral solubility, which may impact water quality over time. Understanding these thermal patterns provides insight into potential seasonal and site-specific variations in microbial and chemical composition.

Turbidity levels varied substantially across the Lanyiru springs, with LP4A and LP4B recording values far above the WHO guideline of 5 NTU. These high turbidity values indicate the presence of suspended particulates such as silt, clay, organic matter, and microbial communities (Davies- Colley & Smith, 2001). The elevated turbidity at these sites may be associated with surface runoff, soil erosion, livestock access, and localized anthropogenic activities. High turbidity can reduce the effectiveness of disinfection and affect water clarity, potentially increasing the risk of waterborne pathogens. For comparison, turbidity measurements in Ethiopia (Shigut *et al.*, 2017), Pakistan (Kanwal *et al.,* 2017), and Iraq (Abduljabar *et al.,* 2020) were substantially lower, indicating lower particulate loads in those water sources. Seasonal rainfall may also contribute to increased turbidity, as observed by Pokhrel *et al.* (2025), who reported elevated particulate concentrations during the wet season, which could explain the extreme values recorded in this study.

Variation in electrical conductivity (EC) was observed across the springs, reflecting differences in ionic strength and mineral content. The highest EC values occurred at LP4A and LP4B, indicating mineral-rich water primarily influenced by geogenic processes rather than direct anthropogenic input. EC correlates with dissolved ions such as chlorides, sulfates, calcium, magnesium, and sodium (Marandi *et al.,* 2013), affecting water taste, corrosivity, and domestic and agricultural suitability. The EC in Lanyiru springs exceeds that reported in Ethiopia (566–627 µS/cm; Shigut *et al.*, 2017), Nepal (393–472 µS/cm; Pokhrel *et al.,* 2025), India (510–684 µS/cm; Singh *et al.*, 2014), and Pakistan (122–600 µS/cm; Kanwal *et al.*, 2017), but aligns with Libya (712–1437 µS/cm; Tyeb *et al.,* 2022), where naturally mineral-rich aquifers explain similar readings. Elevated EC reflects a stable presence of dissolved ions, which may contribute to moderate water hardness, influencing domestic usability while remaining within WHO limits. Monitoring of pH, temperature, turbidity, and EC confirms that Lanyiru spring waters are influenced by both natural hydrogeological processes and localized anthropogenic activities. These results validate the rejection of the null hypothesis and emphasize the need for targeted management strategies, particularly to address turbidity and maintain overall water quality.

4.2 Correlation between Physico-chemical Parameters in Spring Water from Lanyiru Spring, Meru County, Kenya

The analysis of the correlations between various elements in the dataset revealed both strong, significant relationships and some weaker or non-significant associations. A very strong positive correlation was observed between K^{2+} and turbidity [(0.7917, p = 0.002) Figure 2]. This indicates that as the concentration of Potassium increases, the Turbidity value also tends to increase. Similarly, Na^+ and Tub showed a strong positive correlation (0.6235, p = 0.013), suggesting that higher sodium levels are associated with higher Tub values (Figure 2). Sulfate SO_4^{2-}) and Fluoride (F^-) also displayed a strong positive correlation (0.6904, p = 0.004), indicating that an increase in sulfur is linked to higher fluoride concentrations. Iron (Fe) and Calcium Carbonate ($CaCO_3$) had a similarly strong positive correlation (0.8143, p = 0.001), suggesting that higher iron concentrations are associated with higher calcium carbonate levels (Figure 2). On the negative side, a moderate negative correlation was found between Pb^{2+} and Tub (-0.6407, p = 0.008), indicating that higher lead concentrations tend to correspond with lower Tub values. In contrast, Fe^{2+} and temperature (Temp) showed a weak negative correlation (-0.2444, p = 0.226), which was not statistically significant. Similarly, potassium and Mg^{2+} exhibited a moderate negative correlation (-0.3423, p = 0.071), but this was also not statistically significant (Figure 2).

