Enhanced Iron Removal from Aqueous Solutions: Evaluating the Synergistic Effects of Dolomite and Aeration Technologies

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Abstract

This study conducts a critical analysis of iron removal from water and groundwater quality assessment in El-Kharga Oasis, Egypt, using a combination of dolomite treatment and aeration. Groundwater is vital for irrigation in arid regions like El-Kharga but often has high iron content, which risks soil and irrigation system integrity. The research introduces an innovative approach to reduce iron concentrations, with preliminary water quality assessments indicating iron levels above Food and Agriculture Organization (FAO) irrigation standards. Controlled experiments conditions of 2 L aqueous solution containing 25 mg L-1 Fe determined the optimal dolomite dosage and aeration time for effective iron removal. Results showed the treated water's pH and electrical conductivity were ideal for irrigation, though high turbidity and iron emphasized the need for treatment. Chemical analysis revealed acceptable alkalinity and sodium hazard levels, with essential plant nutrients like calcium and magnesium present. The study concludes that dolomite-aeration treatment significantly improves water quality, offering a sustainable solution for irrigation management in dry regions. Statistical analyses affirm the method's effectiveness, providing a feasible option to enhance agricultural water quality, crucial for the sustenance of desert communities.

Keywords: Ground water, Iron, Water quality, Aeration, Dolomite

Introduction

Groundwater is a critical resource for human consumption, industrial use, and agricultural irrigation. However, the presence of contaminants such as iron (Fe) in groundwater can lead to a range of serious problems. Elevated iron levels are global issues that affect not only the quality of drinking water but also the operational integrity of advanced irrigation systems which are vital for modern agriculture (Thinojah, et al., 2020; Abdelhafez et al., 2020 and 2021). The environmental impact of iron in groundwater is multifaceted, affecting ecosystems, human health, and infrastructure. Elevated iron levels can disrupt aquatic ecosystems by altering water pH and oxygen levels, negatively impacting aquatic life. This degradation in water quality not only affects taste and smell but can also promote iron bacteria growth, leading to clogged pipes and systems. Excessive iron in irrigation water can accumulate in soil, affecting its fertility and plant growth. For humans, high iron intake can cause health issues, especially in individuals with conditions like hemochromatosis. Furthermore, iron-rich water corrodes plumbing, leading to infrastructure damage and increased maintenance costs. The need for additional treatment processes to remove iron adds economic and environmental burdens, highlighting the importance of managing and mitigating these impacts.

Iron is a prevalent groundwater contaminant that naturally occurs in both soluble forms, such as ferrous iron (Fe^{2+}), and insoluble forms like ferric iron (Fe^{3+}). While Fe in small quantities is not considered a health hazard, when concentrations exceed certain thresholds, it can cause aesthetic, structural, and functional issues. High Fe levels in irrigation water can lead to the clogging of micro-irrigation systems, including drip and sprinkler systems, which are designed to deliver water efficiently to crops (Abdelhafez et al., 2020). When Fe concentrations go above 0.1 mg L-1, there is a potential for the clogging of emitters, and levels above 0.3 mg L-1 can result in rust stains and discoloration on foliage from overhead irrigation systems (Zinati & Shuai, 2005, Carrow et al., 2008). These problems are not only cosmetic but can lead to significant yield reductions due to uneven water distribution and increased maintenance requirements for irrigation infrastructure.

Moreover, Fe-rich water can precipitate, causing blockages and corrosion in pipes and nozzles, leading to costly repairs and replacements. The presence of iron-fixing bacteria further complicates the scenario, as these organisms can produce a gelatinous slime after oxidizing the soluble iron, which adheres to the irrigation equipment and prevents proper water flow (Carrow et al., 2008, Grabić, et al., 2019). Such bacterial activity, along with the physical deposition of Fe, can severely impact the effectiveness of precision irrigation systems, leading to increased operational costs and reduced plant health due to improper irrigation (Oram, 2014).

