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Effectiveness of reducing Ca–Mg hardness using NaOH precipitation, in Ghardaïa groundwater

Kheira Bouamer [1]*, Hamed Boukhari [1], Khaled Mansouri [2]

[1] Laboratory of Materials, Energy Systems Technology and Environment, Université de Ghardaia, Ghardaia, Algeria
[2] Department of Process Engineering, Faculty of Science and Technology, Mathematics and Applied Science, Ghardaïa University, Ghardaïa, Algeria

Abstract

In Saharan regions, ensuring fresh water to consumers is very difficult, as the predominant source is groundwater loaded with mineral salts from reservoir rocks. The study is based on the choice of caustic soda (NaOH) as a treatment element by chemical precipitation. The protocol followed includes treatment with different doses of NaOH: (500 mg/L of NaOH), (250 mg/L of NaOH and 250 mg/L of Na_2CO_3 adjusting once with acetic acid CH_3COOH and another time with hydrochloric acid HCl), then optimized doses of NaOH alone. The results are then examined, on the one hand, on the reduction of hardness (TH) and, on the other hand, on its impact on pH, electrical conductivity (EC) and salinity. The results indicate that the first dose significantly reduces permanent calcium and magnesium hardness (TH) from 558 mg/L exceeding (Algerian standard limited 500 mg/L) to 328 mg/L, with increases in pH exceeding the potability threshold, while treatment with sodium hydroxide and sodium carbonate are effective in reducing or even eliminating Ca^{2+} and Mg^{2+} ions, but there is still a strong increase in alkalinity. The solution is adjusted by an acid still presents additional effects such as solubility of salts and therefore the need to adjust the electrical conductivity (EC). Finally, the treatment is optimized at a low dose of NaOH (20 mg/L) without the addition of sodium carbonate. This dose has proven to be the most adequate, thus allowing a substantial reduction in TH (615 reaching 400 mg/L) while balancing the pH and electrical conductivity (EC) parameters. These results demonstrate the effectiveness of NaOH in the treatment of hard water, while keeping control of its influence on other parameters such as sodium (225.77 mg/L of Na+) where it presents an increase of up to 10%, although it is a significant increase, it is found that the waters of the region exceed this dose in their natural state. Overall, the experience still offers promising and practical solutions for domestic, agricultural and industrial applications and guaranteeing compliance with water quality standards.

Keywords: Water analysis, Permanent hardness, Sodium hydroxide, Sodium carbonate, TH reduction

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*Corresponding Author, E-mail: bouamer.khaira@univ-ghardaia.dz

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1. Introduction

Groundwater is an essential resource and a vital element for human existence. In the Sahara, it is the only source of drinking water and daily consumption (Tang et al., 2021). Although water resources are accessible, improving their quality remains a major challenge. One major concern is water hardness, which continues to attract considerable scientific and environmental attention. Water hardness is associated with high concentrations of dissolved mineral ions, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), which are absorbed as water passes through mineral-rich geological formations (Van der gun, 2021). These ions result from the interaction of water with limestone or gypsum rocks, leading to an increase in dissolved mineral content. The impacts of water hardness are evident in various areas. At home, limescale clogs pipes, especially in arid areas with very hot climates. The hardness also damages household appliances such as water heaters and kettles.

Furthermore, hard water requires larger quantities of soap and detergents to produce effective lather, which increases costs and reduces cleaning effectiveness. From a health perspective, while calcium and magnesium are essential nutrients, their high concentrations can lead to health problems such as the formation of kidney stones and other physiological disturbances. On an industrial scale, water hardness compromises the efficiency of processes using pure water and leads to costly equipment malfunctions and scaling (Aureli et al., 2008). High concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions reduce nutrient availability, increase soil alkalinity, and cause salinity buildup, leading to lower soil fertility and crop productivity. Despite their poor chemical quality, regional waters are still used for irrigation, which intensifies these effects. Effective monitoring and management of water hardnes are therefore essential to maintain soil health and ensure sustainable agricultural production.

In the face of these challenges, it has become crucial to develop effective technologies to reduce water hardness. These technologies include ion exchange, reverse osmosis, and chemical precipitation. Among these methods, water treatment with sodium hydroxide (NaOH) has proven particularly effective in reducing water hardness and improving water quality. These efforts are an essential step towards environmental sustainability and access to high-quality water resources that meet the needs of communities and industries (Adu-Manu; et al., 2017).

The objective of this study was to address the problem of water hardness by using sodium hydroxide (NaOH) as an effective method to reduce the concentrations of ions responsible for hardness, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). (Karlsson Faudot, 2021). The aim is to evaluate the impact of sodium hydroxide on reducing water hardness and to analyze its effects on physical properties of water, including pH, electrical conductivity, and sodium concentration (Patil; et al., 2012). The study will test the effectiveness of chemical precipitation in removing these ions through laboratory experiments designed to determine the optimal dosage of sodium hydroxide. These experiments will help evaluate the effectiveness of this method while minimizing potential side effects and providing a detailed understanding of how the treatment influences water quality and usability (Siemens, 2018).

2. Materials and Methods

This work focused on three main mechanisms for treating hard water. First, ion exchange technology, in which hard water passes through a layer of sodium-saturated cation resins, allowing the exchange of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions with sodium (Na^{+}) ions, thereby reducing hardness (Thiel; et al, 2017). Second, reverse osmosis, where water is forced under high pressure through a semi-permeable membrane, allowing pure water to pass through while retaining the minerals responsible for hardness.

Finally, chemical precipitation with sodium hydroxide (NaOH), where calcium and magnesium are precipitated as solid carbonates (Nayar, 2020). This method was preferred due to its simplicity and effectiveness. The results of this method will be analyzed, including the measurement of calcium and magnesium ion concentrations before and after treatment, the evaluation of pH and electrical conductivity variations, and the determination of the sodium concentration introduced by caustic soda (Nayar, 2020). In addition, the optimal dosage of caustic soda for maximum hardness reduction with minimal side effects on either alkalinity or sodium levels will be determined (Couture I.

2004). Improvement of water quality and its suitability for domestic, agricultural and industrial use will also be assessed against international standards (Luo; Wan, 2013).

2.1. Materials

The equipment used in this study included chemical reagents and laboratory equipment to ensure accurate and effective water hardness treatment. Sodium hydroxide (NaOH) was used as the primary reagent for chemical precipitation to reduce hardness, along with buffer solutions to calibrate the pH meter and maintain pH stability during measurements. Calcium and magnesium standard solutions were used to calibrate ion concentration, while deionized water was used to prepare the solutions and clean the equipment to avoid contamination. The laboratory equipment included a pH meter (WTW-LF-538) to measure acidity/alkalinity changes, a conductivity meter to assess electrical conductivity and total dissolved solids (TDS), and titration equipment to determine calcium and magnesium concentrations. A spectrophotometer (HACH-ODYSSY-UV/VIS) was used to analyze ionic absorption at specific wavelengths, complemented by an analytical balance for accurate weighing of reagents. In addition, beakers, flasks, stirrers, a filtration apparatus, and micropipettes were used for the preparation, mixing, and separation of precipitated solids from treated water samples. The study was conducted on tap water samples collected at the ADE laboratory in Ghardaïa, thus ensuring the relevance of the results in the real world.

2.2. Method

The methodology of this study included several key steps to address water hardness with sodium hydroxide (NaOH).

