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Research Paper

Effectiveness of Ultrafiltration Membrane Technology Combined with Zeolite–Ginger Coral Adsorbent in pH, TDS, EC, Fe, and Mn in Groundwater for Clean Water Production

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Abstract

Groundwater is a vital water source for many communities, especially in rural areas, but its quality often fails to meet clean water standards due to contaminants such as heavy metals, organic compounds, and unsuitable pH, TDS, and EC levels. This study examines an integrated water treatment system combining adsorption and ultrafiltration technologies. The process begins with adsorption using zeolite and coral ginger stone to remove contaminants through ion exchange and Van der Waals interactions. The pre-treated water is then filtered through an ultrafiltration membrane to eliminate suspended solids and microorganisms based on pore size exclusion. The novelty of this study lies in the variation of adsorbent compositions, namely 100 g zeolite, 100 g coral ginger stone, and a 50:50 g mixture. Results indicate that the 50:50 combination provides the highest efficiency in improving groundwater quality. Under optimal conditions, TDS decreased to 38 ppm, EC to 76 μS/cm, temperature reached 29.8°C, and pH approached neutral at 6.28, meeting clean water standards.

Keywords
Groundwater, Zeolite, Coral Ginger Stone, Ultrafiltration Membrane, TDS, pH

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1. INTRODUCTION

Water is an essential source of life for humans. The quality of natural water is often contaminated, especially in areas that still rely heavily on well water. Well water may contain contaminants such as heavy metals, organic substances, and pathogens that can cause various health problems if consumed without proper treatment. In addition, the pH of well water tends to be acidic (4-5), which can pose health risks and reduce overall water quality. Untreated well water has been reported to have an acidic pH of around 4.6, a high TDS of 218 mg/L, an Fe concentration of 2.11 mg/L, and an Mn concentration of 0.18 mg/L-far exceeding the quality standards set by the Indonesian Ministry of Health Regulation No. 2 of 2023. This contamination problem significantly affects water quality, aquatic ecosystems, and the surrounding environmental health (Yang et al., 2011).

This highlights the importance of innovation in groundwater treatment to support the achievement of the Sustainable Development Goals (SDGs), particularly Goal 6 on access to clean water and proper sanitation. Conventional methods such as sedimentation or simple filtration are often insufficient to significantly reduce organic and inorganic pollutants. Therefore, a new approach with higher efficiency is required.

One promising alternative is the combination of ultrafiltration membrane technology with adsorption methods using natural materials. Ultrafiltration membranes function to filter colloidal particles and organic macromolecules sized 0.010-.1 microns, while zeolite has a large surface area and strong ion-exchange properties that enable the adsorption of both organic and inorganic pollutants (Singh, 2005). Mean-while, ginger coral stone, with its high porosity, has potential as an additional adsorptive medium to enhance pollutant removal efficiency. Variations in adsorbent ratios 100 g of zeolite, 100 g of ginger coral stone, and a 50:50 g mixture of zeolite and ginger coral stone are expected to demonstrate optimal performance in reducing TDS and EC levels as well as stabilizing the pH of clean water.

This integrative technology combining ultrafiltration membranes with adsorption using natural materials is expected to offer an applicable solution that is more environmentally friendly, economical, and sustainable. Access to clean groundwater is a critical public health issue in Indonesia, particularly in peri-urban and rural communities that rely on shallow wells as their primary water source. Groundwater contamination issues are directly linked to the global development agenda, particularly Sustainable Development Goal 6 (Clean Water and Sanitation), which emphasizes the importance of sustainable water management and improving water quality. Therefore, this research represents an urgent effort to support the achievement of SDG 6 targets, particularly in ensuring the availability of clean water and reducing the environmental and community health impacts caused by contaminated well water (Anderson, 2005).

Conventional treatment methods are often ineffective in significantly reducing organic pollutants and generally require high operational costs. Previous studies have demonstrated the feasibility of hybrid adsorption–ultrafiltration (UF) systems for water treatment (Li et al., 2020b; Elma et al., 2022; Khulbe and Matsuura, 2018), however, most have focused on synthetic adsorbents or a single-adsorbent configuration. The use of locally available natural materials-specifically zeolite combined with ginger coral stone-as a dual-adsorbent system integrated with UF membrane technology has not been thoroughly investigated for acidic groundwater treatment in Indonesian settings. This study addresses this research gap by evaluating the performance of a polyethersulfone (PES) hollow-fiber UF membrane (pore size 0.01-0.05 μm; MWCO= 100,000 Da) combined with KOH-activated zeolite and ginger coral adsorbents for the simultaneous removal of pH, TDS, EC, Fe, and Mn from shallow well water. The novelty of this work lies in the use of ginger coral stone as a complementary adsorbent to zeolite-exploiting its $CaCO_3$ content for pH buffering—and in the systematic evaluation of adsorbent mass ratios and flow rates on treatment efficiency (Zhang et al., 2023; Susanti et al., 2025).

Furthermore, membrane fouling remains a critical challenge in ultrafiltration systems, particularly when treating groundwater with high concentrations of dissolved and suspended contaminants. Fouling can reduce permeate flux, increase operational pressure, and ultimately decrease system efficiency over time. The integration of adsorption pretreatment using natural materials such as zeolite and ginger coral stone is expected to mitigate fouling by removing a significant portion of contaminants prior to membrane filtration. This synergistic approach not only enhances overall removal performance but also extends membrane lifespan and reduces maintenance requirements, making the combined system more viable for long-term and large-scale clean water production applications (Dewi et al., 2021).

