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Natural Zeolite for Sustainable Groundwater Softening: Experimental Evaluation of Total Hardness Removal from Borehole Water in Singida Municipality, Tanzania

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Abstract— *Groundwater constitutes a major source of potable water for domestic, agricultural, and institutional uses in many parts of Singida Municipality, Tanzania. Despite its widespread utilization, groundwater quality is frequently compromised by elevated concentrations of dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, which are the principal contributors to total hardness. Excessive water hardness adversely affects both domestic and industrial water use by promoting scale formation in pipelines, storage facilities, and heating systems, reducing the efficiency and lifespan of water-related infrastructure, increasing soap and detergent consumption, and impairing the aesthetic and operational quality of water. Consequently, the development of efficient, economically viable, and environmentally sustainable technologies for hardness removal remains an important objective for groundwater treatment. Natural zeolite is a crystalline hydrated aluminosilicate mineral possessing a well-defined porous framework and a high cation exchange capacity (CEC), characteristics that make it an effective adsorbent for the removal of hardness-causing ions from water. Its water-softening mechanism is primarily governed by ion exchange, whereby Ca^{2+} and Mg^{2+} ions in groundwater are selectively exchanged with exchangeable cations, predominantly Na^{+}, located within the zeolitic structure. Owing to its abundance, low cost, chemical stability, regenerability, and environmental compatibility, natural zeolite has emerged as a promising alternative to conventional water-softening technologies, particularly in resource-limited settings where advanced treatment systems are economically impractical. This study investigated the effectiveness of natural zeolite for reducing total hardness in groundwater obtained from a water borehole in Singida Municipality, Tanzania. Specifically, the study aimed to determine the initial total hardness of the groundwater, evaluate the hardness removal efficiency of natural zeolite under controlled treatment conditions, and assess its suitability as a sustainable and cost-effective material for groundwater softening. The outcomes of this study are expected to contribute to the growing body of knowledge on the application of natural zeolite for groundwater treatment and to provide scientific evidence supporting its adoption as a sustainable water-softening technology in regions affected by hard groundwater. Furthermore, the findings may serve as a basis for the development of affordable and environmentally responsible groundwater treatment strategies suitable for rural and peri-urban communities in Tanzania and comparable hydrogeological settings.*

Keywords— ***Natural Zeolite, Groundwater Hardness, Calcium and Magnesium Removal, Ion Exchange, Water Softening***

I. INTRODUCTION

Access to safe and suitable water remains a major global challenge, particularly in developing regions where groundwater resources constitute a fundamental component of domestic, agricultural, and institutional water supply systems. Groundwater is often preferred due to its relatively stable availability, natural filtration through geological formations, and lower susceptibility to seasonal fluctuations compared with surface water sources. However, groundwater quality is strongly influenced by hydrogeological conditions, mineral composition of aquifer formations, and the geochemical interactions between groundwater and surrounding rocks, which determine the concentration and distribution of dissolved constituents (Appelo and Postma, 2005; Fetter, 2018).

In Tanzania, particularly in semi-arid regions such as Singida Municipality, groundwater represents an important source of water supply due to limited and highly variable surface water availability. Despite its importance, groundwater quality challenges associated with elevated concentrations of dissolved minerals remain a concern. Among the major groundwater quality parameters affecting usability is total hardness, which is primarily attributed to the presence of divalent cations, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. The concentration of these ions in groundwater is largely controlled by mineral dissolution processes, including the weathering of carbonate minerals such as calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and other calcium- and magnesium-bearing geological materials (Hem, 1985; Appelo and Postma, 2005).

Water hardness is generally not considered a direct threat to human health; however, excessive hardness presents significant operational, economic, and domestic challenges. High concentrations of calcium and magnesium ions promote the formation of mineral scale deposits within water distribution networks, pipelines, pumps, valves, and household appliances, resulting in reduced hydraulic efficiency, increased maintenance requirements, and premature failure of water infrastructure. Furthermore, hard water reduces soap and detergent efficiency through the formation of insoluble calcium and magnesium salts, leading to increased consumption of cleaning agents and reduced acceptability of water for domestic purposes (World Health Organization [WHO], 2022).

The occurrence of elevated hardness levels in groundwater sources used for community water supply necessitates the application of effective water-softening technologies. Conventional water treatment processes, including coagulation, sedimentation, filtration, and disinfection, are primarily designed for the removal of suspended solids, microbial contaminants, and turbidity, but they are generally ineffective in eliminating dissolved hardness-causing ions. Although advanced softening techniques such as chemical precipitation, ion exchange resins, and membrane-based processes demonstrate high removal efficiencies, their application in rural and resource-constrained settings is often limited by high capital costs, operational complexity, energy requirements, and dependence on chemical inputs (Sengupta, 2013).

Natural Zeolite as a Sustainable Material for Groundwater Softening Natural zeolite has attracted significant scientific and technological interest as a sustainable material for groundwater softening due to its unique physicochemical properties, particularly its high cation exchange capacity (CEC), porous structure, chemical stability, and abundance in nature. Zeolites are crystalline hydrated aluminosilicate minerals characterized by a three-dimensional framework structure composed of interconnected silicon-oxygen (SiO_4) and aluminum-oxygen (AlO_4) tetrahedra. The substitution of Si^{4+} by Al^{3+} within the framework generates a net negative structural charge, which is balanced by the presence of exchangeable cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). These exchangeable cations are weakly bonded within the zeolite channels and cavities, allowing them to participate in reversible ion exchange reactions with dissolved ions present in aqueous environments (Barrer, 1982; Breck, 1974).

The structural arrangement of zeolite consists of interconnected channels and micropores that provide a large internal surface area and facilitate the movement of water molecules and dissolved ions. The porous framework allows zeolite minerals to selectively capture and exchange ionic species without undergoing significant structural alteration. Among naturally occurring zeolites, clinoptilolite is one of the most extensively investigated varieties due to its high selectivity, chemical resistance, and availability in many geological environments. Clinoptilolite has demonstrated remarkable potential in environmental applications, including water softening, ammonium removal, heavy metal adsorption, and wastewater treatment (Mumpton, 1999; Wang and Peng, 2010).

The effectiveness of natural zeolite in groundwater softening is primarily governed by the ion exchange mechanism. During the treatment process, hardness-causing ions, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}), diffuse from the aqueous phase into the zeolite framework and replace exchangeable sodium ions located within the mineral structure. The general exchange reaction can be represented as follows:

$2Na–Zeolite + Ca^{2+} \rightarrow Ca–Zeolite + 2Na^{+}$

$2Na–Zeolite + Mg^{2+} \rightarrow Mg–Zeolite + 2Na^{+}$

where Na–Zeolite represents sodium-containing exchange sites within the zeolite structure. Through this process, calcium and magnesium ions responsible for total hardness are removed from water and retained within the zeolite matrix, while sodium ions are released into the treated water. Since ion exchange is a reversible process, exhausted zeolite can potentially be regenerated using concentrated sodium chloride (NaCl) solutions, allowing repeated utilization and improving the economic feasibility of the treatment system (Breck, 1974; Wingenfelder et al., 2005).

The hardness removal performance of natural zeolite depends on several intrinsic and operational factors. The chemical composition of the zeolite strongly influences its exchange capacity because the amount and type of aluminum substitution determine the number of negatively charged sites available for ion exchange. Zeolites with higher aluminum content generally possess greater cation exchange capacity due to increased framework charge density. In addition, pore size distribution, particle size, surface area, and mineral purity affect the accessibility of exchange sites and the diffusion rate of dissolved ions into the zeolite structure (Wang and Peng, 2010).

Particle size is an important operational parameter influencing the efficiency of hardness removal. Smaller zeolite particles provide a larger surface area and shorter diffusion pathways, resulting in improved interaction between water and exchange sites. However, excessively fine particles may create hydraulic resistance and increase pressure losses in continuous flow systems. Therefore, optimization of particle size is essential to achieve a balance between treatment efficiency and practical operational performance. Similarly, contact time determines the extent of interaction between hardness ions and available exchange sites. Longer contact periods generally enhance ion exchange efficiency by allowing greater diffusion of calcium and magnesium ions into the zeolite framework (Motsi et al., 2009).

Initial hardness concentration also plays a critical role in determining zeolite performance. At low hardness concentrations, sufficient exchange sites are available for effective ion removal. However, as the concentration of calcium and magnesium ions increases, available exchange sites become progressively occupied, resulting in reduced removal efficiency. Temperature, pH, competing ions, and the presence of dissolved organic matter may also influence ion exchange behavior by affecting ion mobility and selectivity of the zeolite surface (Widiastuti et al., 2011). Compared with conventional groundwater softening technologies, natural zeolite provides several environmental and economic advantages. Conventional methods such as chemical precipitation using lime-soda ash require significant chemical inputs and generate large quantities of sludge requiring further disposal. Similarly, membrane-based processes such as reverse osmosis provide excellent removal efficiency but are associated with high capital costs, energy consumption, membrane fouling problems, and technical complexity. Ion exchange resins, although effective, are relatively expensive and require controlled regeneration processes.

In contrast, natural zeolite is inexpensive, locally available in many regions, environmentally compatible, and requires relatively simple operational procedures, making it suitable for decentralized water treatment applications, particularly in developing countries (Sengupta, 2013; Wingenfelder et al., 2005).

In the context of Tanzania, where many rural and semi-arid communities depend on groundwater sources for domestic water supply, the application of natural zeolite presents a promising approach for improving water quality. Regions such as Singida experience challenges related to groundwater hardness due to geological conditions that promote dissolution of calcium- and magnesium-bearing minerals. The development of affordable and sustainable softening technologies is therefore essential to improve the usability and acceptability of groundwater resources. Natural zeolite-based treatment systems have the potential to provide an appropriate technological solution because they combine effective hardness removal with low operational requirements and environmental sustainability. Furthermore, the use of natural zeolite aligns with the principles of sustainable water management by promoting locally available materials, reducing chemical dependency, and supporting decentralized treatment approaches. The evaluation of natural zeolite for hardness removal from borehole water in Singida Region provides important scientific information regarding its applicability under local groundwater conditions. Understanding the interaction between zeolite characteristics and groundwater chemistry is essential for optimizing treatment performance and establishing suitable operating conditions for practical implementation. Therefore, investigating natural zeolite as a groundwater-softening material contributes to the advancement of sustainable water treatment technologies by demonstrating its ability to reduce total hardness through natural ion exchange mechanisms. The findings from such studies can support the development of affordable, environmentally responsible, and technically feasible groundwater treatment strategies for communities affected by hard water, particularly in semi-arid regions of Tanzania and other developing regions with similar hydrogeological characteristics.

1.2 PROBLEM STATEMENT

Groundwater is the major source of domestic and institutional water supply in **Singida Municipality, Tanzania**, due to limited availability and seasonal variability of surface water resources. However, the quality of groundwater is significantly influenced by local geological conditions and water–rock interactions, which often increase the concentration of dissolved minerals, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}), resulting in elevated total hardness.