First, carbon dioxide reacts with sodium hydroxide to form sodium carbonate and water.

$$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O. \quad (1)$$

The remaining sodium hydroxide can then be reacted with calcium bicarbonate and magnesium bicarbonate.

$$Ca(HCO_3)_2 + 2NaOH \rightarrow CaCO_3 + Na_2CO_3 + 2H_2O \quad (2)$$

$$Mg(HCO_3)_2 + 4NaOH \rightarrow Mg(OH)_2 + 2Na_2CO_3 + 2H_2O \quad (3)$$

Sodium hydroxide can also react with non-magnesium carbonate hardness, as shown below. Also note that the reaction between sodium hydroxide and carbonate hardness produces sodium carbonate, which also reacts with non-carbonate hardness (Associates R.1997).

$$MgSO_4 + 2NaOH \rightarrow Mg(OH)_2 + Na_2SO_4 \quad \mathbf{(4)}$$

Water samples were collected at the ADE laboratory in Ghardaia and stored in clean, airtight containers to avoid contamination (Bouamer et al., 2019). Chemical solutions of NaOH at different concentrations were prepared to test optimal dosages, as well as standard solutions of calcium and magnesium ions for calibrating analytical instruments. The analytical method was based on three tests. First, different amounts of sodium hydroxide were introduced into a series of beakers containing 1 liter of drinking water. The mixture was stirred for different durations at (T: 22°C). The physicochemical parameters were analyzed at the central laboratory (ADE) unit in Ghardaia.

-Second test is based on the results of first tests to minimize the impact on pH, where we minimize the amount of NaOH 250 mg/L first combine with 250 mg/L Na_2CO_3 alone under stirring for 40 minutes. Decantation is done for one day. The supernatant is analyzed to determine the physicochemical parameters. After studying the results, we separate the solution into two to do the following treatment; In 100 ml of this solution, we start stirring by adding 25 drops of HCl while measuring the pH in parallel; In the other beaker we put 100 ml of this solution, we start stirring by adding 15 drops of acetic acid and measuring the pH. The reaction was allowed to proceed for a determined time in order to precipitate calcium and magnesium in the form of insoluble hydroxides or carbonates (Himmi et al., 2005). After the reaction, the precipitated solids were separated using a filtration device, and the treated water was collected for analysis.

- In the final tests, we adapted NaOH alone to lower concentrations. Analysis was performed before and after each test. Post-treatment analysis included pH measurement to assess the changes induced by the addition of NaOH, electrical conductivity measurement to determine the dissolved ion concentration, while water hardness was assessed by titration with 0.01 mol/L EDTA (ethylenediaminetetraacetic acid) as a reagent in a pH 10 buffer medium and in the presence of

Mordant Black 11, as an indicator to assess the remaining concentrations of calcium and magnesium ions. The sodium concentration of the treated water was also analyzed to estimate the impact of NaOH.

Finally, the results were studied to determine the optimal dosage of NaOH to achieve maximum hardness reduction with minimal side effects, while ensuring that the treated water complies with international and local standards for quality and ease of use. This systematic approach enabled a comprehensive assessment of the effectiveness of sodium hydroxide in the treatment of water hardness (Bouamer; et al., 2019).

3. Results and discussion

In this section, the study results will be presented and analyzed to assess the effectiveness of sodium hydroxide (NaOH) in reducing water hardness and improving water quality. The results will include changes in calcium (Ca^{2+}) and magnesium (Mg^{2+}) ion concentrations before and after treatment, highlighting the effectiveness of chemical precipitation. The impact of NaOH addition on pH will be analyzed to determine whether the treated water remains within acceptable limits. Electrical conductivity measurements will be analyzed to assess the reduction in dissolved salts, while the increase in sodium ion (Na^+) concentration resulting from NaOH treatment will be evaluated. The effectiveness of chemical precipitation will be examined by comparing the amount of precipitate formed under different NaOH dosages, and the optimal dosage for maximum hardness reduction with minimal side effects will be identified. Finally, the improvement in water quality will be assessed against local and international standards for drinking and industrial water, providing insight into the practical application of this treatment method. Through this analysis, the study aims to draw conclusions on the feasibility and sustainability of using caustic soda (NaOH) for water hardness treatment and to make recommendations for its future implementation.

3.1 - first test: Dosage of 500 mg/L of caustic soda (NaOH)

In this section, the effect of a 500 mg/L sodium hydroxide (NaOH) dosage on water quality will be evaluated in order to reduce total hardness (TH). and improve its physicochemical properties (Table 1).

Table 1. First test-analysis results

parameters	Before treatment	After treatment
T (°C)	16,5	18,4
pH	6,6	13,5
CE (µS/cm)	2210	2760
Ca^{2+} (mg/l)	157,113	123,44
Mg^{2+} (mg/l)	47,682	4,86
TH (mg/l)	558	328

The main parameters analyzed include total hardness (TH), calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations, as well as electrical conductivity (EC) and pH. The results obtained before and after treatment will be compared to the Algerian Standard to ensure compliance with water quality requirements. This evaluation will determine the effectiveness of the selected dosage in achieving the desired improvements and assess any potential side effects associated with its application.

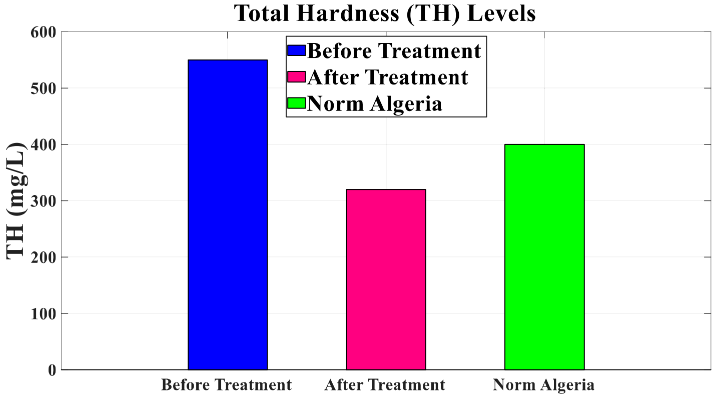

Figure .1. Total Hardness (TH) at different treatment stages

Figure 1 illustrates the total hardness (TH) levels at three stages: before treatment, after treatment, and according to the Algerian Standard. Before treatment, the TH value was 550 mg/L, exceeding the maximum permissible limit of 400 mg/L set by the Algerian standard, indicating that the water was unfit for general use. After treatment with sodium hydroxide (NaOH), the TH value significantly decreased to 320 mg/L, which is within the permissible range. This reduction underlines the effectiveness of the treatment method in reducing the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions responsible for water hardness. The improvement in water quality makes it suitable for various general uses, including human and domestic consumption. These results highlight the success of the treatment process and the achievement of the main objective of the study: to improve water quality so that it meets acceptable standards for safe and reliable use.