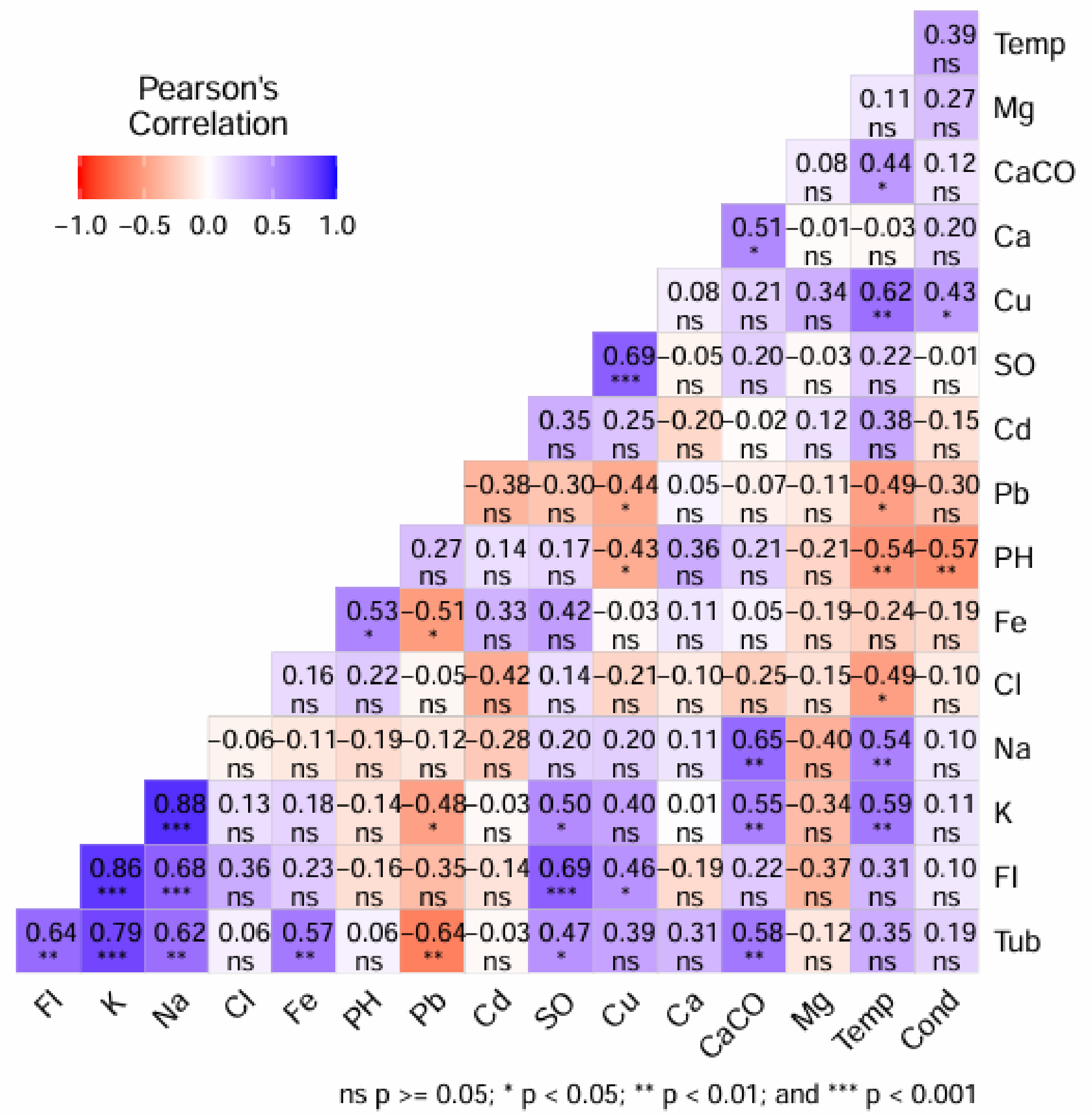

Figure 2: Correlation between physico-chemical parameters in spring water from Lanyiru Spring, Meru County, Kenya. Where CaCO = calcium carbonate ($CaCO_3$), PH =pH, Fl= Fluoride , SO = Sulfates, Mg= Magnesium, Temp = Temperature, K = Potasium, Cl = chloride, Turbidity, Cu = Copper, Ca = Calcium, Pb = Lead, Fe = Iron.

Furthermore, a moderate positive correlation was found between Na^+ and $CaCO_3$ (0.6468, p = 0.012), suggesting that as Na^+ concentration increases, $CaCO_3$ levels tend to rise as well. However, the correlation between K and pH (-0.1426, p = 0.478) was very weak and not statistically significant. A similarly weak negative correlation was observed between Na^+ and pH (-0.1857, p = 0.344), indicating that this relationship is also not statistically significant (Figure 2).

4.3 Total and Faecal Coliform Bacteria in the Water from Lanyiru Spring, Meru County

4.3.1 Levels of Total and Faecal Coliform Bacteria

The Kruskal-Wallis test revealed a significant difference in *T_Coli* concentration across the sample groups, H(11) = 31.03, p = 0.00109, indicating that at least one sample group differed significantly from the others (Table 5). Based on the median values of total Coliform level, the sample groups with the highest levels were LP1B (median = 79 cfu), LP1A (median = 70 cfu), and LP3B (median = 40 cfu). In contrast, the sample groups with the lowest total coliform levels were LP3A (median = 3.7), followed by LP4 (median = 4.5 cfu), and LP4A with a median of 6.8 cfu (Table 5).

Table 5: Levels of total coliform bacteria (CFU) in Lanyiru spring water in Meru County in Kenya

Sample	Mean (CFU)	Min (CFU)	Max (CFU)	Median (CFU)	Rank Median (CFU)
LP1	21	17	25	21	19.5
LP1A	57.7	33	70	70	33.5
LP1B	68.3	47	79	79	35.5
LP2	20.7	17	24	21	19.5
LP2A	35	31	41	33	27.5
LP2B	5.9	5.6	6.1	6	8
LP3	29.1	9.3	68	10	13
LP3A	3.77	3.6	4	3.7	2
LP3B	31	26	40	27	25
LP4	5.9	4	9.2	4.5	5.5
LP4A	7.77	4.5	12	6.8	10
LP4B	17	12	24	15	16
			Kruskal-Wallis H(*11*) = 31.03, p = 0.00109		

The Kruskal-Wallis test revealed a significant difference in feacal coliforms levels across the sample groups, H(*11*)=28.38 p=0.0028, indicating that at least one sample group differed significantly from the others. Based on the median values of feacal coliforms levels, the sample groups with the highest feacal coliforms levels were LP1B, LP1A, and LP3B, each having a median of 6.8 cfu or higher. In contrast, the sample group with the lowest feacal coliforms levels was LP3A, with a median of 1.8, followed by LP2B, with a median of 3.6 cfu.

Table 6: Levels of feacal coliform bacteria in Lanyiru spring Water in Meru County in Kenya

Sample IDs	Mean (CFU)	Min (CFU)	Max (CFU)	Median (CFU)	Rank Median (CFU)
LP1	5.63	4	6.8	6.1	21.5
LP1A	7.23	6.8	8.1	6.8	27.5
LP1B	7.6	6.8	9.2	6.8	27.5
LP2	4.93	4	6.8	4	15
LP2A	4.93	4	6.8	4	15
LP2B	3.03	1.8	3.7	3.6	7.5
LP3	3.87	3.6	4	4	15
LP3A	1.87	1.8	2	1.8	2.5
LP3B	7.3	6.8	8.3	6.8	27.5
LP4	3.27	1.8	4	4	15
LP4A	3.33	2	4	4	15
LP4B	6.9	6.1	7.8	6.8	27.5
Kruskal-Wallis $H(11) = 28.38$, $p = 0.0028$					

Pairwise comparisons using Wilcoxon rank-sum tests with Bonferroni correction were conducted to identify specific differences between sample groups. The pairwise results showed that the feacal coliforms levels were significantly different between several pairs of sample groups (Table 6). Total coliform levels in Lanyiru Spring water exhibited significant spatial variation, with counts ranging from 3.7 CFU/100 mL at LP3A to 79 CFU/100 mL at LP1B. These values exceed the World Health Organization (WHO, 1993) guideline, which stipulates that drinking water should contain no detectable coliforms in 100 mL, underscoring the unsuitability of the water for direct human consumption without adequate treatment. The observed contamination levels are comparable to those reported by Kanwal *et al.* (2017) in Danyore Springs, Gilgit-Baltistan, where total bacterial counts ranged between 11 and 83 CFU/100 mL. Similarly, Islam *et al.* (2021) noted total bacterial counts of 0 CFU/100 mL at the spring eye of Mishto Uch during winter, but other sampling sites exhibited significantly higher values, ranging from 26.4 to 127.7 CFU/100 mL closely mirroring the upper limits observed at Lanyiru Spring. However, the current results differ from the findings by Rawat and Joshi (2019) in the Central Himalayan region, where coliform presence exceeded WHO. Conversely, the Lanyiru Spring samples all failed to meet the WHO guideline across the board, even at the eye of the spring, indicating a more consistent contamination issue possibly linked to human or animal activities near the spring source. These findings also contrast with the Mishto Uch spring in the study by Islam *et al.* (2021), where the eye of the spring had 0 CFU/100 mL.