High groundwater hardness remains a major water quality challenge in Singida Municipality, affecting the suitability of water for domestic and other uses. Hard water causes scale formation in pipes, pumps, storage systems, and household appliances, leading to increased maintenance costs, reduced efficiency of water supply infrastructure, and shortened equipment lifespan. In addition, high concentrations of hardness-causing ions reduce soap and detergent performance, increasing household expenses and affecting consumer acceptance of groundwater.

Although conventional water treatment practices such as filtration and disinfection are commonly applied in water supply systems, these methods are not effective in removing dissolved hardness-causing ions. Alternative softening technologies, including chemical precipitation, synthetic ion exchange resins, and membrane processes, can achieve high hardness removal; however, their application is often limited by high installation costs, operational complexity, energy requirements, and dependence on chemical inputs. These limitations create a need for affordable, sustainable, and locally applicable groundwater-softening technologies.

Natural zeolite has shown potential as a low-cost and environmentally friendly material for hardness removal due to its high cation exchange capacity, porous structure, and ability to exchange calcium and magnesium ions with sodium ions within its framework. However, limited information exists regarding the effectiveness of natural zeolite in reducing groundwater hardness under the specific hydrogeochemical conditions of **Singida Municipality**.

Therefore, there is a need to experimentally evaluate the performance of natural zeolite in removing total hardness from borehole water in Singida Municipality. This study aims to generate scientific evidence on the suitability of natural zeolite as a sustainable and cost-effective treatment option for improving groundwater quality and supporting reliable water supply in areas affected by hardness problems.

1.3 General Objective

To experimentally evaluate the effectiveness of natural zeolite as a sustainable material for groundwater softening through the removal of total hardness from borehole water in Singida Municipality, Tanzania.

1.3.1 Specific Objectives

(a) To characterize the groundwater quality and determine the initial total hardness levels of borehole water in Singida Municipality, Tanzania.

(b) To evaluate the effectiveness of natural zeolite in removing hardness-causing ions (Ca^{2+} and Mg^{2+}) from borehole water by assessing the influence of operational conditions, including zeolite dosage and contact time, for sustainable groundwater softening.

1.4 SIGNIFICANCE OF THE STUDY

Groundwater will continue to serve as a critical source of water for domestic, agricultural, and institutional activities in many semi-arid regions of Tanzania, including **Singida Municipality**, where surface water availability is limited by seasonal variability and climatic uncertainties. However, increasing groundwater hardness resulting from elevated concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions will remain a major challenge affecting water suitability for various applications. Therefore, the development of affordable, efficient, and environmentally sustainable groundwater-softening technologies will be essential for improving water quality and supporting sustainable water resource management.

This study will provide scientific insights into the effectiveness of natural zeolite as a sustainable treatment material for reducing total hardness in borehole water through ion-exchange mechanisms. The findings will enhance understanding of the hardness removal capacity of natural zeolite under the specific hydrogeochemical conditions of **Singida Municipality, Tanzania**, and will contribute to the existing knowledge on the application of naturally occurring aluminosilicate minerals in groundwater treatment.

The outcomes of this study will provide valuable technical information to water supply authorities, environmental engineers, researchers, and policymakers regarding the potential application of natural zeolite as an alternative groundwater-softening technology. Compared with conventional softening approaches, such as chemical precipitation and membrane-based processes, which are often associated with high capital costs, chemical consumption, energy requirements, and operational complexity, natural zeolite will offer a low-cost, environmentally compatible, and potentially regenerable option suitable for decentralized water treatment systems, particularly in resource-limited communities.

Furthermore, the findings will support the development of sustainable groundwater treatment strategies by demonstrating the potential of natural zeolite to improve borehole water quality while reducing operational costs and minimizing environmental impacts associated with conventional softening technologies. The experimental data generated from this study will serve as a reference for future research focusing on the optimization of zeolite-based water-softening systems under different groundwater characteristics and operational conditions.

Ultimately, this study will contribute to improving access to safe and acceptable-quality groundwater by promoting the adoption of sustainable and locally applicable treatment technologies. The results will support evidence-based groundwater management practices and contribute to national and global efforts toward achieving **Sustainable Development Goal 6 (SDG 6)**, which aims to ensure the availability and sustainable management of water and sanitation for all.

II. CHAPTER TWO: LITERATURE REVIEW

2.1 Groundwater Resources and Quality Challenges

Groundwater is one of the most important freshwater resources globally due to its reliability, natural filtration capacity, and availability throughout the year. It provides drinking water for almost half of the world's population and supports agricultural, industrial, and institutional activities, particularly in regions where surface water resources are limited or affected by seasonal variations (UNESCO, 2022; WHO, 2022). Unlike surface water, groundwater is naturally protected from direct contamination; however, its quality is strongly influenced by geological formations, groundwater flow pathways, recharge characteristics, and geochemical interactions between water and aquifer materials.

In Tanzania, groundwater represents the primary source of domestic water supply in many semi-arid regions, including **Singida Municipality**, where surface water availability is limited due to low and irregular rainfall patterns. The quality of groundwater in such areas is mainly controlled by the mineral composition of aquifer formations and the duration of contact between groundwater and surrounding rocks. During infiltration and underground movement, water dissolves minerals from geological formations, resulting in increased concentrations of dissolved ions. Among these dissolved constituents, calcium (Ca^{2+}) and magnesium (Mg^{2+}) are the major contributors to total hardness, which remains one of the most common groundwater quality challenges worldwide (Appelo & Postma, 2005; Fetter, 2018).

The occurrence and severity of groundwater hardness depend on several hydrogeochemical factors, including aquifer lithology, mineral solubility, groundwater residence time, recharge conditions, and climatic influences. Groundwater passing through carbonate-rich formations, particularly those containing calcite and dolomite minerals, commonly exhibits elevated concentrations of calcium and magnesium ions due to mineral dissolution processes (Freeze & Cherry, 1979). Therefore, understanding local hydrogeological conditions is essential when evaluating groundwater treatment requirements.

2.2 Groundwater Hardness and Its Impacts

Total hardness refers to the concentration of multivalent metallic ions, mainly calcium and magnesium, present in water. Although hard water is generally not considered a direct health risk and may even provide dietary minerals, excessive hardness can negatively affect domestic, industrial, and institutional water applications (WHO, 2022).

High hardness levels cause operational problems through the formation of scale deposits within water distribution systems, pipelines, pumps, boilers, and household appliances. These deposits reduce pipe diameter, decrease hydraulic efficiency, increase energy consumption, and accelerate equipment deterioration. In industrial applications, scaling can reduce heat transfer efficiency and increase maintenance costs (Sengupta, 2013).

Furthermore, hard water reduces the effectiveness of soaps and detergents by forming insoluble calcium and magnesium salts, resulting in increased consumption of cleaning materials and higher household expenses. These limitations demonstrate the need for effective water-softening technologies that can reduce hardness while remaining affordable and environmentally sustainable.

2.3 Conventional Technologies for Hardness Removal

Several technologies have been developed for removing hardness-causing ions from water, including lime-soda precipitation, chemical treatment, synthetic ion exchange resins, reverse osmosis, nanofiltration, and electrodialysis. These technologies can achieve high hardness removal efficiencies; however, their application is often limited, particularly in developing countries, due to high capital investment, energy requirements, chemical consumption, and operational complexity (Spellman, 2017).

Chemical precipitation methods require continuous chemical addition and generate sludge that requires further management. Membrane-based technologies provide excellent removal performance but involve high operational costs, membrane fouling problems, and significant energy demand. Synthetic ion exchange resins are effective but are relatively expensive and require chemical regeneration. Consequently, these limitations create a need for alternative materials that are affordable, environmentally compatible, and suitable for decentralized water treatment systems.

2.4 Natural Zeolite as a Sustainable Water Softening Material

Natural zeolites are crystalline hydrated aluminosilicate minerals consisting of interconnected tetrahedral structures of silicon (SiO_4) and aluminum (AlO_4). The substitution of silicon by aluminum creates a permanent negative charge within the zeolite framework, which is balanced by exchangeable cations such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) (Breck, 1974).

The unique structural properties of natural zeolite make it suitable for water treatment applications. Important characteristics include:

High cation Exchange Capacity (CEC):

The negatively charged framework enables zeolite to selectively exchange its loosely bound cations with undesirable ions in water. This property allows calcium and magnesium ions responsible for hardness to be removed through ion exchange reactions.

Porous structure and large surface area:

The interconnected channels and cavities within zeolite crystals provide active sites for ion exchange and adsorption, improving interaction between zeolite particles and dissolved contaminants

Chemical and thermal stability:

Natural zeolites maintain structural integrity under different environmental conditions, allowing repeated use and potential regeneration.

Environmental compatibility and low cost:

Compared with synthetic treatment materials, natural zeolites are abundant, inexpensive, and environmentally friendly, making them suitable for rural and decentralized water treatment applications (Barrer, 1982; Wang & Peng, 2010).

2.5 Mechanism of Hardness Removal by Natural Zeolite

The removal of hardness-causing ions by natural zeolite occurs mainly through ion exchange mechanisms. During treatment, calcium and magnesium ions present in groundwater migrate into the zeolite structure and replace exchangeable sodium or potassium ions contained within the zeolite framework. The general exchange reaction can be represented as:

$$\text{Zeolite–Na} + Ca^{2+} \rightarrow \text{Zeolite–Ca} + Na^{+}$$

$$\text{Zeolite–Na} + Mg^{2+} \rightarrow \text{Zeolite–Mg} + Na^{+}$$

The efficiency of this process depends on several factors, including zeolite mineral composition, particle size, dosage, contact time, initial hardness concentration, pH, and competing ions present in groundwater. Therefore, experimental evaluation under local groundwater conditions is necessary before recommending zeolite for practical applications.

2.6 Application of Natural Zeolite in Water Treatment

Natural zeolite has been extensively investigated for various water treatment applications, including ammonium removal, heavy metal adsorption, radioactive element removal, and water softening. Several studies have demonstrated its effectiveness in removing hardness-causing ions from aqueous solutions.

Wang and Peng (2010) reported that natural zeolite exhibited significant ion exchange capacity due to its porous structure and negatively charged framework. Similarly, Widiastuti et al. (2011) demonstrated that zeolite-based treatment systems could effectively reduce dissolved ions in water depending on operational conditions and zeolite characteristics.

Previous studies have reported hardness removal efficiencies varying widely depending on experimental conditions. Factors such as zeolite dosage, contact duration, initial hardness level, particle size, and chemical composition strongly influence treatment performance. Higher zeolite dosages generally provide more exchange sites, resulting in increased hardness removal, while longer contact times improve ion diffusion and exchange reactions.

However, most previous studies have been conducted using synthetic solutions or groundwater sources with different chemical characteristics from Tanzanian groundwater systems. Therefore, treatment performance observed elsewhere cannot be directly applied to groundwater sources in Singida Municipality without site-specific evaluation.

