



International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 -6435 (Online)), Volume 15, Issue 4, April 2026)

Bio-Material Based Barrier for Controlling Saltwater Intrusion

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Abstract— Groundwater not only disrupts the freshwater supply but also poses severe health risks to local populations, including hypertension and skin ailments. While advanced technologies such as reverse osmosis and industrial Saltwater intrusion remains a critical global challenge, significantly compromising the availability of potable water in coastal ecosystems. The infiltration of saline content into desalination offer solutions, their high operational costs often make them inaccessible for individual domestic use in developing coastal regions. This study investigates a cost-effective, decentralized filtration system designed specifically for residential wells. The proposed method utilizes a composite unit consisting of non-woven geotextile fabric integrated with natural and thermally activated zeolite. The zeolite acts as a dual-action agent, facilitating both physical filtration and chemical adsorption. Experimental results demonstrate a significant correlation between filter thickness and the reduction of Electrical Conductivity (EC) and Total Dissolved Solids (TDS). Specifically, chloride ion concentrations were notably lowered across various salt-loading scenarios. The findings suggest that thermally activated zeolite provides superior performance compared to its natural counterpart, offering a sustainable and economically viable barrier to mitigate the impacts of saline intrusion in coastal drinking water sources.

Index Term – Saltwater Intrusion, Zeolite, Geotextile Filter, Total Dissolved Solids (TDS)

I. INTRODUCTION

Saltwater intrusion occurs when saline water encroaches into freshwater aquifers, contaminating groundwater, particularly in coastal areas. It is caused by over-extraction of groundwater, sea-level rise, reduced recharge, and land-use changes, which disrupt the natural hydraulic balance. Saltwater intrusion deteriorates water quality, making it unsuitable for drinking, agriculture, and industry. Indicators such as EC, chloride concentration, and SAR help monitor affected areas. Mitigation strategies include managed aquifer recharge, controlled pumping, physical barriers, and sustainable water management.

This study focuses on reducing salinity in groundwater from saltwater-intruded areas, improving water quality for domestic and drinking purposes. ION

II. LITERATURE REVIEW

Fernandez et al. (2025) investigated nano-modified zeolite for advanced water filtration, focusing on enhanced removal of dissolved salts from saline and brackish water. Nanoscale modification increased surface area, pore volume, and active adsorption sites, significantly improving ion exchange capacity. Nano-zeolite showed higher affinity for sodium ions, reducing EC and TDS more effectively than natural zeolite. Adsorption followed pseudo-second-order kinetics, indicating chemisorption, and equilibrium data fit well with adsorption isotherms. Operational factors like contact time, initial concentration, and dosage influenced performance. The study concluded that nano-zeolite is a high-efficiency, scalable, and sustainable solution for desalination and water treatment in salt-affected regions.

Ali et al. (2024) evaluated natural zeolite in household-scale filtration systems for saline water in rural/coastal areas. Multi-layer units (sand, gravel, and zeolite) effectively removed suspended solids and reduced dissolved salts via ion exchange. Increasing the zeolite layer thickness improved EC and TDS removal due to longer contact time. The system was cost-effective, easy to construct, low maintenance, and electricity-free, making it suitable for domestic applications in low-income regions. The study concluded that natural zeolite filters provide a practical and sustainable solution for improving drinking water quality in salt-affected communities.

Kumar and Singh (2023) evaluated activated zeolite for removing dissolved salts and contaminants from water. Activation increased porosity, surface area, and ion exchange capacity, making it more effective than raw zeolite in reducing TDS and EC. Adsorption followed the Langmuir isotherm, indicating monolayer adsorption, and kinetics suggested chemisorption as the dominant mechanism. The study also showed that activated zeolite can be regenerated and reused, making it a cost-effective and sustainable option for domestic and industrial water purification.

III. MATERIALS USED

A. Natural Zeolite

Natural zeolite is a group of naturally occurring microporous, crystalline aluminosilicate minerals formed by the reaction of volcanic ash with alkaline groundwater over long geological periods. It consists mainly of a three-dimensional framework of silicon, aluminium and oxygen atoms, creating a highly stable structure with uniform pores and channels. These pores contain loosely held water molecules and exchangeable cations such as sodium, potassium and calcium, which give zeolite its unique ability to perform ion exchange, adsorption and molecular sieving. Due to the negative charge created by the presence of aluminium in its structure, natural zeolite attracts and holds positively charged ions, making it highly effective in removing dissolved salts, heavy metals, and other impurities from water. Its high surface area, porosity and chemical stability make it an eco-friendly and cost-effective material widely used in water treatment, agriculture, environmental protection.

