Original Research Article

Iron-Manganese Correlation and Community Perception of Groundwater Quality

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Abstract

Groundwater contamination with iron (Fe) and manganese (Mn) remains a significant challenge in rural areas with limited access to modern water treatment technologies. In the Margorejo Village, Tempel District, Sleman, groundwater from domestic wells exhibited elevated Fe and Mn concentrations related to local geochemical conditions. This study investigated the efficacy and acceptance of a hybrid phytocoagulation system combining extracts from *Eichhornia crassipes* and *Moringa oleifera seeds* to enhance metal removal through a combination of biosorption, biooxidation, and protein-induced flocculation. Variations in plant biomass (0–30 leaves), Moringa dose (0–100 mg/L), and contact time (0–16 days) were investigated in a factorial randomized block trial. The optimal configuration (30 leaves, 100 mg/L, 16 days) reduced the iron concentration to 0.082 mg/L (97.77%) and the manganese concentration to almost zero (98.71%). Pearson correlation analysis revealed a strong positive correlation between iron and manganese concentrations (r=0.821), indicating similar geochemical behavior. A public perception analysis with 30 respondents showed high acceptance (75.72%), particularly in households directly affected by contamination. These results demonstrate that hybrid phytocoagulation is a cost-effective, environmentally sustainable, and socially acceptable method for decentralized groundwater treatment and underscore the importance of public participation for long-term implementation.

Keywords: Community participation; groundwater quality; iron; manganese; natural bioremediation

1. Introduction

Water is a fundamental natural resource that enables human survival, domestic activities, and industrial development (Zikirov, 2022). The availability of clean and sufficient water is widely considered a crucial indicator of societal well-being and environmental sustainability. However, increasing anthropogenic pressures, primarily from industrial expansion and uncontrolled waste disposal, have accelerated the deterioration of water quality in various regions. In Indonesia, major rivers, such as the Cisadane and Angke Pesanggrahan, reportedly exhibit pollution levels that exceed quality standards for domestic and recreational use (Makarim, 2024; Prayoga et al., 2023). In rural and peri-urban areas of Indonesia, groundwater from dug wells remains the primary source of drinking water, cooking water, and other household needs (Utami et al., 2024). This dependence is often accompanied by water quality problems, such as turbidity, metallic odor, and discoloration, which are typical indicators of heavy metal

contamination. Among the most frequently detected contaminants are iron (Fe) and manganese (Mn). Although both are essential micronutrients, long-term exposure to high concentrations can pose chronic health risks.

This situation was identified in Margorejo Village, Tempel District, Sleman, Yogyakarta Special Region. The results of the environmental impact assessment (EIA), conducted under Regulation No. 38 of 2019 issued by the Indonesian Minister of Environment and Forestry, indicate that the community remains reliant on well water as a clean water source. Laboratory analyses revealed iron and manganese concentrations of 2.7548 mg/L and 0.2376 mg/L, respectively. Both values exceed the national drinking water standards according to SNI 6989.84-2019, which stipulate limits of 0.2 mg/L for iron and 0.1 mg/L for manganese. In addition to impairing aesthetic water quality, long-term exposure to high iron and manganese concentrations has been linked to organ dysfunction and neurological problems (Ngibad, 2023). Various conventional water treatment methods, such as chemical oxidation, ion exchange, filtration, and the use of synthetic resins, have proven effective in reducing iron and manganese concentrations. However, their application is typically associated with high costs, complex infrastructure, and additional chemicals that can potentially cause secondary environmental pollution (Alghamdi et al., 2024). These limitations highlight the need for simpler, more cost-effective, and environmentally friendly alternative water treatment methods, particularly for rural areas with limited access to technology.

Nature-based remediation approaches offer promising solutions. *Eichhornia crassipe leaves* are known for their high biosorption capacity, which is based on their hydroxyl, carboxyl, and amino groups, capable of binding heavy metals (Muktamar et al., 2021). *Moringa oleifera seeds* contain cationic proteins that act as natural coagulants, promoting the aggregation and sedimentation of metal ions in water (Stanikina, 2023). The combination of these two substances has the potential to create a synergistic mechanism that integrates biosorption, flocculation, and biological oxidation processes, thereby increasing the efficiency of iron and manganese removal compared to individual methods.

Against this background, the present study investigated the efficacy of phytoremediation and natural coagulation processes using *Eichhornia crassipes* and *Moringa oleifera* to reduce iron and manganese concentrations in contaminated well water. The study evaluated the effects of different biomass quantities, coagulant concentrations, treatment durations, and assessed the feasibility of this hybrid system as a cost-effective, practical, and sustainable groundwater remediation solution for communities with limited water treatment infrastructure. Although several studies have addressed iron and manganese removal techniques and community-based water management, few studies have explicitly linked groundwater iron and manganese contamination conditions to public perception and acceptance of bioremediation technologies. Most previous studies tend to separate water quality analysis from social aspects, creating a gap in understanding the interaction between environmental conditions and social readiness for the successful implementation of household-scale water remediation technologies.

The unique aspect of this study is its integrated approach, which simultaneously analyzes the correlation between iron and manganese concentrations in well water and the population's perception of phytoremediation and natural coagulation processes in a volcanically influenced, semi-rural area. This approach provides a more comprehensive basis for assessing the technical and social feasibility of sustainable groundwater treatment. Therefore, the main objectives of this study are to analyze the relationship between iron and manganese levels in well water and to assess the perception and acceptance of the application of natural bioremediation technologies as the first groundwater treatment method in Margorejo Village.

