RESEARCH PAPER

Electrocoagulation as a Sustainable Approach for Groundwater Hardness Removal

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Abstract

Water usage in households, companies, and the environment is severely restricted by groundwater hardness, which is mostly caused by high concentrations of calcium and magnesium ions. Water consumption in homes, businesses, and the environment is severely hampered by groundwater hardness, which mainly comes by elevated calcium and magnesium ion concentrations. With current softening methods, issues like high chemical consumption, sludge formation, and operational complexity are frequent. In order to remove hardness from groundwater under continuous flow conditions, this study investigated electrocoagulation (EC) using aluminum electrodes. Groundwater samples from Pune, India, had an exceptionally high total hardness (840 mg/L as $CaCO_3$), above both the WHO and BIS permissible standards. A laboratory-scale EC reactor operating at various current densities (8–24 A m^{-2}) and detention times (5–80 min) has been used to assess the removal efficacy of total hardness, calcium, magnesium, alkalinity, and total dissolved solids (TDS). The results demonstrated that both current density and detention duration had a significant impact on treatment efficiency. Approximately 90% of the overall hardness was removed at current densities of 22–24 A m^{-2} after 20–30 minutes of detention. Under ideal circumstances, the removal efficiencies of calcium and magnesium were over 85% and 95%, respectively. Within an ideal working window of 20–22 A m^{-2} and 35–50 minutes of detention time, zeta potential investigation verified efficient charge neutralization and floc destabilization, ensuring stable floc formation without excessive charge reversal. The results demonstrate that electrocoagulation is an efficient, chemical-free, and ecologically friendly method of removing hardness from groundwater, with great promise for real-world and expandable water treatment uses.

Keywords: Electrocoagulation; Hardness removal; Groundwater; Aluminium electrodes; Continuous flow treatment

Introduction

Rapid population growth, industrial expansion, and the combined effects of anthropogenic and natural pollution sources are gradually limiting the availability of clean and acceptable water for human use (Phu et al., 2025). About 85% of accessible freshwater worldwide falls under the hard water category (Sun et al., 2026).

Hardness is one of the main factors controlling water quality, and it continues to have a significant impact on industrial processes, residential use, and environmental sustainability (Medina-Collana et al., 2023). Dissolved divalent and trivalent metal ions, mainly calcium and magnesium, with trace amounts of iron and aluminium, are the main cause of water hardness (El Mahjoub et al., 2025). In industrial systems involving heat transfer, cooling, and washing processes, excessive hardness impairs operating efficiency and product quality, while in drinking water sources it reduces palatability and customer acceptance.

In pipelines, boilers, heat exchangers, and household appliances, excessive hardness causes scale formation that results in membrane fouling, decreased heat transfer efficiency, increased energy consumption, and greater maintenance costs (Al Jaberi, 2022). Excessively hard water poses serious technical, financial, and aesthetic difficulties, even while extremely soft water is not thought to be optimal for human health. In order to guarantee system performance and customer acceptance, worldwide drinking water recommendations suggest upper limits for hardness expressed as calcium carbonate. Long-term rock weathering worsens groundwater hardness in many tropical areas and is frequently associated by high fluoride concentrations (Babu et al., 2020).

Although they are frequently used for hardness control, conventional water softening technologies like lime softening, ion exchange, reverse osmosis, and nano filtration have disadvantages such as high capital and operating costs, chemical consumption, membrane fouling, excessive sludge generation, and the requirement for post-treatment waste disposal. For the treatment of hard and extremely hard waters, these constraints have prompted the quest for affordable, eco-friendly, and straightforward solutions.

Electrocoagulation (EC) and other electrochemical treatment techniques have become viable options for simultaneously removing contaminants and softening water. Recently, electrodeposition (EP) softening has emerged as a promising technology because it eliminates the need for external chemicals, operates effectively across various water matrices, and offers high environmental compatibility (Sun et al., 2026)

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In order to create metal hydroxide species that destabilize and agglomerate dissolved and suspended pollutants, EC depends on the in situ creation of coagulants by the controlled dissolution of sacrificial metal electrodes under an applied electric current. Charge neutralization, adsorption, sweep flocculation, and separation by sedimentation or flotation are some of the methods used to remove pollutants (El Mahjoub et al., 2025).

Electrocoagulation yields denser, bigger flocs with better settling and less sludge volume than traditional chemical coagulation. In addition to having a straightforward reactor architecture, quicker treatment periods, reduced sludge output, better sludge dewater ability, and increased environmental compatibility, the process runs without the need for external chemical addition.

Precipitation and adsorption of calcium and magnesium ions onto metal hydroxide flocs at near-neutral pH are the main processes in EC that remove hardness. Electrochemical precipitation removes hardness by generating a high-pH environment near the cathode through hydroxyl ion production (Zhi and Zhang 2014). Stepwise mechanism of total hardness removal through electrocoagulation Using Al Electrodes given bellow.

Step 1. Dissolution of sacrificial Al anode

($Al(s) \rightarrow Al^{3+} + 3e^-$) Release of Al^{3+} [1]

Step 2. Hydrolysis of Al ions and formation of ($Al(OH)_3$ flocks

($Al^{3+} + 3H_2O \rightarrow Al(OH)_3\downarrow + 3H+$) [2]

Step 3. Adsorption and charge neutralization of Ca^{2+} and Mg^{2+} ions

$Al(OH)_3 + Ca^{2+} \rightarrow Al(OH)_3 \cdot Ca^{2+}$ [3]

$Al(OH)_3 + Mg^{2+} \rightarrow Al(OH)_3 \cdot Mg^{2+}$ [4]

Step 4. Precipitation of hardness-forming ions

$Ca^{2+} + 2OH^- \rightarrow Ca(OH)_2\downarrow$ [5]

$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2\downarrow$ [6]

Step 5. Electro flotation (H_2 bubbles at cathode) and sedimentation

$Flocs + H2\uparrow \rightarrow$ Flotation to surface [7]

Step 6. microbial inactivation (electric field + enmeshment)

$Microorganisms + Al(OH)_3 \rightarrow$ Entrapped biomass [8]

Step 7. Softened (treated) water with reduced total hardness

$Microorganisms + Al(OH)_3 \rightarrow$ Entrapped biomass [9]

Electrocoagulation is appealing for multi-contaminant treatment of groundwater and brackish water since it has proven to be highly effective in eliminating fluoride, silica, inorganic ions, organic compounds, colour, oil, grease, and turbidity, and other pollutants in addition to hardness (Halpegama et al., 2021). According to research, fluoride and hardness can be eliminated at the same time under ideal circumstances; however, more research is needed to understand how various ions interact with treatment settings (Pouretedal et al., 2021). Although the majority of EC experiments have been carried out in batch settings, research on continuous-flow systems is growing, and new reactor designs appear promising for practical, scalable applications. Operational factors like reactor geometry, hydraulic conditions, and current density affect these systems' performance. Despite these gains, the combined optimization of hydraulic and electrical parameters under continual charge loading remains an ongoing topic of research (Ait El Mahjoub et al., 2025).