The faecal coliform levels in the Lanyiru spring water also showed significant variation across sites, with the highest median values recorded at LP1B, LP1A, and LP3B (6.8 CFU/100 mL) and the lowest at LP3A (1.8 CFU/100 mL). According to WHO (1993) standards, faecal coliforms, particularly thermotolerant coliforms like *E. coli*, should be absent in 100 mL of drinking water, thus all samples in this study indicate faecal contamination and are not fit for drinking without disinfection. These results are similar to those of Simiyu *et al.* (2009), who found thermotolerant coliforms in eight springs in Tongaren division in Kenya, including protected springs, showing that even protection measures may not fully prevent microbial contamination if the surrounding environment is compromised. The Lanyiru spring findings are also in line with those of An and Breindenbach (2005), who found detectable *E. coli* in 78% of samples from natural springs in recreational mountain areas, with concentrations ranging from 0 to 15 CFU/mL.

In contrast, the results from Lanyiru differ significantly from those reported by Boyer and Kuczynska (2003), where faecal coliform counts during storm events reached as high as 40,000 CFU/100 mL, illustrating the extreme microbial loading. Further, Haruna *et al.* (2005) reported faecal coliform counts ranging from 1 to 60,080 CFU/100 mL in protected springs in Kampala, Uganda. Additionally, the findings support the observations of Colín-Carreño *et al.* (2023) in Southern Mexico, where a majority of springs were categorized as medium to high risk for human health based on faecal coliform presence. The Lanyiru spring would similarly fall under at least a moderate risk category based on WHO risk classification for microbial contamination.

4.3.2 Correlation Between Total Coliforms and Fecal Coliforms with Cations

The results revealed a significant positive correlation between total coliforms (T_Coli) and fecal coliforms (F_Coli), with a correlation coefficient of $r = 0.620$ ($p < 0.001$). This suggests that as the concentration of total coliforms increases, the levels of fecal coliforms also tend to rise. Additionally, total coliforms was strongly positively correlated with several heavy metals, particularly lead ($r = 0.7498$, $p < 0.001$), indicating that higher concentrations of Pb are associated with elevated levels of total coliforms. In contrast, a significant negative correlation was found between total coliforms and iron [(Fe) r = -0.441, p = 0.007], suggesting that as the concentration of Fe increases, the level of total coliforms decreases (Figure 3).

For fecal coliforms, a significant positive correlation with lead was observed (r = 0.5204, p = 0.00114), further confirming that high levels of lead are associated with increased fecal coliform levels. Additionally, fecal coliforms showed a weak negative correlation with cadmium (Cd) (r = -0.36436, p = 0.02891), but no significant correlation was found with other metals like sodium (Na) (r = 0.2037, p = 0.2335) or copper (Cu) (r = 0.14743, p = 0.391). further, no significant correlation was observed between fecal coliforms and magnesium (Mg) (r = -0.1845, p = 0.2815), nor with $CaCO_3$ [(r = -0.1107, p = 0.520) Figure 3].

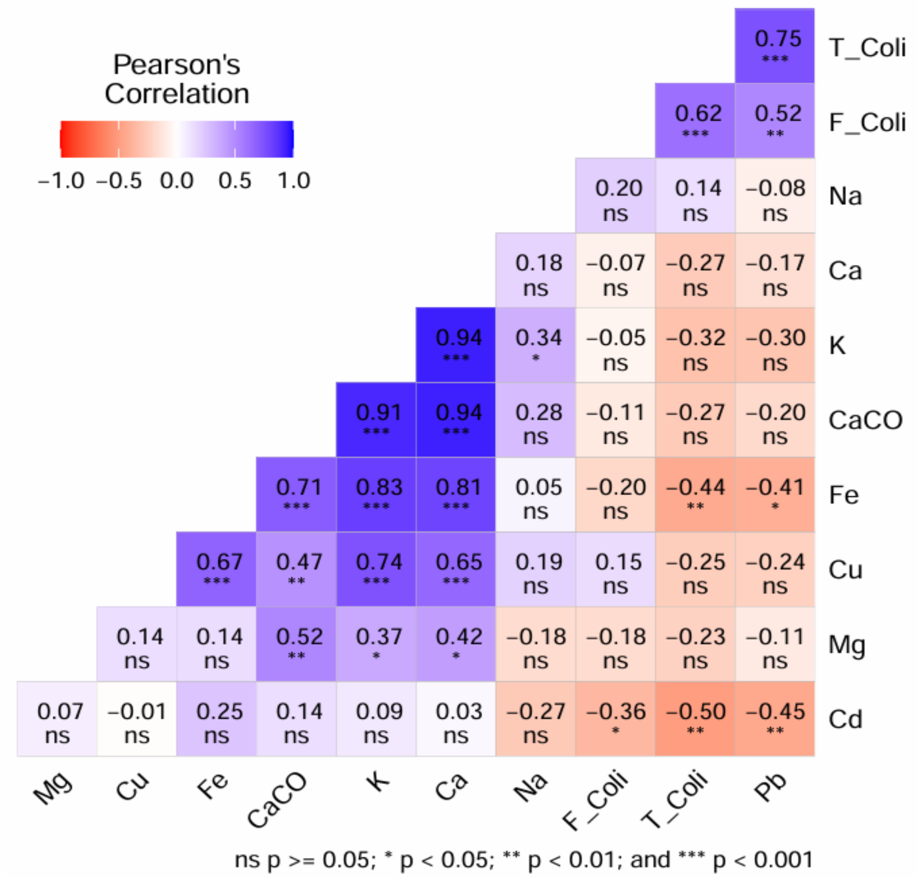

Figure 3: Correlation between cations parameters with total and feacal coliforms in spring water from Lanyiru Spring, Meru County, Kenya. Where F_Coli = Feacal coliforms, F_Coli = Total coliforms, Pb = Lead, K= Potassium, CaCO= Calcium carbonate, Cu= Copper, Mg= Magnesium, Fe = Iron, Cd= Cadmium, Ca= Calcium.