2. EXPERIMENTAL SECTION

2.1 Material and Instrumentation

The material used in this study included ginger coral stone (obtained locally from Banyuasin, South Sumatra), natural zeolite (clinoptilolite type, sourced from a commercial supplier), tapioca flour (as binder for pellet formation), wheat starch (as secondary binder), KOH solution (10%, analytical grade, for chemical activation of adsorbents), distilled water (for washing and rinsing), and shallow well water (collected from a residential well in Talang Buluh, Banyuasin, at a depth of 7 meters below ground level). Natural zeolite (clinoptilolite type) was selected as the primary adsorbent due to its well-documented ion-exchange capacity and large surface area, which enable effective removal of heavy metal cations such as Fe^{2+} and Mn^{2+} from groundwater (Rao et al., 2012; Kowalcyzk et al., 2006). Prior to use, the zeolite was chemically activated using a 10% KOH solution to enhance its surface area and ion-exchange capacity, following the activation protocol reported by Palentin et al. (2021). Tapioca flour was used as a binder during the initial shaping stage due to its adhesive properties when mixed with water, while wheat starch served as a secondary binder to improve the mechanical strength and cohesion of the pellets during drying and carbonization. KOH solution (10%, analytical grade) was employed as a chemical activating agent to open pore structures and increase the active surface area of the adsorbents, as KOH activation has been shown to significantly improve adsorption performance (Palentin et al., 2021; Syafi'i et al., 2023). Distilled water was used throughout the washing and rinsing steps to ensure removal of residual activation agents and to achieve a neutral pH prior to drying. The ultrafiltration membrane used was a polyethersulfone (PES) hollow-fiber type with a pore size of 0.01-0.05 μm and a molecular weight cut-off (MWCO) of approximately 100,000 Da. PES was chosen as the membrane material owing to its high chemical stability, suitable mechanical strength, and wide application in water treatment systems (Ismail et al., 2015; Susanti et al., 2025). The equipment used included a jaw crusher, ball mill, oven, furnace, 50 mesh sieve, analytical balance, storage tank, pH meter, TDS meter, EC meter, turbidity meter, cartridge water filter, peristaltic pump, and Scanning Electron Microscope–Energy Dispersive X-ray (SEM-EDX) instrument for adsorbent characterization.

2.2 Research Procedures

The research procedures in this study were carried out in a systematic and sequential manner, consisting of five main stages: (1) groundwater sample collection, (2) preparation of zeolite and ginger coral stone adsorbents, (3) characterization of adsorbents using SEM-EDX, (4) formation of adsorbents into pellets, and (5) the adsorption and ultrafiltration process. Each stage was designed to ensure consistent experimental conditions and reliable data quality. The overall workflow was structured to first prepare and characterize the adsorbent materials, followed by their application in treating groundwater samples, and finally to evaluate treatment performance by measuring key water quality parameters including pH, TDS, EC, temperature, turbidity, Fe, and Mn. This procedural design is consistent with the methodology reported by Susanti et al. (2025) in their evaluation of the same integrated treatment system for groundwater purification in Banyuasin, South Sumatra. The integration of adsorption pre-treatment with ultrafiltration filtration was applied as a two-step water treatment approach to maximize pollutant removal efficiency, in accordance with established hybrid adsorption–UF treatment protocols (Elma et al., 2022; Dewi et al., 2021; Susanti et al., 2025).

2.2.1 Groundwater Sample Collection

The well water was taken from a residential well located in the Talang Buluh area, Banyuasin, at a depth of 7 meters below ground level. The collected samples were placed into sample containers for initial testing of pH, TDS, EC, and concentrations of Fe, Mn, and nitrate. After the initial characterization, the well water was stored in a 70-liter jerry can to be used as a temporary storage tank prior to the treatment process.

2.2.2 Preparation of Zeolite and Ginger Coral Stone Adsorbents

The zeolite and ginger coral stone were first crushed into a fine powder. The powder was then mixed with tapioca flour as a binder and shaped into a solid form. The formed materials were dried in an oven at 110°C for 24 hours. Subsequently, the materials were carbonized in a furnace at 500°C for 1 hour under inert conditions (limited N_2/air). The resulting carbon was ground and sieved to obtain a particle size of 120 mesh. To activate the surface, the carbon was soaked in a 10% KOH solution (1.78 M) with a ratio of 1:3 for 24 hours. After activation, the adsorbent was washed with distilled water until a neutral pH was achieved, and then dried again in an oven at 105°C for 24 hours.

2.2.3 Characterization of Ginger Coral Stone Adsorbents

The characterization of ginger coral adsorbent was carried out by testing its morphological characteristics using Scanning Electron Microscope (SEM) to observe the condition of the pores on its surface. Characterization using Energy Dispersive X-ray (EDX) to identify elements and their composition based on the interaction of X-rays with the surface of the material.

2.2.4 Forming Adsorbents into Pellets

The zeolite and ginger coral stone adsorbents were mixed with wheat starch as a binder, followed by the gradual addition of water until a thick paste was formed. The paste was then molded into pellets with a diameter of 2 cm and a height of 1 cm. The formed pellets were dried prior to characterization.

2.2.5 Adsorption and Ultrafiltration Procedure

The well water was first filtered using a cartridge water filter. The zeolite and ginger coral stone adsorbents were then placed inside the cartridge with mass variations of 100 g for each individual adsorbent and a 50:50 g mixture for the combined adsorbents. The adsorption process was conducted by flowing the well water through the cartridge at flow rates of $3\ L \cdot min^{-1}$ and $5\ L \cdot min^{-1}$. After the adsorption process, the treated water was re-analyzed to determine pH, TDS, EC, and temperature.