In this regard, the current work examines how to optimize electrocoagulation for efficient hardness removal. To optimize treatment efficiency and prove electrocoagulation as a practical, effective, and ecologically sustainable substitute for integrated groundwater treatment, important operational factors such as pH, current density, and flow conditions are methodically assessed.

Figure 1. The image illustrates the primary sources of water hardness, which can be broadly divided into geogenic, anthropogenic, and other environmental factors that influence the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in water. Geogenic energy is produced by natural geological processes such as the weathering and dissolution of silicate and carbonate minerals like dolomite ($CaMg(CO_3)_2$) and limestone ($CaCO_3$), water seeping through mineral-rich formations, and ion-exchange reactions in rocks and soil. Common minerals that contribute to natural hardness include calcite, dolomite, gypsum, magnesite, feldspar, and mica (Maurya et al., 2023).

Anthropogenic causes include excessive groundwater extraction, urban runoff, agricultural runoff, irrigation return flows, and residential wastewater discharge, all of which raise hardness levels and promote mineral disintegration. Other environmental factors that influence water hardness include seawater intrusion in coastal areas, high evaporation rates that concentrate dissolved ions, longer groundwater residence durations that for more mineral interaction, and the mixing of hard and soft water sources. Overall, the image illustrates how water hardness is determined by a confluence of environmental processes, human-induced impacts, and natural geological causes.

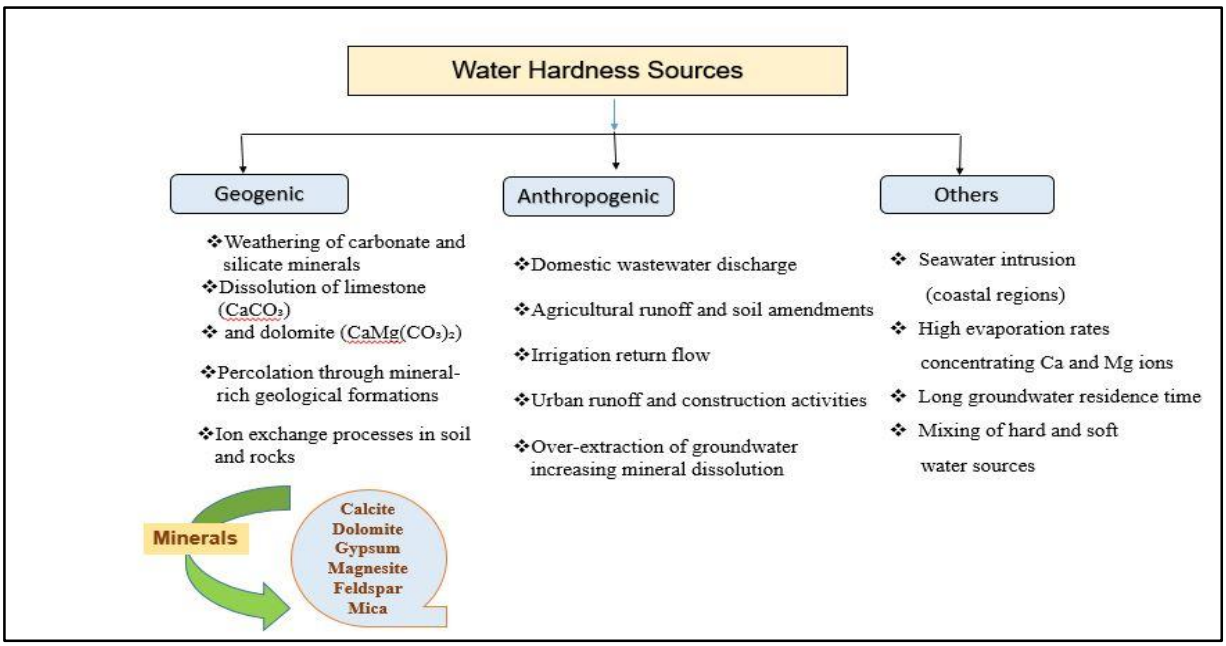

Fig: 1 Schematic representation of hardness sources in groundwater

2. Material and Method

2.1 Study area and groundwater sampling

The study was conducted in Pune city, Maharashtra, India, where groundwater samples were collected from the vicinity of Dr. D. Y. Patil College of Engineering, Akurdi. Pune is located between 18°22′–18°35′ N latitude and 73°44′–73°57′ E longitude, with an average elevation of approximately 559 m above mean sea level. The sampling was done twice in a month using grab sampling method.

