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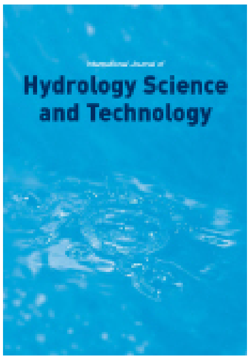

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Technology for separation of iron in groundwater to support drinking water supply

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Abstract: Groundwater is the main water source in Yogyakarta (45.92%), followed by rivers (33.71%), springs (17.85%), and reservoirs (2.52%). Most residents rely on wells for drinking water, which often contain excessive iron (Fe), posing health risks. This study aimed to develop a household-scale technology to reduce Fe concentrations in groundwater. Samples were collected from Kasihan, Bantul, and treated using an aeration method with an aerator installed in the pump pipe, producing bubbles of 300–500 microns. Five aeration durations ranging from 0.5 to 11.5 hours were tested. Initial Fe levels measured 0.5 mg/L, the maximum permissible limit under Minister of Health Regulation No. 2/2023. After aeration, Fe levels decreased to 0.05 mg/L, showing a reduction of 0.45 mg/L. These findings demonstrate the effectiveness of aeration in improving water quality. The research will continue to optimise technological solutions tailored to household-scale community needs.

Keywords: aeration; groundwater; iron; Fe; well water.

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1 Introduction

Water resources are currently facing major challenges due to climate change, population growth, and increased human activities, particularly in developing countries. These impacts include reduced rainfall, more frequent droughts, water quality degradation, and growing pressure on both groundwater and surface water resources that are used to meet domestic, agricultural, and industrial needs (Gazal, 2021). Domestic water use per capita varies significantly between regions. In many developing countries, daily water use may be as low as 20–30 liters per person due to limited access and infrastructure, whereas in developed countries, average use often exceeds 100 litres per person per day, depending on service level and availability (WHO, 2017). Water is primarily used for drinking, cooking, washing, and other purposes (Leluno et al., 2020). Several cities especially in the developing world are facing rising pressures on organisations and infrastructure due to population growth and urbanisation (Kumar Goyal et al., 2016).

In Yogyakarta, the majority of residents still rely on well water for drinking, which has been found to contain high levels of iron (Fe). This poses a significant risk to public health. Consequently, a device was developed to reduce the Fe concentration in the water.

The requirement for clean water for consumption must ensure safety from pathogens and other harmful substances (Dewanti and Sulistyorini, 2017). According to Badan Pusat Statistik (2022), between 2017 and 2021 the availability of clean water in Indonesia predominantly relied on groundwater (45.92%), with the remainder sourced from springs, rivers, and reservoirs (17.85%, 33.71%, and 2.52%, respectively). Currently, water management in Indonesia is centralised through drinking water companies (PAM) or regional drinking water companies (PDAM). Indonesia is committed to achieving universal and equitable access to drinking water by 2030 (Bappenas, 2017).

Despite this commitment, national water management in Indonesia remains inadequate (Ministry of Health RI, 2023; WHO, 2022, 2017). Studies have documented widespread water contamination, consistently increasing due to pollutants in water bodies, particularly groundwater (Madhav et al., 2020; Makmur, 2013; Lahkar and Bhattacharyya, 2019). Groundwater is the most utilised water source in Indonesia, especially in the Special Region of Yogyakarta. Many people assume groundwater is safe for consumption; however, urban development has led to a decline in both groundwater and surface water quality. Key factors include inadequate wastewater management, land conversion, and limited waste disposal space (Shaibur et al., 2024).

Nonetheless, groundwater remains a popular choice due to its accessibility, year-round availability, and low cost (Ali et al., 2022). Human activities introduce various pollutants, including organic and inorganic substances (heavy metals), into the environment, contributing to both anthropogenic and natural pollution (Astuti et al., 2021). One prevalent contaminant in groundwater is iron (Fe), which can exist in water as dissolved iron (Fe^{2+}) and ferric ions (Fe^{3+}) (Yazid et al., 2021).

Heavy metal pollution in groundwater is a significant concern due to its potential toxicity, which poses risks to human health and the environment (Elmanfe et al., 2022). High iron concentrations in groundwater often result in reddish or brown discoloration (Hilary et al., 2022). Prolonged contact with polluted water may cause various respiratory conditions, such as fatigue, coughing, breathing difficulties, bronchopneumonia, fluid accumulation in the lungs, bluish skin discoloration, and methemoglobinemia (Sunarsih et al., 2018).