Subsequently, the water that had undergone pre-treatment and adsorption was pumped into the ultrafiltration holding tank using a pump at flow rates of $3\ L \cdot min^{-1}$ and $5\ L \cdot min^{-1}$. The ultrafiltration permeate samples were collected using beaker glasses and analyzed to measure pH, TDS, EC, and temperature as the final results. After each experiment, the ultrafiltration membrane was cleaned using distilled water to remove residual contaminants and prevent membrane fouling.

3. RESULTS AND DISCUSSION

This study uses ginger coral as an adsorbent. After obtaining the adsorbent, SEM-EDX tests were conducted to apply it as an adsorbent in groundwater. After the adsorption process was completed, it was followed by an ultrafiltration membrane. Tests on groundwater were analyzed using liquid waste from the tofu industry were analyzed using TDS, and pH parameters.

The main experimental results are collectively presented in Tables 1-3 to facilitate a structured comparison of treatment performance. Table 1 summarizes the initial groundwater characteristics and their compliance with regulatory standards. Table 2 illustrates the impact of adsorption using various adsorbent compositions, while Table 3 presents the final water quality obtained after the integrated adsorption–ultrafiltration process. These tables serve as the basis for the subsequent discussion of treatment efficiency and underlying mechanisms.

3.1 Water Sample Analysis Results for pH

pH is one of the crucial parameters for determining clean water quality. The initial groundwater pH was 4.65, which is acidic and does not comply with the clean water quality standards set by Ministry of Health Regulation No. 2 of 2023, requiring a range of 6.5–8.5. This condition may be caused by dissolved metal minerals such as Fe and Mn, as well as organic matter resulting from soil decomposition.

Table 1. Groundwater Characteristics

Parameter	Unit	Initial Value	Standard
pH		4.65	6.5-8.5
TDS	mg/L	218	<300
EC	μS/cm	129	-
Fe	mg/L	2.41	0.2
Mn	mg/L	0.18	0.1
Turbidity	NTU	47.96	<3

After adsorption using 100 g of zeolite, the pH slightly increased to 4.83, whereas using 100 g of ginger coral resulted in a pH of 4.52. The combination of both adsorbents (50:50 g) yielded a pH of 4.93, indicating that the mixture has a better capacity to neutralize pH compared to single adsorbent usage. When the adsorbed water was passed through an ultrafiltration (UF) membrane at a flow rate of 5 LPM, a significant pH increase occurred. The pH rose to 5.18 for zeolite, 5.28 for ginger coral, and 6.28 for the combination of zeolite and ginger coral. This increase demonstrates that the integrated adsorbent and ultrafiltration system effectively reduces acidic ion (H^+) concentrations through ion exchange and surface adsorption processes while simultaneously removing organic particles that contribute to acidity.

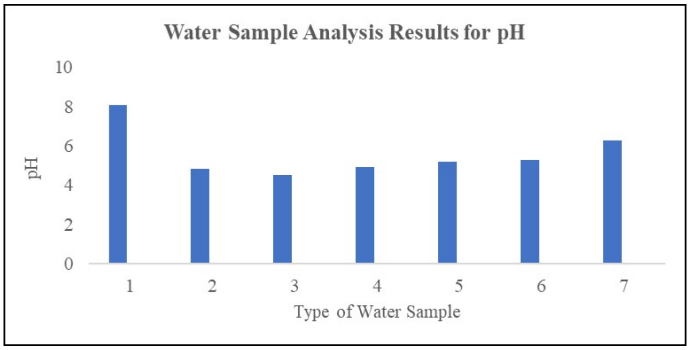

Figure 1. Graph of Water Sample Analysys for pH

The highest pH increase was obtained with the 50:50 g adsorbent combination after UF, with the pH approaching neutral (6.28). This suggests a complementary effect between the two adsorbents: zeolite contributes cation-exchange capacity for heavy metal removal, while ginger coral provides $CaCO_3$-mediated alkalinity to neutralize acidic ions. Notably, the pH achieved by the 50:50 combination (6.28) exceeds the arithmetic mean of the individual adsorbent results (average of zeolite UF is 5.18 and ginger coral UF is 5.28, giving a predicted additive value of 5.23), suggesting a potentially cooperative interaction.

3.2 Water Sample Analysis Results for TDS (ppm)

Total Dissolved Solids (TDS) represent the total amount of dissolved solids in water, including mineral ions, salts, and metals. Based on the initial groundwater analysis, the TDS of the raw well water 218 mg/L, while commercial mineral water had a TDS of 201 mg/L. Although the raw TDS value is below the threshold set by Ministry of Health Regulation No. 2 of 2023 (<300 mg/L), reducing TDS is important to improve water clarity and overall quality.

After adsorption using 100 g of zeolite (3 LPM), TDS decreased to 48 mg/L; 100 g of ginger coral reduced it to 4 mg/L; and the 50:50 g combination yielded 45 mg/L. After passing through the UF membrane (5 LPM), tds further decreased significantly to 40 mg/L (zeolite), 39 mg/L (ginger coral), and 38 mg/L (combination). These results are consistent with those reported by Susanti et al. (2025), where the same combined adsorption–UF system achieved a final TDS of 38 mg/L under optimal conditions, confirming the reproducibility and reliability of the treatment approach.