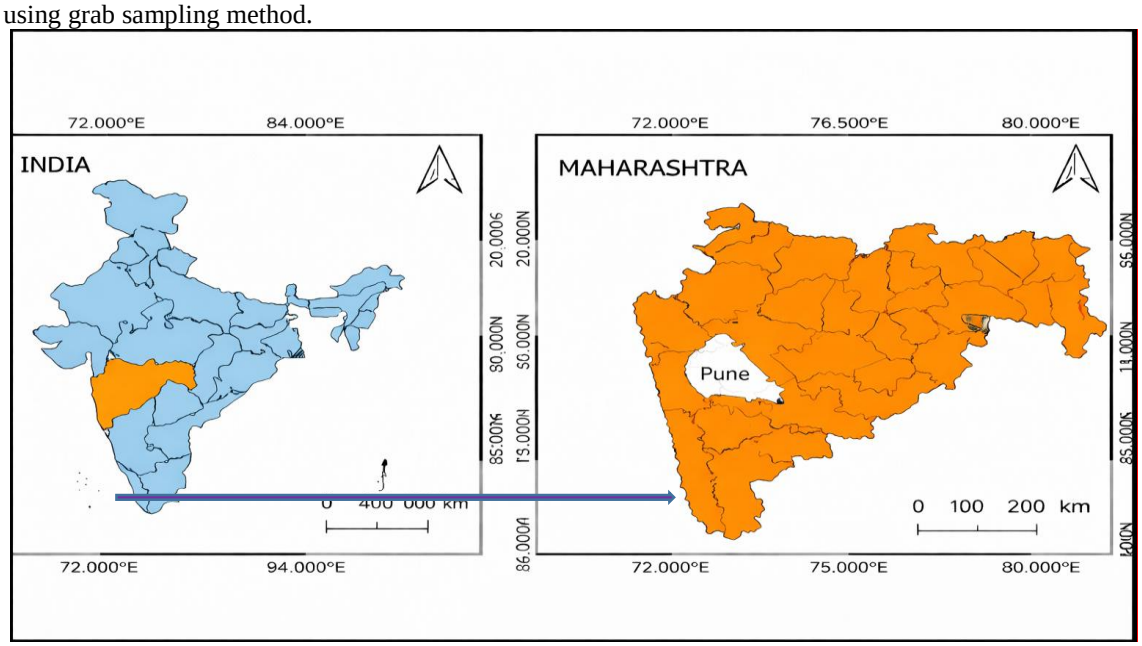

Fig:2 Illustrates the location of the study area

Groundwater samples were obtained from dug wells, borewells, and community water supply sources to ensure representative coverage of the study area. Sampling locations were selected based on well distribution, accessibility, and proximity to potential contamination sources. The geographical coordinates of each site were recorded using a Global Positioning System (GPS) to support spatial analysis. In total, 30 groundwater samples were collected following standard sampling procedures.

2.2 Physico-Chemical Analysis

Electrical conductivity (EC) and pH were measured on-site as soon as the sample was collected. An ion-selective electrode method was used for laboratory studies.

A complexometric titration with EDTA was used to measure the overall hardness of the water. First, a flask containing 50 mL of the water sample was filled with 1 mL of ammonia buffer and 5–6 drops of Eriochrome Black T indicator. After the solution turned wine red, titration against EDTA was carried out until the colour

changed to blue, signifying the end point.The amount of EDTA used was used to compute the overall hardness, which is represented in mg/L as $CaCO_3$. 50 mL of the sample was put in a 250 mL flask, and sodium hydroxide was used to raise the pH to 12–13 in order to measure calcium hardness. A pink solution was created by adding 0.1–0.2 g of murexide (ammonium purpurate) indicator. Calcium hardness was determined by titrating this with EDTA until the color became purple at the end. Since total hardness is the sum of the calcium and magnesium ions in water, magnesium hardness was therefore calculated by deducting calcium hardness from total hardness.

As shown in Table 1, the results were compared to the drinking water quality requirements set out by the Bureau of Indian standard (BIS 2012 and WHO 2011).

Table1: Drinking Water Quality Standards for Selected Parameters

S. No.	Parameters	WHO (2011)	BIS (2012)
2	pH	7.0 -8.5	6.8-8.5
3	Electric conductivity (EC)	750	750
4	Total Dissolved Solids (TDS)	500	600
10	Total Hardness(TH)	250	600
11	Bicarbonate (HCO_3^-)	500	500
14	Calcium(Ca^{2+})	75	100
15	Magnesium (Mg^{2+})	30	30

Table 2: Characteristics of groundwater parameter before treatment

Parameter	Before treatment
pH	7.2
Electrical Conductivity	4.2
Total Hardness (mg/L)	840
Ca^{2+} hardness (mg/L)	120
Mg^{2+} hardness (mg/L)	480
TDS (mg/L)	1240
Alkalinity (mg/L)	520

2.3 Experimental setup

The laboratory-scale experimental setup adopted in this study is schematically presented in Fig. 1. The continuous-flow electrocoagulation system comprised of a feed tank (60 L capacity), a plexiglass electrocoagulation (EC) reactor, a DC power supply, and a settling tank. Groundwater was expressed from the feed tank to the EC reactor using a peristaltic pump.

The EC reactor was fitted with 12 aluminium plate electrodes having dimensions of 10 cm × 1 cm × 13.5 cm. Of these, six electrodes acted as anodes and six as cathodes. The inter-electrode distance was kept at 1 cm throughout the experiments. The electrodes were connected in a monopolar configuration to a laboratory DC power supply (Aplab, Model 7162).

To promote floc formation and hydraulic mixing, the electrodes were arranged to function as baffle walls, resulting in a horizontal zigzag flow pattern within the reactor. The effective working volume of the EC unit was 2 L, considering for the outlet level and the volume occupied by the submerged electrodes. The influent flow rate was regulated using the peristaltic pump.

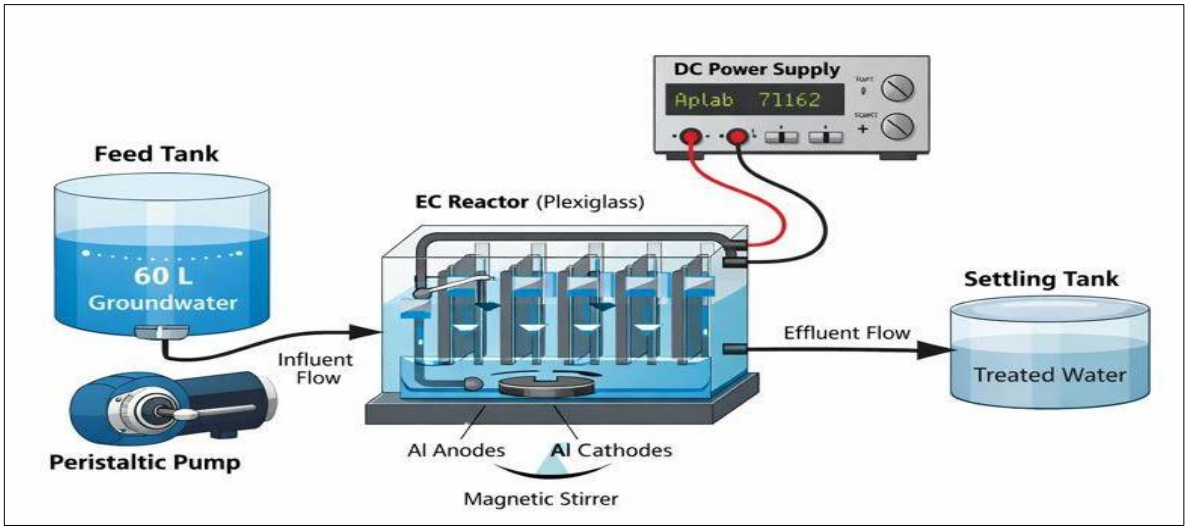

Fig. 3. Schematic diagram of the laboratory-scale electrocoagulation (EC) experimental setup