2. Methods

2.1 Location and Time of Study

This study was conducted in Margorejo Village, Tempel District, Sleman, Yogyakarta Special Region. The village comprised 14 hamlets. The local population relies largely on surface water and

groundwater from dug and drilled wells for their daily needs. Two hamlets, Tegal Domban and Jlegongan, were selected because of the high density and even distribution of groundwater use, as well as preliminary investigations. These investigations revealed recurring water quality problems, both aesthetic and chemical, reported by residents. These problems suggest potential heavy metal contamination related to local geological conditions and surrounding anthropogenic activities. Groundwater samples were collected from nine domestic wells: two in Jlegongan 1, three in Jlegongan 2, two in Tegal Domban 1, and two in Tegal Domban 2. Composite sampling was conducted to obtain a representative assessment of groundwater quality. The study area is located at coordinates 7°39'29.53" S and 110°19'37.61" E, and the study was conducted from April to August 2024.

2.2 Materials and Equipment

The primary material consisted of groundwater samples collected from nine domestic wells in the hamlets of Jlegongan and Tegal Domban. Approximately 30 L of water was collected from each well and mixed before laboratory analysis. Water hyacinth leaves (*Eichhornia crassipes*) were obtained from a nearby stream, while *Moringa oleifera seeds* were processed into a natural coagulant extract. Chemical analyses of iron(Fe) and manganese (Mn) were performed using atomic absorption spectrometry (AAS; Shimadzu AA-7000). Additional equipment included a reactor, mixer, 100-mesh sieve, drying oven, analytical balance, DR200-HACH spectrophotometer, beakers, pipe tester, and magnetic stirrer. Analytical reagents (ferrover and sodium periodate) were used to determine Fe and Mn, and pH and temperature were measured using a pH meter and thermometer, respectively.

2.3 Research Design

A factorial experiment with a randomized full-block design was conducted. The first factor comprised a combination of *Eichhornia crassipes* biomass (stems and leaves) and the dose of *Moringa oleifera seed* extract as a natural coagulant. The second factor was the treatment duration. This design allowed us to evaluate both the individual and interaction effects of these two factors on the reduction of iron and manganese concentrations in well water.

Table 1. Treatment for experimental

Name	Treatment
K0	No water hyacinth (0 stems + leaves) and no moringa seed coagulant (0 mg/L)
K10	10 stems + leaves of water hyacinth with 25 mg/L moringa seed coagulant
K20	20 stems + leaves of water hyacinth with 50 mg/L moringa seed coagulant
K30	30 stems + leaves of water hyacinth with 100 mg/L moringa seed coagulant
W0	Treatment duration of 0 days
W4	Treatment duration of 4 days
W8	Treatment duration of 8 days
W12	Treatment duration of 12 days
W16	Treatment duration of 16 days

Forty experimental units were prepared, consisting of 20 treatment combinations, each of which was repeated twice. The complete treatment interaction matrix is shown in the experimental design table.

Table 2. Experimental design table

Treatment interaction variations (k)	Treatment time (w)	Test (r)	
		1	2
K0	W0	R1K0W0	R2K0W0
	W1	R1K0W1	R2K0W1
	W2	R1K0W2	R2K0W2

Treatment interaction variations (k)	Treatment time (w)	Test (r)	
		1	2
	W_3	$R_1K_0W_3$	$R_2K_0W_3$
	W_4	$R_1K_0W_4$	$R_2K_0W_4$
K_1	W_0	$R_1K_1W_0$	$R_2K_1W_0$
	W_1	$R_1K_1W_1$	$R_2K_1W_1$
	W_2	$R_1K_1W_2$	$R_2K_1W_2$
	W_3	$R_1K_1W_3$	$R_2K_1W_3$
	W_4	$R_1K_1W_4$	$R_2K_1W_4$
K_2	W_0	$R_1K_2W_0$	$R_2K_2W_0$
	W_1	$R_1K_2W_1$	$R_2K_2W_1$
	W_2	$R_1K_2W_2$	$R_2K_2W_2$
	W_3	$R_1K_2W_3$	$R_2K_2W_3$
	W_4	$R_1K_2W_4$	$R_2K_2W_4$
K_3	W_0	$R_1K_3W_0$	$R_2K_3W_0$
	W_1	$R_1K_3W_1$	$R_2K_3W_1$
	W_2	$R_1K_3W_2$	$R_2K_3W_2$
	W_3	$R_1K_3W_3$	$R_2K_3W_3$
	W_4	$R_1K_3W_4$	$R_2K_3W_4$

This study used a quantitative-descriptive approach with a correlation design to analyze the relationship between pH, temperature, and concentrations of iron (Fe) and manganese (Mn) in groundwater. Additionally, a survey of the local population was conducted to gather opinions on water quality and the use of natural remediation technologies on a household scale.

2.4 Data Analysis

Groundwater samples were collected from nine private wells and analyzed for ion and manganese concentrations using atomic absorption spectrometry (AAS). Other parameters, such as pH and temperature, were recorded on site using calibrated field instruments. The correlations between iron, manganese, pH, and temperature were investigated using Pearson 'scorrelation analysis. Statistical analyses were performed using IBM SPSS Statistics with a significance level of 95%. Data on public perception were collected using a questionnaire distributed to 30 respondents. The respondents comprised residents affected by groundwater problems and those who were not. Responses were recorded using a Likert scale and descriptively analyzed to determine the acceptance of water quality and natural remediation technologies.

3. Result and Discussion

3.1 Water Quality Analysis

To determine the pollution level of the well water in the village of Margorejo, Tempel District, Sleman, a basic water quality analysis was conducted. Table 1 summarizes the composite values of the main physical and chemical parameters compared with the World Health Organization (WHO) guidelines of 2017 and Regulation No. 2/2023 of the Indonesian Ministry of Health.