Among the variables, lead showed a highly significant positive relationship with total coliforms, with a coefficient of 14680 (p = 0.000418), suggesting that higher concentrations of Pb are strongly associated with elevated total coliform levels. However, iron, cadmium, and magnesium, did not show significant contributions to the model (Table 7). A multiple linear regression model was performed to further investigate the relationship between total coliforms and the heavy metals. Analysis showed that the model was statistically significant, with an F-statistic of 5.448 (p = 0.0003171) with the model accounting for up to 65% of the variability in total coliform levels (Table 7).

Table 7: Matrix for regression analysis of total coliform bacteria in Lanyiru spring Water in Meru County in Kenya

Variable	Estimate	Std. Error	t value	p-value
(Intercept)	-61.099	162.8	-0.375	0.711
Pb	14680	3631	4.042	0.000418 ***
Fe	-0.441	2.352	-0.171	0.865
Cd	-365.9	398.3	-0.919	0.367
K	0.545	1.867	0.292	0.773
Na	0.029	0.065	0.453	0.654
Cu	-14.92	84.1	-0.177	0.861
Ca	-0.751	1.851	-0.406	0.688
Mg	-0.914	2.048	-0.446	0.659
$CaCO_3$	0.043	0.662	0.066	0.948

The assessment of correlations among physico-chemical parameters provides critical insight into the interrelationships that govern water quality, as these parameters often reflect underlying geochemical and environmental processes. In this study, several significant correlations were identified, highlighting the interdependence of ions, suspended solids, and mineral content in Lanyiru spring waters. A very strong positive correlation was observed between potassium (K^+) and turbidity, as well as between sodium (Na^+) and turbidity, indicating that higher concentrations of these ions are associated with increased levels of suspended solids. This relationship aligns with established water chemistry principles, where the presence of certain dissolved ions can correspond with elevated particulate matter in the water column. The elevated K^+ and Na^+ levels, together with higher turbidity, may result from both natural processes, such as leaching from mineral-rich soils and rock weathering, and anthropogenic influences, including agricultural runoff and wastewater discharge. The association between these cations and turbidity suggests that ionic composition contributes to particulate aggregation or sediment transport within the spring system.

Positive correlations between sulfate (SO_4^{2+}) and fluoride (F^-) suggest that these ions may share similar sources or be governed by the same geochemical processes. Both are frequently associated with local geological formations, such as mineralized rocks, and can also originate from anthropogenic sources, including industrial effluents. The correlation between iron (Fe) and calcium carbonate ($CaCO_3$) further illustrates the interconnectedness of water chemistry. Increases in iron concentrations are associated with higher levels of calcium carbonate, potentially reflecting precipitation processes in which iron participates in mineral formation or influences carbonate solubility. This observation is consistent with literature indicating that transition metals can affect mineral solubility and precipitation, thereby altering overall water chemistry.

A notable finding was the negative correlation between lead (Pb) and turbidity. This suggests that higher lead concentrations are not necessarily linked to elevated suspended solids, which contrasts with the typical expectation that heavy metals associate with particulates. The negative correlation implies that lead may enter the spring system primarily through dissolution from soils, rocks, or localized anthropogenic sources rather than via particulate transport. This has important implications for understanding lead mobility and potential health risks, as its occurrence may be independent of visible turbidity, emphasizing the need for targeted chemical monitoring.

Comparison with findings from Shigut *et al.* (2017) reveals both similarities and differences. In the Ethiopian study, negative correlations were observed among several parameters, including pH, electrical conductivity, total dissolved solids, and calcium, suggesting that increases in ion concentrations influenced physical properties such as conductivity and turbidity. However, significant correlations between turbidity and most chemical parameters were not reported in that study, highlighting regional variation in the drivers of water quality. In contrast, in Lanyiru springs, turbidity showed significant associations with K^+ and Na^+ , suggesting that particulate matter may be more influenced by the ionic composition and geochemical environment than in the Ethiopian context. These differences may arise from variations in geological composition, land-use practices, or the intensity of anthropogenic activities, such as agriculture and livestock rearing, which can mobilize both ions and sediments.

Water pH also differed markedly between the two study regions. Shigut *et al.* (2017) reported pH values within the neutral range, consistent with WHO guidelines (6.5–8.5), whereas Lanyiru springs exhibited higher pH levels ranging from 8.90 to 10.47. Elevated pH in Lanyiru likely reflects higher alkalinity due to the weathering of carbonate and feldspathic minerals, with possible contributions from anthropogenic activities such as the discharge of alkaline wastewater or runoff from agricultural lands. These differences emphasize the influence of local geology and human activity on water chemistry and demonstrate that correlations observed in one region may not universally apply.

The significant correlations identified in this study confirm that water quality parameters in Lanyiru springs are interrelated. These findings support the rejection of the null hypothesis that physico-chemical parameters are independent across the spring sites. The observed associations indicate that changes in one parameter can influence others, reflecting the integrated nature of the spring water system. Understanding these relationships is essential for effective water quality management, as it enables the identification of key factors contributing to contamination or mineral enrichment and informs strategies for monitoring, treatment, and public health protection.

4.3.3 Correlation Analysis of Total and Fecal Coliform with Anions

A correlation analysis was conducted to examine the relationships between total coliform (T_Coli), fecal coliform (F_Coli), and the anions sulfate (SO), fluoride (Fl), and chloride (Cl). The analysis revealed notable associations between the coliforms and the anions.

Total coliform was found to have a significant negative correlation with sulfate ($r = -0.441$, $p = 0.007$), indicating that higher sulfate concentrations are associated with lower levels of total coliforms (Figure 4). A moderate negative correlation was also observed between total coliform and fluoride $r = -0.283$, $p = 0.094$], suggesting a potential trend where higher fluoride levels may be linked to reduced total coliform levels, though this relationship did not reach statistical significance at the conventional 0.05 level. Despite a weak negative correlation between total coliform and chloride ($r = -0.188$, $p = 0.271$), the effect of chloride on total coliforms appears minimal, and this correlation was not statistically significant.