2.5. Data Analysis

2.5.1. Determination of Removal Efficiency (%)

The removal efficiency of hardness, specifically calcium, was determined using the following expression

Removal Efficiency R (%) = $C_O - C_t \,/\, C_O \times 100$ [10]

Equation (10), where R represents the removal efficiency (%), C_O initial calcium hardness concentration and Ct represent the calcium concentration after treatment.

2.5.2. Estimation of Electrode Consumption during Electrocoagulation

Faraday's law, which links the quantity of ions produced to the applied current and treatment period, can be used to determine the anode material consumption in the electrocoagulation (EC) process. The dissolved anode material's theoretical mass is determined by

:

$M_{thO} = MIt/zF$ [11]

where M_{thO} is the mass of anode dissolved (g), M is the molar mass of aluminium (26.98 g/mol), I is the current (A), t is the electrolysis time (s), z is the number of electrons participating in the reaction (3 for Al), and F is Faraday's constant (96,486 C/mol).

If the current shows variation with time, the total electrode consumption can be calculated as:

$M_{thO} = M/zF \int_0^t Idt$ [12]

2.5.3. Specific Energy Consumption (SEC)

The specific energy consumption (SEC) depicts the energy required per unit volume of treated water. It was calculated using the formula

SEC kWh/m^3= Ecell $\int_0^t Idt$/Vs [13]

where Ecell is the applied cell voltage (V), I is the current (A), t is the process time (h), and Vs is the volume of solution treated (m^3).

Result and Discussion

3.1 Initial groundwater quality

The physicochemical characteristics of the collected groundwater samples prior to treatment are presented in Table 2. The groundwater exhibited a near-neutral pH of 7.2, while electrical conductivity and total dissolved solids were recorded as 4.2 mS/cm and 1240 mg/L, respectively, indicating high mineralization.

The total hardness of the groundwater was found to be 840 mg/L as $CaCO_3$, which significantly exceeds the desirable and permissible limits prescribed by WHO (2011) and BIS (2012). Calcium and magnesium hardness were measured as 120 mg/L and 480 mg/L, respectively, confirming that magnesium ions contributed dominantly to the overall hardness. The elevated alkalinity value (520 mg/L) further supports the presence of carbonate and bicarbonate species responsible for hardness.

These results classify the groundwater as very hard, necessitating treatment prior to domestic or industrial use.

3.2 Experimental study

Groundwater samples were used in the electrocoagulation (EC) studies under continuous flow conditions. In order to achieve hydraulic detention times between five and eighty minutes, the influent was fed into the EC reactor from the feed tank at regulated flow rates.

The EC procedure was run at various current densities between 8 and 24 A/m^2 for each chosen detention period. To aid in solid-liquid separation, the treated effluent was sent to a settling tank after electrocoagulation and left there for 30 minutes. While some of the impurities gathered on the cathode surfaces during this time, dense flocs settled in the bottom of the tank. After that, the cleared supernatant was gathered and subjected to standard water quality parameters analysis.

Every experiment was carried out at room temperature. Before and after every experimental run, the aluminum electrodes were taken out of the EC reactor and properly cleaned with tap water to ensure repeatability and avoid surface passivation. The electrodes were then carefully cleaned with clean water after being submerged in a 5% (v/v) hydrochloric acid solution for 20 minutes to remove any adherent deposits. To evaluate electrode consumption during the EC process, the mass of each electrode was measured both before and after each run.

3.3 Effect of detention time and current density on total hardness removal

Figure 4 shows how total hardness (TH) removal effectiveness during the electrocoagulation (EC) process is affected by detention duration and applied current density. The findings show that for all examined current densities, TH removal rose steadily as detention duration increased. Relatively low removal efficiencies (around 12–35%) were seen at the beginning of the process (5–10 min), which can be explained by the insufficient development of flocs and the limited creation of coagulant species. A notable improvement in removal effectiveness was observed with longer detention times, especially between 20 and 50 minutes, suggesting active electrode dissolution and efficient $Al(OH)_3$ coagulant complex formation.

The performance of the EC was significantly impacted by the applied current density. In within 20 to 30 minutes of treatment, approximately 90% of the hardness was removed due to higher current densities (22 and 24 A/m^2). In contrast, longer detention times (70–85 min) were needed to achieve optimum removal efficiencies of around 75–82% at lower current densities (8 and 12 A/m^2). Moderate performance was shown by intermediate current densities (16 and 20 A/m2), which removed over 90% of the material in 50–70 minutes. Increased anodic dissolution, increased coagulant ion generation, and improved hydrogen bubble formation are linked to the enhanced removal at higher current densities. These factors work together to support

calcium and magnesium ion coagulation, adsorption, and flotation.

For the majority of current densities, the removal efficiency showed a steady trend after 60–70 minutes of detention time, indicating the achievement of equilibrium conditions and decreased availability of removable hardness ions. Overall, the results indicate rising current density considerably shortens treatment times and increases removal efficiency. Maximum TH removal efficiencies of about 90% were attained under ideal operating circumstances, which were 22–24 A/m² with a detention time of nearly 20–30 min.