Table 3. Preliminary analysis results on water

No.	Parameter	Unit	Test result	Parameter value
1.	Temperature	℃	24.0	Air temperature ± 3
2.	pH	-	7.1	6.5 – 8.5
3.	Iron (Fe)	mg/L	2.7548	0.2
4.	Manganese (Mn)	mg/L	0.2376	0.1

Water quality analysis was performed according to national standards (SNI 6989.84:2019) using accredited laboratory methods. Iron and manganese concentrations were measured using atomic absorption spectrometry. The values of 2.7548 mg/L for iron and 0.2376 mg/L for manganese exceeded the permissible limits of 0.2 mg/L and 0.1 mg/L, respectively, and thus indicated non-compliance with drinking water standards. Chronic manganese exposure poses serious health risks. The World Health Organization (WHO) reports impairments in the neurological development of children, whereas Ziegler et al. (2022) found that manganese concentrations as low as 100 ppb can cause cognitive deficits, reduced IQ, and Parkinson's-like symptoms. Under neutral pH conditions (pH 7.1), dissolved oxygen and oxidizing agents can mobilize iron and manganese from corroded pipes. Temperature also influences metal mobility and oxidation kinetics. Although a temperature of 24°C is common in tropical regions, it can accelerate the oxidation of Fe^{2+} to Fe^{3+}, leading to the precipitation of iron oxides and a reduction in water clarity (Al-Abadleh et al., 2022). Furthermore, inadequate well construction and maintenance, such as the absence of filter layers or infrequent cleaning, increases the likelihood of metal accumulation, particularly in sediment-rich soil layers in direct contact with groundwater flow (Hemakumar et al., 2024).

3.2 Post Water Treatment

3.2.1 pH Level

The ANOVA results showed that pH of the water was not significantly affected by the individual effects of the bioremediation agents on treatment duration (p>0.05). However, the interaction between the two factors showed a highly significant effect (p=0.002; p<0.01), suggesting that the pH change was mainly due to the combined effects of phytoremediation and natural coagulation.

Table 4. pH level test

Indicator	Result
Combination of bioremediation agents	0.061
Treatment time	0.071
Combination of bioremediation agents and treatment time	0.002

DMRT analysis revealed that the three treatments, K0W4, K0W12, and K20W8, differed significantly from the control group. K0W12 exhibited the highest pH value (8.463), which was approximately 2.58% higher than that of the control group (8.25). However, this value did not differ significantly from the other treatments (K0W16, K10W16, K20W4, K30W4, K30W16, K10W10, and K10W12). In contrast, K20W0 showed the lowest pH value (8.150), which was approximately 1.21% lower than that of the control group but was statistically comparable to the values of K0W4 and K20W8. These results suggest that K0W12 has a relatively higher pH-raising capacity than the single-agent treatments.
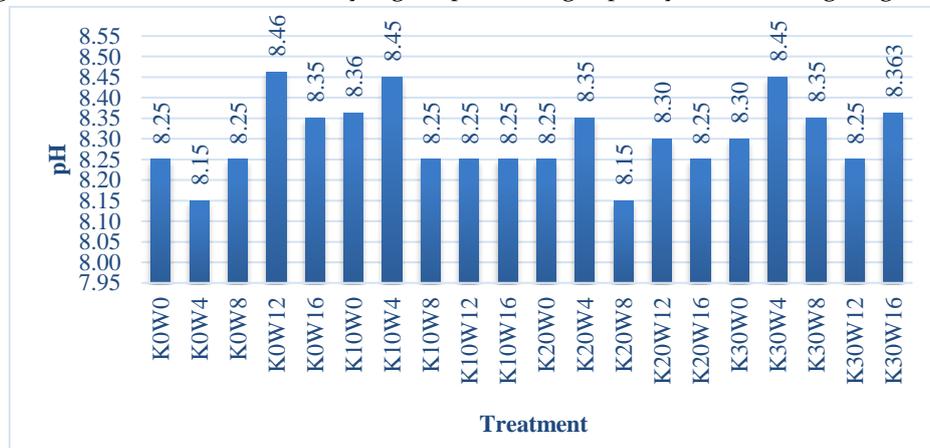

Figure 1. Effect of treatment on pH

The highest pH value was recorded in K0W12 without the addition of water hyacinth or moringa extract, presumably due to natural processes in stagnant water. Microbial decomposition can produce carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-), which neutralize H^+ ions and increase the pH. Ambaye et al. (2022) reported that the degradation of organic matter produces alkaline substances, while amino acids and humic acids released by planktonic organisms can further influence the pH depending on their composition. pH is a key factor for the efficiency of heavy metal removal. Nonh et al. (2023), showed that Pb adsorption at pH 4.5 with Corbula trigona shell powder was over 99%, indicating that even small pH changes can significantly affect metal sorption. Root exudates also regulate nutrient availability and microbial communities in the rhizosphere, thereby promoting pollutant degradation (Shi et al., 2024). The observed pH drops in K0W4 and K20W8 are likely due to different mechanisms. In K20W8, the combined application of water hyacinth and moringa may have stimulated microbial metabolism, producing organic acids via fermentation. In K20W8, the combined application of water hyacinth and moringa may have stimulated microbial metabolism, producing organic acids via fermentation.

3.2.2   Temperature Levels

ANOVA results showed that water temperature was significantly influenced by both treatment factors, particularly by their interaction ($p<0.05$) (Table 5). Among the treatments, K20W12 exhibited the highest temperature (27.73°C), representing a 2.51% increase compared to the control group (27.05°C). The lowest temperature (26.95°C) was measured for K20W0 and K20W4, approximately 0.37% lower than that for the control group. These variations suggest that the combined effects of *Eichhornia crassipes* and *Moringa oleifera seeds* can influence the thermal conditions in the treatment system. A longer treatment duration tended to lead to increased water temperature, likely due to enhanced oxidation of dissolved metals, accelerated degradation of organic matter, and increased microbial activity, processes known to release heat via metabolic pathways.