This research aims to identify the correlation between aeration duration and the effectiveness of iron removal, leading to the development of a practical product design for users relying on groundwater for daily needs. Indriatmoko et al. (2018) indicate that Fe removal can be achieved through aeration, sedimentation, and filtration. This study will primarily focus on aeration, as previous research has demonstrated its efficacy in reducing iron levels in groundwater (Indriatmoko et al., 2018; Rizkiyah et al., 2023). This activity will be conducted on a laboratory scale, representing the preliminary research phase with a technology readiness level (TRL) of 3, which indicates proof-of-concept for essential functions and characteristics, both analytically and experimentally.

2 Materials and methods

This study utilised a quantitative methodology, primarily relying on experimental techniques. The study took place from July to August 2023 and included a literature review, planning, instrument development, testing, and refinement. The research was carried out at the Environmental Laboratory of the Civil Engineering Department at UGM Vocational School, using groundwater samples from wells in the Kasihan area, Bantul Regency.

The sampling method used was simple random sampling, involving a single location point with a sampling volume of one jug, amounting to 20 litres. The collected water samples were placed into a test vessel designed according to the aeration pattern. The aeration system design is illustrated in Figure 1, which consists of three distinct containers. The first container is equipped with an aeration pump capable of producing bubbles ranging from 300 to 500 microns.

The second container features a filter and sediment trap, incorporating a fine dacron filter. In the third container, water is aerated for varying durations. The durations of aeration were divided into five different time intervals: 2, 6, 12, 18, and 24 hours.

The selected aeration method employs a diffused air aerator model, which injects pressurised air into the water to provide oxygen. The air released from the aerator forms bubbles that enhance water turbulence in the first stage of the process. The efficiency of the fine bubble aerator (utilising a capacity of 300–500 microns) is presented in Table 1, corresponding to the duration of the experiments. The oxygen transfer rate for aeration via air injection (diffused aeration) is represented by the following equation (Eckenfelder and Ford in Reynolds, 1996):

$$N = CG_a^{(1-n)} D^{0.67} \left(C_{sm} - C_L\right) 1.02^{(T-20)} \alpha ... \qquad (1)$$

with

C, n constant

$G\alpha$ air discharge at 200 C and 1 atm (m^3/minute)

D diffuser depth (m)

Csm saturated gas concentration at half tank depth (mg/l)

α KLa (water) or KLa (clean water).

Because oxygen solubility changes depending on pressure, the oxygen saturation concentration (Csm) is calculated at the midpoint depth of the aeration tank, and can be estimated by applying the formula below:

$$C_m = C_s \left(\frac{P_r}{203} + \frac{O_e}{42} \right) \qquad (2)$$

with

Cs saturated gas concentration (mg/l)

Pr absolute pressure at air release depth (kPa)

Oe gas in the air flow released (%).

The energy requirements for an air compressor can be calculated using the equation:

$$P = \frac{FRT_1}{CnE}\left[\left(\frac{\rho_2}{\rho_1}\right)^n - 1\right] \tag{3}$$

with

P power (kW)

F air flow mass (kg/sec)

$$Ga\left(m^3/\text{sec}\right) \times Air\ Density\left(kg/m^3\right)$$

R gas constant = 0.288

T_1 inlet air absolute temperature, 0K

ρ_1 absolute pressure of incoming air (kPa)

ρ_2 outgoing air absolute pressure (kPa)

n 0.283 for air

E compressor efficiency usually ranges from 70%–80%

C 1.0.

The test results of well water samples aerated for predetermined durations were analysed through manual laboratory examinations, which assessed the extent of iron reduction using the aeration method. Following the laboratory experiments, this research resulted in a product design integrated with a groundwater pump.

3 Result

The water samples utilised in this research were obtained from groundwater sources, specifically from wells in Kasihan, Bantul Regency. Interestingly, the water showed a yellow hue and noticeable smell, indicating non-compliance with the standards specified in Indonesia's Ministry of Health Regulation No. 2 of 2023. According to this regulation, clean water should be free from any discernible odour, and the true colour unit (TCU) should not exceed 50 TCU. The observed characteristics of the water sample clearly indicate non-compliance with these criteria, highlighting significant deviations from the mandated requirements for clean water.