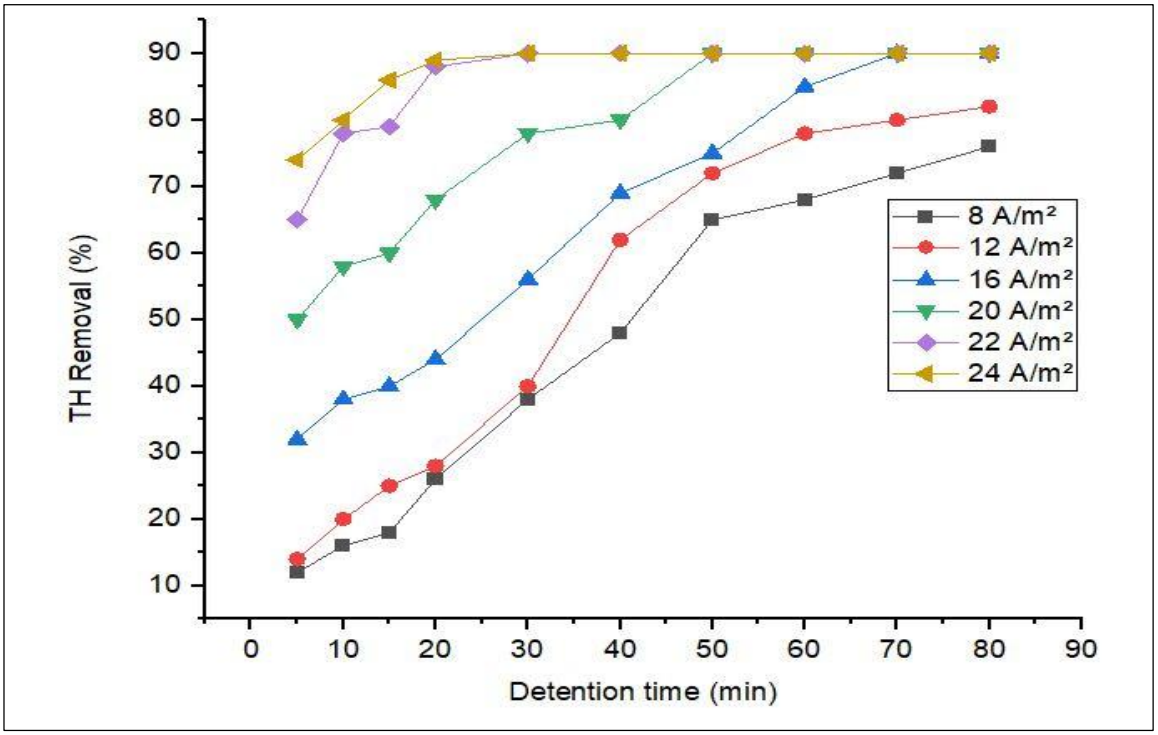

Fig:4 Effect of Detention Time and Current Density on Total Hardness Removal

3.4 Effect of detention time and current density on calcium removal

The fluctuation in Ca^{2+} removal effectiveness as a function of detention time at various applied current densities (8–24 A m^{-2}) is shown in Figure 5. The elimination effectiveness of Ca^{2+} is found to be positively correlated with both detention period and current density.

The elimination of Ca^{2+} progressively increased from around 20% at 5 minutes to nearly 80% at 80 minutes at the lowest current density of 8 A m^{-2} Ca^{2+}, showing slow electrochemical reaction kinetics and minimal coagulant species production. Higher current densities, on the other hand, greatly improved the removal performance, especially during shorter detention times.

Ca^{2+} removal efficiencies of nearly 52–55% were reached in 20 minutes for intermediate current densities (12 and 16 A m^{-2}), and these improved to 82–85% at 80 minutes. Increased anodic dissolution and faster electrochemically generated hydroxide species generation, which facilitate efficient precipitation and adsorption of Ca^{2+} ions, are responsible for this improvement.

Even during shorter detention times, fast Ca^{2+} elimination was seen at higher current densities (20, 22, and 24 A m^{-2}). For example, removal efficiency at 24 A m^{-2} surpassed 75% in 5 minutes and reached an equilibrium of around 88–89% after 40 minutes, after which very slight improvement was seen.

For 22 A m^{-2}, a similar saturation trend was noted, indicating that either mass transfer limitations or the depletion of free Ca^{2+} ions led to the achievement of equilibrium conditions.

The decreased incremental advantage at higher current density and longer detention times suggests that excessive current input may result in needless energy consumption and does not proportionately improve removal efficiency. In order to balance high Ca^{2+} removal efficiency (>85%) with energy efficiency, an ideal operating window seems to be between 20 and 22 A m^{-2} with a detention time of 40 to 50 minutes.

Overall, the findings show that while detention time controls the amount of ion removal, increasing current density speeds up Ca^{2+} removal kinetics. Both factors are essential for maximizing the effectiveness of electrochemical treatment.