Table 5. Temperature level test

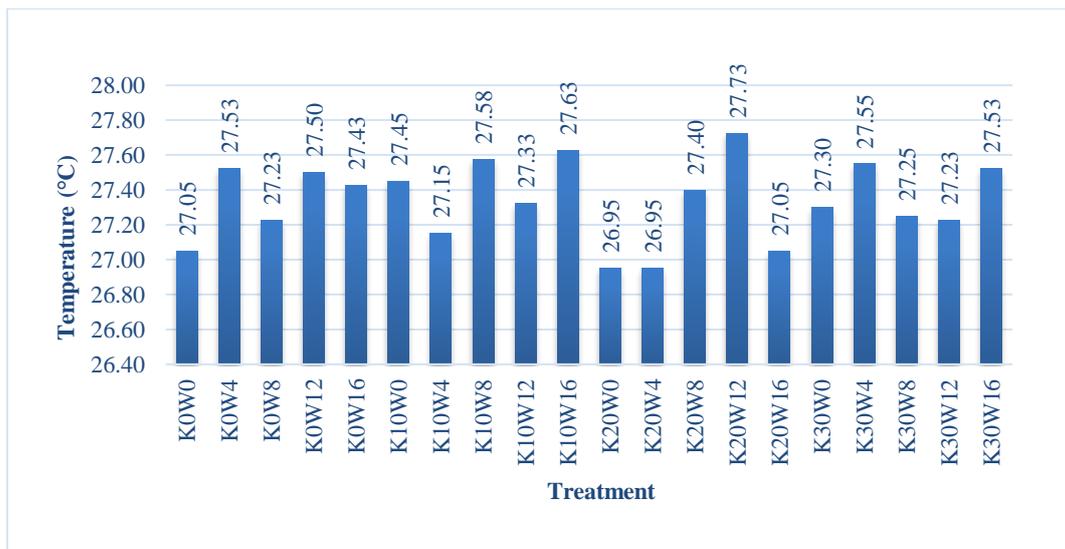| Indicator	Result
Combination of bioremediation agents	0.002
Treatment time	0.001
Combination of bioremediation agents and treatment time	0.000

Figure 2. Effect of treatment on temperature

As shown in Figure 2, the post-treatment temperatures ranged from 26.95 to 27.73°C. Although statistically significant differences were observed between some treatments, the overall temperature fluctuations remained small and within the typical range for shallow groundwater in tropical regions. For instance, treatments K20W12, K0W0, K10W8, and K20W16 did not differ significantly from each other, even though the highest temperature was measured with K20W12.

3.2.3   Iron (Fe)

ANOVA results showed that the reduction in Fe concentration was significantly influenced by the bioremediation agent used and treatment duration ($p<0.001$), with the interaction between the two also having a highly significant effect ($p<0.01$) (Table 6). These results suggest that the effectiveness of Fe removal strongly depends on an adequate amount of biomass and contact time.

Table 6. Iron (Fe) level test

Indicator	Result
Combination of bioremediation agents	0.000
Treatment time	0.000
Combination of bioremediation agents and treatment time	0.000

DMRT analysis revealed significant differences among the treatments. K30W16 achieved the highest iron removal, reducing the concentration from 3.674 mg/L to 0.082 mg/L (97.77%). The results were statistically comparable to those of K10W12, K10W16, K20W12, K30W8, and K30W12. These results suggest that a higher biomass combined with longer residence times consistently increased iron removal. In contrast, K20W0 showed the lowest efficiency (33.71%; 2.435 mg/L), indicating that limited biomass and short contact times restricted the interaction between iron and bioremediation. The lack of significant differences between K10W4 and K10W0 further supports this pattern. Overall, the K30 group achieved a higher average Fe reduction (73.53%) than the K20 group (50–60%), which is consistent with previous studies that reported increased Fe removal at higher doses of *Moringa oleifera* (Trisnawati & Damajanti, 2023).
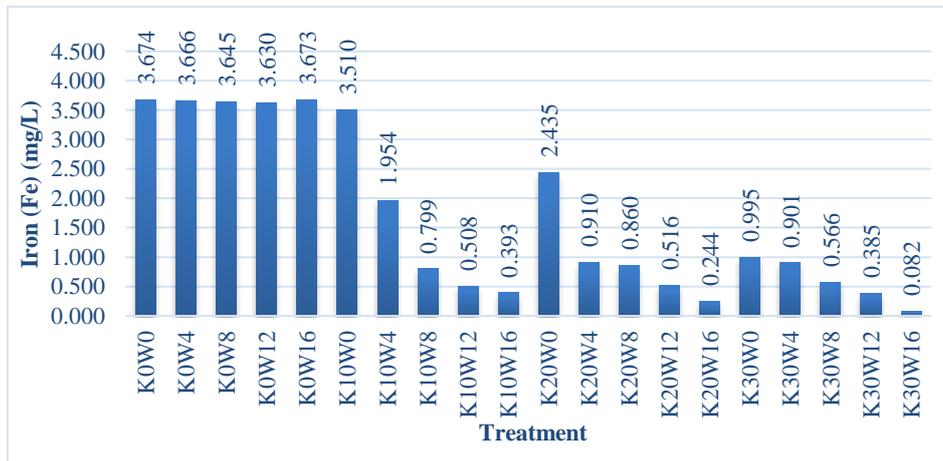

Figure 3. Effect of treatments on iron

Iron removal in this system is controlled by a synergistic biochemical and physicochemical mechanism. Microbial activity likely promotes the precipitation of biominerals by extracellular polymeric substances, resulting in iron-rich minerals, such as jarosite and ferrihydrite (Ding et al., 2024). Simultaneously, the roots of Eichhornia crassipes act as effective biosorbents through carboxyl and hydroxyl groups, whereas seed proteins of *Moringa oleifera* enhance coagulation and sedimentation via neutral magnetophoresis (Ruiz et al., 2024). Furthermore, the ability of Fe^{2+} and Fe^{3+} to form stable

aqueous complexes supports efficient interactions with plant tissue and the coagulation matrix. In summary, these results confirm that sufficient biomass loading and treatment duration are crucial for effective iron reduction, with K30W16 showing the greatest potential for a hybrid phytoremediation–coagulation treatment for sustainable groundwater remediation.