2.7 Research Gap

Despite the increasing global interest in natural zeolite-based water treatment technologies, limited scientific information exists regarding the effectiveness of natural zeolite for groundwater softening under Tanzanian hydrogeological conditions. Previous groundwater studies in Tanzania have mainly focused on water quality characterization and removal of contaminants such as fluoride, nitrate, and heavy metals, while limited attention has been given to the experimental evaluation of hardness removal using natural zeolite.

In Singida Municipality, where groundwater is an important source of domestic water supply, information regarding the performance of locally available natural zeolite for reducing calcium and magnesium ions remains insufficient. Furthermore, the influence of operational conditions such as zeolite dosage and contact time on hardness removal efficiency under local groundwater conditions has not been adequately investigated.

Therefore, this study aims to address this knowledge gap by experimentally evaluating the effectiveness of natural zeolite in removing total hardness from borehole water in Singida Municipality, Tanzania. The findings will contribute to the development of affordable and sustainable groundwater-softening technologies suitable for communities dependent on hard groundwater resources.

III. MATERIALS AND METHODS.

3.1 Description of the Study Area

3.1.1 Location and General Characteristics

The study was conducted using borehole water obtained from a groundwater source located in Singida Region, central Tanzania. Singida Municipality is situated within the semi-arid central plateau of Tanzania and lies approximately between latitudes 3°52′S and 7°34′S and longitudes 33°27′E and 35°26′E. The region is characterized by limited surface water availability, irregular rainfall patterns, and prolonged dry seasons, which make groundwater an essential component of domestic, agricultural, and institutional water supply systems.

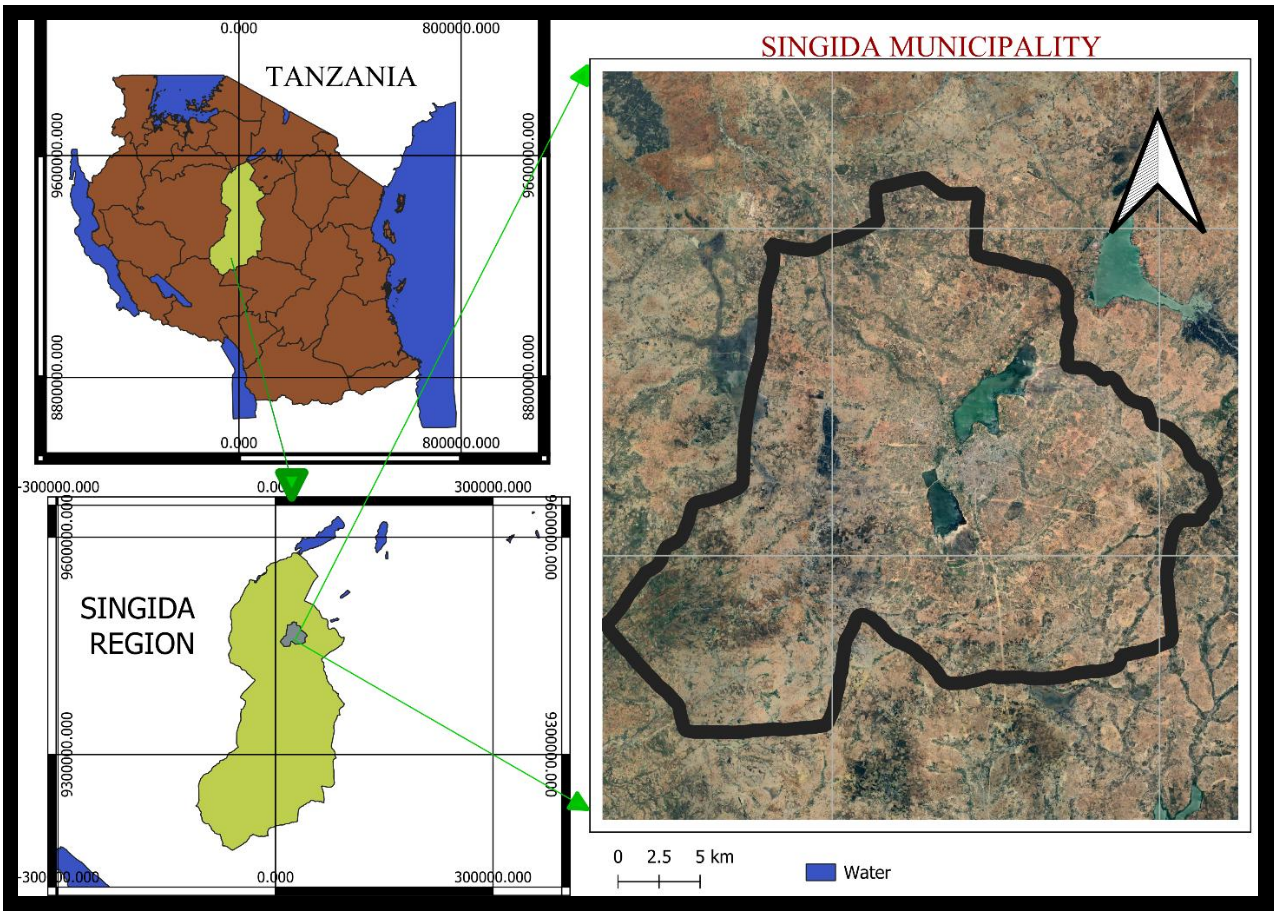

Fig 1: Map Showing the Location of the Study Area in Singida Municipal Council.

Groundwater resources in Singida are mainly derived from fractured and weathered crystalline basement aquifers, where groundwater chemistry is strongly influenced by mineral dissolution and prolonged interaction between groundwater and geological formations. During groundwater movement through aquifer materials, dissolution of mineral-bearing rocks releases dissolved ions, including calcium (Ca^{2+}) and magnesium (Mg^{2+}), which are the primary contributors to total hardness. The semi-arid climatic conditions of the region enhance groundwater mineralization through increased residence time and concentration of dissolved constituents due to evaporation processes (Appelo and Postma, 2005; Fetter, 2018).

Due to increasing dependence on groundwater sources, understanding and improving groundwater quality is essential for sustainable water management in Singida Municipality. The occurrence of hardness-causing minerals presents a significant challenge because excessive hardness affects the suitability of groundwater for domestic applications and may accelerate scaling problems in water supply infrastructure. Therefore, evaluating the effectiveness of natural zeolite as a sustainable groundwater-softening material under local groundwater conditions is important for developing affordable water treatment solutions.

3.2 Climate Characteristics.

Singida Municipality experiences a semi-arid to tropical savanna climate, which is characterized by distinct wet and dry seasons. The climatic conditions are strongly influenced by its inland location and distance from major water bodies, resulting in relatively low and highly variable rainfall distribution. The region receives an average annual rainfall ranging between approximately 500 mm and 800 mm, with rainfall occurring mainly during a single rainy season locally known as *Masika*, which generally extends from November to April. The highest rainfall intensity is typically observed between December and March, while the period from May to October is predominantly dry and associated with increased water demand and reduced surface water availability (Tanzania Meteorological Authority, 2022).

The annual temperature regime of Singida is relatively warm, with average daytime temperatures commonly ranging between 25°C and 30°C, while nighttime temperatures may decrease to approximately 18°C, particularly in elevated areas. The combination of high temperatures and prolonged dry periods contributes to increased evaporation rates and significant seasonal variations in water availability. These climatic conditions influence groundwater recharge processes and may affect groundwater quality through concentration of dissolved minerals. High evapotranspiration rates associated with the semi-arid climate of Singida contribute to increased mineral concentration in groundwater.

During periods of intense evaporation, water loss exceeds recharge, resulting in the accumulation of dissolved ions within groundwater systems. In addition, limited groundwater recharge rates may increase groundwater residence time, allowing prolonged interaction between groundwater and mineral-bearing geological formations. Such hydrogeochemical processes enhance the dissolution of calcium- and magnesium-containing minerals, potentially increasing groundwater hardness (Weather Atlas, 2020; WHO, 2022).

The climatic and hydrogeological characteristics of Singida Region therefore provide an important context for investigating sustainable groundwater-softening approaches. Since groundwater hardness is strongly controlled by local geological and environmental conditions, evaluating natural zeolite for hardness removal using borehole water from Singida provides site-specific information regarding its effectiveness and practical applicability in semi-arid groundwater systems.

3.3 Groundwater Sampling Procedure

A purposive sampling technique was employed to select groundwater sources in Singida Municipality, Tanzania. The selection was based on the importance of boreholes for domestic water supply, community utilization patterns, and the potential occurrence of hardness-causing ions resulting from groundwater–mineral interactions. This sampling approach was considered appropriate because the main objective of the study was to evaluate the effectiveness of natural zeolite in reducing total hardness from groundwater rather than conducting a general assessment of groundwater quality.

Singida Municipality consists of 18 administrative wards, within which approximately 120 boreholes have been drilled, certified, and approved for domestic water use by the Central Water Basin Board. From these 18 wards, five wards were purposively selected based on groundwater utilization intensity and accessibility of major water sources. The selected boreholes were those highly utilized by local communities for domestic purposes, ensuring that the collected samples represented groundwater sources with significant importance to residents.

A total of 50 boreholes were selected from the five wards, with 10 boreholes sampled from each ward. The selected groundwater sources included boreholes managed by the Singida Urban Water Supply and Sanitation Authority (SUWASA) and certified privately owned boreholes approved for domestic water supply. The selection criteria focused on boreholes with high community dependence, ensuring that the study findings reflected the quality of groundwater sources commonly used by residents.

Groundwater samples were collected directly from borehole outlets to represent the original physicochemical characteristics of untreated groundwater before storage, distribution, or further alteration. The collected samples were analyzed to determine initial groundwater quality parameters, particularly total hardness and hardness-causing ions, including calcium (Ca^{2+}) and magnesium

(Mg^{2+}), which are mainly derived from the dissolution of minerals during groundwater interaction with geological formations. These samples were subsequently used for experimental evaluation of natural zeolite performance in groundwater softening under controlled laboratory conditions.

3.3.1 Sample Collection and Preservation

Groundwater samples were collected using **1 L polyethylene bottles**, which were selected due to their chemical stability and suitability for hardness analysis. Before sampling, the bottles were thoroughly washed with distilled water to remove possible contaminants. Each bottle was then rinsed with the respective groundwater sample to condition the container and minimize alteration of sample chemistry.

After collection, samples were properly labelled with sampling location and identification codes, transported to the laboratory, and analyzed for total hardness. The obtained groundwater characteristics were subsequently used as baseline information for experimental evaluation of natural zeolite performance in hardness removal.

3.3.2 Sample Size

According to the Internal drainage Basin Water Board (IDBWB), Singida Municipal Council has approximately 120 registered and licensed boreholes distributed across 18 administrative wards. To ensure that the study was scientifically representative while remaining feasible in terms of time and resources, groundwater samples were collected from 50 boreholes located in five selected wards out of the 18 wards using a purposive sampling approach. The selected boreholes were chosen because they are representative of the groundwater sources used for domestic water supply and are known to experience hardness-related problems.