In a study conducted by Proshad et al. (2017), researchers noted that groundwater samples exhibited a distinct yellowish tint, indicating the presence of iron (Fe). Similarly, findings by Xiao et al. (2015) corroborate this observation, emphasising the substantial impact of iron on water coloration. This research highlighted that Fe significantly influences water colour, surpassing the effects of non-algal particles and phytoplankton.

Given that the study detected 0.2 mg/L of Fe in the water, exceeding the standard limit, it is understandable that the sample displays a yellowish hue. This aligns with the theory that water with high Fe content exhibits distinctive characteristics.

A prominent visual indicator of high iron levels is the formation of reddish-brown or yellow stains on fixtures, appliances, laundry, and dishes, resulting from the oxidation of iron into rust. High iron content also poses challenges for water quality, as discoloration can range from a slight yellowish tint to a deep brown hue, depending on the iron concentration and its oxidation state (Asmawati et al., 2022; Nurani and Maulana, 2020).

Numerous studies and surveys in Bantul have revealed that elevated iron concentrations in groundwater are relatively common. Nurani and Maulana (2020) reported high Fe content in 14 groundwater samples. This issue is not recent but has been documented over a significant period. The region's geological composition and natural conditions contribute to the elevated levels of iron, which local authorities and residents have consistently reported. Such results are frequently linked to the natural process of iron seeping from soil and rock formations into the groundwater.

The presence of significant quantities of iron can result in water appearing cloudy or containing visible sediment. Such visual alterations detract from the aesthetic quality of the water and raise concerns regarding its portability and suitability for various applications. These undesirable sensory characteristics can significantly reduce the acceptability of the water for consumption, even if it meets safety standards from a chemical and microbiological perspective.

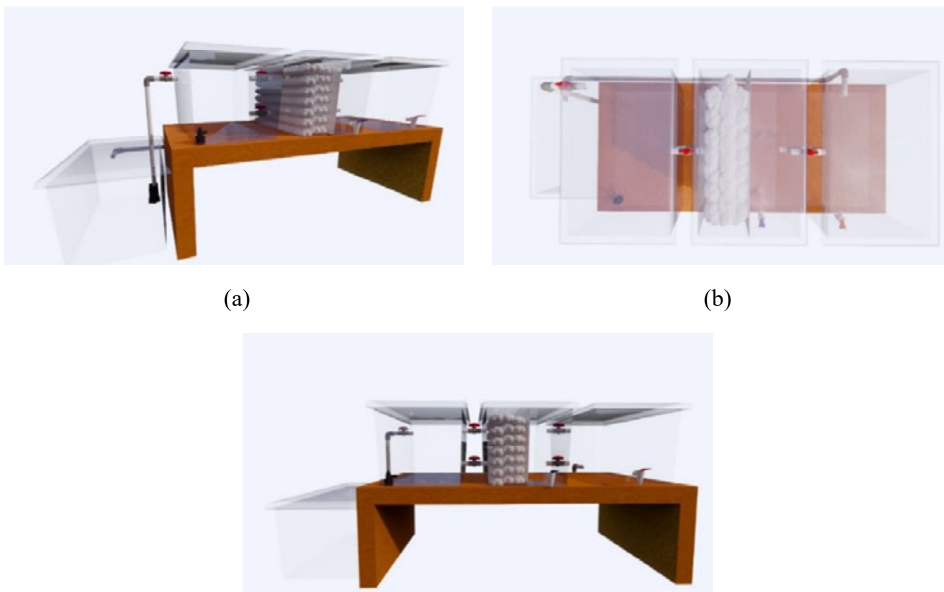
From a technical standpoint, elevated iron levels can have detrimental effects on plumbing systems and household appliances. Iron tends to accumulate in pipes, showerheads, and other fixtures, leading to clogging and reduced water flow and system efficiency. This accumulation necessitates more frequent maintenance and can result in substantial repair costs. Moreover, iron accelerates the corrosion of plumbing materials and water heaters, diminishing their operational lifespan and increasing the likelihood of system failures. These impacts underscore the critical need for effective iron management in water treatment processes.

Sedimentation presents another challenge, as iron particles can settle out of the water, forming a sediment layer that requires regular removal to maintain system functionality. Additionally, the proliferation of iron bacteria in iron-rich water can lead to slimy deposits and biofilms, further obstructing water systems and degrading water quality. Alterations in the water's pH, often skewing towards increased acidity, can affect its overall chemical properties and interactions with other substances, impacting its suitability for domestic and industrial uses.