B. Activated Zeolite

Activated zeolite is a specially treated form of natural zeolite in which its efficiency is improved by a controlled heating process. In this method, the natural zeolite is heated in an oven at around 250°C for about 3 hours, which removes the physically held water molecules and moisture present inside its pores. This heating process, known as thermal activation, opens up the internal pore structure and increases the available surface area. As a result, the zeolite becomes more active and capable of adsorption and ion exchange, allowing it to effectively remove dissolved salts, heavy metals, and other impurities from water. The activation at 250°C is important because it is high enough to remove moisture without damaging the crystalline structure of zeolite. After heating, the material is cooled and stored properly to prevent reabsorption of moisture. Due to this enhanced performance, activated zeolite is widely used in water treatment systems, especially for reducing salinity, EC and TDS, and it performs better than untreated natural zeolite.

C. Geotextile Fabric

The non-woven needle-punched geotextile is used as a separation and filtration layer between materials like sand and zeolite. It allows water to pass through easily while preventing fine particles from moving between layers, thereby avoiding clogging and maintaining proper flow. This helps in protecting the filter media and ensures uniform distribution of water throughout the system. By keeping the layers intact and clean, the geotextile enhances the performance of zeolite in removing dissolved salts, which leads to better reduction of EC and TDS. Thus, geotextile fabric acts as a crucial component that improves durability, efficiency, and overall effectiveness of the filtration.

D. River Sand

River sand is a naturally available material widely used in water filtration due to its effective physical filtering properties. Its uniform grain size helps remove suspended solids, turbidity, and impurities such as silt and organic matter. It acts as a mechanical

filter by trapping particles between sand grains while allowing smooth water flow due to its high permeability. Being chemically stable and durable, it does not react with water and can be used for a long time. Its low cost and availability make it suitable for use in multi-layer filtration systems.

IV. METHODOLOGY

A. Sample collection

Water samples were collected from an open well located at Eravipuram (Coastal Road area), Kollam.

B. Initial Test

Before initiating any water treatment process, it is essential to understand the baseline characteristics of the raw water sample. This helps in evaluating the efficiency of the treatment methods.

Parameters Analysed Electrical Conductivity (EC)

EC measures the water's ability to conduct electricity, which is directly related to the concentration of dissolved salts (ions). If High EC indicates high salinity, which may affect water suitability for drinking or irrigation.

Total Dissolved Solids (TDS)

TDS represents the total concentration of dissolved inorganic salts in water, usually expressed in mg/L. High TDS can lead to scaling, taste issues, and potential health effects if used for drinking.

Sodium (Na⁺)

Sodium ions contribute to water alkalinity and hardness and are critical for assessing the suitability of water for irrigation and domestic use. Excess sodium can cause soil dispersion in agriculture and health issues in drinking water.

Chloride (Cl⁻)

Chloride is a negatively charged ion (anion) commonly found in natural water. It is one of the main contributors to salinity in groundwater, especially in coastal area.

Potassium (K⁺)

Potassium is an essential nutrient for plants but must be monitored in high concentrations in drinking water.

Calcium (Ca²⁺)

Calcium contributes to water hardness and is vital for human health. High calcium levels can cause scaling in pipes and reduce soap efficiency.

Magnesium (Mg²⁺)

Magnesium also contributes to hardness. Excess magnesium may cause bitter taste in water.

Bicarbonate (HCO₃⁻) & Carbonate (CO₃²⁻)

These ions influence water alkalinity and buffering capacity.

Table 2 Initial reading of sample 2

SAMPLE NAME	pH	EC (µS/cm)	TDS (mg/l)	Na (ppm)	Cl (mg/L)	K (ppm)	Ca (ppm)	Mg (ppm)	Carbonate (ppm)	Bicarbonate (ppm)
Raw sample	8.2	4200	2940	1900	1911	80	4.3	12.1	60	12.2

C. Material Collection

The required filtration material was collected. Zeolite for ion exchange and adsorption, River sand for physical filtration, Geotextile cloth for fine particle removal. Four plastic tanks also collected to regulate the flow of water.

D. Experimental Setup

D.a. Design of Collection and Filtration Tank

The collection and filtration tank was designed to hold raw water and allow filtration through different media layers such as zeolite, sand, and geotextile cloth.