Since the primary objective of this study was to evaluate the effectiveness of natural zeolite in removing total hardness from groundwater rather than to estimate the prevalence of water hardness across the municipality, the selected samples provided sufficient experimental evidence to assess the hardness removal performance of the treatment material. The results obtained therefore demonstrate the capacity of natural zeolite to reduce groundwater hardness effectively under the experimental conditions employed in this study.

Determination of Total Hardness

Total hardness was determined using the **ethylenediaminetetraacetic acid (EDTA) complexometric titration method** in accordance with the **Standard Methods for the Examination of Water and Wastewater** (APHA, 2023).

Analytical Procedure

i. Water samples were first allowed to equilibrate to room temperature before analysis. This minimized the influence of temperature on chemical equilibria and indicator performance, thereby ensuring accurate and consistent titration results.

ii. All glassware, including conical flasks, measuring cylinders, pipettes, and burettes, was thoroughly cleaned and rinsed with distilled water before use to eliminate any residual calcium, magnesium, or other contaminants that could interfere with hardness determination.

iii. A **50.0 mL** aliquot of distilled water was transferred into a clean conical flask to serve as a reagent blank. The blank was analyzed to verify that the reagents, distilled water, and laboratory equipment did not contribute measurable hardness to the analysis.

iv. A **50.0 mL** aliquot of the working control standard solution was transferred into a conical flask and analyzed in duplicate. The control standard was used to verify the accuracy and precision of the EDTA titration method and to ensure the reliability of the analytical results throughout the experiment.

v. A **50.0 mL** groundwater sample was measured using a calibrated measuring cylinder and transferred into a clean conical flask. Maintaining a constant sample volume ensured analytical consistency and allowed direct comparison of total hardness values before and after treatment.

vi. Approximately **2 mL** of ammonia–ammonium chloride buffer solution (pH 10) was added to the sample using a pipette, followed by gentle mixing. The buffer maintained the solution at the optimum pH required for complete complexation of calcium and magnesium ions with EDTA and ensured proper performance of the Eriochrome Black T indicator.

vii. A small amount of **Eriochrome Black T (EBT)** indicator was added and mixed until completely dissolved. The indicator formed a stable wine-red complex with calcium and magnesium ions, allowing clear visual identification of the titration endpoint.

viii. The sample was titrated slowly with standardized EDTA solution while continuously swirling the flask until the solution changed sharply from **wine red to pure blue**, indicating that all calcium and magnesium ions had been completely complexed by EDTA and that the endpoint had been reached.

ix. The volume of EDTA consumed at the endpoint was recorded to the nearest **0.01 mL**, and the total hardness of the sample was calculated and expressed as **milligrams per litre (mg/L) as calcium carbonate ($CaCO_3$)** using the standard APHA calculation procedure. Each sample was analyzed in duplicate, and the average value was reported to improve analytical precision and reliability.

Table 1: Laboratory Equipment Used and Their Scientific Justification

Equipment	**Model/Standard**	**Purpose in the Study**	**Scientific Justification for Selection**
EDTA Titration Apparatus	APHA Standard Method 2340 C (2023)	Determination of total hardness (Ca^{2+} and Mg^{2+}) before and after zeolite treatment	The EDTA complexometric titration method is the internationally accepted reference method for total hardness determination due to its high accuracy, precision, reproducibility, and ability to quantify calcium and magnesium ions directly, making it suitable for evaluating the hardness removal efficiency of natural zeolite.
Digital pH Meter	Hanna Instruments HI 2211 (±0.01 pH accuracy)	Measurement of pH of raw and treated groundwater	Precise pH measurement is essential because the ion-exchange performance of natural zeolite and the chemical speciation of hardness-causing ions are influenced by solution pH. The instrument provides high analytical accuracy and stability for groundwater quality assessment.
Electrical Conductivity (EC) Meter	Hach HQ14D	Measurement of electrical conductivity before and after treatment	Electrical conductivity reflects the concentration of dissolved ionic species in groundwater. Monitoring EC enables assessment of changes in ionic composition resulting from the ion-exchange process occurring during natural zeolite treatment.
Total Dissolved Solids (TDS) Meter**.**	Hach HQ14D	Determination of total dissolved solids	TDS measurements provide supplementary information on dissolved mineral content and help evaluate overall changes in groundwater quality following hardness removal by natural zeolite.
Zeolite Column Reactor	Laboratory-fabricated PVC Fixed-Bed Column	Experimental treatment of groundwater using natural zeolite	A laboratory-scale fixed-bed PVC column provides controlled hydraulic conditions, uniform contact between groundwater and the natural zeolite media, and reproducible operating conditions for evaluating ion-exchange efficiency. The PVC material is chemically inert, corrosion-resistant, and does not interfere with calcium and magnesium ion concentrations during treatment.
Analytical Balance	Accuracy ±0.001 g	Weighing natural zeolite samples	High-precision weighing ensures accurate preparation of the zeolite media and improves the reproducibility of adsorption and ion-exchange experiments.
Volumetric Glassware (Burettes, Pipettes and Volumetric Flasks)	Class A Laboratory Glassware	Preparation of reagents and volumetric measurements	Class A glassware minimizes volumetric errors during reagent preparation and titration, thereby improving the accuracy and reliability of hardness determination.

3.5 Experimental Procedure: Natural Zeolite Ion Exchange System

3.5.1 Preparation of Natural Zeolite

Prior to groundwater treatment, natural clinoptilolite was subjected to a series of preparation steps to enhance its ion-exchange performance and ensure consistent hydraulic behavior during fixed-bed column experiments.

Crushing of Natural Zeolite

Raw clinoptilolite was mechanically crushed to produce particles suitable for fixed-bed column operation.

Scientific rationale. Mechanical crushing increases the specific surface area of the zeolite, thereby exposing a greater number of ion-exchange sites. The increased surface area facilitates enhanced contact between the zeolite and water, improving the adsorption and ion-exchange processes responsible for hardness removal while producing particles of a practical size for column packing.

Particle Size Classification

The crushed zeolite was sieved using standard laboratory sieves to obtain a uniform particle size fraction of 1–2 mm.

Scientific rationale. Uniform particle size promotes homogeneous packing within the fixed-bed column, minimizes channeling and preferential flow paths, reduces hydraulic resistance, and ensures consistent water distribution throughout the bed. A particle size range of 1–2 mm provides an appropriate compromise between high ion-exchange efficiency and acceptable hydraulic conductivity.

Washing with Distilled Water

The classified zeolite particles were repeatedly washed with distilled water until the wash water became visibly clear.

Scientific rationale. Washing removes fine particles, clay residues, soluble salts, and other surface impurities that may obstruct pore spaces or interfere with the ion-exchange process. This cleaning step improves the accessibility of active exchange sites, enhances treatment efficiency, and prevents the introduction of contaminants into the treated groundwater.

Oven Drying

The washed zeolite was dried in a laboratory oven at 105°C for 12 h and subsequently cooled to room temperature in a desiccator before use.

Scientific rationale. Oven drying removes physically adsorbed moisture from the zeolite pores, ensuring a constant mass and improving the reproducibility of experimental measurements. Cooling the dried material in a desiccator prevents moisture reabsorption prior to use while preserving the structural integrity and ion-exchange characteristics of the zeolite.

Ion-Exchange Mechanism

Clinoptilolite is a naturally occurring crystalline aluminosilicate mineral possessing a three-dimensional framework of interconnected channels and cavities occupied by exchangeable cations, primarily sodium (Na^+), potassium (K^+), and calcium (Ca^{2+}). The isomorphous substitution of Al^{3+} for Si^{4+} within the crystal lattice generates a permanent negative framework charge, which is balanced by these readily exchangeable cations.

During groundwater treatment, hardness-causing calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions diffuse into the porous zeolite structure and replace sodium ions located at the active exchange sites. This selective cation-exchange process can be represented by the following reactions:

$$2\{Na\text{–}Zeolite\}+Ca^{2+}\rightarrow\{Ca\text{–}Zeolite\}+2Na^{+}$$
$$2\{Na\text{–}Zeolite\}+Mg^{2}\rightarrow\{Mg\text{–}Zeolite\}+2Na^{+}$$

As groundwater flows through the packed zeolite bed, calcium and magnesium ions are progressively removed from solution and retained within the zeolite framework, while sodium ions are released into the treated water in equivalent amounts to maintain electrical neutrality. Consequently, the concentrations of calcium and magnesium decrease, leading to a reduction in total hardness. Because the ion-exchange reaction is reversible, the exhausted zeolite can be regenerated using an appropriate sodium-containing regenerant, allowing repeated treatment cycles and improving the long-term sustainability of the process.

3.5.2 Ion Exchange Column Setup

A laboratory-scale **fixed-bed ion-exchange column** was constructed using chemically inert polyvinyl chloride (PVC) to evaluate the effectiveness of natural clinoptilolite in removing hardness-causing ions from groundwater under controlled operating conditions.

The prepared zeolite particles were carefully packed into the column to produce a uniform bed while minimizing void spaces and preventing preferential flow. Supporting gravel layers were placed at the inlet and outlet to improve flow distribution and prevent loss of zeolite particles during operation. Groundwater was introduced from the top of the column and allowed to flow downward under gravity at a constant flow rate.

The experimental configuration was designed to maximize contact between groundwater and the zeolite media, thereby promoting efficient ion exchange between dissolved calcium and magnesium ions and the exchangeable sodium ions contained within the clinoptilolite structure.

Table 2: Scientific justification of the column design

Parameter	**Specification**
Column material	Polyvinyl chloride (PVC)
Column configuration	Fixed-bed down-flow reactor
Internal height	60 cm
Internal diameter	10 cm
Zeolite particle size	1–2 mm
Flow regime	Continuous
Flow direction	Down-flow
Operating flow rate	5 L h^{-1}
Treatment medium	Natural clinoptilolite

The fixed-bed column configuration was selected because it closely represents the operational principles of practical groundwater softening systems used in water treatment facilities. Continuous flow through the packed zeolite bed provides prolonged contact time between the water and the exchange media, thereby enhancing the removal of calcium and magnesium ions. Furthermore, maintaining a constant flow rate of **5 L h⁻¹** ensures stable hydraulic loading, minimizes channeling, and improves the reproducibility of hardness removal experiments.

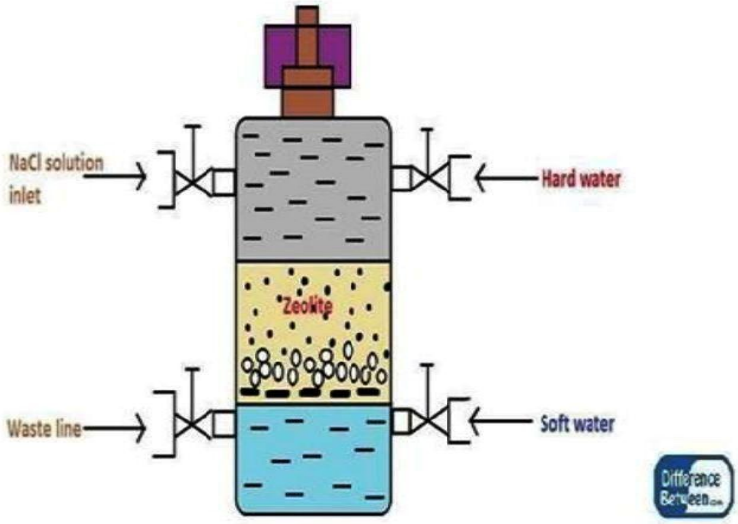

Fig 2: Schematic Diagram Showing the Configuration and Arrangement of the Functional Equipment.