3.2.4. Effectiveness of Iron (Fe) Bioremediation

ANOVA results showed that the bioremediation agent, treatment duration, and their interaction had a highly significant influence on iron reduction ($p < 0.001$). This suggests that remediation efficiency depends on the optimal combination of biomass quantity and contact time. DMRT analysis confirmed significant differences between the treatments. Highly efficient treatments, such as K30W16, K30W8, K10W12, and K10W16, showed no significant differences among themselves. This suggests that iron removal reached an optimal level with higher biomass quantities and no longer exposure times.
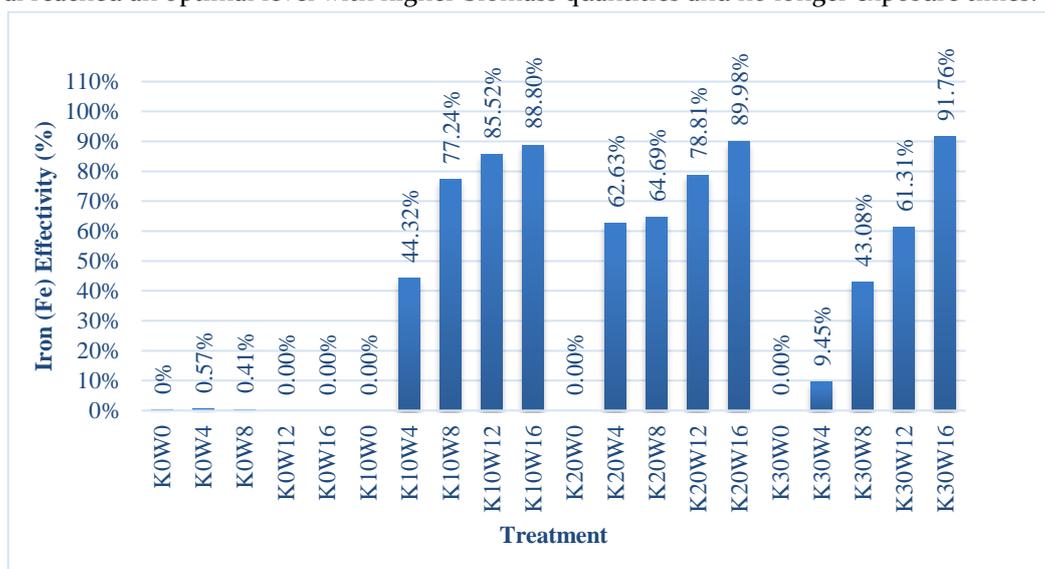

Figure 4. Effectiveness of reducing iron levels in well water

As shown in Figure 4, iron removal efficiency varied significantly between treatments. The highest efficiency was achieved with K30W16 (91.76%), followed by K30W12 (89.98%) and K20W16 (88.59%). This confirms that a higher biomass combined with a longer treatment duration consistently improves iron removal. In contrast, the control treatment and the low-biomass treatments (K0W8, K0W12, K0W16, and K10W4) showed negligible reduction. K0W8 achieved only 0.41%, indicating that passive oxidation alone is insufficient for effective iron reduction. The superior performance of K30W16 reflects a strong biochemical synergy. Increased biomass provides a larger adsorption surface area and promotes microbial biosorption, flocculation, and oxidation. Mechanistically, iron removal is facilitated by cationic proteins in *Moringa oleifera seeds* that promote flocculation (Stanikina, 2023), functional groups in water hyacinth roots that bind metal ions, and microorganisms such as *Pseudomonas* and *Bacillus* that oxidize Fe^{2+} to insoluble Fe^{3+} (Rani et al., 2024). Overall, the combination of water hyacinth and Moringa seed extract represents a cost-effective, environmentally friendly, and highly effective strategy for iron removal. The consistent superiority of K30W16 underscores the importance of optimizing biomass loading and contact time, particularly for communities with limited access to modern water treatment facilities.

3.2.5. Manganese (Mn)

ANOVA results showed that the bioremediation agent, treatment duration, and their interaction had a highly significant influence on manganese reduction ($p < 0.001$). This confirms that removal efficiency is strongly dependent on the synergy between biomass composition and sufficient contact time.

Further DMRT analyses revealed that treatments with higher biomass and longer exposure times consistently yielded better results than treatments with lower biomass or shorter durations.

Table 7. Manganese (Mn) level test

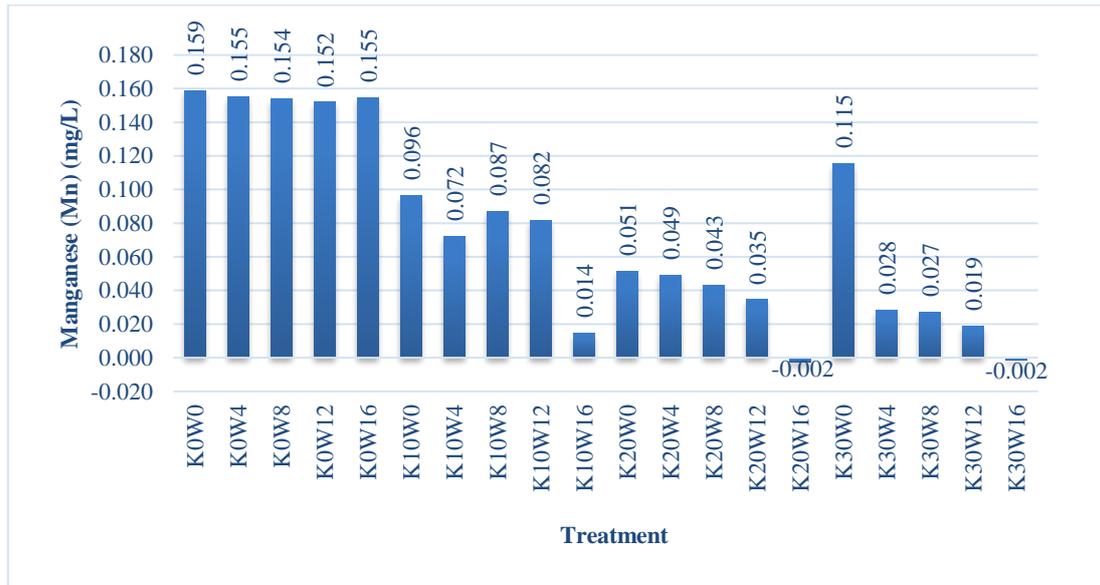| Indicator	Result
Combination of bioremediation agents	0.000
Treatment time	0.000
Combination of bioremediation agents and treatment time	0.000