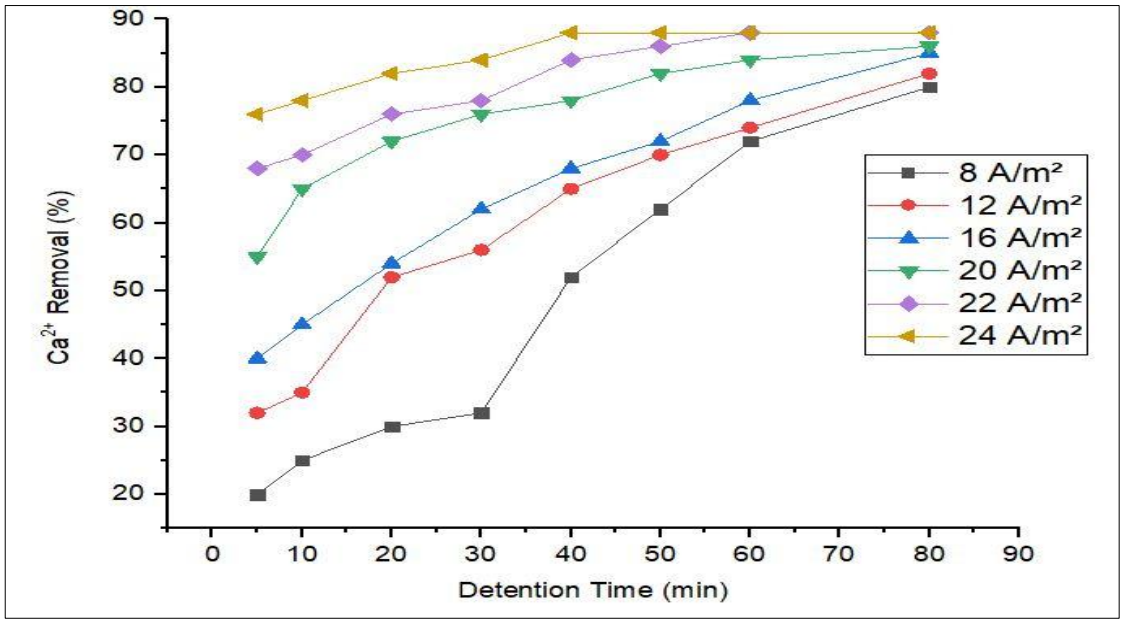

Fig:5 Effect of Current Density and Detention Time on Ca^{2+} Removal

3.5 Effect of detention time and current density on magnesium removal

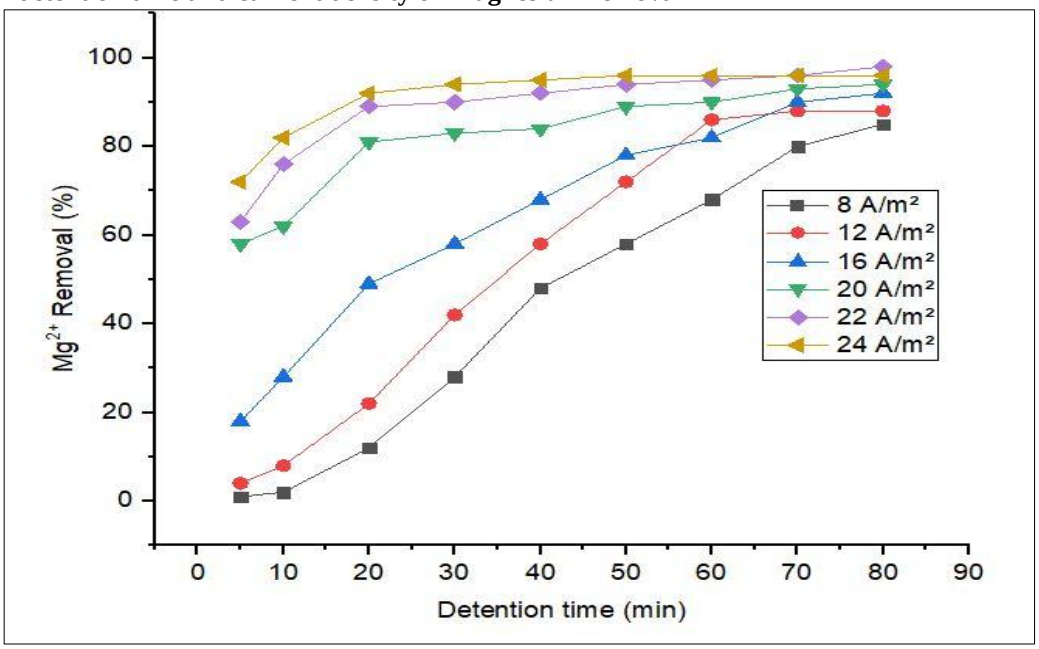

Fig:6 Effect of Current Density and Detention Time on Mg^{2+} Removal

The fluctuation of Mg^{2+} removal effectiveness as a function of detention time under various applied current densities ranging from 8 to 24 A m^{-2} is shown in Figure 6. The findings unequivocally show that Mg^{2+} removal efficacy is significantly impacted by both current density and detention period. Efficiencies were less than 5% in the first 10 minutes at the lowest current density of 8 A m^{-2} Mg^{2+}, showing inadequate electrochemical production of coagulant species. However, when the detention time increased, the removal efficiency gradually increased as well, reaching about 85% at 80 minutes. This pattern implies that the decreased reaction rate at lower current density is partially offset by extended exposure.

Mg^{2+} removal significantly improved at moderate current densities (12 and 16 A m^{-2}), especially in the early detention phase. Removal efficiency rose from about 18% at 5 minutes to almost 50% at 20 minutes and then to over 90% at 80 minutes at 16 A m^{-2}. Increased anodic dissolution and faster metal hydroxide floc formation, which enhance Mg^{2+} precipitation and adsorption, are the reason for this improvement.

Even with brief detention times, Mg^{2+} removal was accomplished quickly at higher current densities (20, 22, and 24 A m^{-2}). For example, at 24 A m^{-2} Mg^{2+}, removal surpassed 70% in 5 minutes and hit 95–97% in 40–50 minutes, after which the removal efficiency only slightly improved.A similar plateau behavior was observed at 22 A m^{-2}, indicating that near-complete Mg^{2+} removal was

attained under these conditions. Near-complete Mg^{2+} removal was achieved under these circumstances, as demonstrated by a similar equilibrium behavior seen at 22 A m^{-2}.

3.6 Effect of current density and detention time on alkalinity removal

The alkalinity removal effectiveness as a function of detention time under various applied current densities (8–24 A m^{-2}) is shown in Figure 7. The findings clearly demonstrate that alkalinity removal is highly impacted by both current density and detention time, indicating behavior similar to hardness removal trends but with more rapid started kinetics.