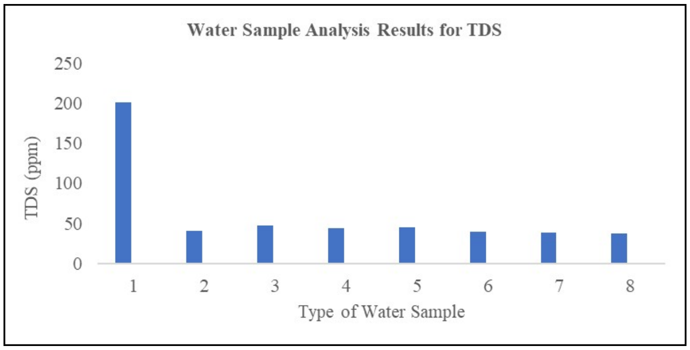

Figure 2. Graph of Water Sample Analysys for TDS

This progressive TDS reduction demonstrates the effectiveness of the sequential adsorption–UF system. Zeolite functions through the ion-exchange mechanism (Na^+, Ca^{2+}, Mg^{2+}), while ginger coral (containing $CaCO_3$) acts as an ion balancer and natural buffer (Franklin and Townsend, 1985). The combination of both adsorbents produced the lowest TDS of 38 mg/L, substantially below the regulatory limit, indicating a marked improvement in water quality.

3.3 Water Sample Analysis Results for EC (μS/cm)

Electrical Conductivity (EC) values are directly proportional to the amount of dissolved ions in water. The initial groundwater exhibited an EC of 129 μS/cm, indicating the presence of inorganic ions such as dissolved metal cations and anions. After the adsorption stage (3 LPM), EC slightly increased to 90 μS/cm (zeolite) and 88 μS/cm (ginger coral), remaining at 90 μS/cm for the 50:50 g combination of zeolite and ginger coral. This temporary increase is attributable to initial desorption of Na^+ ions from the zeolite lattice or mild mineral leaching from the coral adsorbent during the early stage of treatment.

After passing through the UF membrane (5 LPM), EC decreased substantially to 80 μS/cm (UF + zeolite), 78 μS/cm (UF + ginger coral), and 76 μS/cm (UF + combination)-representing reductions of 38-41% from the initial value of 129 μS/cm. The lowest EC value (76 μS/cm) was achieved

Table 2. Result of Adsorption Before UF

Adsorbent	Flowrate (LPM)	pH	TDS	EC	Turbidity	Fe	Mn
Zeolite 100 g	3	4.83	48	90	1.46	0.02	0.08
Ginger Coral 100 g	3	4.52	44	88	1.46	0.02	0.08
Zeolite + Coral (50:50)	3	4.93	45	90	1.46	0.02	0.08

Table 3. Result of Adsorption (After UF)

Adsorbent	Flowrate (LPM)	pH	TDS	EC	Turbidity	Fe	Mn
Zeolite 100 g	5	5.18	40	80	0.13	0.01	0.08
Ginger Coral 100 g	5	5.28	39	78	0.68	0.01	0.08
Zeolite + Coral (50:50)	5	6.28	38	76	0.43	0.01	0.10

Table 4. Water Sample result for pH

Type of Water Sample	pH
Mineral Water	8.06
Zeolite Adsorbent	4.83
Ginger Coral Stone Adsorbent	4.52
Combination of Zeolite and Ginger Coral Stone	4.93
Ultrafiltration (UF) and Zeolite	5.18
Ultrafiltration (UF) and Ginger Coral Stone	5.28
Ultrafiltration (UF) and Combination	6.28

Table 5. Water Sample result for TDS (ppm)

Type of Water Sample	TDS (ppm)
Mineral Water	201
Groundwater	41
Zeolite Adsorbent	48
Ginger Coral Stone Adsorbent	44
Combination of Zeolite and Ginger Coral Stone	45
Ultrafiltration (UF) and Zeolite	40
Ultrafiltration (UF) and Ginger Coral Stone	39
Ultrafiltration (UF) and Combination	38

Table 6. Water Sample result for EC (μS/cm)

Type of Water Sample	EC (μS/cm)
Groundwater	82
Zeolite Adsorbent	90
Ginger Coral Stone Adsorbent	88
Combination of Zeolite and Ginger Coral Stone	90
Ultrafiltration (UF) and Zeolite	80
Ultrafiltration (UF) and Ginger Coral Stone	78
Ultrafiltration (UF) and Combination	76

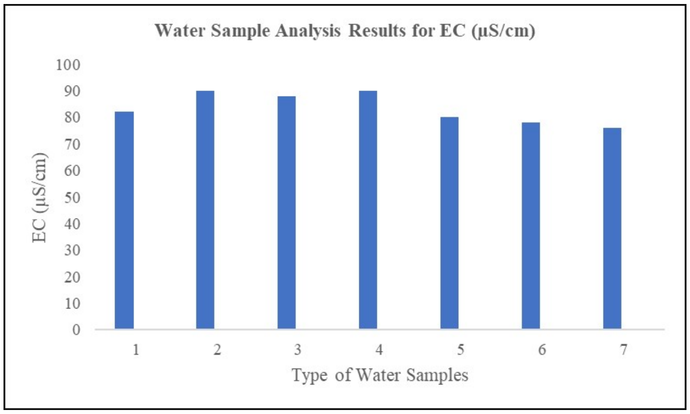

Figure 3. Graph of Water Sample Analysys for EC (μS/cm)

with the 50:50 combination, consistent with the complementary ion-removal mechanisms of zeolite (cation exchange) and ginger coral ($CaCO_3$-mediated buffering). Compared to similar hybrid adsorption-UF systems reported by Elma et al. (2022), who achieved EC reductions of approximately 30% for peat water treatment, the present system demonstrated comparable removal efficiency. This EC reduction to 76 μS/cm aligns with the findings of Susanti et al. (2025), in which the same integrated zeolite-ginger coral-UF system achieved an EC of 76 μS/cm under a 5 LPM flow rate using a 50:50 adsorbent combination.