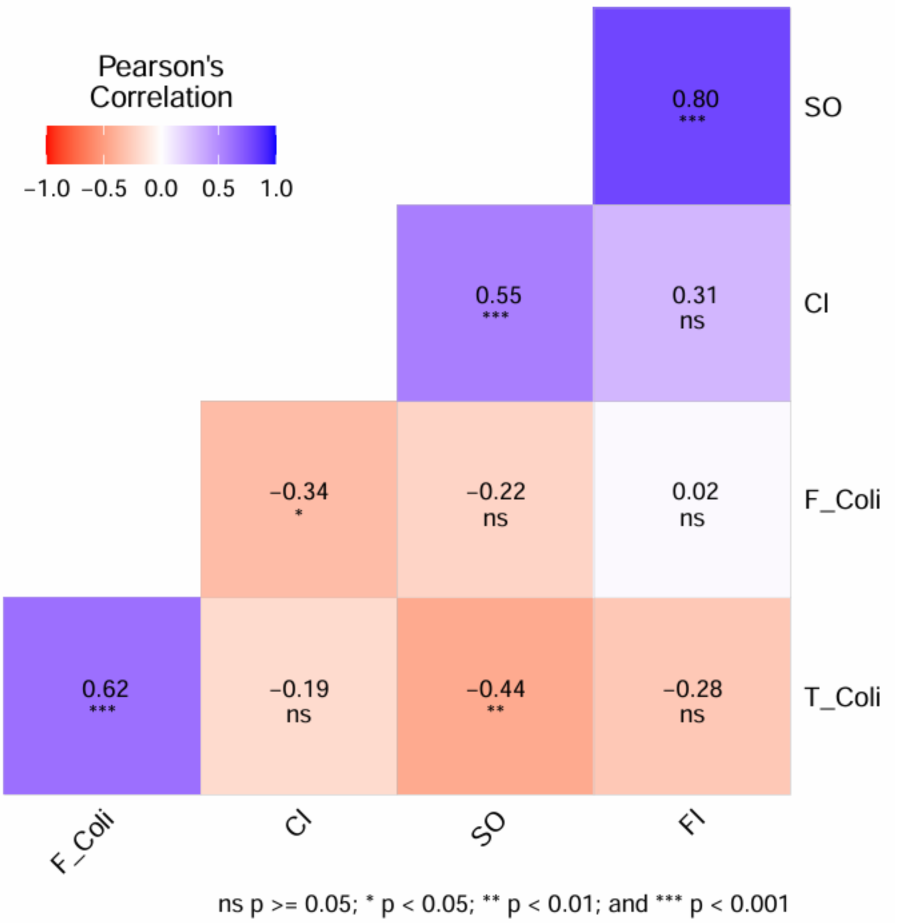

Figure 4: Correlation between anions parameters with total and feacal coliforms in spring water from Lanyiru Spring, Meru County, Kenya. Where F_Coli = Feacal coliforms, F_Coli = Total coliforms, Cl = Chlorine, Fl= Fluorine, SO= Sulphates.

Fecal coliform was significantly positively correlated with total coliform ($r = 0.620$, $p < 0.001$), indicating a strong association between the two types of coliforms (Figure 4). This suggests that as total coliform levels increase, fecal coliform levels tend to rise as well. In contrast, F_Coli exhibited a weak non-significant negative correlation with sulfate [SO ($r = -0.218$, $p = 0.201$)]. However, a moderate negative significant correlation was found with chloride ($r = -0.343$, $p = 0.040$), suggesting that higher chloride concentrations may reduce levels of fecal coliforms. No significant correlation was observed between fecal coliform and fluoride [(Fl) $r = 0.022$, $p = 0.899$], indicating that fluoride concentrations do not appear to have a meaningful relationship with fecal coliform levels in the samples (Figure 4).

The correlation analysis between total coliforms, fecal coliforms, and anions in the Lanyiru spring revealed significant associations, contributing to the understanding of water quality dynamics. A significant negative correlation between total coliforms and sulfate ($r = -0.441$, $p = 0.007$) suggests that higher sulfate concentrations may reduce total coliform levels. Previous studies have indicated that sulfate can inhibit bacterial growth, supporting this finding (Zhang *et al.,* 2022; Zhao *et al.,* 2024; Kazemi *et al.,* 2024). The moderate negative correlation between total coliforms and fluoride ($r = -0.283$, $p = 0.094$) aligns with literature suggesting fluoride has antimicrobial properties (Bhat *et al.*, 2024). While not statistically significant in this case, future studies should explore whether higher fluoride concentrations could exert a bactericidal effect in Lanyiru spring. The weak negative correlation between chloride and total coliforms ($r = -0.188$, $p = 0.271$) suggests chloride may have minimal impact on coliform levels. This finding is consistent with other studies, where chloride's role in water quality is ambiguous unless combined with other chemical factors (Shomar *et al.,* 2021).

The strong positive correlation between total and fecal coliforms ($r = 0.620$, $p < 0.001$) is expected, as these bacteria often co-occur as indicators of fecal contamination (Noble *et al.*, 2003). This association reinforces the use of total coliforms as a general marker for fecal contamination in the absence of more specific indicators. Fecal coliforms also showed a moderate negative correlation with chloride ($r = -0.343$, $p = 0.040$), aligning with studies suggesting that higher chloride concentrations can reduce microbial survival (He *et al.,* 2023). Finally, the lack of a significant correlation between fecal coliforms and fluoride ($r = 0.022$, $p = 0.899$) may be due to the low fluoride concentrations in Lanyiru spring, which may not be sufficient to influence microbial populations significantly. This finding is in line with previous studies reporting no significant effect of low fluoride concentrations on coliforms (Kazemi *et al.,* 2024). In conclusion, the correlation analysis highlights the potential influence of sulfate, fluoride, and chloride on coliform levels in Lanyiru spring. The significant relationship between total and fecal coliforms further supports their use as indicators of fecal contamination.