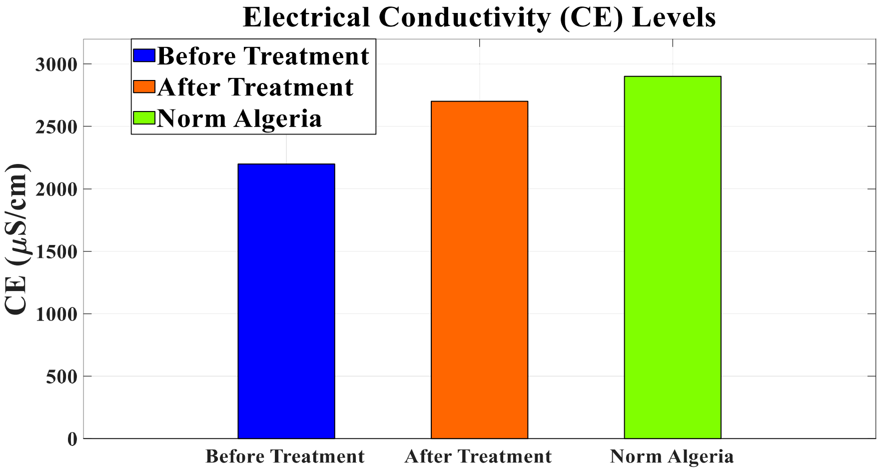

Figure 2. Electrical Conductivity (CE) at different treatment stages

Figure 2 illustrates the variation in electrical conductivity (EC). Initially, the conductivity is approximately 2,200 µS/cm at the "Before Treatment" stage, which reflects the concentration of dissolved salts and ions in the raw water. After treatment, the conductivity reaches 2,700 µS/cm, mainly due to the introduction of sodium ions (Na^+) when using sodium hydroxide (NaOH). While the treatment has indeed reduced the total hardness (TH) as observed previously, the increase in conductivity highlights a secondary effect, indicating a higher dissolved salt content. Compared to the Algerian standard of 2,900 µS/cm, the conductivity after treatment remains within acceptable limits, but tends towards the upper threshold. Since lower conductivity is a positive indicator of better water quality, especially for domestic applications, further optimization of the treatment process is required to reduce conductivity while maintaining its effectiveness in improving water quality.

Figure 3 illustrates the pH levels at different stages of water treatment. Before treatment (BT), the pH was recorded at 8.0, which is within the acceptable range specified by Algerian standards (6.5-9.0), indicating that the water was relatively neutral and balanced. After treatment (PT), the pH increased sharply to 13.5 due to the addition of NaOH, resulting in excessive alkalinity far exceeding the maximum permissible limit (9.0) set by the standards, making the water unsuitable for domestic use. In contrast, Algerian standards indicate a minimum threshold (NA 1) of 6.5 and a maximum threshold (NA 2) of 9.0, which ensure water safety and quality. This analysis highlights the need for strict control of NaOH dosage during treatment, as excessive use disrupts the pH balance, compromising water quality and limiting its suitability for domestic use

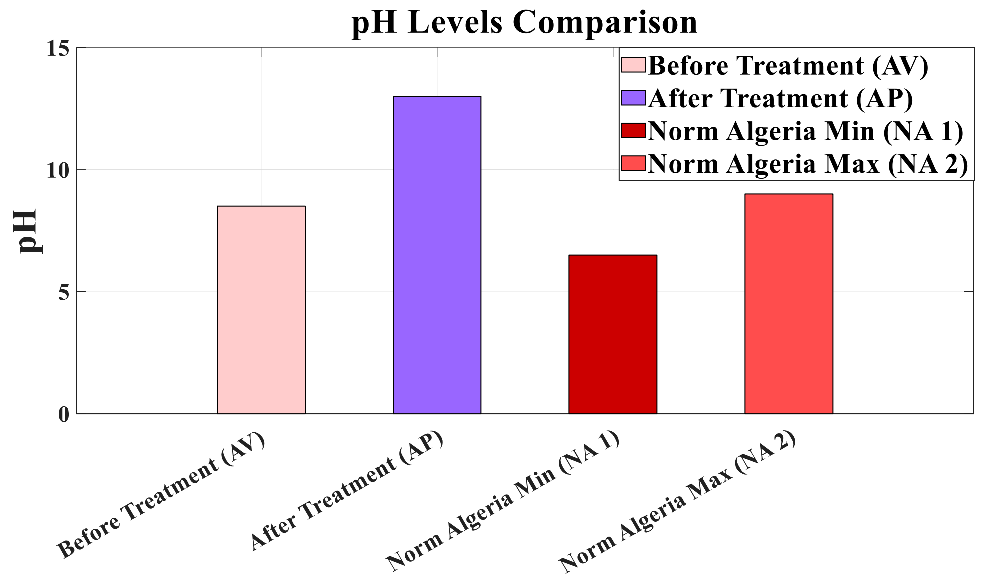

Figure 3. pH levels across treatment stages

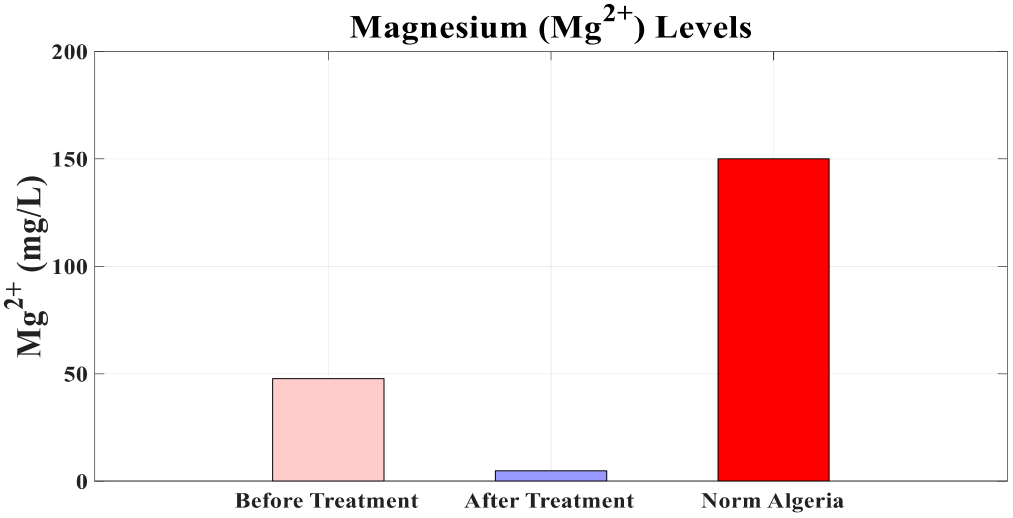

Figure 4. Magnesium (Mg^{2+}) levels across treatment stages

Figure 4 illustrates the magnesium (Mg^{2+}) levels in the water before and after treatment, compared to Algerian standards. Before treatment, the magnesium concentration was approximately 45 mg/L, indicating moderately hard water. After treatment with sodium hydroxide (NaOH), magnesium levels decreased to very low values, demonstrating the effectiveness of the treatment process in removing magnesium ions, the main contributors to magnesium hardness in water. In contrast, the Algerian standard sets a maximum permissible limit for magnesium at 150 mg/L, meaning that the post-treatment results are well within acceptable limits. This significant reduction is favorable for improving water quality and reducing hardness, making it more suitable for general applications. However, it is essential to monitor final magnesium levels to ensure they do not fall below the minimum threshold recommended for human health, as magnesium is an essential mineral for physiological functions.