Figure 5. Effect of treatment on manganese

As shown in Figure 5, manganese concentrations differed significantly between the treatments. The control sample (K0) exhibited high manganese levels (0.152–0.159 mg/L), whereas the combined treatment with water hyacinth and moringa reduced the manganese content to almost zero. The greatest reduction was achieved with K30W16, which lowered the manganese content from 0.155 mg/L to 0.002 mg/L (98.71%), followed by K30W12 and K20W16. These results confirm that higher biomass and longer contact time are crucial for maximum manganese reduction, whereas short treatment duration or low treatment intensity (e.g., K30W4 and K10W10) showed only limited efficacy. The superior performance of K30W16 is based on synergistic groups in the roots of water hyacinth, microbial oxidation of Mn^{2+} to insoluble Mn^{4+}, and flocculation caused by cationic proteins in the seeds of *Moringa oleifera* (Priya et al., 2023).

Contact time proved to be a crucial factor, as demonstrated by the comparison between K30W16 and K30W4. Mn sorption was pH-dependent and generally followed pseudo-second-order chemisorption kinetics (Alghamdi et al., 2024). Furthermore, the strong positive correlation between Fe and Mn (r=0.821) suggests simultaneous removal owing to similar geochemical properties. Overall, the hybrid phytocoagulation approach offers an effective, cost-efficient, and environmentally sound solution for manganese-contaminated groundwater, provided that the invasive biomass is properly disposed of after harvesting.

3.2.6. Effectiveness of Manganese (Mn) Bioremediation

Figure 6 shows that the efficacy of manganese reduction varied considerably between treatments. Treatment K3W16 achieved the highest reduction efficiency (98.84 %), followed by K3W12 (98.19%) and K2W16 (87.41%). These values suggest that the combination of K3 with a longer application time (12–16

h) was able to reduce manganese concentrations to almost zero. In contrast, all control treatments (K0W0–K0W16) showed very low efficacy (0–1.52%), confirming that treatment duration alone, without an active bioremediation agent, did not significantly lower manganese levels.
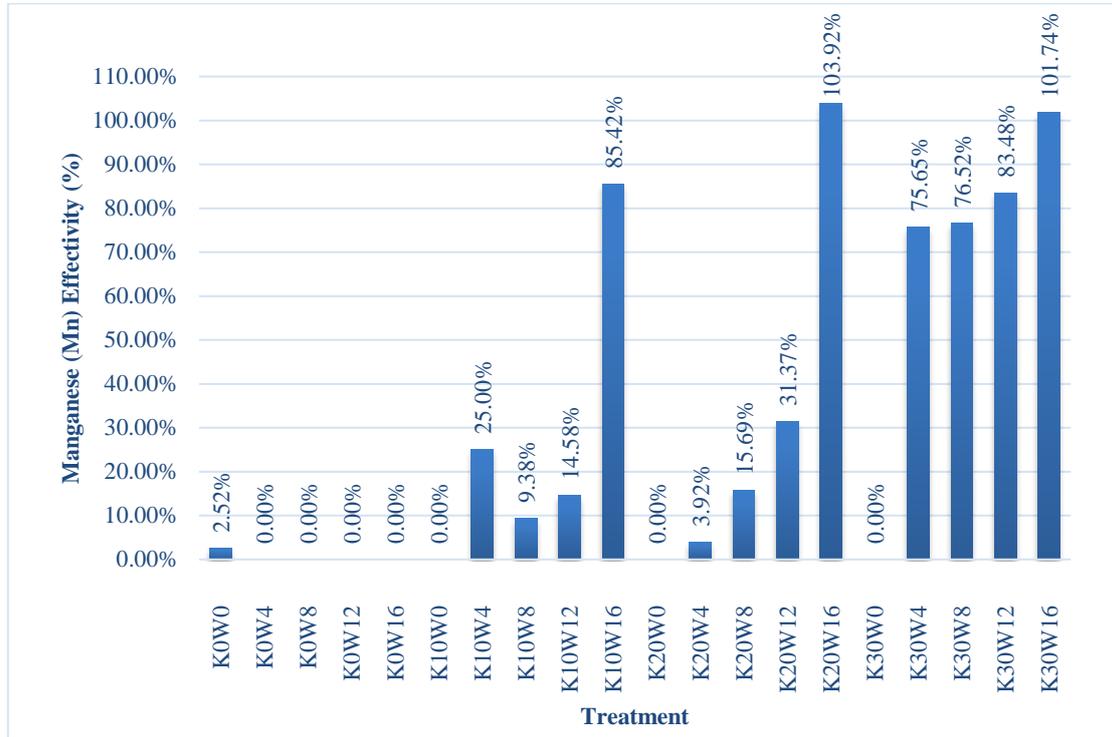

Figure 6. Manganese reduction effectiveness in well water

DMRT analysis revealed significant differences among the treatments. K20W16 showed the highest manganese removal efficiency (103.92%) and did not differ statistically from K30W8, K30W12, and K30W16, all of which fell into the high-efficiency category (≥80%). This suggests that sufficient biomass combined with adequate contact time is crucial for effective manganese removal. In contrast, all control treatments (K0W0–K0W16) showed an efficiency of 0.00%, even with the longest contact time, confirming that passive processes, such as natural oxidation or sedimentation, were ineffective. The highly efficient treatments reflect a synergistic mechanism involving biosorption by functional groups in the roots of water hyacinth, microbial oxidation of Mn^{2+} to insoluble Mn^{4+}, and flocculation by cationic proteins in the seeds of *Moringa oleifera*. This mechanism is consistent with previous studies reporting Mn removal efficiencies of up to 99.7% using water hyacinth and 75–99% using Moringa seeds, depending on the dose and pH.