These complex issues underscore the need to manage iron contamination in order to maintain both the quality and consistency of water resources. Various advanced technologies are employed to mitigate iron (Fe) concentrations in potable water, including media filtration, aeration, chemical precipitation, reverse osmosis (RO), ion exchange systems, activated carbon filtration, and electrocoagulation. In aeration, oxygen is pumped into the water to promote the oxidation of dissolved iron into insoluble forms that can be precipitated and filtered.

The study of aeration technology for reducing Fe levels in groundwater has been explored by Asmawati et al. (2022), who varied air discharge and aeration time. Their research found that the most significant reduction occurred at the highest discharge and longest exposure time (2 L discharge and 60 minutes residence time). The combination of various methods for Fe removal has been investigated in recent years. In 2023, Rizkiyah et al. conducted experiments on Fe removal using aeration and sedimentation, revealing that the most effective combination involved a tray aerator (measuring two metres) and an extended sedimentation period (lasting three hours), achieving iron content levels compliant with drinking water standards. Unlike earlier experiments, this study incorporates filtration into the treatment system, aiming for improved Fe removal outcomes.

Figure 1 Design of test vessel for reducing iron (Fe) content in well water, (a) side view of the product (b) top view of the product (c) front view of the product (see online version for colours)



(a) (b)

(c)

Source: Personal documents (2023)

In contrast to the previous study that employed a tray aerator, this experiment selected a bubble aerator as the aeration system. This choice was made based on the understanding that the oxidation process, coupled with subsequent sedimentation or filtration, underscores the importance of aeration pressure as a significant parameter in the iron (Fe) oxidation process (Sun et al., 2021). The aerator's ease of reproduction and its suitability for experimentation in this study are noteworthy. Furthermore, its practicality for daily use makes it a viable solution for mitigating iron (Fe) contamination in groundwater, warranting its consideration as an effective approach.

During the study, it was observed that the initial chamber of the aeration process exhibited yellow particles (Fe) that dispersed upon the introduction of air microbubbles. Introducing microbubbles of air, pure oxygen, or oxygen-enriched air into the solution elevated the level of dissolved oxygen and expanded the interface between gas and liquid. As a result, the transformation of ferrous iron (Fe^{2+}) into ferric iron (Fe^{3+}) occurred more rapidly, promoting efficient iron removal from the solution (Fu et al., 2021). In the second chamber, any remaining suspended impurities were captured by a fine mesh filter made from dacron.

Figure 2 Laboratory scale aeration system model, (a) pumped well water sample (b) aeration process (c) filtration process (see online version for colours)

(a) (b) (c)

Source: Personal documents (2023)

Analysis of treated well water samples, as illustrated in Figure 2, demonstrated a notable decline in iron levels, from 0.2 mg/L to 0.05 mg/L, which is equivalent to a 75% reduction after undergoing 12 hours of aeration. This result suggests a lower removal rate compared to outcomes reported in earlier studies. Goutomo and Purwoto (2022) demonstrated that utilising a Bubble Aerator for 60 minutes achieved the highest removal rate, with a reduction of 98.37% (equivalent to 0.994 mg/L).

Laboratory analysis of the water samples, taken both prior to and following the aeration process, evaluated key quality indicators such as pH, temperature, and iron (Fe) levels. The measurement outcomes are provided in Table 1, with the overall water quality results after aeration presented in both Table 1 and Figure 3.

Before aeration process:

pH	7.15
Temperature	26ºC
Fe	0.5 mg/l.

In contrast, the results of this study demonstrate a higher percentage of iron removal compared to those reported by Indriatmoko et al. (2018), who investigated iron (Fe) reduction via aeration and observed removal efficiencies ranging from 38% to 56% when using microbubbles. Research conducted by Rosidah et al. (2022) further revealed that the length of the aeration process plays a crucial role in determining the extent of Fe reduction in water.

The differences in analytical results may be influenced by various factors. As noted by Sun et al. (2021), besides the aeration process, factors such as pH and aeration pressure also play critical roles in optimising Fe removal. Additionally, the choice of filtration media can impact Fe reduction in the treatment system, contributing to variations in results. While some studies have employed sand filters in their treatment procedures (Febiary et al., 2016; Syahrir and Gani, 2019), this experiment utilised dacron as the filtration medium. Dacron was chosen for its durability and ease of cleaning. Sahetapy et al. (2021) noted that dacron, composed of synthetic fibres, has minute pores that effectively filter water-soluble particles.