Given the importance of water quality for irrigation purposes, there is a clear need for effective strategies to remove iron from groundwater. Conventional treatment methods are often chemical-intensive and not environmentally sustainable. In response, this paper investigates the potential of dolomite and aeration technology as alternative treatments. Dolomite, a natural mineral, has shown promise in adsorbing and precipitating iron from water, while aeration aids in oxidizing soluble ferrous iron to insoluble ferric iron, facilitating its subsequent removal (Thinojah, et al., 2020; Liang-Tong, et al., 2022). Dolomite is an anhydrous carbon mineral consisting of calcium and magnesium-CaMg $(CO_3)_2$. It offers 21.7 kg of calcium and 13 kg of magnesium per 100 kg. Dolomite can be dissolved in slightly acidic water. This research aims to elucidate the effectiveness of these methods in reducing iron concentrations to acceptable levels for irrigation use, thus preventing damage to advanced irrigation systems.

The objectives of this study are to evaluate the quality of ground water in El-Kharga Oasis, New Valley, Egypt, determine the effectiveness of dolomite and aeration combined technology for Fe removal from aqueous solutions and determine the optimal operational parameters for this combined treatment method. Through a series of controlled experiments, this research will provide insights into the potential of a dolomite-aeration system to alleviate the challenges posed by high iron levels in groundwater, with a

view to enhancing the sustainability and efficiency of irrigation systems and ensuring the protection of vital water resources.

Materials and Methods
Study Area and Water Sampling

The research location is situated in the lower region of Egypt's Western Desert (Mohamaden et al., 2017), approximately 232 kilometers to the south of the Assiut Governorate (Elshraway and Mahmoud, 2017). The predominantly sandy soil composition in this region includes formations of carbonate ridges (Bakr & Bahnassy, 2019). Characterized by an arid climate, the area experiences minimal rainfall, with temperature fluctuations ranging from a high of 46 °C during the summer months to a low of 8 °C in the colder winter season (Nasreldin et al., 2020). The primary means of sustenance for inhabitants is through aquifers (El-Zeiny & Elbeih, 2019). For the purposes of this investigation, an Oasis within the region, namely El-Kharga was chosen. In, ten locations were identified to collect samples from a range of groundwater wells, with depths spanning from 283 to 762 meters. Samples were collected in acid-washed polyethylene bottles and transported to the laboratory within 4 hours of collection, preserved at 4°C to prevent changes in water chemistry, which is a standard practice designed to minimize biological and chemical changes in the samples until analysis (Abdelhafez & Li, 2015).

Dolomite Preparation and Characterization

Dolomite rock was sourced from a local quarry, crushed to a specific particle size range (1-3 mm), and washed with deionized water to remove dust and impurities. The material was then dried at 105°C for 24 hours. The chemical formula of dolomite material used in this study was CaMg (CO3)2. Dolomite was selected as a supplement to calcite in the treatment process due to its superior hardness, which confers the advantage of recyclability. Contrasting with the behavior of dolomite, calcite demonstrates a propensity for disintegration under recurrent utilization. This characteristic poses significant obstacles in its reapplication, often culminating in its substantial attrition during water treatment procedures. Consequently, the inherent resilience of dolomite markedly augments the sustainability and efficacy of the treatment process. It achieves this by substantially diminishing the necessity for frequent media replenishment.

Aeration System Setup

A laboratory scale aeration system was designed by using an aeration pump with a capacity of 2.5 liters and pressure of 0.02×2 mpa. The used air pump supplemented with 2 outlets (Fig. 1).
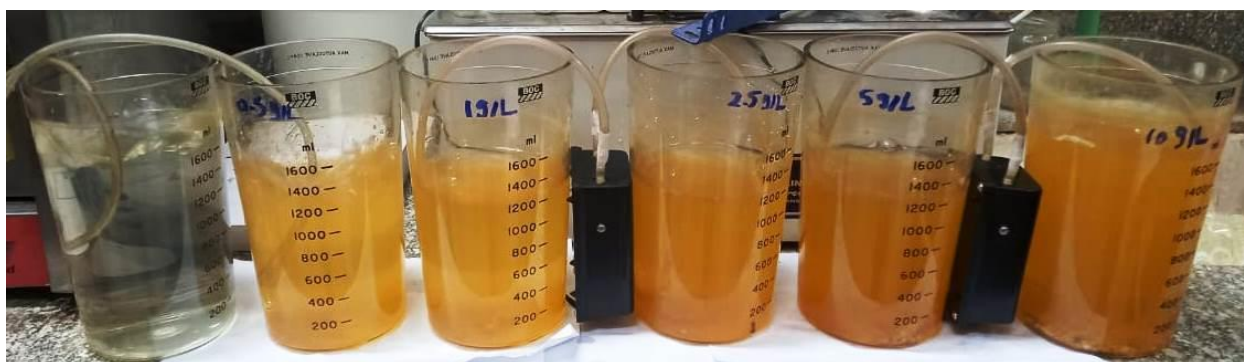