3.4 SEM Characterization of Zeolite Adsorbent Before Adsorption

The morphology of the zeolite appeared finely porous, layered, and exhibited an irregular crystalline surface. This structure reflects the characteristic features of natural clinoptilolite -type zeolite, where the aluminosilicate framework (AlO_4-SiO_4) is arranged in an orderly manner forming three-dimensional cavities. Based on the SEM images, the surface appears to contain visible inter-particle spaces and irregular surface roughness consistent with a porous morphology; however, precise pore-size quantification from SEM images alone is limited. For reference, the literature reports that clinoptilolite-type zeolite pore channels and surface features observed via SEM typically range from tens to hundreds of nanometers (Kowalcyzk et al., 2006; Lin et al., 2013a), though BET analysis would be required to confirm actual surface area and pore-size distribution.

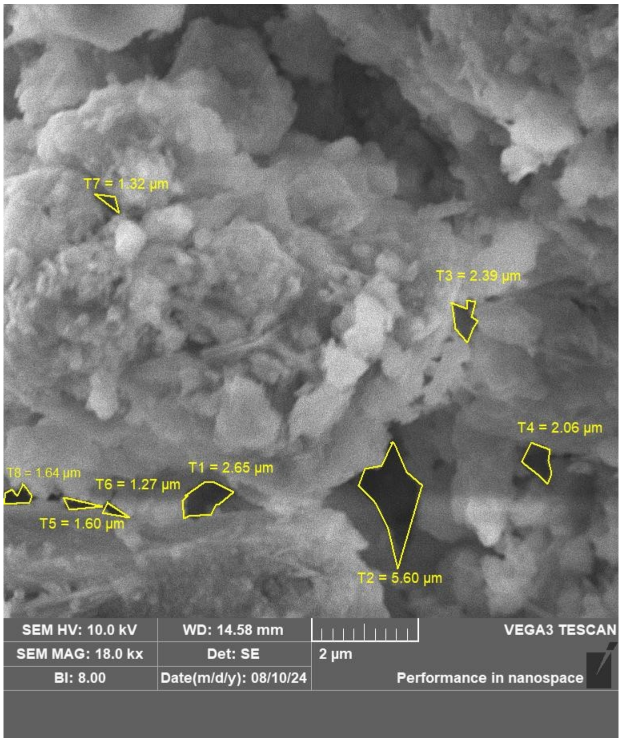

Figure 4. SEM Micrograph of Zeolite Adsorbent Before Adsorption at 18,000× Magnification

The pores within the zeolite framework, such as in clinoptilolite, function as diffusion channels for heavy metal ions (Fe^{2+}, Mn^{2+}, Pb^{2+}) through an ion-exchange mechanism. Chemical treatments, such as base activation using KOH, have been reported to open previously blocked pores, increasing the active surface area and ion-exchange capacity (Palentin et al., 2021). Local studies indicate that KOH activation of natural zeolite can increase the surface area from approximately 75 m^2/g to around 126 m^2/g (Fatin et al., 2021; Ramesh et al., 2023).

This condition aligns with the findings of (Rao et al., 2012) which stated that activating zeolite with a strong base can increase pore volume and optimize heavy metal adsorption capacity. Furthermore, improved surface area and enhanced ion exchange sites contribute significantly to adsorption efficiency, promoting stronger interactions between adsorbent and metal ions under various aqueous environmental conditions with higher stability.

3.5 SEM Characterization of Ginger Coral Adsorbent Before Adsorption

The surface morphology of the ginger coral adsorbent before the adsorption process was analyzed using Scanning Electron Microscopy (SEM) to evaluate its structural characteristics and potential adsorption capacity. The SEM images reveal that the ginger coral exhibits a highly irregular and heterogeneous surface with a porous structure (Li et al., 2020a). These pores vary in size and distribution, forming interconnected cavities that provide a large surface area for potential interaction with contaminants.

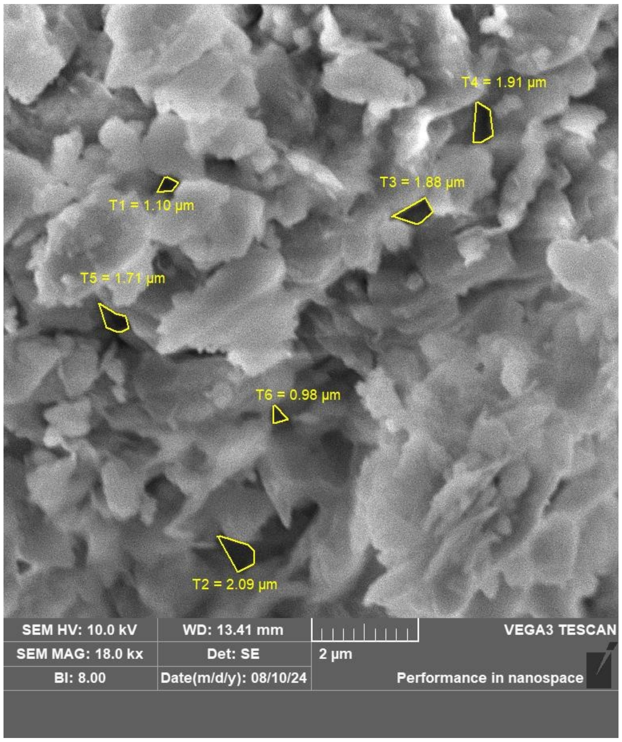

Figure 5. SEM Micrograph of Ginger Coral Adsorbent Before Adsorption at 18,000× Magnification