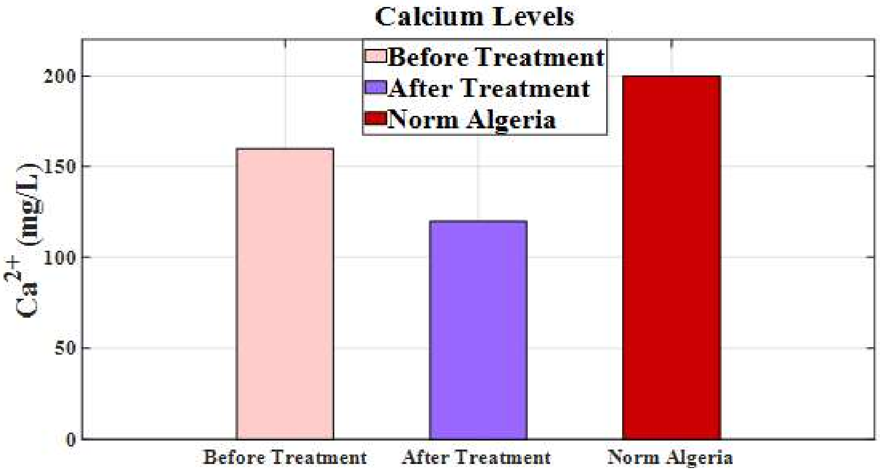

Figure 5. Calcium (Ca^{2+}) levels across treatment stages

Figure 5 illustrates the calcium (Ca^{2+}) levels in the water before and after treatment, compared to the Algerian standard. Before treatment, the calcium concentration was 157 mg/L, a relatively high value that contributes significantly to the calcium hardness of the water. After treatment, the calcium content decreased to 121 mg/L, demonstrating the effectiveness of the treatment process in reducing calcium ion concentrations. This value remains well below the maximum permissible limit of 200 mg/L set by the Algerian standard. The observed reduction highlights a clear improvement in the quality of the water after treatment, making it more suitable for general applications owing to the reduction in hardness.

In conclusion of the first trial; This 500 mg/L NaOH treatment effectively reduced key water quality parameters, such as total hardness (TH), magnesium (Mg^{2+}) and calcium (Ca^{2+}) levels, thus significantly improving the water quality, even the electrical conductivity (EC) still remains within the standard threshold. However, the pH exceeded the acceptable range, which requires careful adjustment. Overall, while the dosage is very effective in reducing hardness, further optimization leading us to the second trial is necessary to ensure compliance with the standard limits for drinking water.

Table 2. Second test analysis results

Parameters	Unit	Bef. Treat	Aft. T (NaOH+CaCO3)	Aft. T (NaOH+CaCO3+HCl)	Aft. T (NaOH+CaCO3+Ac. acetiq)	NA
T	°C	19,6	19,6	15	15	25
Ph	-	7,48	13,13	7,28	6,36	6,5
Sal	-	1,1	10,3	7	5	
CE	µS/cm	2250	1574	9330	7990	2800
Ca2+	mg/l	158,716	0	12,024	20,04	200
Mg2+	mg/l	54,432	0	4,86	9,72	150
TH	mg/l	620	0	50	90	500
TAc	mg/l	170,8	4367,6	378,2	4404,2	500
Cl-	mg/l	377,219	521,868	2684,6	425,436	500

3.2 – Second test: 250 mg/L of NaOH and 250 mg/L of Na_2CO_3

In this section, water treatment was carried out with three different dosages: the first dosage included 250 mg/L of sodium hydroxide (NaOH) and 250 mg/L of sodium carbonate (Na_2CO_3); the second dosage included the same combination with the addition of hydrochloric acid (HCl); and the third dosage included the same combination with the addition of acetic acid, (Table 2).

The study aimed to evaluate the effectiveness of these three dosages in reducing total hardness (TH) and improving pH value, as well as electrical conductivity (EC). The results obtained before and after treatment were analyzed and compared with the standards in order to assess the compliance of the treated water with the acceptable quality limits. The main objective was to identify the most effective dosage to obtain an optimal improvement in water quality.

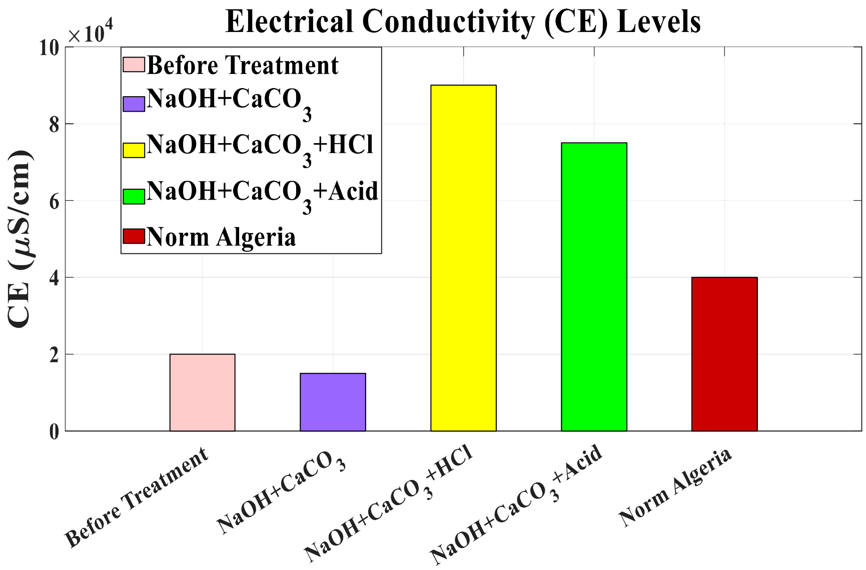

Figure 6. Electrical Conductivity (CE) across treatment scenarios for the final dos

Figure 6 illustrates the electrical conductivity (EC) values before and after treatment and dosage including 250 mg/L NaOH and 250 mg/L Na_2CO_3, with additional treatments of HCl and acetic acid (Acid), compared to the Algerian standard. Before treatment, the conductivity was 2,200 µS/cm, indicating a high concentration of dissolved ions. After treatment with NaOH + $CaCO_3$, the conductivity decreased significantly to 1,500 µS/cm, giving a good result, demonstrating the effectiveness of this treatment in reducing ion concentrations and improving water quality. However, the addition of HCl caused a sharp increase in conductivity to 9,500 µS/cm, attributed to the release of additional ions resulting from acid reactions. Similarly, the use of acetic acid increased the conductivity to 8,000 µS/cm, a level lower than that of HCl, but still significantly higher than the acceptable standard

. Compared to the Algerian standard, which sets a maximum limit of 2800 µS/cm, treatment with NaOH + $CaCO_3$ proved to be the most effective. On the other hand, the introduction of acids led to substantial deviations from the standard, highlighting the need to carefully evaluate the use of chemical agents and optimize dosages to achieve better compliance with water quality standards.

Figure 8 illustrates the calcium ion (Ca^{2+}) concentration before and after water treatment with different chemical combinations, compared to the Algerian standard (Norme Algérie). Before treatment, the calcium concentration was 152 mg/L, which is within the acceptable range defined by the Algerian standard, with a maximum limit of 200 mg/L. After treatment with NaOH+$CaCO_3$, the calcium concentration dropped to 3 mg/L, indicating excessive removal, falling outside the acceptable range. With the treatment with NaOH+$CaCO_3$+HCl, the concentration increased slightly to 11 mg/L, while the addition of NaOH+$CaCO_3$+Acid resulted in a concentration of 23 mg/L. These results reveal that all three treatments reduced calcium levels below the required range, highlighting a significant deficiency. According to Algerian standards, calcium levels must remain balanced to ensure optimal mineral content in water, which was not achieved in these results. This requires adjustments to the treatment process to maintain calcium concentrations within acceptable limits for safe and balanced water quality.