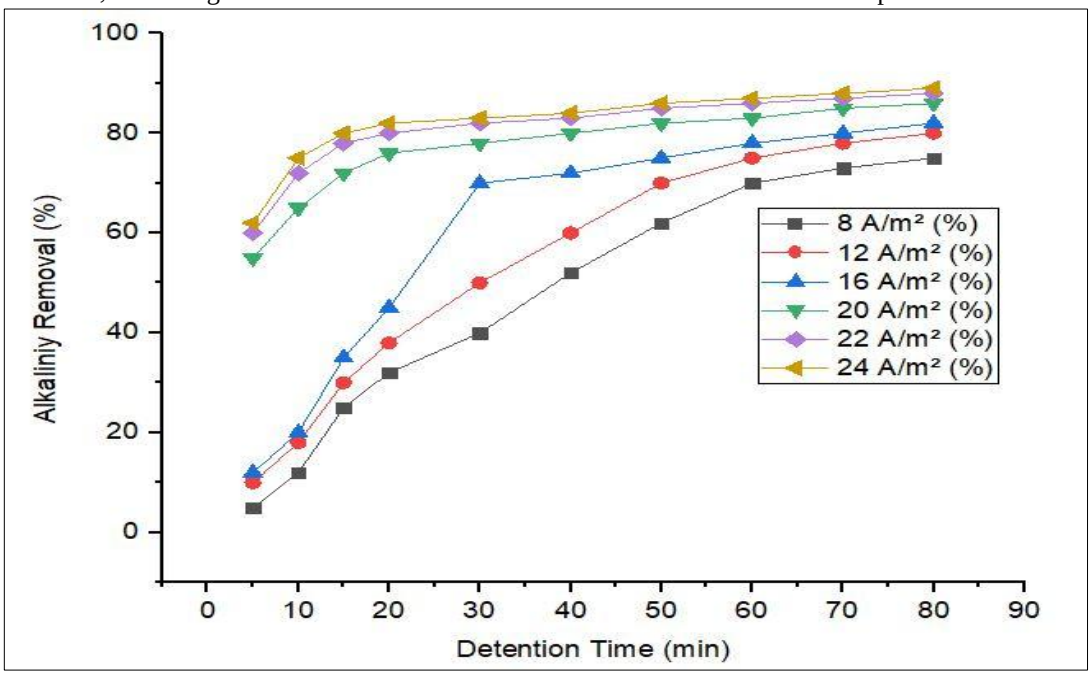

Fig:7 Effect of Current Density and Detention Time on Alkalinity Removal

Alkalinity removal increased gradually at the lowest current density of 8 A m^{-2}, increasing from approximately 5 percent at 5 minutes to almost 75% at 80 minutes. The low production of hydroxyl ions and insufficient electrochemical processes to efficiently neutralize the bicarbonate and carbonate species in the solution are suggested by the slow elimination rate at low current density.

There was a discernible improvement in alkalinity removal for moderate current densities (12 and 16 A m^{-2}), particularly in the early detention phase. Alkalinity removal increased gradually at 16 A m^{-2}, from around 12% at 5 minutes to about 70% in 30 minutes, and then to 82–84% at 80 minutes.

Increased anodic dissolution and faster metal hydroxide complex formation, which enable the consumption of alkalinity through precipitation and adsorption mechanisms, are responsible for this improvement.

Even with shorter detention times, alkalinity removal was quick and achieved high efficiency at higher current densities (20, 22, and 24 A m^{-2}). For example, alkalinity removal at 24 A m^{-2} achieved 60% in 5 minutes and neared 85–88% in 40–50 minutes, after which the removal efficiency only slightly improved. At greater current densities, alkalinity depletion neared equilibrium levels, as evidenced by a similar saturation trend for 22 A m^{-2}.

The plateau seen at longer detention times indicates that the majority of carbonate and bicarbonate ions had either precipitated or been neutralized, and that additional electrochemical input had little effect on further removal. Furthermore, the diminishing advantages at increasing current densities raise attention to the possibility of excessive energy use without corresponding increases in the efficiency of alkalinity removal.

Overall, the results show that alkalinity removal kinetics are greatly improved at higher current density. Removal efficiencies above 80% are obtained at optimal performance of 20–22 A m^{-2} and a detention time of 40–50 min. These circumstances make them appropriate for real-world electrochemical water treatment applications since they strike a compromise between treatment efficacy and operational efficiency.

3.7 Effect of current density and detention time on tds removal

The impact of applied current density and detention duration on the removal efficiency of total dissolved solids (TDS) is depicted in Figure 8.

Although the removal kinetics show a non-linear trend with declining benefits at longer treatment durations, the data show that TDS removal rises with both increasing detention time and current density.

TDS removal was initially constrained at the lowest current density of 8 A m^{-2}, with efficiency falling below 10% in the first ten minutes. With longer detention times, a progressive rise was seen, reaching roughly 70–72% at 80 minutes. This suggests that low current density does not offer enough electrochemical driving power for the efficient removal of dissolved solids.

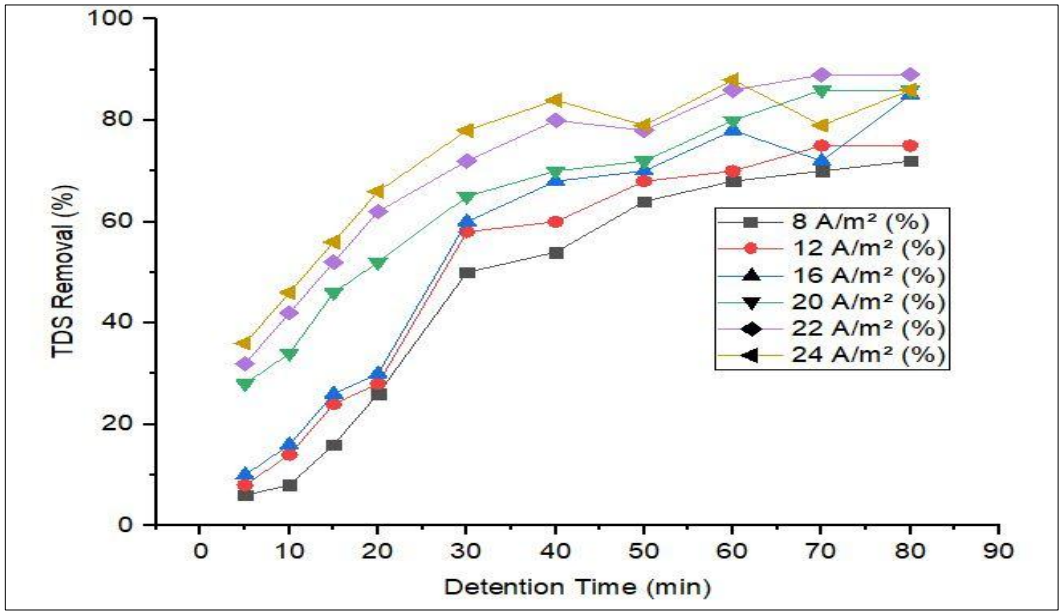

Fig: 8 Effect of Current Density and Detention Time on TDS Removal

There was a noticeable improvement in TDS removal for intermediate current densities (12 and 16 A m^{-2}), particularly within 10 and 30 minutes. TDS elimination rose from around 10% at 5 minutes to about 60% at 30 minutes and then to ~85% at 80 minutes at 16 A m^{-2}. Increased anodic dissolution and the formation of metal hydroxide flocs, which encourage the adsorption and aggregation of dissolved ionic species, are responsible for this improved performance.

Even with shorter detention times, faster TDS removal was accomplished at greater current densities (20, 22, and 24 A m^{-2}). For example, removal efficiency at 24 A m^{-2} surpassed 35% in 5 minutes and reached roughly 80–85% in 30–40 minutes.