The presence of abundant pores and surface roughness indicates that ginger coral has a favorable physical structure for adsorption processes (Kowalcyzk et al., 2006). The porous nature allows contaminants to diffuse into the internal structure of the material, enhancing contact between the adsorbent surface and dissolved substances in the groundwater. This structural feature is particularly important for facilitating mass transfer during the adsorption process (Lin et al., 2013b).

In addition, the surface of the ginger coral appears to consist of granular and clustered formations, which are typical of calcium carbonate-based materials (Syah et al., 2025). These formations contribute to the mechanical stability of the adsorbent while also increasing the number of active sites available for adsorption. The irregular morphology further enhances the probability of contaminant attachment through physical adsorption mechanisms (Kuldeyev et al., 2023).

The dominance of a porous and rough surface prior to adsorption suggests that the material has not yet been occupied by contaminants, meaning that its active sites are still fully available (Li et al., 2020a). This condition is essential for maximizing adsorption efficiency, as it allows for optimal interaction between the adsorbent and pollutants during the treatment process.

Furthermore, the observed morphology supports the role of ginger coral as an effective complementary adsorbent, particularly in combination with zeolite (Syah et al., 2025). While zeolite primarily relies on ion-exchange mechanisms, the physical structure of ginger coral contributes to adsorption through pore diffusion and surface interactions. Therefore, the SEM characterization before adsorption confirms that ginger coral possesses suitable structural properties to support contaminant removal and enhance overall treatment performance (Kowalcyzk et al., 2006).

3.6 SEM Characterization of Zeolite Adsorbent After Adsorption

After the adsorption process, SEM observations reveal noticeable changes in the surface morphology of the zeolite. The previously well-defined porous and layered structure appears partially covered and less distinct, indicating that the pores and surface cavities have been occupied by adsorbed species. Several pore openings observed prior to use become narrower or blocked, suggesting successful diffusion and retention of metal ions within the zeolite framework.

The surface texture after adsorption shows increased agglomeration and the presence of deposited particles, which are attributed to the accumulation of metal ions such as Fe^{2+}, Mn^{2+}, and other dissolved species from the treated water. This phenomenon is commonly reported in clinoptilolite-type zeolite after adsorption, where ion exchange between exchangeable cations (K^+, Na^+, Ca^{2+}) and heavy metal ions leads to changes in surface roughness and pore visibility.

Furthermore, the reduction in apparent porosity confirms that the internal channels of the aluminosilicate framework actively functioned as adsorption and ion-exchange sites during operation. This morphological transformation supports the adsorption mechanism dominated by ion exchange and surface complexation. Similar structural changes after adsorption have been reported in previous studies, indicating that pore blockage and surface coverage are reliable indicators of effective heavy metal uptake by zeolite.

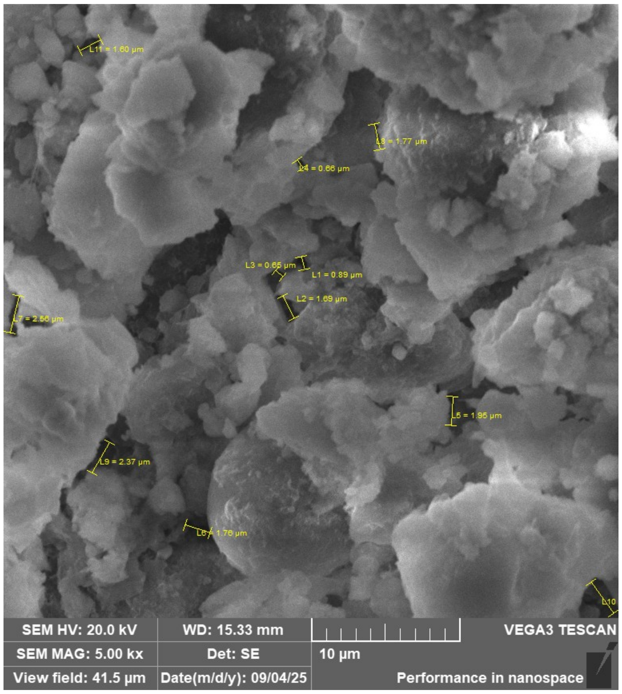

Figure 6. SEM of Zeolite After Adsorption at Magnification 5,000×

Figure 6 presents the SEM micrograph of zeolite adsorbent after the adsorption process at 5,000× magnification. Compared to the pre-adsorption morphology, the surface of the zeolite shows significant changes: the previously well-defined porous and layered crystalline structure appears partially covered and less distinct. This indicates that the pores and surface cavities of the aluminosilicate framework have been occupied by adsorbed ionic species from the treated groundwater. Several pore openings that were clearly visible before adsorption appear narrower or partially blocked, suggesting successful diffusion and retention of dissolved contaminants within the zeolite channels. The surface texture after adsorption exhibits increased agglomeration and the presence of deposited particles, consistent with the accumulation of heavy metal ions such as Fe^{2+} and Mn^{2+} that were present in the well water. This structural transformation confirms that the internal channels of the zeolite functioned actively as ion-exchange and adsorption sites during the treatment process. Similar morphological changes following adsorption have been widely reported in studies on clinoptilolite-type zeolite, where surface blockage and pore narrowing are considered reliable indicators of effective heavy metal uptake (Kowalcyzk et al., 2006; Ramesh et al., 2023). The reduction in apparent surface porosity observed in Figure 6 is thus consistent with the substantial decrease in Fe, Mn, and TDS concentrations recorded in the water quality analysis results.