The volume of the tank is calculated using the formula:

Volume=L×B×H Where:

Length (L) = 45 cm = 0.45 m Width (B) = 21 cm = 0.21 m

Depth (H) = 38cm = 0.38 m

Volume=0.45×0.21×0.38=0.03591m³

Since: 1m³=1000litres

Volume=0.03591×1000=35.91≈36litres

This tank has a capacity of approximately 36 litres which is suitable for holding sufficient raw water and providing enough contact time for filtration. The rectangular shape helps in proper layering of filtration materials and uniform water distribution.

D.b. Design of Storage Tank

The storage tank is used to collect filtered water after passing through the filtration media. Dimensions:

Length = 34 cm = 0.34 m Width = 21 cm = 0.21 m

Depth = 28 cm = 0.28 m

Volume=0.34×0.21×0.28=0.01999m³

Volume=0.01999×1000=19.99≈20litres

The storage tank has a capacity of 20 litres, which is designed to safely collect filtered water. The smaller size compared to the filtration tank ensures controlled flow and easy handling of treated water.

D.c. Flow Rate Calculation

1. Basic Flow Rate

Flow rate calculation is an essential part of the filtration system as it determines the speed at which water passes through the filter. It helps in ensuring sufficient contact time between water and the filtration media, especially Adsorption in zeolite, which is responsible for removing salts and impurities. A lower flow rate allows better interaction, improving the efficiency of ion exchange and overall treatment performance. Additionally, flow rate helps in evaluating the effectiveness of the system, designing appropriate tank sizes, and estimating the time required for filtration of a given volume of water. Therefore, calculating flow rate is crucial for optimizing the performance and practical application of the filtration unit.

1 litre of water fills in 15 minutes

Convert to seconds =15 minutes=15×60=900 seconds
 Flow rate=Volume/Time=1000ml/900sec

Flow rate=1.11ml/sec

This means the system filters water at a slow and steady rate, which is ideal for better adsorption and ion exchange by zeolite.

Time Required for 10 Litres 10litres=10000ml

Time=Volume/Flow rate=10000/1.11

Time=9009seconds

Dosage	EC (µs/cm)	TDS (mg/l)	% reduced in EC	% reduced in TDS
0	4200	2940	0	0
2	3600	2500	14.29	14.97
4	3200	2250	23.81	23.47
6	2700	1900	35.71	35.37
8	2600	1800	38.10	38.78
10	2500	1750	40.48	40.48

Convert to minutes=9009÷60=150minutes

=2 hours 30 minutes

The low flow rate (1.11 ml/sec) is beneficial because it increases contact time between water and zeolite. Improves adsorption of sodium and salts. Enhances filtration efficiency. The 36 L filtration tank ensures enough water volume for treatment. The 20 L storage tank is adequate for collecting filtered output.V.

E. Optimization of Dosage

The optimal dosage and contact time of activated zeolite for reducing water salinity were determined using jar tests. Dosages from 0–10 g/L and contact times of 15 and 45 minutes were tested. EC and TDS measurements showed that higher dosages and longer contact times improved removal efficiency, but beyond a certain point, gains were minimal. The study identified the conditions that maximized ion removal while remaining cost-effective, highlighting the importance of both dosage and contact time in zeolite-based filtration.

Table 3 initial EC and TDS values of Raw sample

Sample	EC(µs/cm)	TDS (mg/l)
RAW SAMPLE	4200	2940

Table 4 Effect of adsorbent dosage after 15 min

Dosage	EC (µs/cm)	TDS (mg/l)	% reduced in EC	% reduced in TDS
0	4200	2940	0	0
2	3600	2400	14.29	18.37
4	2900	2050	30.94	30.27
6	2300	1600	45.24	45.58
8	2150	1500	48.81	48.98
10	2000	1400	52.38	52.38