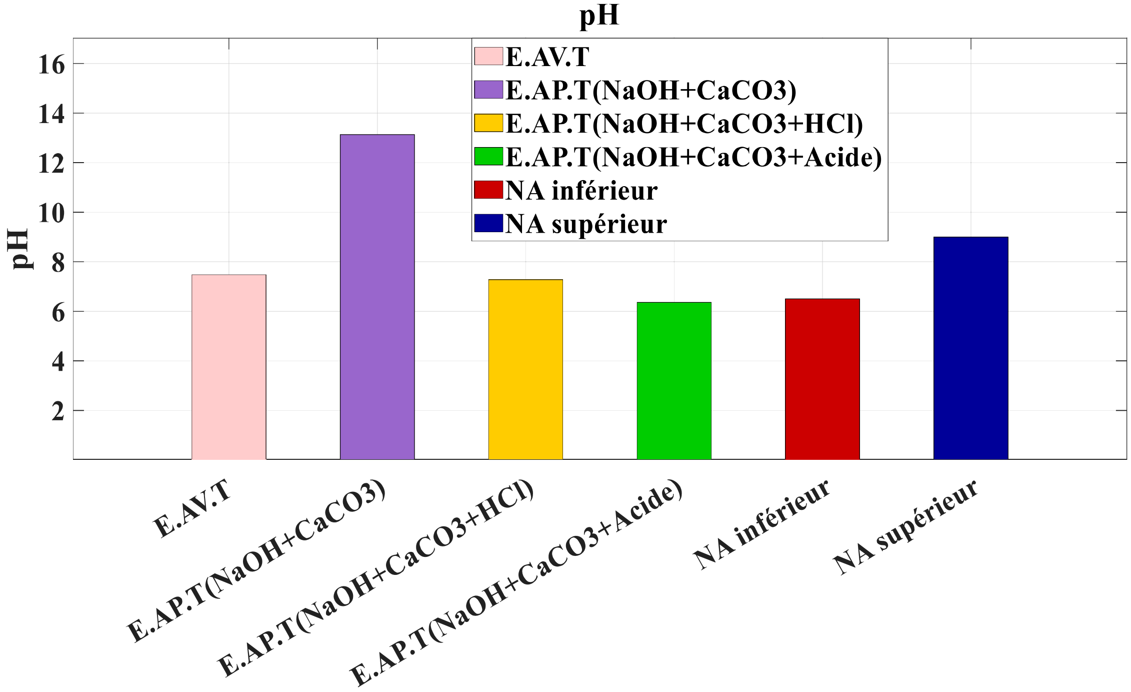

Figure 7. pH levels across treatment scenarios

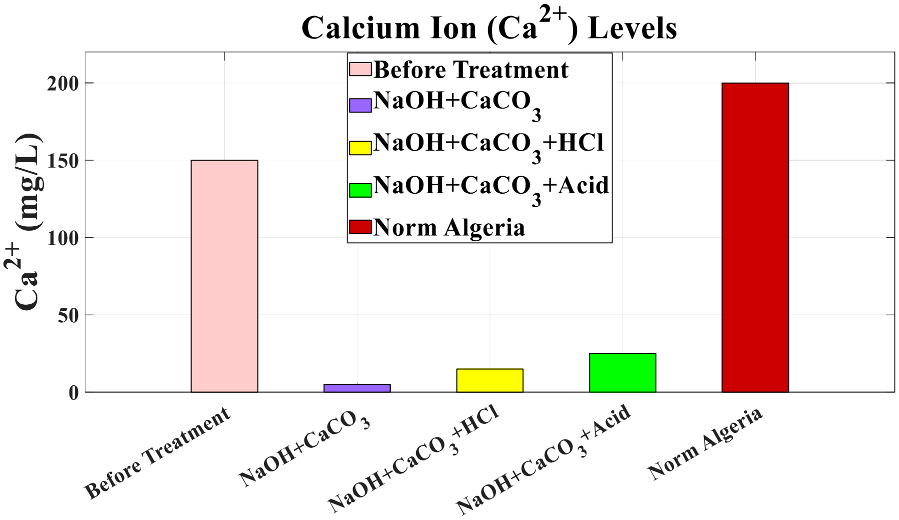

Figure 8. Calcium (Ca^{2+}) levels across treatment scenarios

Figure 9 shows the total hardness (TH) values of the water before and after treatment, compared to the Algerian standard, which sets a maximum limit of 500 mg/L, while emphasizing the need to avoid excessively low levels to ensure water quality. Before treatment, the total hardness was 620 mg/L, exceeding the maximum permitted limit. After treatment with NaOH + $CaCO_3$, the total hardness fell to near zero, which shows the effectiveness of this method in reducing permanent hardness, but the absence of calcium and magnesium in the water is undesirable because maintaining moderate hardness is essential for water quality. Treatment with NaOH + $CaCO_3$ + HCl gave a TH value of 50 mg/L, while NaOH + $CaCO_3$ + Acid reached 90 mg/L. These results are better in comparison, but remain below the optimal range. The Algerian standard provides a reference value of 500 mg/L as an upper limit. In conclusion, all three treatments effectively reduced total hardness, but adjustments are needed to prevent TH from falling below acceptable levels to ensure that the water remains safe for consumption and meets established standards.

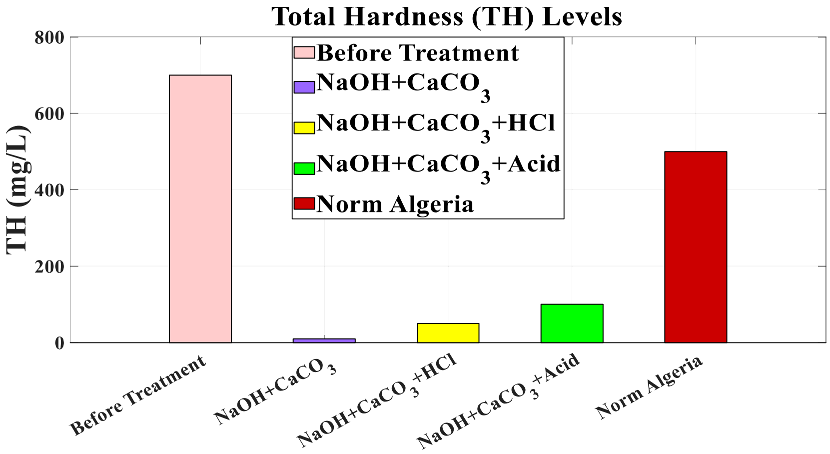

Figure 9. Total Hardness (TH) across treatment scenarios

Figure 10 shows the magnesium (Mg^{2+}) concentrations in the water before and after treatment, compared to the Algerian standard. Before treatment, the Mg^{2+} concentration was 54.432 mg/L, which is within acceptable limits but relatively high. After treatment with $NaOH+CaCO_3$, the concentration dropped to 0 mg/L, indicating complete removal of magnesium. Although this demonstrates the effectiveness of the treatment, it is not desirable because magnesium must remain at low but non-zero levels to maintain water quality. The addition of $NaOH+CaCO_3+HCl$ resulted in a slight increase to 4.86 mg/L, and then a further increase to 9.72 mg/L with $NaOH+CaCO_3$+Acid. Although these values are better than with complete removal, they are still significantly below the acceptable range.The Algerian standard allows a maximum limit of 150 mg/L, highlighting the gap between post-treatment levels and the required optimal range. In conclusion, although treatment effectively reduces magnesium concentrations, excessively low values indicate an imbalance that could negatively impact water quality, as moderate magnesium levels are essential for a safe and balanced water composition.