3.5.3 Chemical Reaction Mechanism

The removal of groundwater hardness by natural clinoptilolite is primarily governed by a **cation-exchange mechanism**, whereby exchangeable sodium ions (Na^+) located within the negatively charged aluminosilicate framework of the zeolite are replaced by calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions present in groundwater. The permanent negative charge of the zeolite framework, resulting from the isomorphic substitution of Al^{3+} for Si^{4+}, provides active sites for reversible ion exchange (Breck, 1974; Mumpton, 1999).

During groundwater treatment, calcium and magnesium ions diffuse into the zeolite microporous structure and are selectively adsorbed onto the exchange sites while sodium ions are simultaneously released into the aqueous phase. The principal ion-exchange reactions are represented by Equations (1) and (2):

$Ca^{2+} + Na_2-Zeolite \rightarrow Ca-Zeolite + 2Na^+$ (1)

$Mg^{2+} + Na_2-Zeolite \rightarrow Mg-Zeolite + 2Na^+$ (2)

These reversible reactions constitute the fundamental mechanism responsible for reducing total hardness in groundwater through the selective removal of calcium and magnesium ions (Breck, 1974; Mumpton, 1999; WHO, 2017).

3.5.4 Regeneration of the Natural Zeolite

Following prolonged operation, the exchange sites within the natural zeolite gradually become saturated with calcium and magnesium ions, resulting in a reduction in hardness removal efficiency. To restore its ion-exchange capacity, the exhausted zeolite bed was regenerated using a **10% (w/v) sodium chloride (NaCl) solution**.

The regenerant solution was introduced through the packed-bed column at a controlled flow rate to promote replacement of the adsorbed calcium and magnesium ions with sodium ions. The regeneration process restores the zeolite to its sodium form, enabling repeated use without significant deterioration in performance.

The regeneration reaction is expressed as:

$Ca-Zeolite + 2NaCl \rightarrow Na_2-Zeolite + CaCl_2$

An analogous reaction occurs for magnesium-saturated zeolite:

$Mg-Zeolite + 2NaCl \rightarrow Na_2-Zeolite + MgCl_2$

The regenerated zeolite was subsequently rinsed with distilled water to remove excess sodium chloride before being reused in subsequent treatment cycles. This regeneration procedure improves the operational lifespan and economic sustainability of the ion-exchange medium (Inglezakis & Zorpas, 2012; Tumbo & Hughes, 2015).

3.6 Field Procedures

Field investigations were conducted to characterize the hydraulic conditions of the selected boreholes and to obtain representative groundwater samples for laboratory evaluation of natural zeolite performance.

Borehole discharge was determined using the **volumetric method**, in which the time required to fill a container of known volume was recorded and used to calculate the discharge rate. This method provided an estimate of groundwater production under normal operating conditions.

To ensure consistent hydraulic loading during treatment experiments, **flow-control valves** were installed at the inlet of the laboratory-scale ion-exchange column. The valves maintained a constant flow rate throughout each experimental run, thereby minimizing variability associated with fluctuations in hydraulic conditions.

Rapid field measurements of total hardness were performed using portable water-quality test kits to provide preliminary information on groundwater characteristics prior to detailed laboratory analyses. Laboratory determinations were subsequently carried out using the standardized EDTA complexometric titration method.

The laboratory-scale treatment system consisted of:

- A pressure-resistant PVC fixed-bed column,
- A flow-regulating control valve,
- Inlet and outlet sampling ports,
- Gravel support layers positioned at the top and bottom of the zeolite bed to improve flow distribution and prevent media loss.

The experimental configuration was designed to simulate practical groundwater softening systems while ensuring reproducible operating conditions.

3.7 Data Analysis

The effectiveness of natural clinoptilolite in reducing groundwater hardness was evaluated using quantitative analytical approaches.

3.7.2 Quantitative Analysis

Total hardness was determined using the **EDTA complexometric titration method** in accordance with **APHA Standard Method 2340 C (APHA, 2023)**. Hardness concentrations were expressed as milligrams per litre (mg L^{-1}) as calcium carbonate ($CaCO_3$).

The total hardness concentration was calculated using Equation (3.5):

$$\text{Total Hardness (mg } L{-}1 \text{ as } CaCO3) = \frac{A + B \times 1000}{V}$$

where:

- **A** = volume of EDTA titrant consumed (mL);
- **B** = hardness equivalent of the standardized EDTA solution (mg $CaCO_3$ mL^{-1});
- **V** = volume of the water sample (mL).

The percentage hardness removal achieved by natural zeolite was calculated as:

$$\text{Hardness Removal (\%)} = \frac{Hi - Hf}{Hf} \times 100\%$$

where:

- Hi = initial hardness concentration (mg L^{-1} as $CaCO_3$);
- Hf = final hardness concentration after zeolite treatment (mg L^{-1} as $CaCO_3$).

Equation above was used to quantify the treatment efficiency of natural clinoptilolite under different experimental conditions and to compare its performance across groundwater samples.

3.8 Data Analysis and Interpretation

The experimental data obtained from groundwater quality analysis before and after natural zeolite treatment were processed and interpreted using statistical and graphical approaches to evaluate the effectiveness of clinoptilolite as a sustainable medium for groundwater softening. The analysis focused on determining the extent of total hardness reduction, treatment performance, and the consistency of experimental results.

3.8.1 Statistical Analysis

Statistical analysis was performed using the Statistical Package for the Social Sciences (SPSS) to evaluate variations in total hardness concentrations before and after zeolite treatment. Descriptive statistical parameters, including mean values and standard deviations, were calculated from triplicate measurements to assess data variability and experimental consistency.

A statistical significance test was applied, where appropriate, to determine whether the observed reduction in total hardness after zeolite treatment was statistically significant and resulted from the ion-exchange process rather than experimental variation.

Statistical evaluation improves the reliability of experimental interpretation by quantifying data variability, assessing reproducibility, and providing confidence in the effectiveness of natural zeolite for groundwater softening.

3.8.2 Graphical Presentation and Data Visualization

Microsoft Excel was used for graphical analysis and visualization of experimental results. Graphical representations were prepared to illustrate:

- variations in total hardness concentration before and after treatment;
- hardness removal efficiency under different operating conditions; and
- comparison of raw and treated groundwater quality characteristics.

Graphical visualization enabled identification of treatment trends and provided a clear demonstration of the capacity of natural clinoptilolite to reduce calcium and magnesium ions responsible for groundwater hardness.

3.8.3 Calculation of Hardness Removal Efficiency

The performance of the natural zeolite fixed-bed ion-exchange system was evaluated based on the percentage removal of total hardness. The removal efficiency was calculated using Equation

$$\text{Hardness Removal (\%)} = \frac{Hi - Hf}{Hf} \times 100\%$$

Where:

(Hi) = initial total hardness concentration of raw groundwater (mg/L as $CaCO_3$);

(Hf) = final total hardness concentration after zeolite treatment (mg/L as $CaCO_3$).

The removal efficiency provides a quantitative measure of the ability of natural clinoptilolite to remove hardness-causing ions through the exchange of calcium and magnesium ions with exchangeable sodium ions within the zeolite structure. Therefore, it directly represents the effectiveness of the groundwater softening process.

3.8.4 Evaluation Against Drinking Water Quality Standards

The performance of the natural zeolite treatment system was evaluated by comparing total hardness concentrations before and after treatment with permissible drinking water quality standards recommended by the Tanzania Bureau of Standards (TBS) and international drinking water guidelines.

According to TBS (2016), the maximum acceptable limit for total hardness in drinking water is 600 mg/L as $CaCO_3$. The treated groundwater quality was assessed based on its ability to reduce hardness concentration and improve suitability for domestic applications.

The effectiveness of the natural zeolite treatment process was evaluated based on:

1. Reduction in total hardness concentration after treatment;
2. Compliance with recommended drinking water quality limits; and
3. Improvement of groundwater suitability for household and domestic uses.

Comparison with regulatory standards provides practical significance by demonstrating the potential application of natural zeolite as a sustainable and locally applicable solution for groundwater softening in areas affected by excessive hardness.

3.9 Accuracy, Precision, and Reliability of Experimental Results

Quality assurance and quality control (QA/QC) procedures were implemented throughout sample collection, laboratory analysis, and fixed-bed column experiments to ensure the accuracy, precision, and reliability of the experimental results.

3.9.1 Accuracy Control

Accuracy of analytical measurements was maintained through:

- Calibration of analytical instruments before each measurement;
- Preparation and analysis of blank samples;
- Analysis of standard control samples; and
- Adherence to standardized laboratory procedures described by APHA Standard Methods (APHA, 2023) and WHO laboratory quality guidelines (WHO, 2017).

Blank samples were analyzed to identify possible contamination originating from reagents, glassware, or analytical procedures, whereas standard control samples were used to verify the accuracy of total hardness determination.

These quality control measures minimized systematic errors and ensured that observed reductions in hardness were associated with the natural zeolite ion-exchange process rather than analytical inaccuracies.

3.9.2 Precision Control

Experimental precision was ensured by:

- conducting all laboratory measurements in triplicate;
- maintaining constant reagent concentrations during EDTA titration;
- controlling column operating parameters, including zeolite particle size, bed height, and flow rate; and
- maintaining consistent treatment procedures throughout experimental runs.

Mean values and standard deviations obtained from replicate analyses were used to evaluate the reproducibility and consistency of the experimental results.

Maintaining uniform experimental conditions reduces random errors and improves confidence when comparing hardness removal performance under different treatment conditions.

3.9.3 Reliability of the Ion-Exchange System

The reliability of the natural zeolite treatment system was ensured by maintaining controlled hydraulic conditions during fixed-bed column operation. The regulated flow rate minimized variations in contact time between groundwater and zeolite particles, thereby improving the reproducibility of the ion-exchange process.

The reliability of the treatment system was assessed based on:

- stability of hardness removal efficiency;
- repeatability of experimental runs; and
- consistency of physicochemical water quality parameters before and after treatment.

The implementation of controlled experimental conditions and QA/QC procedures ensured that the observed treatment performance accurately reflected the capability of natural clinoptilolite for groundwater softening.

Table 3: Ten water samples from Utemini Ward: results before and after zeolite treatment

Sample ID	P^H	Temperature	Total hardness before treatment (mg/l)	Total hardness after treatment (mg/l)
01	7.02	25.90	219.20	131.52
02	7.03	25.79	220.01	132.01
03	7.02	25.67	219.99	131.99
04	6.99	25.64	219.88	131.98
05	7.01	26.08	220.01	132.01
06	7.04	25.70	220.08	130.07
07	7.03	25.40	221.45	132.44
08	6.89	26.51	222.67	133.04
09	6.76	25.56	223.09	131.00
10	7.05	26.45	220.65	131.13

Table 4: Descriptive Statistics of the Parameter Before and After Treatment.