Figure (1): A laboratory scale aeration basins

Batch Experiments

Batch experiments were conducted to assess the effectiveness of dolomite and aeration, both separately and in combination, for Fe removal from an aqueous solution containing 25 mg L-1 soluble Fe. Water samples were treated with dolomite at varying dosages (0.5, 1, and 2.5, 5 and 10 g L-1) and aerated at different airflow times (5, 15, 30 and 60 min.). The experiments were conducted in 2 L glass reactors, with samples taken at predetermined intervals (5, 15, 30 and 60 min.) for iron concentration analysis.

Water Analyses

Initial water quality parameters including turbidity, pH, and electrical conductivity (EC)

were quantified in the sampled water by using pH/Conductivity Meter (PC 100 Model, China). Reagents utilized throughout the analyses were of analytical reagent quality, with the majority sourced from Sigma Aldrich Company. Glassware employed in the experiments was prepared by an overnight soak in 10% nitric acid, followed by extensive rinsing with distilled water to ensure decontamination. Analytical procedures were performed in triplicate to ensure replicability of results. Quality control measures, including the use of blanks and spiked samples, were implemented to verify the precision of iron concentration measurements. Iron recovery rates, as determined by spectrophotometry, ranged between 97.6% and 98.82%. The concentrations of principal cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-}) in the water samples were assessed employing methodologies delineated by Baird et al. (2017). Iron quantification adhered to the ASTM E394 standard test method, utilizing the 1,10-Phenanthroline method (ASTM E394-22, 2023) by using spectrophotometer (UV VIS Spectrophotometer, UV 2400).

Data Analysis

Statistical analysis of data was performed using a post-hoc test, which was performed to measure specific differences between treatments using the Duncan's Multiple Range Test (DMRT) in a completely randomized block design. The significant differences between treatment means were determined using analysis of variance and mean separation at a 5% significance level ($p \leq 0.05$).

Results and Discussions

The results from the water quality assessment in the El-Kharga region, with sampling depths ranging from 278 to 762 meters, indicate that the pH values are between 6.78 and 7.03 (Table 1). These levels are consistent with the ideal pH range for irrigation water (6.5-8.5) as suggested by Ayers & Westcot (1985) in their guidelines for water quality for agriculture. The EC measurements ranged from 0.35 to 0.60 dS m-1, which are below the maximum allowable concentration of 1.50 dS m-1 for irrigation purposes (Ayers & Westcot, 1985), indicating low to moderate salinity that is unlikely to pose a salinity risk to soil or crops.

Comparatively, turbidity levels were found to be quite variable, with some levels such as 39.05±3.48 NTU at El-Kharga-24 considerably higher than what is typically preferred for irrigation, which may lead to the clogging of irrigation systems and affect soil permeability (FAO, 1994). The iron concentration in all locations exceeded the suggested limits for irrigation water (0.10-0.30 mg L-1) set forth by the FAO, 1985), with levels ranging from 0.33 mg L-1 to 0.47 mg L-1. This is of particular concern as excessive iron, while necessary for plant growth, can contribute to soil contamination and potentially affects the long-term suitability of water for irrigation (Bauder et al., 2011). When compared to previous published data, such as the study by Richards (1954) on the diagnosis and improvement of saline and alkali soils, the current EC levels are considerably lower, suggesting an improvement in water quality or a difference in geographical characteristics affecting salinity. However, the iron levels observed are higher than previous observations by Smedley & Kinniburgh (2002) in their detailed report on iron in groundwater, indicating a rising trend or localized geological factors contributing to higher iron dissolution into the groundwater.