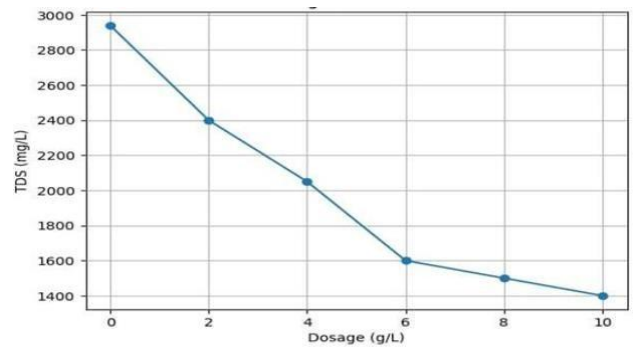


Fig 5.3 graph of TDS After 45 min

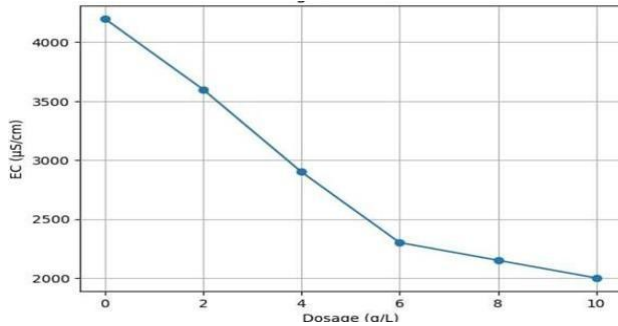


Fig 5.4 graph of EC After 45 min

E. Filtration Using Natural Zeolite

Filtration using natural zeolite was performed with a multi-layer unit consisting of 3 cm geotextile cloth, 20 cm sand, and 15 cm zeolite (used unwashed). Raw well water was analysed for EC, TDS, Na⁺, Cl⁻, Ca²⁺, and Mg²⁺ before passing through the column by gravity. Filtration relied on adsorption and ion exchange, but the 15 cm zeolite layer produced only slight reductions in EC, TDS, and sodium, while chloride, calcium, and magnesium remained largely unchanged. This indicates limited water quality improvement, suggesting that greater zeolite thickness, activation, or longer contact time is needed for effective salinity reduction.

G. Filtration Using Activated Zeolite

Natural zeolite was thermally activated at 250 °C for 3 hours to increase surface area and ion exchange capacity, then used in a layered filter bed with geotextile cloth and sand. Raw well water passed through this gravity-driven setup, allowing the activated zeolite to adsorb dissolved ions while sand removed fine particles. Filtration significantly reduced EC, TDS, sodium, calcium, and magnesium, demonstrating that activated zeolite in an optimized layered design effectively improves water quality. H. Comparison of Result

Filtration using activated zeolite significantly improved water quality compared to natural zeolite. Raw well water had high EC, TDS, sodium, calcium, and magnesium. Natural zeolite reduced these parameters only slightly due to limited surface area and ion exchange capacity. Thermal activation at 250 °C for 3 hours increased zeolite’s surface area and adsorption sites, enabling the layered filter (geotextile, 15 cm activated zeolite, 20 cm sand) to effectively lower EC, TDS, and cation concentrations, producing water suitable for domestic use. This highlights the crucial role of activation and optimized filter design in enhancing removal efficiency.

V EXPERIMENTAL SET UP

A. Experimental Setup

The experimental setup is a gravity-driven, four-tank water filtration system with a vertical frame. Raw water enters the first tank for settling, flows through a multi-layer filtration tank with sand, geotextile, and zeolite to remove physical and chemical impurities, then passes through a fine-particle filtration tank, and finally collects in a storage tank for testing. This design ensures uniform flow, maximizes contact with filter media, reduces energy use, and efficiently lowers TDS, salinity, and other contaminants using natural and activated zeolite.

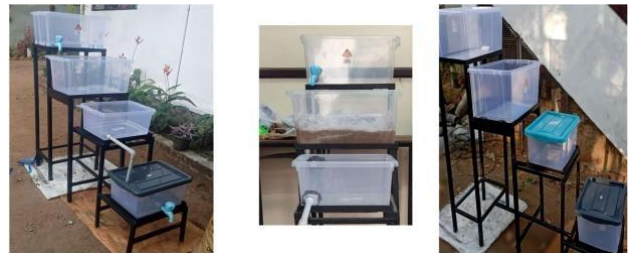


Fig A. experimental setup

B. Design Parameter

The effect of zeolite layer thickness on filtration efficiency was studied by testing 5, 7, 9, 10, 12, and 15 cm layers with natural and activated zeolite. Water was analysed for EC and TDS after filtration. Results showed that removal efficiency increased with layer thickness, with the 15 cm layer providing the highest reduction in EC and TDS due to longer contact time and greater surface area. Thus, 15 cm zeolite is optimal for reducing salinity in water.