4.3.4 Correlation Between Coliform Bacteria with Physical Parameters

A correlation analysis was performed to examine the relationship between total coliforms (T_Coli), fecal coliforms (F_Coli), and various physical parameters (pH, temperature, conductivity, and turbidity). The correlation matrix was calculated using Pearson's correlation coefficient. The analysis revealed a significant positive correlation between total coliforms and fecal coliforms ($r = 0.62$, $p < 0.001$), indicating that as total coliform levels increase, fecal coliform levels tend to increase as well (Figure 5). However, no significant correlations were observed between pH and either total coliforms ($r = -0.007$, $p = 0.966$) or fecal coliforms ($r = -0.125$, $p = 0.466$), suggesting that pH has little influence on coliform concentrations in this dataset. Similarly, temperature showed a weak negative correlation with both total coliforms ($r = -0.127$, $p = 0.461$) and fecal coliforms ($r = -0.210$, $p = 0.218$), but these correlations were not statistically significant (Figure 5).

Conductivity was negatively correlated with total coliforms ($r = -0.342$, $p = 0.041$), suggesting that higher conductivity levels may be associated with lower total coliform concentrations (Figure 5). However, conductivity showed no significant relationship with fecal coliforms ($r = -0.021$, $p = 0.902$). Lastly, turbidity was moderately positively correlated with fecal coliforms ($r = 0.151$, $p = 0.380$), but this relationship was not significant for total coliforms ($r = -0.220$, $p = 0.197$)

This study examined the relationship between total and fecal coliform bacteria and selected physical parameters (pH, temperature, conductivity, and turbidity) in the Lanyiru spring. The significant positive correlation between total coliforms and fecal coliforms ($r = 0.62$, $p < 0.001$) reinforces the established principle that total coliforms can serve as a reliable proxy for fecal contamination in surface water systems (Nascimento *et al.,* 2023). This strong association suggests a common source of contamination, likely anthropogenic, such as improper sanitation practices or surface runoff. In contrast, pH showed no significant correlation with either total coliforms ($r = -0.007$, $p = 0.966$) or fecal coliforms ($r = -0.125$, $p = 0.466$), indicating that within the observed pH range, microbial survival or proliferation was not strongly influenced. This finding aligns with Aram *et al.* (2021), who also reported a non-linear or weak influence of pH on coliform bacteria, especially when the pH remained within a tolerable range for microbial persistence. However, in groundwater systems in gold mining regions, Armah (2014) found pH to be a significant predictor of coliform presence, suggesting the influence of pH may vary more substantially in chemically extreme or disturbed environments.

Temperature also exhibited weak negative but non-significant correlations with both total ($r = -0.127$, $p = 0.461$) and fecal coliforms ($r = -0.210$, $p = 0.218$). This suggests that the natural thermal variation in the spring was not a major determinant of microbial concentrations along the spring, consistent with similar findings in surface water studies, where only extreme temperature shifts showed microbial sensitivity (Blaustein *et al.,* 2013). A more pronounced finding was the significant negative correlation between conductivity and total coliforms ($r = -0.342$, $p = 0.041$). This indicates that higher levels of dissolved ionic substances may suppress the presence or viability of total coliforms. A possible explanation is osmotic stress or ionic toxicity affecting microbial survival, although fecal coliforms showed no such relationship ($r = -0.021$, $p = 0.902$). This aligns partially with Armah (2014), who identified conductivity as a significant predictor of *E. coli* and total coliform presence in groundwater contaminated by mining activities, highlighting that the type of water system and pollution source may influence the nature of this relationship. Turbidity showed a moderate but non-significant positive correlation with fecal coliforms ($r = 0.151$, $p = 0.380$) and a slight negative correlation with total coliforms ($r = -0.220$, $p = 0.197$). This suggests that suspended particles might support microbial attachment or shield bacteria from environmental stressors, though the effect was not strong enough to reach statistical significance. In contrast, both Aram *et al.* (2021) and Armah (2014) identified turbidity as a significant predictor of coliform presence, particularly in groundwater where particulate content often co-occurs with heavy metals or organic matter that influence microbial viability.

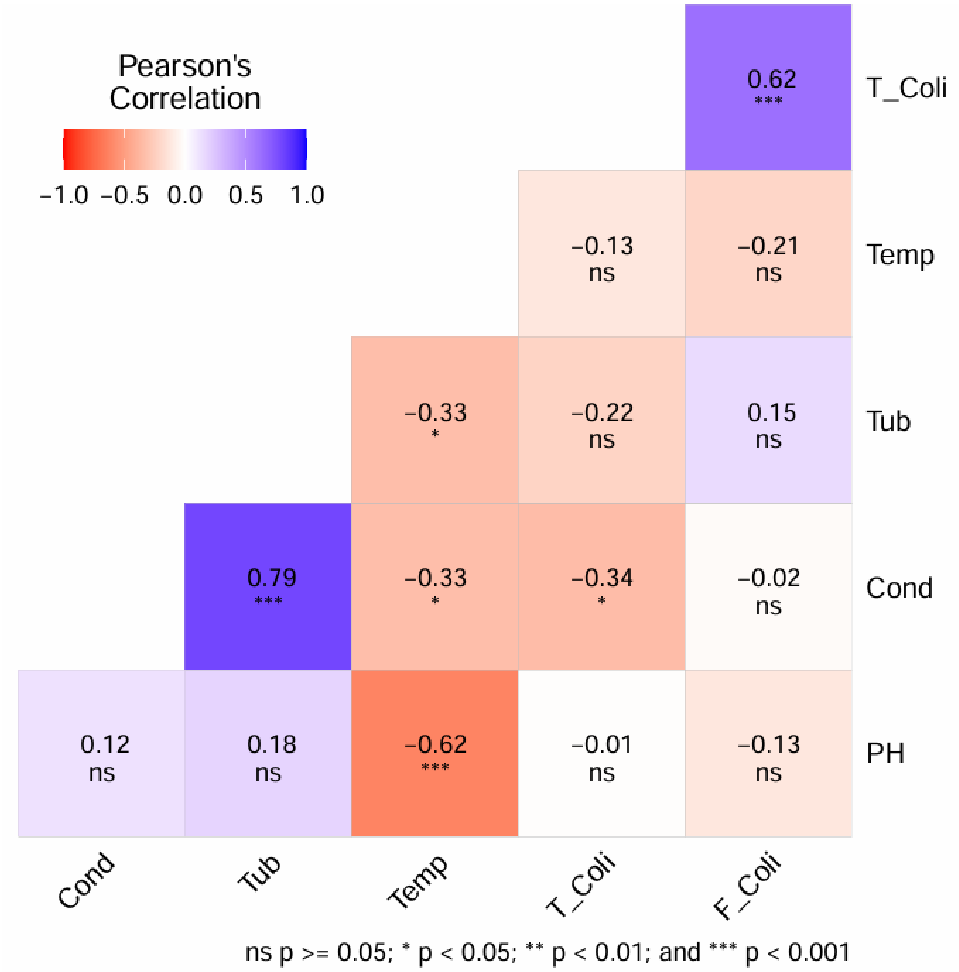

Figure 5: Correlation between Physical parameters with total and feacal coliforms in spring water from Lanyiru Spring, Meru County, Kenya. Where F_Coli = Feacal coliforms, F_Coli = Total coliforms, Cond = Conductivity, Tub= Turbidity, Temp= Temperature,