The dose of 250 mg/L of NaOH and 250 mg/L of Na_2CO_3, combined with HCl and acid, demonstrated advantages and disadvantages in water treatment. Among the advantages, this dose effectively reduced total hardness (TH) to levels below the maximum limit of the Algerian standard (500 mg/L), thus significantly improving water quality for everyday uses. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels were also significantly reduced, minimizing scaling problems associated with hard water. In addition, the treatment achieved a relatively balanced pH, close to the Algerian standard (between 7 and 10).

However, the drawback is the very high pH value despite the good reduction of Mg^{2+} and Ca^{2+} ions, but the reduction of hardness on one side increases the pH on the other side by $NaOH + CaCO_3$. To adjust this result, we dosed this sample once with acitic acid and again with hydrochloric acid. The addition of the acid balances the pH and at the same time increases salt dissolution.

From this second test, we can conclude that NaOH plays a remarkable role in reducing hardness, and the impact of the dose on pH and salt dissolution guides us to optimize the NaOH dose in the treatment.

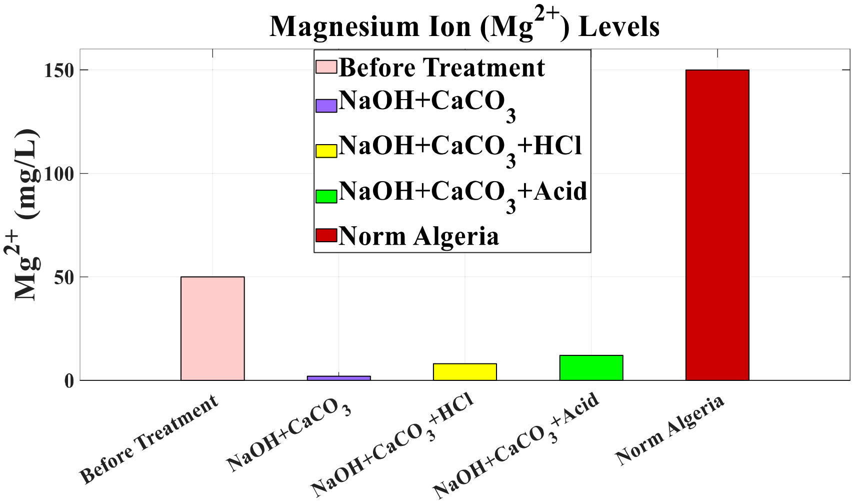

Figure 10. Magnesium (Mg^{2+}) levels across treatment scenarios

3.3- Third test: Optimized NaOH Dosages: 10 mg/L, 20 mg/L, and 30 mg/L

This section examines the impact of optimized sodium hydroxide (NaOH) dosages at concentrations of 10 mg/L, 20 mg/L, and 30 mg/L on water quality parameters. This analysis aims to evaluate the effectiveness of these dosages in improving total hardness (TH), reducing calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations, adjusting pH, and assessing their influence on electrical conductivity (EC). The results will be compared to standards and pre-treatment water quality to highlight the improvements achieved through these dosages. This phase aims to determine the optimal NaOH dosage that ensures compliance with regulatory standards and water quality suitable for general use, including drinking and domestic use.

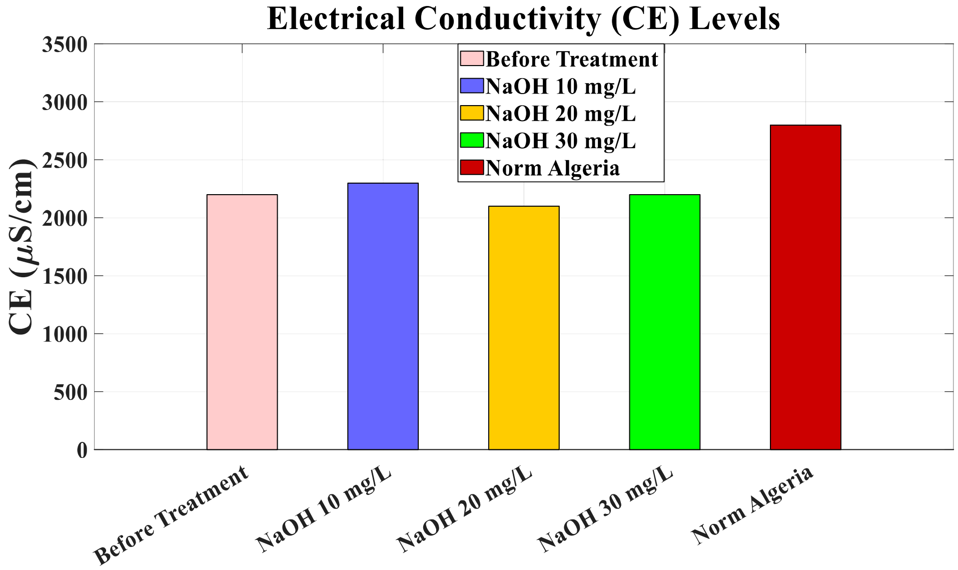

Figure ۱۱. Electrical Conductivity (CE) across different NaOH dosages

Figure 11 illustrates the electrical conductivity (EC) values before and after treatment with different doses of NaOH (10 mg/L, 20 mg/L, and 30 mg/L), compared to the Algerian standard. Before treatment, the conductivity was 2,130 µS/cm, indicating a high concentration of dissolved salts. After application of 10 mg/L of

NaOH, the conductivity decreased slightly to 2,100 µS/cm, showing minimal improvement. Increasing the dose to 20 mg/L resulted in a further reduction to 2,030 µS/cm, demonstrating better effectiveness in reducing conductivity. However, at 30 mg/L, the conductivity increased slightly to 2,070 µS/cm, probably due to the reaction of excess NaOH with salts present in the water. Despite this slight increase, all post-treatment values remain significantly lower than the Algerian standard of 2,800 µS/cm, indicating that the applied NaOH dosages effectively improved water quality. The results suggest that the 20 mg/L NaOH dose was the most effective in reducing electrical conductivity without approaching the upper limit of the standard.