Table 6 Effect of natural zeolite filter Thickness on EC and TDS

SAMPLE NAME	FILTER THICKNESS	EC (µS/cm)	TDS (mg/L)	% REDUCTION IN EC	%REDUCTIO N IN TDS
SAMPLE 1	5	4120	2850	1.90	3.06
	7	4000	2752	4.76	6.46
	9	3935	2630	5.12	10.54
	12	3850	2620	8.33	10.88
	15	3700	2590	11.90	11.90

Table 7 effect of activated zeolite filter Thickness on EC and TDS

SAMPLE NAME	FILTER THICKNESS	EC (μS/cm)	TDS (mg/L)	% REDUCTION IN EC	%REDUCTIO N IN TDS
	5	2090	1500	52.38	48.98
SAMPLE 1	7	1830	1300	62.14	55.78
	9	1610	1100	60.24	62.59
	12	1436	950	65.95	67.69
	15	1200	840	71.43	71.43

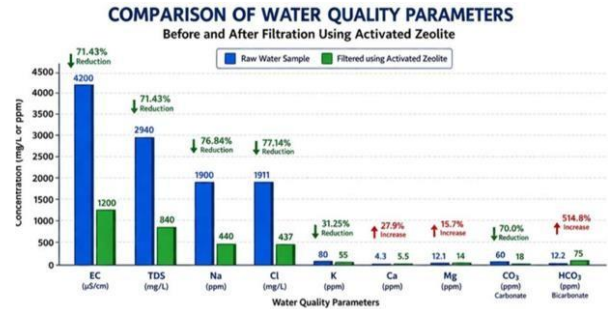


Fig 8.2 graph for comparison of water quality parameters before and after filtration using activated zeolite

VI. RESULT AND DISCUSSION

Table 8 Raw and Filtered Sample Result

Parameter	Raw Water	Natural Zeolite	Activated Zeolite
pH	8.2	8.1	8.1
EC (μS/cm)	4200	3700	1200
TDS (mg/L)	2940	2590	840
Na (ppm)	1900	1800	440
Cl (mg/L)	1911	1680	437
K (ppm)	80	75	55
Ca (ppm)	4.3	4.4	5.5
Mg (ppm)	12.1	13.3	14
CO ₃ (ppm)	60	36	18
HCO ₃ (ppm)	12.2	97.6	75

The pH remains nearly constant (8.2 to 8.1), indicating that the filtration process does not significantly affect the acid–base balance of water. A major improvement is observed in electrical conductivity (EC) and total dissolved solids (TDS), which decrease slightly with natural zeolite but drop significantly with activated zeolite, showing its superior ion removal efficiency. Similarly, sodium and chloride concentrations are greatly reduced after activated zeolite treatment, confirming its effectiveness in removing salinity-causing ions. Potassium shows moderate reduction, while calcium and magnesium slightly increase due to ionexchange processes, which replace sodium with less harmful hardness ions. Carbonate decreases consistently, whereas bicarbonate fluctuates due to chemical equilibrium changes. Overall, natural zeolite provides limited treatment, while activated zeolite demonstrates high efficiency due to its enhanced adsorption and ion-exchange capacity, making it a reliable method for treating saline groundwater.

VII. CONCLUSION

The study confirms that the developed multi-stage filtration system effectively reduces saline content in well water, particularly EC, TDS, chloride, and sodium, thereby improving water quality for domestic use. Both natural and activated zeolite contribute to ion removal, with activated zeolite showing higher efficiency due to better adsorption properties, while natural zeolite remains a cost-effective alternative. The use of locally available materials makes the system affordable and suitable for rural and coastal areas. The system also proven effective in treating groundwater affected by seawater intrusion. Additionally, factors such as media thickness and contact time were found to enhance adsorption efficiency. Overall, the study presents a simple, economical, and sustainable solution for improving groundwater quality.

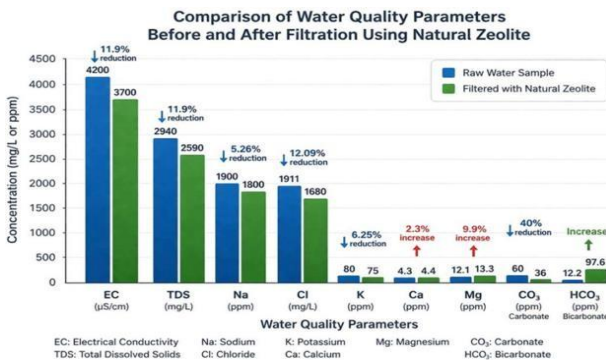


Fig8.1graph for comparison of water quality parameters before and after filtration using natural zeolite

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International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 -6435 (Online)), Volume 15, Issue 4, April 2026)

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