In summary, while the pH and EC values are within acceptable limits indicating suitability for irrigation, the elevated turbidity and iron concentrations highlight the need for treatment and suggest that the quality of water may have changed when compared to historical data. It is essential to continue regular monitoring and compare against historical data to understand trends and develop appropriate water management strategies to maintain and improve water quality for sustainable agricultural practices.

Table 1. Major characteristics of groundwater samples collected from El-Kharga Oasis locations

Location	Depth	pH	EC, dS m^{-1}	Turbidity, NTU	Fe mg L^{-1}
El-Kharga–23	322	7.03±0.01	0.44±0.01	28.60±0.71	0.47±0.04
El-Kharga–24	283	6.90±0.08	0.48±0.01	39.05±3.48	0.33±0.02
El-Kharga–26	278	6.82±0.02	0.60±0.01	36.90±0.28	0.36±0.06
El-Kharga–38	740	6.94±0.06	0.35±0.0	26.90±0.71	0.37±0.04
El-Kharga–41	762	6.78±0.06	0.36±0.0	16.35±3.61	0.34±0.04
Maximum allowable concentration (Irrigation)*	--	6.5–8.5	1.50	--	0.10-0.30

*(FAO, 1985; Zinati and Shuai, 2005; Duncan et al., 2009)

Chemical analyses of collected water samples are shown in Table 2. In the El-Kharga region, the analysis of ionic composition in water samples from various locations revealed that carbonate (CO_3^{2-}) was not detected across all samples. Bicarbonate (HCO_3^-) levels varied from 0.30±0.14 to 0.90±0.14 meq L-1, indicating low alkalinity which could suggest minimal influence on soil pH when used for irrigation (Ayers & Westcot, 1985). Chloride (Cl^-) concentrations were generally below the FAO standard for irrigation water, with a range of 1.00±0.28 to 1.80±0.28 meq L-1, signifying a low risk of soil salinity (FAO, 1994). Sulfate (SO_4^{2-}) levels were slightly higher, with the highest concentration recorded at 5.32±1.36 meq L-1 in El-Kharga–26, which could potentially impact soil structure and plant growth if not managed appropriately (Richards, 1954). In this study, sodium ion (Na^+) concentrations were consistently below the threshold of 20 meq L-1 set by the FAO, indicating a minimal risk of sodium-induced harm to soil structure and plant vitality (Ayers & Westcot, 1985). The concentrations of calcium ($Ca2+$) and magnesium ($Mg2+$) both pivotal for plant nutrition, were observed within the range of 2.33±0.04 to 3.73±0.04 meq L-1 for calcium and 0.50±0.14 to 1.35±0.4 meq L-1 for magnesium. These levels align well within the established safe limits, suggesting the water's appropriateness for a majority of irrigation applications (Bauder et al., 2011). Furthermore, potassium ($K+$) an essential nutrient for plant growth, manifested in concentrations spanning from 0.81±0.02 to 1.15±0.0 meq L-1. These concentrations are deemed non-hazardous for use in irrigation, as per the guidelines set forth by the FAO (1985). Comparing these results with FAO guidelines for irrigation water quality, it appears that the water in the El-Kharga region is generally suitable for agricultural purposes, with some parameters such as sulfate in El-Kharga–26 slightly exceeding the recommended FAO standards. Careful management and regular monitoring would be required to prevent soil degradation over time, especially in areas with higher sulfate concentrations (FAO, 1985; Bauder et al., 2011).

Table (2): Chemical characterization of collected ground water samples in El-Kharga Oasis