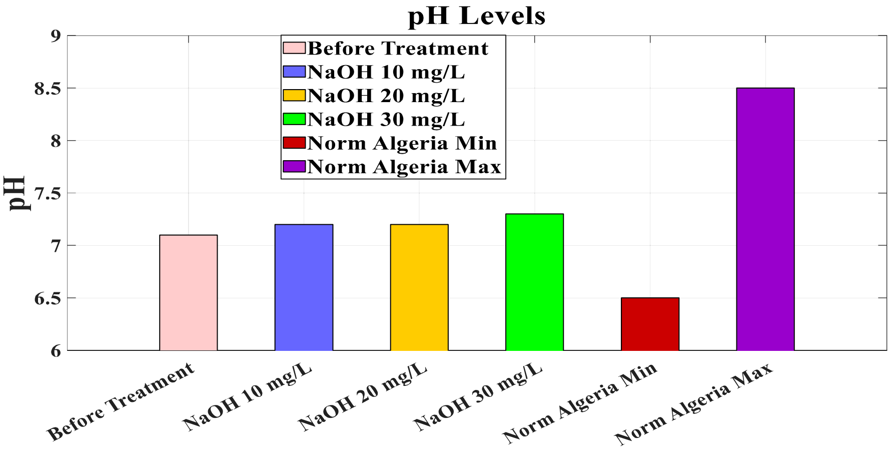

Figure 12. Variation in pH levels with different NaOH dosages

Figure 12 presents the pH values of the water before and after treatment with different dosages of NaOH (10 mg/L, 20 mg/L and 30 mg/L), compared to the Algerian standards, which set a minimum limit of 6.5 and a maximum limit of 9. The pH value before treatment was 7.21, indicating a neutral environment. After treatment, the pH remained relatively stable at 7.2 for the 10 mg/L and 20 mg/L doses, while it increased slightly to 7.3 with the 30 mg/L dose. These results demonstrate that the optimization of the NaOH dose contributed to the treatment goal by decreasing dissolved salts and keeping alkalinity stable since all pH values remained within the acceptable range of the Algerian standards. Therefore, it can be concluded that the selected dosages were effective in maintaining pH stability while ensuring the suitability of the water for various applications.

Figure 13 illustrates the total hardness (TH) values under different sodium hydroxide (NaOH) dosages compared to the Algerian standard of 500 mg/L. Before treatment, the TH was 615 mg/L, exceeding the permissible limit. After treatment, the TH decreased to 450 mg/L with a 10 mg/L NaOH dosage, while the 20 mg/L dosage provided the most significant reduction, bringing the TH down to 400 mg/L, the lowest value recorded and well within the acceptable range. At a higher dosage of 30 mg/L, the TH increased slightly to 420 mg/L, while remaining within the standard. These results demonstrate that the 20 mg/L NaOH dosage is the most effective in reducing total hardness while ensuring compliance with Algerian water quality standards.

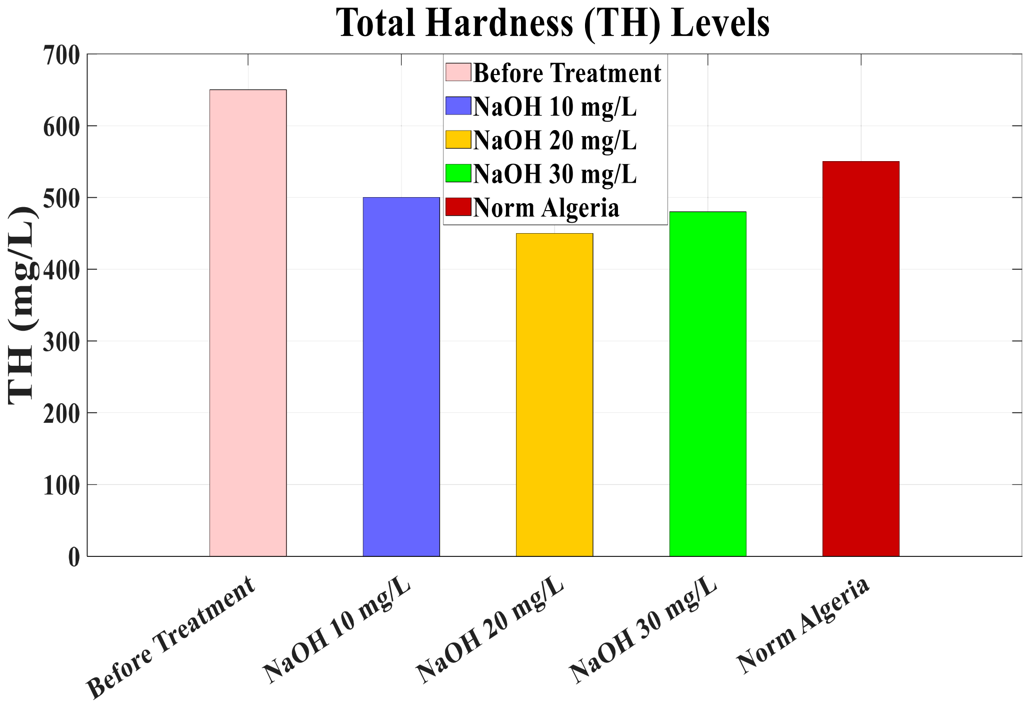

Figure 1٣. Total Hardness (TH) with different NaOH dosages

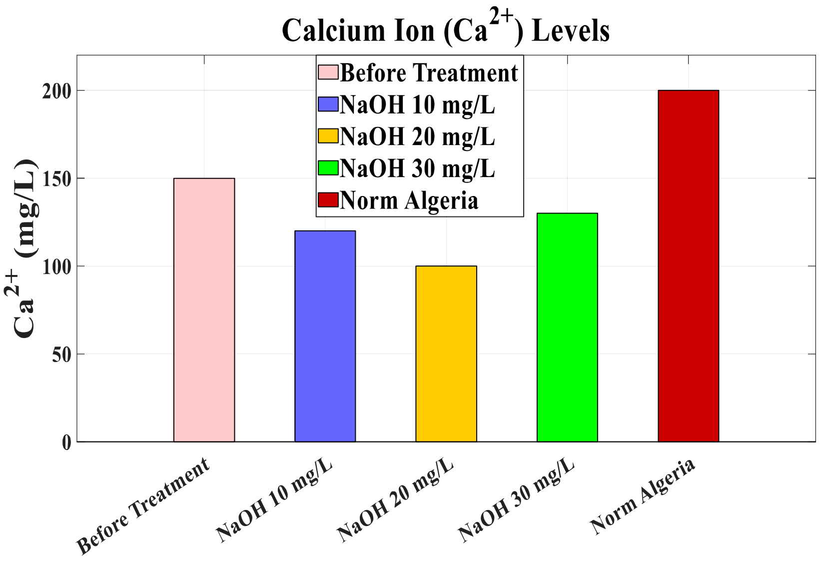

Figure 1٤. Variation in Calcium (Ca^{2+}) concentration with different NaOH dosages

Figure 14 illustrates the evolution of calcium ion (Ca^{2+}) concentrations in water before and after treatment with different dosages of sodium hydroxide (NaOH), compared to the Algerian standard. Before treatment, the calcium concentration was 148.3 mg/L, which exceeds the optimal range. After application of 10 mg/L of NaOH, the concentration decreased to 120 mg/L, indicating a significant improvement but still slightly above the ideal range. At 20 mg/L, the calcium concentration further decreased to 85.176 mg/L, reaching the acceptable range. At 30 mg/L, the concentration increased slightly to 104 mg/L, but remained well below the permissible limit. Compared to the Algerian standard (200 mg/L), these results demonstrate the effectiveness of NaOH dosages in significantly reducing calcium levels. Furthermore, the observed variations in calcium concentration are consistent with trends in total hardness (TH), reinforcing the effectiveness of the treatment in improving water quality. However, careful adjustment of dosages is necessary to avoid excessive reduction that could compromise water quality.