3.7 SEM Characterization of Ginger Coral Adsorbent After Adsorption

Figure 7 presents the SEM micrograph of ginger coral stone adsorbent after the adsorption process at 5,000× magnification. Compared to the pre-adsorption state, the surface morphology of the ginger coral stone shows notable changes in surface texture and pore characteristics. The surface, which was previously relatively clean and featured accessible pores, appears more irregular and partially coated with deposited material after adsorption.

This surface alteration is indicative of contaminant accumulation on the adsorbent surface, consistent with the physical adsorption and precipitation mechanisms that gov-

Table 7. Energy Disperse X-Ray (EDX) of Zeolite After Adsorption

Element	O	Si	C	Ca	K	Fe	Na	Mg	Ba
%mass	45.97	22.04	10.67	4.62	2.40	1.15	0.83	0.33	0.17

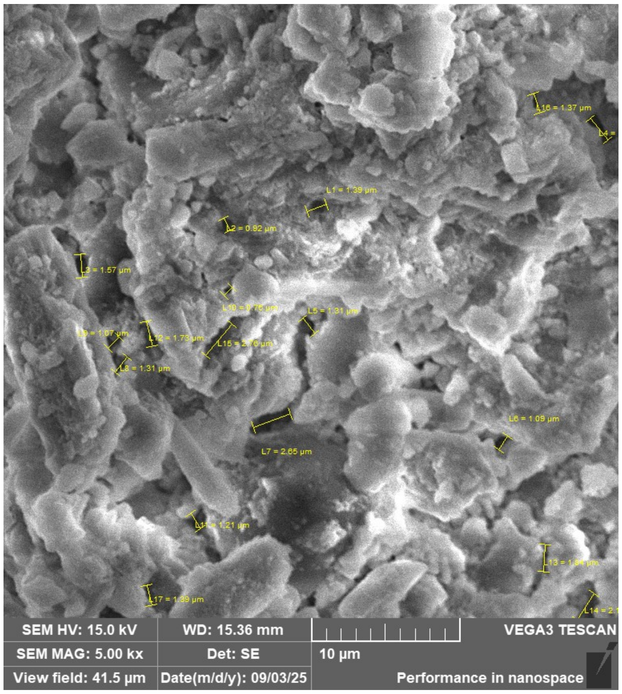

Figure 7. SEM of Ginger Coral Stone After Adsorption at Magnification 5,000×

ern the behavior of $CaCO_3$-based materials. The primary removal mechanism of ginger coral stone is associated with its high $CaCO_3$ content, which reacts with dissolved acidic ions (H^+) to neutralize pH, and simultaneously facilitates the precipitation of dissolved metal ions such as Fe^{2+} as metal hydroxides or carbonates on the adsorbent surface. The SEM image confirms that contaminant deposition has occurred on the ginger coral surface, as evidenced by the visible surface roughening and partial pore blockage. Although ginger coral stone exhibits a lower ion-exchange capacity compared to zeolite, its role as a pH buffer and secondary adsorbent is clearly supported by the observed morphological changes. The combined effect of surface adsorption and chemical precipitation contributes to the reduction of TDS, EC, and metal concentrations in the treated water, complementing the ion-exchange mechanism of zeolite when the two adsorbents are used together in the integrated treatment system (Zhang et al., 2023; Franklin and Townsend, 1985).

3.8 Energy Dispersive X-Ray Spectroscopy (EDX) Characterization of Zeolite Adsorbent

The Energy Dispersive X-ray (EDX) analysis of the zeolite adsorbent after the adsorption process provides detailed information regarding its elemental composition and confirms the occurrence of adsorption and ion-exchange mechanisms. The dominant elements identified are oxygen (O) at 45.97% and silicon (Si) at 22.04%, which are typical constituents of the aluminosilicate framework of natural zeolite. This framework consists of interconnected SiO_4 and AlO_2 tetrahedra, forming a porous three-dimensional structure with negatively charged sites that are balanced by exchangeable cations such as Na^+, K^+, Ca^{2+}, and Mg^{2+}.

The presence of carbon (C) at 10.67% indicates the adsorption of organic matter from the groundwater. This suggests that, in addition to inorganic ion removal, zeolite is capable of adsorbing organic compounds through physical adsorption and surface interactions such as Van der Waals forces. This is consistent with the observed reduction in TDS and turbidity, as organic substances contribute significantly to dissolved and suspended solids (Hashemi et al., 2019).

Calcium (Ca) and potassium (K), with mass percentages of 4.62% and 2.40%, respectively, represent exchangeable cations originally present in the zeolite structure. During the adsorption process, these cations are partially replaced by heavy metal ions present in the groundwater through ion-exchange reactions. This mechanism can be described as the substitution of native cations (e.g., Na^+, Ca^{2+}) with contaminant ions such as Fe^{2+} and Mn^{2+}, which are subsequently retained within the zeolite framework (Kwakye-Awuah et al., 2019).