Location	CO_3^{--}	HCO_3-	Cl^-	SO_4^{--}	Na^+	Ca^{++}	Mg^{++}	K^+
				meq L^{-1}				
El-Kharga–23	.d.	0.70±0.42	1.80±0.28	3.47±0.34	0.94±0.03	2.98±0.04	1.00±0.28	1.06±0.01
El-Kharga–24	.d.	0.80±0.28	1.40±0.28	4.22±0.89	1.02±0.03	3.28±0.04	0.98±0.08	1.15±0.00
El-Kharga–26	.d.	0.90±0.14	1.00±0.28	5.32±1.36	1.09±0.0	3.73±0.04	1.35±0.4	1.06±0.02
El-Kharga–38	.d.	0.50±0.14	1.60±0.57	3.57±0.73	1.26±0.0	2.38±0.04	1.23±0.04	0.81±0.02
El-Kharga–41	.d.	0.30±0.14	1.00±0.28	3.57±0.65	1.24±0.03	2.33±0.04	0.50±0.14	0.81±0.02
*FAO standard (irrigation)	-	2	<3.0	<4.0	<3.0	20	5.02	2

n.d. not detected
FAO, 1985

The experimental data demonstrate the efficacy of iron removal from an aqueous solution utilizing two different oxidation methods: aeration and dolomite. Over a span of one hour, both methods showed an increase in iron removal efficiency with time (Figure 2). For aeration oxidation, the efficiency of iron removal started at 31.9% at the 5-min. mark and exhibited a gradual increase to 47.06% by the 60-min. interval. This progression indicates a consistent improvement in performance with time, highlighting the effectiveness of aeration as a means to oxidize and precipitate iron out of the solution (Stumm & Morgan, 1996). Dolomite oxidation started at a lower efficiency of 23.12% after 5 min., but also showed a steady increase in iron removal efficiency, reaching 41.84% at the end of the 60-min. period. The slower initial performance could be attributed to the time required for the dolomite to raise the pH to a level where iron oxidation is more efficient (Mayes et al., 2008).

Comparing the two methods, aeration oxidation consistently outperformed dolomite oxidation at all measured time points. However, both methods showed a trend towards higher efficiency over time, suggesting that longer treatment durations could be beneficial. At the 30-min. mark, aeration oxidation reached an efficiency of 38.02%, while dolomite oxidation achieved 34.92%, indicating that the gap in efficiency between the two methods narrows as the reaction proceeds. The differences in removal efficiency between aeration and dolomite oxidation can be explained by the distinct mechanisms at play. Aeration directly introduces oxygen into the water, promoting the oxidation of iron, while dolomite, a source of carbonate and magnesium ions, may enhance iron removal by increasing pH and facilitating the precipitation of iron carbonates and hydroxides (Appelo & Postma, 2005).

These results suggest that while both aeration and dolomite are effective for the removal of iron from aqueous solutions, aeration has a faster onset of action. Nonetheless, dolomite remains a viable option, particularly in systems where the alteration of water chemistry through the addition of carbonate ions is desired or where aeration is not feasible.

The investigation into the efficacy of dolomite in conjunction with aeration for the removal of iron from aqueous solutions yielded positive results across a range of dolomite dosages. The iron removal efficiency increased with higher dosages of dolomite (Fig. 3). At the lowest dosage of 0.5 g L-1, iron removal efficiency ranged from 38.98±2.18% to 57.76±0.74%. As the dolomite dosage was increased to 1 g L-1, there was a noticeable improvement in efficiency, with values ranging between 44.48±0.57% and 70.78±0.25%. Further increases in dolomite dosage to 2.5 g L-1 led to efficiencies ranging from 41.26±0.25% to 72.94±0.20%. A significant increase in efficiency was observed at a dosage of 5 g L-1, with iron removal efficiencies spanning from 49.76±0.62% to an impressive 98.60±0.06%. The highest dosage tested, 10 g L-1, resulted in the highest iron removal efficiencies, ranging from 57.56±0.34% to 98.74±0.03%. The data indicate a clear trend where the removal efficiency of iron from aqueous solutions improves as the dolomite dosage is increased. At lower dosages (0.5 to 2.5 g L-1), the efficiency is moderate but shows a consistent upward trajectory with each incremental increase in dolomite concentration. Notably, dosages of 5 and 10 g L-1 demonstrate a marked improvement in removal efficiency, achieving near-complete removal of iron in some instances.