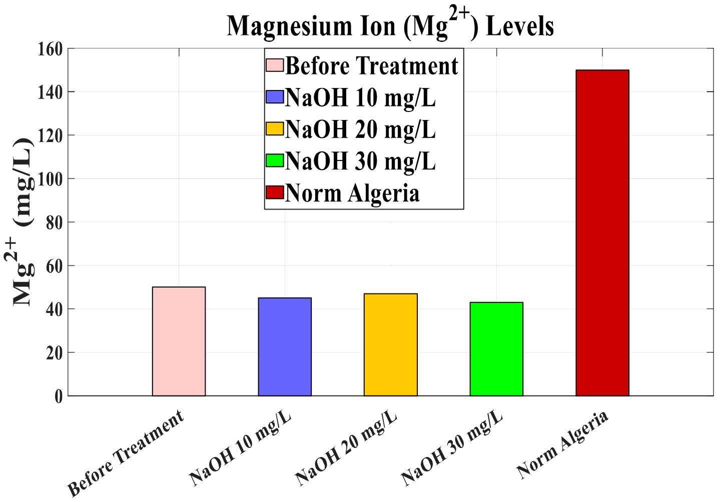

Figure 15. Magnesium concentrations with different NaOH dosages

Figure 15 illustrates the magnesium ion (Mg^{2+}) concentrations at different treatment stages, compared to the Algerian standard. Before treatment, the Mg^{2+} concentration was 54.038 mg/L, which is within an acceptable range. After the addition of sodium hydroxide (NaOH) at increasing doses, the concentrations gradually decreased: to 48 mg/L at 10 mg/L NaOH, 45.17 mg/L at 20 mg/L NaOH, and then 40 mg/L at 30 mg/L NaOH. These results demonstrate the effectiveness of the treatment in reducing magnesium concentrations while maintaining them within an acceptable range. Compared to the Algerian standard (150 mg/L), the final values remain significantly lower, reflecting better water quality without compromising the essential role of magnesium as a mineral necessary for health. Thus, the treatment process proves to be effective and efficient in improving water quality while meeting the required standards.

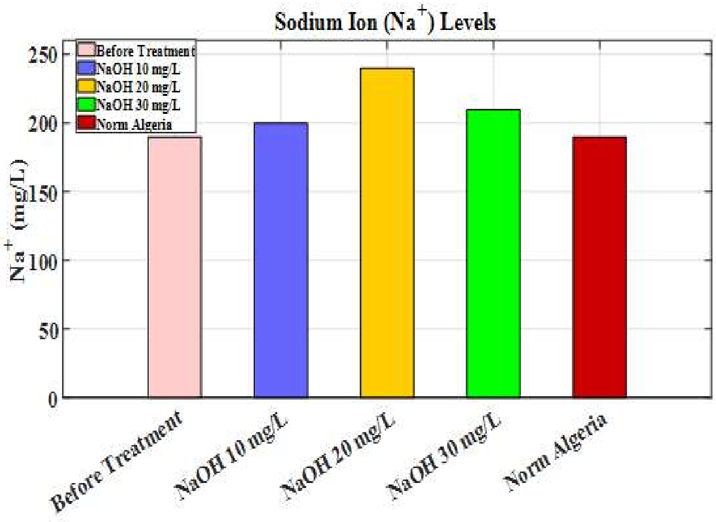

Figure 1٦. Sodium (Na^{+}) concentration with different NaOH dosages

The results presented in Figure 16 illustrate the variation of sodium (Na^+) concentration in water under different NaOH dosages (10 mg/L, 20 mg/L and 30 mg/L) compared to the Algerian standard. Before treatment, the sodium concentration was 204.17 mg/L. After treatment with NaOH 10 mg/L, the concentration increased slightly to 205.55 mg/L. With a higher dosage of 20 mg/L, the sodium concentration reached its peak at 225.77 mg/L, indicating a notable increase due to the addition of sodium. When the dosage was further increased to 30 mg/L, the concentration decreased slightly to 211.11 mg/L, but it remained above the Algerian standard limit of 200 mg/L. These results suggest that moderate NaOH dosages increase the percentage of sodium dosage by 10%. sodium levels, while higher dosages tend to stabilize the concentration closer to the initial conditions. Therefore, precise control of the NaOH dosage is necessary to avoid exceeding the permissible limit defined by the Algerian standard.

The evaluation of the NaOH dosages at 10, 20, and 30 mg/L allows several conclusions regarding the advantages and disadvantages. The NaOH treatment effectively reduced the concentrations of total hardness (TH) and calcium (Ca^{2+}), bringing them closer to the acceptable limits defined by the Algerian standard, thus improving water quality for various applications. In addition, magnesium (Mg^{2+}) concentrations were brought back to acceptable values without reaching excessively low values, which is a positive result. However, the impact on electrical conductivity (EC) was minimal, with only slight improvements observed compared to pre-treatment levels. A notable disadvantage was the increase in sodium (Na^+) concentration, particularly at the 20 mg/L dose, which can be problematic if sodium concentrations exceed permitted health standards. Overall, low and moderate NaOH dosages effectively improve water quality by reducing hardness and balancing calcium and magnesium concentrations. However, careful monitoring of conductivity and sodium concentration is essential to ensure compliance with health standards.

4. Conclusion

In this study, we evaluated the effectiveness of sodium hydroxide (NaOH) in improving water quality by acting on total hardness (TH) and reducing the concentrations of ions responsible for this hardness, such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), while analyzing the impact of different dosages on electrical conductivity (EC) and sodium (Na^+) concentration. The study consisted of three phases: the first dosage (500 mg/L of NaOH) demonstrated effectiveness in reducing total hardness and specifically magnesium hardness, but resulted in a significant increase in pH value and therefore alkalinity. The second dosage (250 mg/L NaOH and 250 mg/L Na_2CO_3) completely eliminated the hardness with its two components magnesium and calcium, but rounding off the highly alkaline medium (adjustment with either HCl or citric acid) showed better results in maintaining calcium and magnesium within acceptable limits, but increasing the electrical conductivity remained a major challenge.

Conversely, the optimized dosages (10, 20 and 30 mg/L of NaOH) proved to be the most balanced and effective, allowing a significant reduction in total hardness to levels in line with Algerian standards, while maintaining calcium and magnesium concentrations within acceptable limits without excessive depletion. In addition, electrical conductivity remained at acceptable levels without significant increase, thus avoiding oversaturation of the water with dissolved salts. Despite a slight increase in sodium concentration, the overall results remained positive and satisfactory. These optimized dosages and specifically the 20 mg/L dose represent the ideal solution for improving water quality, striking a balance between reducing total hardness and preserving essential minerals, with minimal adverse effects and full compliance with Algerian standards.

At the end of this work, it is recommended to continue this research by a real-scale application in hard water sources and finding a mechanism for the etulization of NaOH since its optimized dose is minimal and does not present an expensive consumption.

Author Contributions:

Kheira Bouamer:

Conceptualization, methodology, formal analysis and investigation, manuscript editing.

Hamed Boukhari:

Conceptualization, methodology, formal analysis and investigation, manuscript editing.

Khaled Mansouri:

Conceptualization, methodology, formal analysis and investigation, manuscript editing.

Conflicts of interest

The authors of this article declared no conflict of interest regarding the authorship or publication of this article.

Data availability statement:

All data generated or analyzed during this study are included in this published article.

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