However, at intermediate detention intervals (about 50–60 min), minor variations and a brief drop in removal effectiveness were noted. These could be the result of instability of flocs under more intense electrochemical conditions or re-dissolution of loosely bound ionic species.

For all current densities, TDS removal plateaued after 60 minutes, indicating that most detachable dissolved solids had been removed and that continued electrochemical treatment only slightly increased removal. The decreasing incremental benefit at longer detention periods suggests that equilibrium conditions and mass transfer restrictions control TDS removal behaviour.

Overall, the findings show that, due to the heterogeneous nature of the dissolved ionic species that contribute to TDS, TDS removal necessitates a higher current density and a longer detention period than hardness and alkalinity removal. It seems that 20–22 A m^{-2} with a detention duration of 50–60 min is the ideal operating range for TDS removal, producing removal efficiencies of about 80–85% while preserving process stability and energy efficiency.

3.8 Interpretation of optimum current density and detention time based on zeta potential

In addition to offering insightful information on the electrocoagulation mechanism, the zeta potential data compiled in Table X can be used to determine the ideal operating settings with regard to current density and detention time. The untreated groundwater included stable and negatively charged colloidal particles, as evidenced by the initial strongly negative zeta potential values (−20 to −12 mV) in all trials. Zeta potential gradually shifted toward near-neutral values as electrocoagulation went on, indicating colloidal instability and efficient charge neutralization.

Only after extended detention times (>60 min) were near-neutral zeta potential values reached at lower current densities (8 and 12 A m^{-2}). This suggests that Al^{3+} ions and hydroxide species are generated slowly, which causes delayed coagulation and decreased therapy effectiveness. Despite the eventual destabilization, these conditions are less suitable for real-world uses because to the lengthy detention period necessary.

On the other hand, near-neutral zeta potential was reached in 35–55 minutes at intermediate current densities (16 and 20 A m^{-2}). This range supports steady floc formation and efficient aggregation by effectively neutralizing charges without causing excessive charge reversal. These circumstances point to a balanced electrochemical environment, which is consistent with the noted improvements in hardness, alkalinity, and TDS elimination.

Near-neutral zeta potential was quickly obtained (20–35 min) at greater current densities (22 and 24 A m^{-2}), and with longer detention times, it shifted toward positive values (+11 to +14 mV). Although this quick destabilization improves initial coagulation, too much positive charge might cause charge reversal and minimal improvement outside of the ideal range, which could increase energy use without corresponding improvements in treatment effectiveness.

These findings lead to the identification of an ideal operating window with a detention period of 35–50

minutes and a current density of 20–22 A m^{-2}. In these circumstances, the zeta potential approaches near-neutral values that promote maximum flocculation and particle instability while preventing excessive charge reversal and needless energy input.

The removal efficiency trends for total hardness, Ca^{2+}, Mg^{2+}, alkalinity, and TDS are supported by this ideal range, demonstrating the validity of zeta potential as a mechanistic indication for process improvement.

Table 3. Variation of Zeta Potential with Detention Time and Current Density during Electrocoagulation

Current Density (A m^{-2})	Initial Zeta Potential (mV) (0–5 min)	Zeta Potential Trend with Time	Detention Time to Reach Near-Neutral Zeta Potential* (min)	Zeta Potential at Final Stage (80–90 min) (mV)	Interpretation of Coagulation Behaviour
8	−20 to −18	Gradual rise	>70	+4 to +6	Weak floc generation and slow charge neutralization
12	−19 to −16	Moderate increase	60–70	+6 to +8	Partial destabilization of colloids
16	−18 to −15	Steady rise	45–55	+8 to +10	Effective charge neutralization
20	−17 to −14	Rapid increase	35–45	+9 to +11	Enhanced flocculation and aggregation
22	−16 to −13	Very rapid increase	25–35	+11 to +13	Strong sweep flocculation
24	−15 to −12	Fastest increase	20–30	+12 to +14	Reversal of charge and extremely efficient destabilization

Conclusion

This study demonstrates the technical feasibility and effectiveness of electrocoagulation using aluminium electrodes for the removal of groundwater hardness under continuous-flow operation. The raw groundwater samples from the study area were classified as very hard, with total hardness values significantly exceeding recommended drinking water standards, necessitating appropriate treatment prior to use.

The experimental results clearly indicate that both detention time and applied current density play a critical role in governing the electrocoagulation process. Increasing current density enhanced anodic dissolution and hydroxide generation, leading to rapid formation of $Al(OH)_3$ flocs and improved removal of hardness-forming ions. Maximum total hardness removal efficiencies of approximately 90% were achieved at current densities of 22–24 A m^{-2} with relatively short detention times of 20–30 minutes, while lower current densities required substantially longer treatment durations to reach comparable performance.

Calcium and magnesium ions exhibited distinct removal behaviors, with magnesium showing faster and more complete removal due to its stronger affinity for hydroxide precipitation at elevated pH conditions near the cathode. Alkalinity and TDS removal followed trends similar to hardness removal, although higher current densities and longer detention times were required for effective TDS reduction due to the heterogeneous nature of dissolved ionic species.

Zeta potential analysis provided mechanistic insight into the coagulation process and enabled identification of an optimal operating window. Near-neutral zeta potential values achieved at current densities of 20–22 A m^{-2} and detention times of 35–50 minutes corresponded to maximum floc destabilization, efficient aggregation, and balanced energy consumption. Beyond this range, marginal gains in removal efficiency were observed despite increased energy input, highlighting the importance of process optimization.

Overall, electrocoagulation emerges as a robust, chemical-free, and environmentally sustainable alternative to conventional water softening technologies. The study confirms its suitability for treating hard groundwater and supports its potential for scale-up and real-world implementation, particularly in regions affected by geogenic hardness and high mineralization.

Acknowledgement

The management and authorities of Dr. D. Y. Patil College of Engineering, Akurdi, Pune, are acknowledged by the authors for providing the infrastructure and laboratory facilities required to carry out this work. The authors also genuinely thank their families for their unwavering support and inspiration in carrying out this research.

Author contribution

VG conducted the investigation, developed the methodology and research approach, and prepared the original draft of the manuscript. SJM, ABM, supervised the work and contributed to the review and editing of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest

Funding: No outside funding was obtained for this study.

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