This trend is consistent with other studies that have examined the role of carbonate minerals in the removal of heavy metals from aqueous systems (Qasem et al., 2021; Johnson & Hallberg, 2005). The mechanism of iron removal can be attributed to the adsorption onto dolomite surfaces and subsequent precipitation as carbonates (Chen et al., 2022). The aeration likely enhances this process by oxidizing ferrous iron to ferric iron, which precipitates more readily (Batty et al., 2008). The observed variance within the efficiency ranges could be due to factors such as pH fluctuations, initial iron concentrations, and the presence of competing ions, which are known to affect the adsorption processes (Davis & Kent, 1990). Nonetheless, the high efficiency at larger dolomite dosages suggests that the dolomite-aeration treatment could be a viable method for

iron removal in water treatment processes, especially considering the availability and cost-effectiveness of dolomite (Ilgen, 2011).

It is important to note that while the highest dosages of dolomite yield the greatest efficiency, practical considerations such as cost and potential for increased water hardness must be taken into account. Future studies should also explore the kinetics of the iron removal process and the long-term stability of the precipitated products. The results of this study add to the growing body of literature supporting the use of natural minerals for the remediation of contaminated water and highlight the potential of dolomite as a cost-effective option for iron removal in industrial and municipal water treatment settings.

Conclusion

In conclusion, our study demonstrates the efficacy of a dolomite and aeration treatment system in enhancing groundwater quality for irrigation in El-Kharga Oasis, Egypt. This system not only reduces dissolved iron, preventing soil contamination and clogging of irrigation systems, but also ensures water quality that meets and exceeds FAO guidelines.

Future research should focus on scaling up this system for broader geographical applications, assessing long-term impacts on soil and crop health, and integrating it with other water management practices. Additionally, it is crucial to evaluate the economic feasibility and environmental impacts of this system. Such research will be instrumental in advancing sustainable agricultural practices and water resource management in arid regions, offering a viable solution to the challenges posed by water scarcity.

Conflicts of Interest/ Competing Interest

The authors declare that they have no competing interests.

Ethical Statement

All methods were performed in accordance with the relevant guidelines and legislations.

List of Abbreviations

DMRT   Duncan's Multiple Range Test
EC   Electrical conductivity
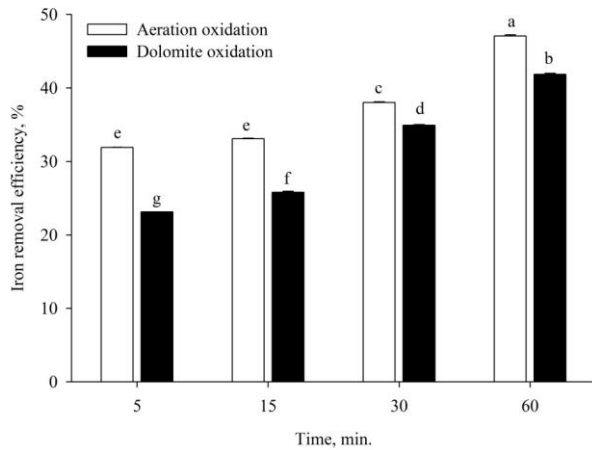FAO   Food and Agriculture Organization

Figure (2): Iron removal efficiency under aeration oxidation and dolomite oxidation processes. The vertical bars followed the different letters were significantly differences according to the LSD test at P < 0.05.
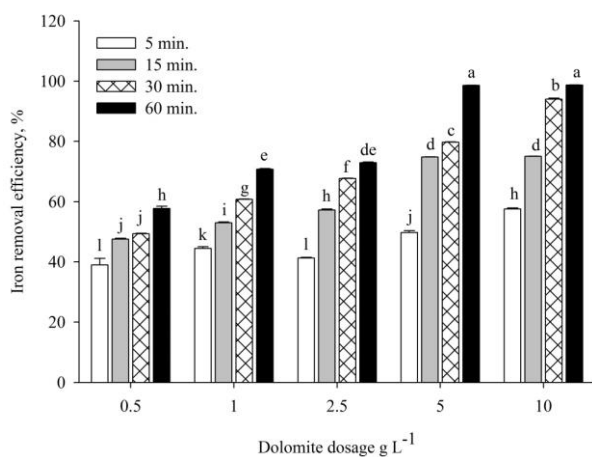

Figure (3): Iron removal efficiency under combined aeration and dolomite oxidation process. The vertical bars followed the different letters were significantly differences according to the LSD test at P < 0.05.

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