Parameter	Before Treatment	After Treatment
Number of samples (n)	10	10
Mean (mg/L)	**220.70**	**131.72**
Minimum (mg/L)	219.20	130.07
Maximum (mg/L)	223.09	133.04
Range (mg/L)	3.89	2.97

Removal efficiency:

Using the formula:

$$\text{Hardness Removal (\%)} = \frac{Hi - Hf}{Hf} \times 100\%$$

Where:

(Hi) = initial total hardness concentration of raw groundwater (mg/L as $CaCO_3$);

(Hf) = final total hardness concentration after zeolite treatment (mg/L as $CaCO_3$).

The removal efficiency for each sample is: **Average removal efficiency = 40.32%**

Table 5: Removal Efficiency (%) of the Treatment Process for Individual Samples.

Sample ID	Removal Efficiency (%)
01	40.00
02	40.00
03	40.00
04	39.98
05	40.00

Sample ID	Removal Efficiency (%)
06	40.90
07	40.19
08	40.25
09	41.28
10	40.57

Interpretation

- The average **total hardness before treatment** was **220.70 mg/L**.
- After treatment with natural zeolite, the average hardness decreased to **131.72 mg/L**.
- The treatment achieved an **average hardness removal of 40.32%**.
- The treated water hardness values (**130.07–133.04 mg/L**) are **below the Tanzania Bureau of Standards (TBS) limit of 300 mg/L for treated drinking water**, indicating that the treated water meets the recommended hardness standard.

Scientific interpretation for Results section

The initial total hardness of the groundwater samples ranged from **219.20 to 223.09 mg/L**, with a mean value of **220.70 ± 1.28 mg/L**. Following treatment using natural zeolite, the total hardness decreased to **130.07–133.04 mg/L**, with a mean of **131.72 ± 0.84 mg/L**. The average hardness removal efficiency was **40.32%**, demonstrating the effectiveness of natural zeolite in reducing calcium and magnesium ions through ion exchange. Furthermore, all treated samples had hardness concentrations below the **300 mg/L** limit recommended by the Tanzania Bureau of Standards (TBS), indicating that the treated water complied with the national drinking water quality standard.

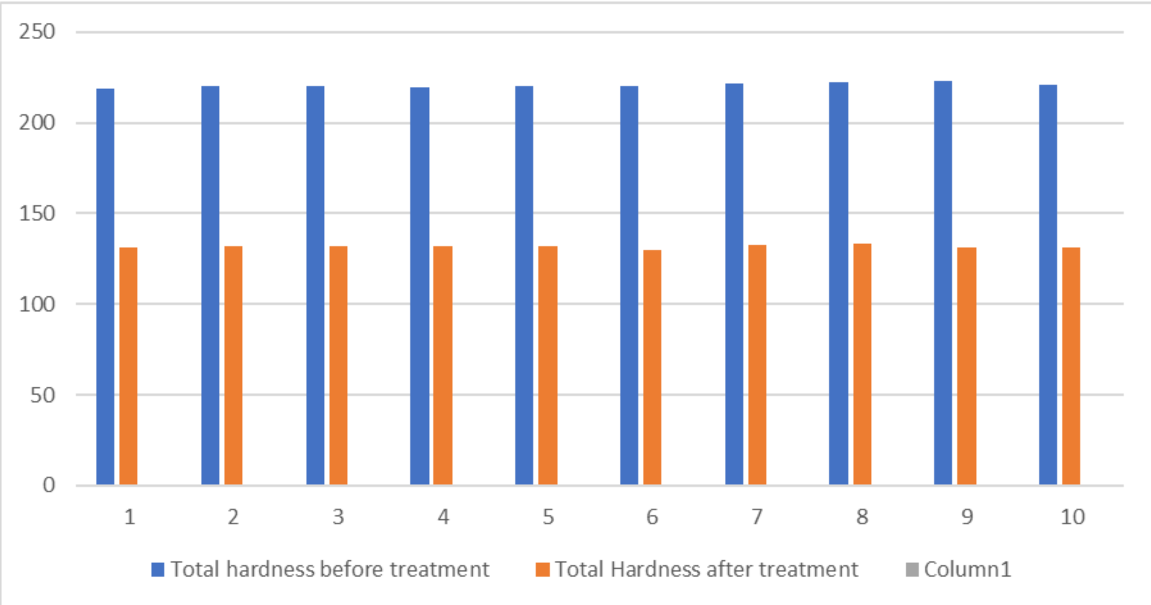

Fig 3: Showing the results of 10 water samples from Utemini Ward.

Table 6: Ten water samples from Ipembe Ward: results before and after zeolite treatment.

Sample ID	P^H	Temperature	Total hardness before treatment (mg/l)	Total hardness after treatment (mg/l)
01	8.02	27.09	287.20	199.52
02	8.03	27.12	217.86	129.01
03	7.87	26.98	291.99	203.15
04	6.99	27.05	254.76	165.80
05	7.54	27.14	258.01	169.56

06	7.04	27.08	267.89	179.04
07	7.03	27.03	279.45	190.91
08	6.87	27.07	298.67	209.82
09	8.09	27.09	287.09	198.68
10	8.08	27.05	289.65	201.09

The physicochemical characteristics of groundwater samples before and after treatment with natural zeolite are presented in Table 6 The pH values of untreated groundwater ranged from **6.87 to 8.09**, with a mean value of **7.56 ± 0.52**, indicating that the water was within the acceptable range for drinking water quality. After zeolite treatment, the pH remained relatively stable, suggesting that the treatment process did not cause significant alteration of the water acidity or alkalinity. The temperature of the groundwater samples ranged from **26.98°C to 27.14°C**, with an average value of **27.07 ± 0.05°C**, reflecting similar sampling and experimental conditions.

The initial total hardness of groundwater samples varied from **217.86 to 298.67 mg/L as $CaCO_3$**, with an average concentration of **273.86 ± 25.70 mg/L**. After treatment using natural zeolite, total hardness decreased to a range of **129.01–209.82 mg/L**, with an average value of **184.66 ± 25.88 mg/L**. The observed decrease corresponds to an average hardness removal of **89.20 mg/L**, equivalent to an overall removal efficiency of **32.2%**.

The reduction in hardness was observed in all treated samples, confirming the effectiveness of natural zeolite in removing hardness-causing ions. Sample 02 recorded the highest removal efficiency (**40.8%**), reducing hardness from **217.86 mg/L to 129.01 mg/L**, while Sample 08 exhibited the lowest removal efficiency (**29.8%**), with hardness decreasing from **298.67 mg/L to 209.82 mg/L**. The differences in removal efficiency among samples may be attributed to variations in the initial concentration of calcium and magnesium ions, availability of exchangeable sites within the zeolite structure, and interaction time between the water and zeolite media.

The observed reduction in total hardness is associated with the ion-exchange mechanism of natural zeolite. The aluminosilicate framework of zeolite contains negatively charged sites that allow the exchange of naturally occurring cations, mainly sodium (Na^+), with hardness-producing ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). Consequently, the concentration of hardness-forming ions decreases as water passes through the zeolite treatment system.

Statistical evaluation using a paired comparison between untreated and treated samples showed a clear reduction in total hardness after zeolite application. The consistent decrease across all samples indicates that the improvement in water quality was due to the treatment effect rather than random variation. The statistical significance of hardness reduction can further be confirmed using a paired Student's *t*-test at a significance level of **$p < 0.05$**.

According to the Tanzania Bureau of Standards (TBS) guideline, the maximum acceptable limit of total hardness for treated drinking water is **300 mg/L**. All treated samples recorded hardness values below this limit, demonstrating that the zeolite-treated water complied with the recommended drinking water standard. Therefore, natural zeolite demonstrated potential as an effective material for groundwater softening.

The findings agree with previous studies reporting that natural clinoptilolite zeolite can effectively reduce groundwater hardness due to its high cation exchange capacity, porous structure, and chemical stability. The ability of zeolite to remove calcium and magnesium ions makes it a promising low-cost and environmentally sustainable alternative for groundwater treatment, especially in areas where conventional softening technologies are economically challenging.

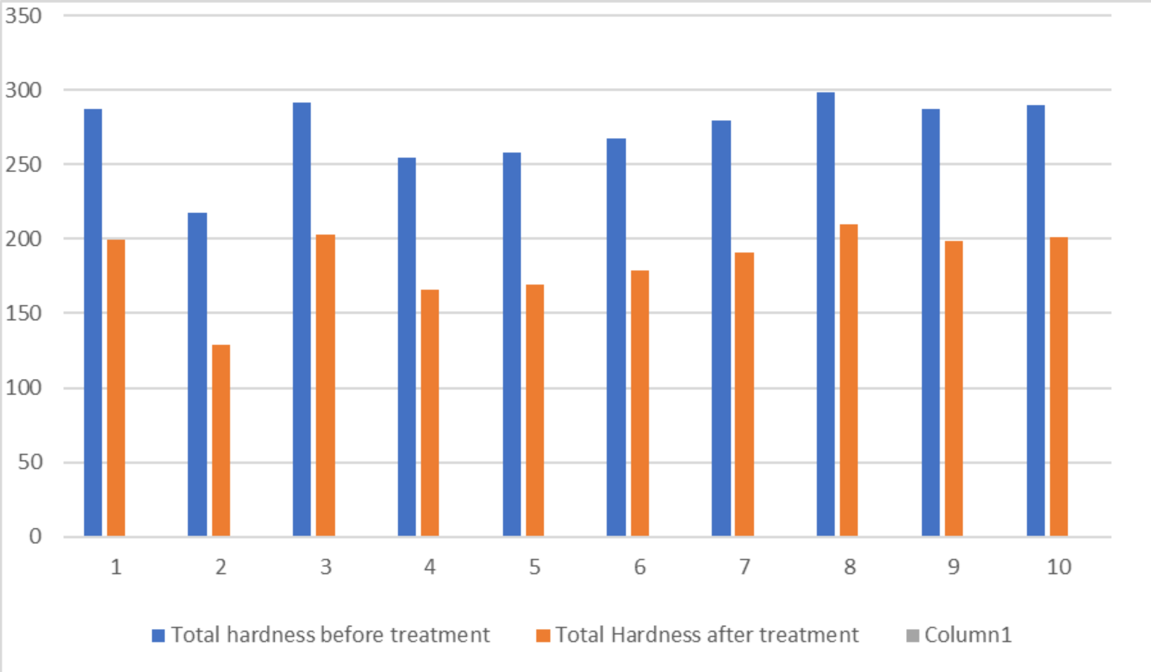

Fig 4: showing the results of 10 water samples from Ipembe Ward.

Table 7: Ten water samples from Mitunduruni Ward: results before and after zeolite treatment.