However, increasing biomass alone does not guarantee greater manganese removal. K30W4 showed low effectiveness (25.81%), comparable to K10W10, highlighting contact time as a limiting factor. The difference between K30W4 and K30W16 demonstrates that a longer treatment duration is crucial for activating biological and physicochemical processes. Overall, K20W16 proved to be the most effective configuration, suggesting that optimal biomass loading and longer contact times are key factors for consistent and efficient manganese bioremediation.

3.3. Correlation Between pH, Temperature, Iron (Fe), and Manganese (Mn)

To determine the correlation between physicochemical parameters, especially iron (Fe) and manganese (Mn) values, which are main indicators of metal contamination of groundwater, and to analyze the quality of well water in the village of Margorejo.

Table 8. Correlation between pH, temperature, iron, and manganese

Parameter	Correlation			
	pH	Temperature	Iron	Manganese
pH	-	0.073	0.057	0,000
Temperature	0.073	-	0.000	0.008
Iron (Fe)	0.057	0.000	-	0.821
Manganese (Mn)	0,000	0.008	0.821	-

Source*: Pearson test, 2025*

Correlation analysis revealed no significant relationships between pH and temperature (r=0.073), pH and iron (r=0.057), pH and manganese (r=0.00), temperature and iron (r=0.00), or temperature and manganese (r=0.008). These results suggest that fluctuations in pH and metal concentrations are not primarily driven by temperature or minor pH variations, but rather by redox conditions, microbial activity, and the geochemistry of the aquifer (Wang et al., 2023). As long as environmental conditions remain within the normal range, pH tends to be buffered by the mineral composition, whereas the behavior of iron and manganese is determined by redox dynamics. In contrast, iron and manganese exhibited a strong positive correlation (r=0.821), reflecting similar geochemical properties, shared redox pathways, and common sources, such as mineral weathering and anthropogenic inputs. This relationship is supported by microbial oxidation processes that can convert both metals simultaneously. The formation of mixed Fe-Mn oxides increases the overall efficiency of metal removal by 30–40%, thus enhancing the effectiveness of nature-based and household-scale bioremediation systems (Artime et al., 2022).

3.4. Public Perception of Water Quality and Bioremediation Technology

The social characteristics of the respondents provide an important basis for understanding the perception of the population regarding the quality of well water and the acceptance of bioremediation-based treatment technologies. This study involved 30 people from the area surrounding the investigation site, who were equally divided into two groups: 15 residents directly affected by well water contamination and 15 residents who were not affected.
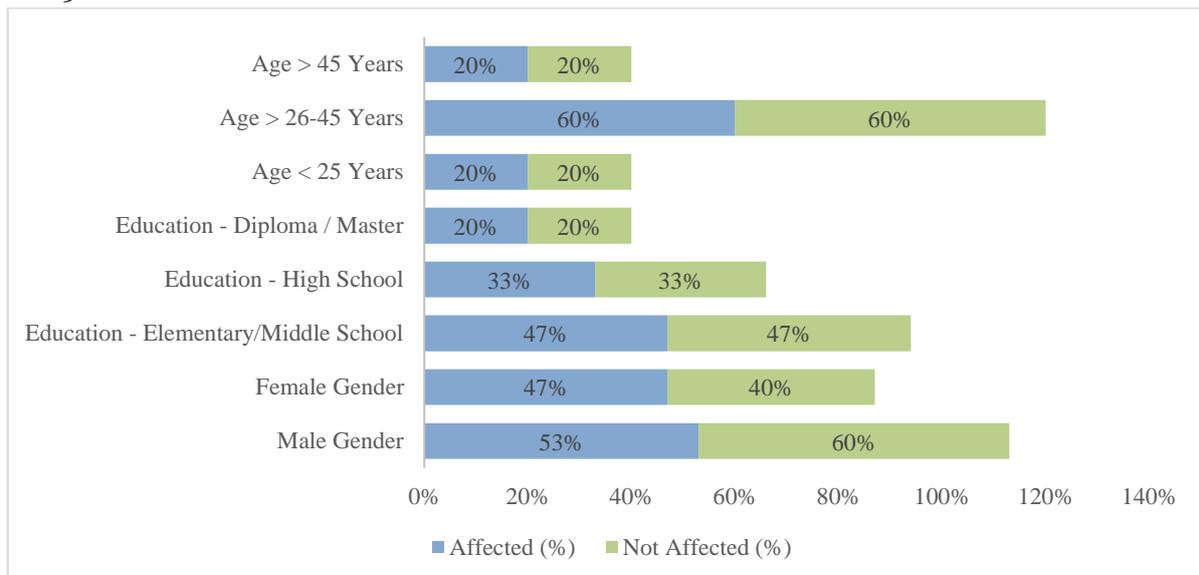
Figure 7. Characteristic of respondent

Figure 7 shows that men were slightly overrepresented in both groups (53% in the affected group and 60% in the unaffected group). This pattern reflects sex-specific social roles: men tend to be more

involved in outdoor and community activities related to environmental impacts, whereas women are more concerned with water use and household hygiene. The respondents were predominantly of working age (26–45 years), comprising approximately 60% in both categories. This suggests a relatively high level of environmental awareness and strong social participation. Individuals in this age group generally respond adaptively and sensitively to environmental issues, whereas older respondents, despite lower participation, possess relevant experience (Okui et al., 2021). Educational attainment was similar in both groups; most respondents had completed primary or secondary education, with only 13–20% holding a university degree.