The detection of iron (Fe) at 1.15% provides direct evidence of successful heavy metal adsorption onto the zeolite surface. This confirms that Fe ions from the groundwater have been immobilized within the adsorbent structure. Similarly, the presence of sodium (Na) and magnesium (Mg) in smaller quantities suggests ongoing ion-exchange processes, where these ions either remain partially in the structure or participate dynamically during adsorption.

Trace elements such as barium (Ba) further indicate the adsorption of minor dissolved species, demonstrating the broad adsorption capability of zeolite for various ionic contaminants. The relatively low concentration of these trace elements suggests selective adsorption behavior, where zeolite preferentially removes certain ions based on charge, size, and affinity (Perez-Botella et al., 2022).

From a mechanistic perspective, the EDX results support that the primary adsorption mechanism of zeolite involves ion exchange, surface complexation, and physical adsorption within its porous structure. The negatively charged aluminosilicate framework facilitates the attraction and retention of positively charged ions, while the high surface area enhances interaction with dissolved species.

Table 8. Energy Disperse X-Ray (EDX) of Ginger Coral Stone After Adsorption

Element	O	C	Ca	Si	Al	Mg	Fe	Na
%mass	65.77	31.23	22.87	3.41	0.92	0.91	0.51	0.46

These findings are consistent with the significant reduction of Fe, Mn, and TDS observed in the experimental results, confirming that zeolite plays a crucial role in removing dissolved metal ions and improving overall water quality. The EDX characterization thus provides strong evidence linking the structural properties of zeolite to its adsorption performance in the integrated treatment system.

3.9 Energy Dispersive X-Ray Spectroscopy (EDX) Characterization of Ginger Coral Stone Adsorbent

The EDX analysis of the ginger coral stone adsorbent after the adsorption process reveals a distinct elemental composition that reflects its unique physicochemical properties and adsorption behavior. The dominant elements identified are oxygen (O) at 65.77%, carbon (C) at 31.23%, and calcium (Ca) at 22.87%, indicating that the material is primarily composed of calcium carbonate ($CaCO_3$). This composition is characteristic of coral-derived materials and is responsible for their strong buffering capacity and alkalinity.

The high calcium content plays a critical role in neutralizing acidic groundwater through chemical reactions involving hydrogen ions (H^+). Specifically, calcium carbonate reacts with H^+ ions to form calcium ions (Ca^{2+}), water (H_2O), and carbon dioxide (CO_2), thereby increasing the pH of the treated water. This buffering mechanism explains the observed improvement in pH during the adsorption and ultrafiltration processes, particularly when ginger coral is used in combination with zeolite (Paul et al., 2017).

The high carbon content further confirms the presence of carbonate compounds, which contribute to the alkalinity and stability of the system. In addition, the porous structure of ginger coral allows for physical adsorption of contaminants, although its primary function is associated with chemical interactions rather than ion exchange (Laine et al., 2008).

The presence of silicon (Si) and aluminum (Al) in smaller amounts suggests the existence of minor silicate impurities or residual mineral components within the material. Magnesium (Mg), also present in low concentrations, can contribute to hardness and may participate in secondary reactions that support pH stabilization (Khurts et al., 2025).

The detection of iron (Fe) at 0.51% indicates that ginger coral is also capable of adsorbing metal ions, although its efficiency in this regard is generally lower than that of zeolite. The mechanism of metal removal in ginger coral is more closely related to precipitation and surface adsorption rather than ion exchange. Under slightly alkaline conditions, metal ions such as Fe^{2+} can precipitate as hydroxides or carbonates, which are then retained on the surface of the adsorbent (Wierzba et al., 2022).

The presence of sodium (Na) suggests interactions with dissolved ions in the groundwater, possibly through weak adsorption or ion exchange at limited active sites. However, compared to zeolite, these interactions are less dominant and do not represent the primary removal mechanism (Profeta et al., 2025).

Overall, the EDX results confirm that ginger coral stone functions primarily as a pH buffer and secondary adsorbent. Its high $CaCO_3$ content enhances alkalinity, promotes the neutralization of acidic conditions, and facilitates the precipitation of dissolved metal ions. This mechanism complements the ion-exchange capacity of zeolite, resulting in a synergistic effect when both materials are used together.

The combination of zeolite and ginger coral thus provides a dual-function system, where zeolite removes dissolved ions through ion exchange, while ginger coral stabilizes pH and supports contaminant removal through buffering and precipitation mechanisms. This complementary interaction explains the superior performance of the combined adsorbent system observed in the overall treatment results.

4. CONCLUSIONS

This study demonstrates that an integrated system combining adsorption using zeolite and ginger coral stone with ultrafiltration (UF) technology is effective in improving the quality of contaminated groundwater. The combination of zeolite and ginger coral adsorbents at a 50:50 ratio exhibited the best performance compared to the use of single adsorbents. The treatment results showed significant improvements in water quality parameters, where pH increased toward near-neutral conditions (6.28), TDS decreased to 38 mg/L, and EC was reduced to 76 μS/cm. In addition, the concentrations of heavy metals such as Fe and Mn were successfully reduced to levels close to or within clean water standards. The synergistic mechanism between zeolite, which functions through ion exchange, and ginger coral stone, which acts as a $CaCO_3$-based pH buffer, was proven to enhance the overall process efficiency. The integration of the adsorption stage as a pretreatment step also contributed to reducing membrane fouling, thereby improving the performance and lifespan of the UF system. Overall, this technology has strong potential as an environmentally friendly, cost-effective, and sustainable solution for groundwater treatment, particularly in areas that still rely on well water as the primary water source.

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