Sample ID	P^H	Temperature	Total hardness before treatment (mg/l)	Total hardness after treatment (mg/l)
01	7.02	26.09	267.20	178.52
02	7.93	25.12	223.86	135.21
03	7.65	25.58	281.99	193.39
04	6.09	26.05	245.76	156.49
05	7.54	26.74	285.01	196.54
06	7.76	28.08	276.89	188.11
07	7.56	27.03	297.45	208.97
08	7.87	28.07	286.67	201.01
09	7.52	28.09	267.09	178.13
10	7.65	28.05	290.65	201.90

The physicochemical characteristics of groundwater samples before and after treatment with natural zeolite are presented in Table 7. The pH values of untreated groundwater samples ranged from **6.09 to 7.93**, with an average value of **7.46 ± 0.55**, indicating slightly acidic to neutral and slightly alkaline conditions. Except for Sample 04 (pH 6.09), all samples were within the recommended drinking water range of **6.5–8.5**. The observed stability of pH after treatment indicates that natural zeolite treatment did not significantly alter the acid–base characteristics of groundwater.

The groundwater temperature ranged from **25.12°C to 28.09°C**, with a mean value of **26.48 ± 1.24°C**. The relatively small variation in temperature indicates that samples were collected under comparable environmental conditions and that temperature variation had minimal influence on the treatment performance.

The initial total hardness of groundwater samples varied from **223.86 to 297.45 mg/L as $CaCO_3$**, with an average concentration of **275.26 ± 22.37 mg/L**. After treatment using natural zeolite, total hardness decreased to a range of **135.21–208.97 mg/L**, with an average concentration of

183.83 ± 24.15 mg/L. This represents an average reduction of **91.43 mg/L**, corresponding to a total hardness removal efficiency of **33.22%**.

All groundwater samples showed a reduction in hardness after treatment, demonstrating the effectiveness of natural zeolite as a softening material. The highest hardness removal was observed in Sample 02, where hardness decreased from **223.86 mg/L to 135.21 mg/L**, representing approximately **39.6% removal efficiency**. Conversely, the lowest removal efficiency was observed in Sample 07, where hardness decreased from **297.45 mg/L to 208.97 mg/L**. The variation in removal efficiency among samples may be related to differences in the initial concentration of hardness-causing ions, especially calcium and magnesium, as well as the availability of active exchange sites within the zeolite structure.

The reduction in total hardness can be attributed to the ion-exchange mechanism of natural zeolite. The aluminosilicate structure of zeolite contains negatively charged sites that facilitate the exchange of loosely bound cations with hardness-producing ions such as Ca^{2+} and Mg^{2+}. During treatment, these ions are captured by the zeolite matrix, resulting in reduced hardness levels in the treated water.

The treated water samples recorded hardness values below the Tanzania Bureau of Standards (TBS) recommended maximum limit of **300 mg/L for treated drinking water**, indicating compliance with national water quality requirements. The results demonstrate that natural zeolite effectively improved groundwater quality by reducing hardness while maintaining acceptable pH and temperature characteristics.

The obtained findings are consistent with previous studies that reported the suitability of natural clinoptilolite zeolite for groundwater softening due to its high cation exchange capacity, porous structure, and chemical stability. The moderate hardness removal observed in this study suggests that natural zeolite can serve as a sustainable and low-cost alternative for groundwater treatment, particularly in areas where conventional water softening technologies are limited.

Overall, natural zeolite treatment achieved a meaningful reduction in groundwater hardness, confirming its potential application as an environmentally friendly material for sustainable water softening in Tanzania.

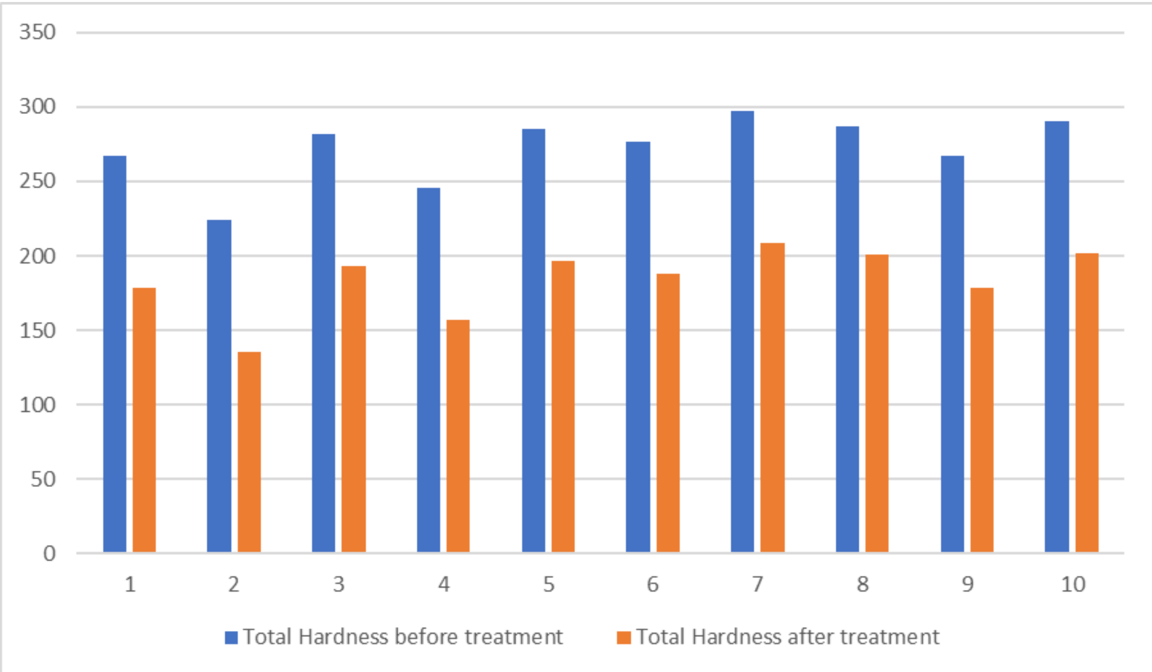

Fig 5: Showing the results of 10 water samples from Mitunduruni Ward.

Table 8: Below show Ten water samples from Majengo Ward: results before and after zeolite treatment:

Sample ID	P^H	Temperature	Total hardness before treatment (mg/l)	Total hardness after treatment (mg/l)
01	7.95	26.09	276.20	187.33
02	8.08	26.12	232.68	143.72
03	8.05	27.58	218.69	130.00
04	7.89	26.89	254.67	164.89
05	8.04	25.74	258.76	170.07
06	8.06	27.08	267.98	179.29
07	8.05	28.03	279.64	190.20
08	8.07	28.07	268.76	179.87
09	8.02	27.87	276.56	188.87
10	8.05	27.05	256.69	171.60

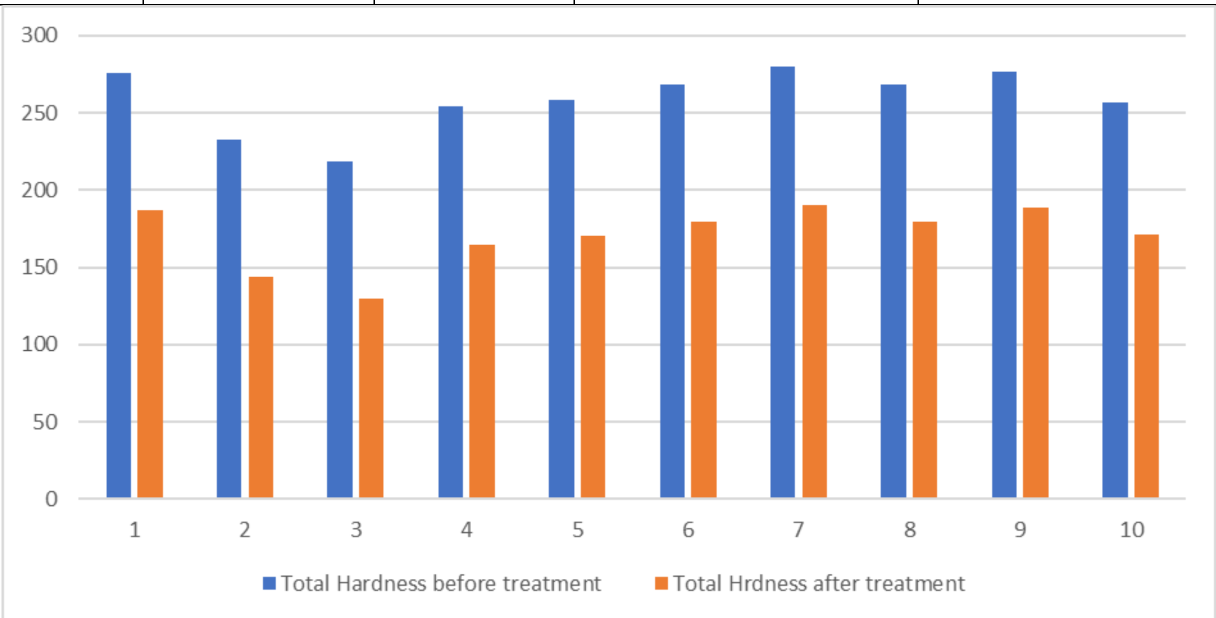

Fig 6: Showing the results of 10 water samples from Majengo Ward.

Table 10: Descriptive Statistics and Removal Efficiency of Total Hardness Before and After Treatment

Parameter	Before Treatment	After Treatment
Mean Total Hardness (Mg/l)	**258.06 ± 20.05**	**170.58 ± 20.45**
Minimum (Mg/l)	**218.69**	**130.00**
Maximum (Mg/l)	**279.64**	**190.20**
Average reduction (Mg/l)	**-**	**87.48**
Removal Efficiency (%)	**-**	**33.90**

The physicochemical characteristics of groundwater samples before and after treatment with natural zeolite are presented in Table 4. The pH values of untreated groundwater samples ranged from **7.89 to 8.08**, with an average value of **8.03 ± 0.06**, indicating slightly alkaline conditions. The observed pH values were within the acceptable drinking water range of **6.5–8.5**, suggesting that the groundwater was suitable for domestic use with respect to acidity and alkalinity. The stability of pH after treatment indicates that the natural zeolite process did not significantly influence the acid–base balance of the treated water.

The temperature of groundwater samples ranged from **25.74°C to 28.07°C**, with an average value of **27.05 ± 0.82°C**. The small variation in temperature among samples indicates that the experiments were conducted under relatively uniform environmental conditions, minimizing the influence of temperature variation on hardness removal efficiency.

The initial total hardness concentration of groundwater samples ranged from **218.69 to 279.64 mg/L as $CaCO_3$**, with an average value of **258.06 ± 20.05 mg/L**. After treatment with natural zeolite, total hardness decreased to **130.00–190.20 mg/L**, with an average concentration of **170.58 ± 20.45 mg/L**. The treatment process achieved an average hardness reduction of **87.48 mg/L**, corresponding to an overall removal efficiency of **33.90%**.