A multiple regression analysis was conducted to predict total coliform based on the physical parameters pH, temperature, conductivity, and turbidity. The model was not statistically significant, $F(4, 31) = 2.085$, $p = 0.1067$, and explained only a small portion of the variance in *total coliforms* ($R^2 = 0.212$).

Table 8: Matrix for regression analysis of coliform bacteria and physical parameters in Lanyiru spring Water in Meru County in Kenya

Predictor	Estimate	Std. Error	t value	p-value
(Intercept)	548.18	237.33	2.31	0.0277 *
pH	-11.07	10.78	-1.027	0.3123
Temperature	-8.19	4.42	-1.853	0.0734
Conductivity	-0.26	0.13	-2.016	0.0526
Turbidity	0.008	0.021	0.406	0.6877

Note: p-values < 0.05 indicate statistical significance, with * and . representing significant and marginal significance, respectively.

The results indicated that conductivity (B = -0.264, p = 0.0526), temperature (B = -8.19, p = 0.0734), and pH (B = -11.07, p = 0.3123) were negatively associated with total coliforms, but none of these relationships were statistically significant. Turbidity (B = 0.008, p = 0.6877) was also not a significant predictor of total coliforms. The regression coefficients, standard errors, and p-values are shown (Table 8).

The multiple regression model predicting total coliform levels from pH, temperature, conductivity, and turbidity was not statistically significant (F = 2.085, p = 0.1067), with an R^2 value of only 0.212. This indicates that these four physical parameters collectively explain just over 21% of the variation in total coliform levels. While conductivity (B = -0.264, p = 0.0526) and temperature (B = -8.19, p = 0.0734) approached significance, none of the predictors individually or collectively could reliably explain the observed microbial variability. The results suggest that physical parameters alone are insufficient to predict microbial contamination in spring water systems with high confidence. In contrast, studies such as Aram *et al.* (2021) and Armah (2014) emphasized that the inclusion of chemical variables (e.g., heavy metals, phosphates, nitrates) and broader geochemical profiles significantly improves predictive accuracy in both surface and groundwater systems. This highlights a key limitation of the present analysis and underscores the need for integrated monitoring approaches that combine physical, chemical, and biological indicators for effective water quality assessments.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Key Findings

The study assessed the physicochemical and microbiological quality of Lanyiru Spring waters across different locations in Meru County, revealing both spatial variations and critical contamination concerns. Key findings indicated that heavy metal concentrations, including lead (Pb^{2+}), iron (Fe^{2+}), cadmium (Cd), and copper (Cu^{2+}), varied significantly across sites. Notably, lead levels peaked at LP1A and LP1B (0.008 mg/L), while iron recorded the highest concentration at LP4B (10.03 mg/L), exceeding recommended limits and pointing to localized contamination from agricultural runoff, improper waste disposal, and natural geological sources. Fluoride concentrations were also found to exceed WHO limits at LP4B (8.40 mg/L), posing potential health risks such as dental and skeletal fluorosis. Other parameters like calcium, magnesium, and calcium carbonate were elevated at LP4A, influenced by the region's lithology. Physical parameters showed consistently alkaline pH values (mean 10.16), while turbidity and conductivity were highest at LP4 sites, suggesting surface runoff and mineral dissolution as major contributors.

Correlation analyses revealed strong positive relationships between potassium and turbidity, and between iron and calcium carbonate, indicating sediment influence and geogenic sources. Conversely, a significant negative correlation between lead and turbidity suggested lead’s presence predominantly in dissolved form. Microbiological analysis showed considerable variation in total and fecal coliform counts, with the highest contamination observed at LP1A, LP1B, and LP3B, linked to proximity to human settlements and poor sanitation practices. A notable positive correlation between coliform levels and lead concentrations indicated shared contamination pathways through surface runoff and improper waste management, while iron exhibited a negative correlation with coliforms, possibly due to its antimicrobial properties or role in sediment interactions. Overall, the findings demonstrated that both anthropogenic activities and natural geological factors significantly influence the quality of Lanyiru Spring waters, with serious public health implications arising from heavy metal and microbial contamination.

5.2 Conclusion

The study established that the water quality of Lanyiru Spring is compromised by high levels of assessed physicochemical parameters, including lead, iron, fluoride, turbidity, and conductivity, with several sites exceeding WHO permissible limits for safe drinking water. These findings indicate that both natural geogenic factors, such as mineral-rich lithology, and anthropogenic influences, such as agricultural activities, poor sanitation, and improper waste disposal, contribute to the deterioration of water quality. Correlation analysis revealed relationships between certain parameters, such as potassium and turbidity, and iron with calcium carbonate, highlighting the interconnectedness of sediment transport and geochemical processes in influencing water composition. In contrast, the negative correlation between lead and turbidity suggested differing contamination pathways. Furthermore, the microbiological assessment confirmed that total and faecal coliform contamination is prevalent in several sites, posing serious health risks to the local community. Overall, the findings indicate that Lanyiru Spring water cannot be considered reliably safe for direct human consumption, and effective treatment measures, such as filtration, disinfection, and routine monitoring, are necessary to protect public health.