Table 9 shows that the public generally has a positive attitude towards improving well water quality and the use of bioremediation technologies. Most respondents expressed positive to very positive views on the use of Eichhornia crassipes and Moringa oleifera as natural and environmentally friendly solutions for reducing iron and manganese contamination. Acceptance varied by gender, education level, and age. Male respondents showed higher acceptance than female respondents, presumably because of their more frequent direct contact with water sources. Respondents with higher levels of education had fewer negative views, suggesting a better understanding of environmental technologies. The working-age group (26 to 45 years) was the most receptive, while older respondents tended to be more cautious. Overall, the survey results suggest that the bioremediation approach is not only technically effective but also socially acceptable. This societal willingness supports the potential use of nature-based groundwater treatment on a household scale as a sustainable solution for improving water quality in rural areas.

Table 9. Perception of demography

No.	Pereception of demography	Criteria		
		Very positive	**Positive**	**Negative**
1.	Man	27.30%	21.20%	6%
2.	Woman	21.20%	21.02%	3.10%
3.	Elementary / middle school	15.01%	19.80%	5.40%
4.	High school	18.20%	13.20%	3%
5.	Diploma / master	14.70%	9.10%	1.50%
6.	Age < 25 years	9.10%	6.10%	3%
7.	Age 26-45 years	27.30%	27.30%	6%
8.	Age > 45 years	12.20%	9%	0%

Most respondents agreed or strongly agreed that they understood the changes in water quality before and after treatment, particularly regarding color, odor, and clarity. High awareness of the health and environmental risks of iron and manganese reflected the effectiveness of practical experience and study-related public outreach in conveying knowledge about environmental issues. Most respondents recognized the use of water hyacinth and moringa seeds as a safe, cost-effective, and practical nature-based solution. The perceived effectiveness of the technology was high, as most respondents confirmed a significant reduction in iron and manganese levels, which increased confidence in the method and willingness to use it. This aligns with technology acceptance theory, which states that perceived benefits promote acceptance. Public behavior also showed positive trends, including taking precautions, participating in water management, and supporting sustainable implementation. Ease of use, low cost, and material availability were crucial factors for acceptance, although some respondents cited barriers related to limited technical knowledge and restricted access to the materials.

Overall, public acceptance was 75.72% (category "Good"), indicating that bioremediation with *Eichhornia crassipes* and *Moringa oleifera* is technically effective and socially feasible. The high level of acceptance in households affected by pollution underscores the importance of direct exposure for risk perception and the willingness to innovate. These results confirm that the sustainability of household-scale bioremediation depends not only on the efficiency of metal removal but also on ongoing education, technical support, and public engagement.

Table 10. Distribution of questionnaire answer

No.	Questionnaire	Criteria				
		Strongly agree	**Agree**	**Neutral**	**Don't agree**	**Strongly disagree**
1.	Understanding well water quality	33.33%	30%	15%	11.67%	10%
2.	Awareness of the impact of water pollution	23.33%	31.67%	21.67%	18.33%	5%
3.	Understanding water pollution solutions	35%	31.67%	23.33%	5%	5%
4.	Perception of the effectiveness of phytoremediation and coagulation	31.67%	38.33%	15%	6.67%	8.33%
5.	Actions that have been done or planned	34.17%	29.17%	16.67%	9.17%	10.83%
6.	Confidence in the method used	37%	36.67%	12.22%	5.56%	7.78%
7.	Community participatuon in water treatment efforts	32%	34.17%	20%	7.50%	6.67%
8.	Factors influencing technology adoption	37.38%	33.33%	18.89%	7.78%	1%
9.	Challenges in implementing the method used	35.83%	33.33%	19.17%	5.83%	5.83%

4. Conclusions

This study demonstrated that the combined application of Eichhornia crassipes and Moringa oleifera seeds is an effective and socially acceptable nature-based solution for reducing iron (Fe) and manganese (Mn) contamination in domestic well water in the Margorejo Village. Experimental results consistently showed that metal removal efficiency increased with higher biomass and longer contact times. Optimal treatment at K20W16-K30W16 achieved Fe and Mn reductions of over 90%. This was supported by a strong positive correlation between Fe and Mn concentrations, suggesting removal mechanisms through biosorption, microbial oxidation, and natural flocculation. Further analysis of public acceptance showed high agreement (75.72%), especially among those directly exposed to contamination. This underscores that the sustainability of household-scale water treatment depends not only on technical capabilities but also on public willingness and trust. However, this study is limited by its relatively small sample size and controlled experimental conditions. Consequently, seasonal variations, long-term system stability, and broader hydrogeochemical dynamics may not be fully represented. Based on these findings, local governments and environmental agencies are encouraged to integrate cost-effective bioremediation systems into rural water security programs, provide ongoing technical guidance and community-based training, and incorporate nature-based treatment options into groundwater management policies, particularly in semi-rural areas affected by volcanic activity. Future studies could focus on long-term field implementation, seasonal performance evaluation, and institutional support mechanisms to ensure the scalability and sustainability of bioremediation-based groundwater treatment.

Acknowledgement

Ethics Statement

All procedures performed in this study involving human subjects complied with institutional and national ethical standards. Informed consent was obtained from all participants prior to data collection. No personal or sensitive data were collected. Sampling and bioremediation trials were conducted in accordance with safe and non-destructive environmental research protocols.

CRedit Author Statement

Wahyu Zolla Rohmatulaeny: Conceived and Designed Analysis, Collected Data, Contributed and Analysis Tools, Performed Analysis, Wrote Paper. **Mohammad Masykuri:** Conceived and Designed Analysis, Performed Analysis. **Retno Rosariastuti:** Conceived and Designed Analysis, Contributed and Analysis Tools. **Callista Fabiola Candraningtyas:** Contributed and Analysis Tools, Wrote Paper.

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