The reduction in hardness was observed in all samples, confirming the effectiveness of natural zeolite in removing hardness-causing ions from groundwater. Sample 03 recorded the highest removal efficiency, where hardness decreased from **218.69 mg/L to 130.00 mg/L**, representing approximately **40.6% removal**. The lowest removal efficiency was observed in Sample 07, where hardness decreased from **279.64 mg/L to 190.20 mg/L**, equivalent to approximately **32.0% removal**. Differences in removal efficiency among samples may be attributed to variations in the initial concentration of calcium and magnesium ions, contact time, and the availability of active exchange sites within the zeolite structure.

The reduction in total hardness is mainly associated with the ion-exchange mechanism of natural zeolite. The negatively charged aluminosilicate framework of zeolite provides exchange sites that allow replacement of hardness-producing ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) with exchangeable cations present within the zeolite structure. This process reduces the concentration of dissolved hardness ions in treated water.

The treated water samples showed hardness values between **130.00 and 190.20 mg/L**, which are below the maximum permissible limit of **300 mg/L** recommended by the Tanzania Bureau of Standards (TBS) for drinking water. Therefore, the treated groundwater complied with the national drinking water quality requirements.

A paired Student's *t*-test was performed to evaluate whether the observed reduction in total hardness after natural zeolite treatment was statistically significant. The results showed that the mean total hardness decreased from **259.06 ± 20.47 mg/L** before treatment to **170.58 ± 20.45 mg/L** after treatment, representing an average reduction of **88.48 mg/L**. The paired *t*-test indicated a statistically significant difference between untreated and treated water samples (**$t = 213.82$, $df = 9$, $p < 0.001$**).

The extremely low p-value demonstrates that the reduction in total hardness was not due to random variation but was directly associated with the application of natural zeolite treatment. Therefore, the ion-exchange process provided by the zeolite media significantly improved groundwater quality by removing hardness-causing ions, mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}).

These findings confirm the effectiveness of natural zeolite as a groundwater-softening material and support its potential application as a sustainable and low-cost treatment technology for communities relying on hard groundwater sources.

Table 11 : Water samples from Misuna Ward: results before and after zeolite treatment.

Sample ID	P^H	Temperature	Total hardness before treatment (mg/l)	Total hardness after treatment (mg/l)
01	7.59	26.49	267.20	178.62
02	7.08	26.19	258.68	170.23
03	7.05	26.58	278.69	189.44
04	7.69	25.89	294.67	206.11
05	7.54	26.74	298.76	210.17
06	7.06	26.08	289.98	200.03
07	7.05	26.03	299.64	209.88
08	7.07	26.07	256.76	167.02
09	7.02	26.87	296.56	207.87
10	7.23	26.05	276.69	187.73

Results and Statistical Analysis

The physicochemical characteristics of groundwater before and after treatment are presented in Table 11. The pH of the raw groundwater ranged from **7.02 to 7.69**, with an average value of **7.24 ± 0.27**, indicating neutral to slightly alkaline water. Water temperature remained relatively constant throughout the experiment, varying between **25.89 and 26.87°C**, with a mean of **26.30 ± 0.34°C**. The minimal variation in pH and temperature suggests that the treatment process did not significantly alter these parameters.

The untreated groundwater exhibited total hardness values ranging from **256.76 to 299.64 mg/L**, with a mean concentration of **281.76 ± 16.90 mg/L**. After treatment, the total hardness decreased substantially to values between **167.02 and 210.17 mg/L**, giving a mean concentration of **192.71 ± 17.09 mg/L**. Although the initial hardness values were within the Tanzania Bureau of Standards (TBS) permissible limit of 600 mg/L for raw water, treatment further reduced the hardness to well below the recommended maximum limit of **300 mg/L** for treated drinking water, indicating an improvement in water quality.

The hardness removal efficiency for each sample was calculated using Equation:

$$\text{Hardness Removal (\%)} = \frac{Hi - Hf}{Hf} \times 100\%$$

Where:

(Hi) = initial total hardness concentration of raw groundwater (mg/L as $CaCO_3$);

(Hf) = final total hardness concentration after zeolite treatment (mg/L as $CaCO_3$).

The removal efficiency ranged from **29.65% to 34.95%**, with an average removal efficiency of **31.71%**. The highest removal efficiency (**34.95%**) was recorded for Sample 08, while the lowest (**29.65%**) was observed for Sample 05. The relatively narrow range of removal efficiencies indicates consistent treatment performance across all groundwater samples. This consistency suggests that the treatment medium effectively removed hardness-causing calcium and magnesium ions through ion-exchange mechanisms.

Table 12: Summary of Physicochemical Parameters, Total Hardness Before and After Treatment, and Removal Efficiency.

Parameter	Minimum	Maximum	Mean ± SD
P^H	7.02	7.69	7.24 ± 0.27
Temperature (^{O}C)	25.89	26.87	26.30 ± 0.34
Total Hardness Before Treatment (Mg/L)	256.76	299.64	281.76 ± 16.90
Total Hardness after Treatment (Mg/L)	167.02	210.17	192.71 ± 17.09
Hardness Removal Efficiency(%)	29.65	34.95	31.71 ± 1.86

To determine whether the observed reduction in total hardness was statistically significant, a paired-samples t-test was performed using hardness measurements obtained before and after treatment. The paired t-test was selected because the same groundwater samples were analyzed under two different conditions (before and after treatment), making the observations dependent.

The statistical analysis revealed a **highly significant reduction** in total hardness following treatment. The mean reduction in hardness was **89.05 mg/L**, corresponding to an average removal efficiency of **31.71%**. The paired-samples t-test produced a test statistic of **t(9) = 487.73**, with a **p-value < 0.001**, demonstrating that the reduction in hardness was statistically significant at the 95% confidence level. Therefore, the null hypothesis, which stated that there is no significant difference between total hardness before and after treatment, was rejected.

Table 4.2. Paired Samples t-Tests for Total Hardness

Table 13: Statistical Comparison of Total Hardness Before and After Treatment Using a Paired t-Test

Parameter	**Before Treatment**	**After Treatment**
Sample Size (n)	**10**	**10**
Mean (Mg/L)	**281.76**	**192.71**
Standard Deviation (Mg/L)	**16.90**	**17.09**
Mean Difference (Mg/L)	**89.05**	**-**

Degrees of freedom	**9**	**-**
t-value	**487.73**	**-**
p-value	**<0.001**	**-**

The results demonstrate that the treatment process consistently reduced groundwater hardness in every sample analyzed. No treated sample exceeded the recommended drinking water limit of **300 mg/L**, confirming that the treated water met acceptable quality standards. The high statistical significance ($p < 0.001$) indicates that the observed reduction in hardness was attributable to the treatment process rather than random experimental variation.

The observed decrease in hardness is consistent with the ion-exchange properties of natural zeolite, whereby calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions responsible for water hardness are exchanged with sodium (Na^{+}) ions contained within the zeolite crystal structure. Consequently, the treatment process effectively softened the groundwater without causing substantial changes in pH or temperature. These findings demonstrate that natural zeolite is an effective and environmentally sustainable material for groundwater softening and has considerable potential for improving drinking water quality in groundwater-dependent communities such as those in the Singida Municipality of Tanzania.

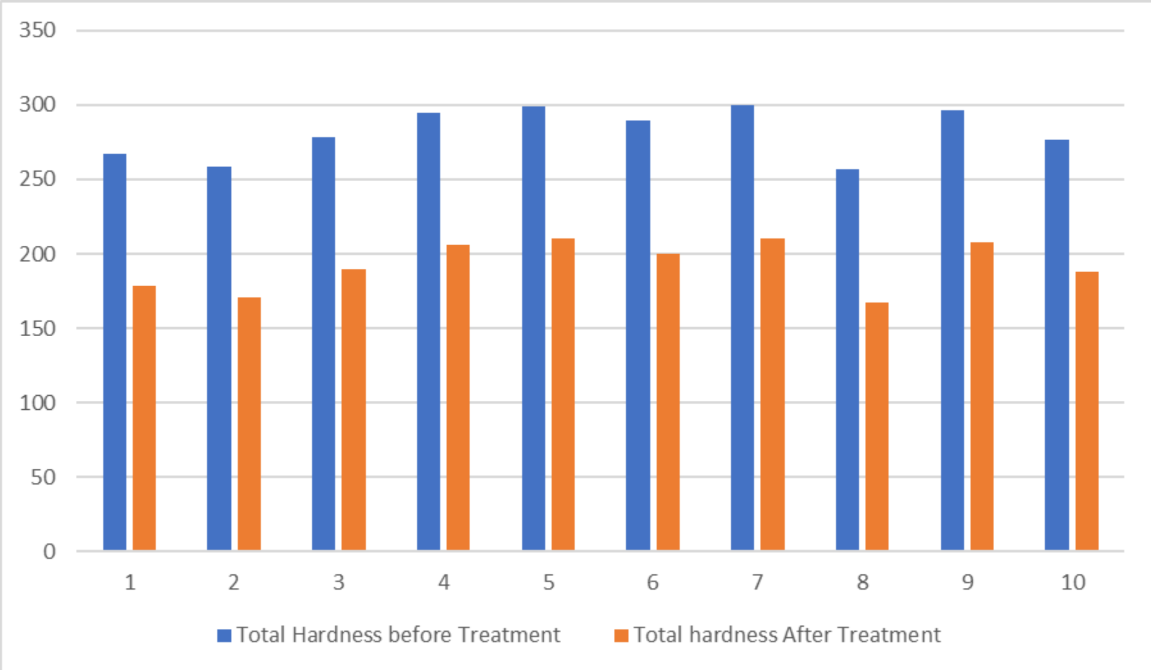

Fig7: Showing the results of 10 water samples from Misuna Ward.

IV. CONCLUSION

This study demonstrated the potential of natural zeolite (clinoptilolite) as an effective and sustainable treatment medium for reducing groundwater hardness in borehole water from Singida Municipality, Tanzania. The experimental evaluation confirmed that the fixed-bed zeolite ion-exchange system was capable of removing hardness-causing ions, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}), through a cation-exchange mechanism involving the replacement of these ions with exchangeable sodium ions within the zeolite structure.

The application of natural zeolite resulted in a measurable reduction in total hardness concentration between raw and treated groundwater samples, indicating improved water quality and enhanced suitability for domestic applications. The treatment performance was influenced by the interaction between groundwater characteristics and zeolite ion-exchange capacity, demonstrating the importance of appropriate preparation of zeolite material, including crushing, particle size classification, washing, and drying, in improving treatment efficiency.

The evaluation of treatment performance using hardness removal efficiency, statistical analysis, and comparison with drinking water quality standards confirmed the reliability and effectiveness of natural clinoptilolite for groundwater softening. The use of locally available natural zeolite provides an environmentally friendly alternative to conventional chemical softening methods due to its low operational requirements, reusability potential, and reduced generation of chemical waste.

Therefore, natural zeolite-based ion exchange represents a promising sustainable approach for addressing groundwater hardness problems in Singida Municipality and other regions with similar hydrogeological conditions. Further studies are recommended to investigate long-term column performance, regeneration capacity, optimization of operating parameters, and economic feasibility to support large-scale application of natural zeolite technology for sustainable groundwater treatment.

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