5.3 Recommendations

Based on the findings of this study, several interventions are necessary to address the identified water quality issues at Lanyiru Spring. These measures are intended to guide policymakers, environmental agencies, and the local community in safeguarding the quality of spring water for safe domestic use.

i. It is recommended that regular monitoring of key physico-chemical parameters, especially lead, iron, fluoride, turbidity, and conductivity, be undertaken to ensure they remain within WHO standards. The County Government and relevant environmental agencies should implement measures to mitigate pollution sources, such as controlling agricultural runoff, managing waste disposal, and reducing soil erosion around the spring catchment. Additionally, raising community awareness on the impacts of human activities on water quality should be prioritized.

ii. Integrated management strategies should be developed to address the interconnected nature of water quality parameters. For instance, interventions aimed at reducing turbidity through erosion control will also help in minimizing associated contaminants like potassium and iron. Resource managers should consider these relationships when designing conservation programs to ensure holistic and effective water quality improvement.

iii. Given the high levels of microbiological contamination, immediate actions are needed to improve sanitation in surrounding communities. Public health campaigns should promote hygienic practices, discourage open defecation, and support the construction of sanitation facilities. Moreover, households should be encouraged and supported to adopt water treatment methods, such as boiling, filtration, or chlorination, before consuming water from the spring. In the long term, investment in alternative safe water supply systems should be considered to reduce reliance on the contaminated spring.

5.4 Recommendations for Further Studies

To build upon the findings of this study and support effective management of Lanyiru Spring water resources, several areas of future research are recommended.

i. First, longitudinal studies should be conducted to monitor seasonal variations in physicochemical and microbiological water quality, providing a better understanding of temporal dynamics and pollution trends. Such studies would help assess the effectiveness of implemented interventions over time.

ii. Secondly, detailed source-tracking studies are needed to identify and quantify specific pollution contributors, such as agricultural runoff, domestic waste, and geological inputs. This would enable the development of targeted mitigation strategies for each contamination source.

iii. Further research should also focus on assessing the effectiveness of low-cost, community-based water treatment methods suitable for rural settings, including the use of bio-sand filters, solar disinfection, and locally available adsorbent materials for heavy metal removal.

iv. Additionally, health impact assessments are recommended to evaluate the actual public health implications of consuming untreated spring water, particularly concerning heavy metal exposure and waterborne diseases. Lastly, socio-economic studies exploring community perceptions, practices, and willingness to adopt water safety measures would provide valuable insights for designing successful community engagement and behavior change programs.

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APPENDICES

Appendix I: Institutional Introductory Letter

CHUKA UNIVERSITY

Knowledge is Wealth *(Sapientia divitia est)* Akili ni Mali

OFFICE OF THE DIRECTOR
BOARD OF POSTGRADUATE STUDIES

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Website: www.chuka.ac.ke

REF: SM11/29006/16 **9th May, 2024**

Director
National Commission for Science Technology and Innovation
Off Waiyaki Way, Upper Kabete
P O Box 30623, 00100
Nairobi.

Dear Sir / Madam,

PAUL MWONGELA IKIAO

The above-named person is a *bona fide* student of Chuka University pursuing MSC in Chemistry proposal titled**: Determination of Physicochemical and Biologoical Properties of Lanyiru Spring Waters of Muthara Ward, Tigania East Constituency-Meru County, Kenya.**

Mr. Mwongela has defended at the Faculty level and is now expected to conduct research. Any assistance accorded will be highly appreciated.

Yours sincerely,

Prof. Moses Muraya, Ph.D.

DIRECTOR
BOARD OF POSTGRADUATE STUDIES

Appendix II: Ethics Review Authorization

CHUKA UNIVERSITY

Knowledge is Wealth *(Sapientia divitia est)* Akili ni Mali

CHUKA UNIVERSITY INSTITUTIONAL ETHICS REVIEW COMMITTEE

Telephones: 020-2310512/18
Direct Line: 0772894438
Email: info@chuka.ac.ke,
P. O. Box 109-60400, Chuka
Website: www.chuka.ac.ke

6th February, 2024

REF: CUIERC/ NACOSTI/470
TO: **Paul Mwongela Ikiao**

RE: Determination of Physicochemical and Biological properties of Lanyiru Spring Waters of Muthara Ward, Tigania East Constituencey – Meru County, Kenya

This is to inform you that *Chuka University IERC* has reviewed and approved your above research proposal. Your application approval number is *NACOSTI/NBC/AC-0812.* The approval period is 6th February, 2024 – 6th February, 2025.

This approval is subject to compliance with the following requirements;

i. Only approved documents including (informed consents, study instruments, MTA) will be used
ii. All changes including (amendments, deviations, and violations) are submitted for review and approval by *Chuka University IERC.*
iii. Death and life threatening problems and serious adverse events or unexpected adverse events whether related or unrelated to the study must be reported to *Chuka University IERC* within 72 hours of notification
iv. Any changes, anticipated or otherwise that may increase the risks or affected safety or welfare of study participants and others or affect the integrity of the research must be reported to *Chuka University IERC* within 72 hours
v. Clearance for export of biological specimens must be obtained from relevant institutions.
vi. Submission of a request for renewal of approval at least 60 days prior to expiry of the approval period. Attach a comprehensive progress report to support the renewal.
vii. Submission of an executive summary report within 90 days upon completion of the study to *Chuka University IERC.*

Prior to commencing your study, you will be expected to obtain a research license from National Commission for Science, Technology and Innovation (NACOSTI) https://oris.nacosti.go.ke and also obtain other clearances needed.

Yours sincerely

Dr. Benjamin Kanga
SECRETARY

Appendix III: National Commission for Science, Technology and Innovation (NACOSTI) Permit

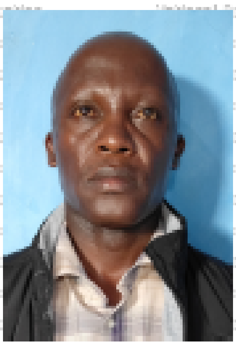
REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 898130

Date of Issue: 03/June/2024

RESEARCH LICENSE



This is to Certify that Mr.. PAUL IKIAO MWONGIRA of Chuka University, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Meru on the topic: DETERMINATION OF PHYSICOCHEMICAL AND BIOLOGICAL PROPERTIES OF LANYIRU SPRING WATERS OF MUTHARA WARD, TIGANIA EAST CONSTITUENCY- MERU COUNTY, KENYA for the period ending : 03/June/2025.

License No: NACOSTI/P/24/36226

898130

Applicant Identification Number

Director General
NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

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See overleaf for conditions