Table 1 Outcomes of the water quality evaluation after the aeration treatment

No.	*Duration (hours)*	*pH*	*Temperature*	*Without aeration*	*After aeration*
1	0.5	7.15	26	0.5	0.5
2	1	7.15	26	0.5	0.4
3	1.5	7.15	26	0.5	0.4
4	2	7.15	26	0.5	0.4
5	2.5	7.15	26	0.5	0.4
6	3	7.15	26	0.5	0.3
7	3.5	7.15	26	0.5	0.3
8	4	7.15	26	0.5	0.3
9	4.5	7.15	26	0.5	0.2
10	5	7.15	26	0.5	0.2
11	5.5	7.15	26	0.4	0.2
12	6	7.15	26	0.4	0.2
13	6.5	7.15	26	0.4	0.2
14	7	7.15	26	0.4	0.2
15	7.5	7.15	26	0.4	0.2
16	8	7.15	26	0.4	0.1
17	8.5	7.15	26	0.4	0.1
18	9	7.15	26	0.4	0.1
19	9.5	7.15	26	0.4	0.1
20	10	7.15	26	0.4	0.1
21	10.5	7.15	26	0.4	0.1
22	11	7.15	26	0.4	0.1
23	11.5	7.15	26	0.4	0.1

Figure 3 The outcomes of the water quality analysis after the aeration process

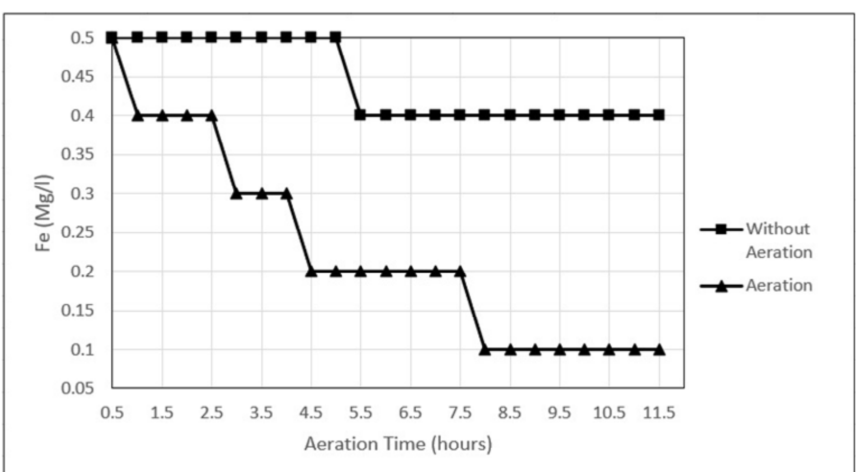


Figure 4 Design plan for implementing aeration technology that is connected to a household scale water tank, (a) full view (b) pump and aerator details (c) filtration (see online version for colours)

(a)

(b)

(c)

Source: Personal documents (2023)

Ongoing research efforts are focused on the continued development and rigorous testing of various aerator products to identify the most effective solutions within a condensed timeframe. A meticulous design process has been undertaken to create a household-scale aerator, ensuring the sustainability and applicability of the study's methodologies. This design, illustrated in Figure 3, is a critical aspect of the research, providing a practical means to implement findings in real-world settings. Within the designated water treatment facility, the use of water pumps serves as a pragmatic approach, aligning with the overarching goal of applying the research outcomes in domestic contexts.

4 Conclusions and recommendation

4.1 Conclusions

The study findings reveal a reduction in iron (Fe) concentration from 0.5 mg/L to 0.05 mg/L through the application of the Bubble Aerator system. Ongoing improvements to the aeration process aim to optimise the duration, as the current time required for significant iron reduction is 11.5 hours. The literature review supporting this research demonstrates that utilising an aeration system is an effective and cost-efficient method for reducing iron levels.

The planned design to integrate an aeration system with a household-scale water pump, based on laboratory results, is currently in the design stage and will proceed to field trials. This approach aims to align with community needs, thereby enhancing water quality.

4.2 Recommendation

It is advisable to further develop and implement the Bubble Aerator system in the field, integrating it with household-scale water pumps to enhance iron removal efficiency in line with community water quality standards. Prioritising the optimisation of aeration time can improve both system practicality and energy efficiency.

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Declarations

All authors declare that they have no conflicts of interest, did not use AI technology in the preparation of this manuscript, and that this study did not involve human participants requiring informed consent.

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