Indonesian Journal of Environmental Management and Sustainability
e-ISSN:2598-6279 *p*-ISSN:2598-6260

Research Paper

Phytoremediation of Fe(III) Using *Pistia stratiotes* L. - Efficiency and Kinetic Insights

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Abstract
The increasing presence of heavy metals (dense metallic elements, such as iron, which can be toxic at high levels) in industrial wastewater poses a substantial threat to environmental and human health, requiring the development of effective, sustainable treatment solutions. This study analyzes the potential of *Pistia stratiotes* L. (also known as Kiambang, a floating aquatic plant) as a phytoremediation agent (an organism that removes pollutants from the environment) for extracting Iron (III) (the trivalent, oxidized form of iron) from synthetic wastewater (water with artificially added contaminants). The experiment was conducted in batch reactors (containers where reactions occur in set amounts) under controlled conditions, with modifications to the number of plants and contact length (the duration plants are exposed to contaminated water) to evaluate the effectiveness of iron removal. Iron concentrations were monitored spectrophotometrically (by measuring the amount of light absorbed by sample solutions) over time, and the phytoremediation kinetics (the rate and mechanism of pollutant removal) were investigated using zero, first, and second-order kinetic models (mathematical approaches to describe how quickly reactions occur). Results indicated that *Pistia stratiotes* L. was highly effective at reducing Fe (III) levels, achieving removal efficiencies exceeding 99% under optimal conditions-specifically with 10 plants and 5 days of contact time. Kinetic analysis indicated that the second-order model provided the best fit, suggesting a chemisorption-dominated process (removal primarily involves chemical bonding between the plant and iron ions). These findings emphasize the potential of *Pistia stratiotes* L. as a green and efficient solution for Fe (III) removal from wastewater and offer significant insight into optimizing phytoremediation system design for industrial applications.

Keywords
Fe(III), Heavy Metals, Phytoremediation, *Pistia stratiotes* L

Received: 24 June 2025, Accepted: 3 March 2026
https://doi.org/10.26554/ijems.2026.10.2.79-89

1. INTRODUCTION

The persistence of heavy metals and organic contaminants in aquatic environments poses a significant threat to ecosystem stability and human health. These pollutants are known to be associated with mutagenic, teratogenic, and carcinogenic effects (Obinnaa and Ebere, 2019). Among various contaminants, heavy metals are particularly concerning due to their nonbiodegradability and tendency to bioaccumulate in soft tissues, where they cannot be metabolized by the human body, leading to toxic effects (Yao et al., 2023). Iron (Fe) is one of the heavy metals frequently detected in industrial effluents. While iron is an essential micronutrient required for various physiological functions in living organisms, its excessive accumulation in the environment can exert toxic effects, disrupting biological processes and posing ecological risks (Oktaviani et al., 2020). The dual role of iron-as both a vital element and a potential contaminant-highlights the importance of monitoring its concentration in industrial wastewater. Therefore, it is essential to treat industrial wastewater before discharge to minimize its detrimental effects. Numerous technologies have been developed for this purpose, including adsorption (Budihardjo et al., 2021; Sawali et al., 2024), photocatalysis (Hidalgo-Carrillo et al., 2021; Rakanović et al., 2022), and coagulation–flocculation methods (Budihardjo et al., 2021; Pangeran et al., 2023). In addition, recent studies have demonstrated the potential of membrane-based technologies for wastewater treatment (Asif et al., 2021; Huang and Xu, 2006; Lou et al., 2020; Pan et al., 2017) as well as the effectiveness of combined coagulation–membrane filtration processes, particularly for treating laundry wastewater (Šostar-Turk et al., 2005). Among these treatment strategies, phytoremediation (the use of specific plants or organisms to clean up contaminated water or soil) has attracted attention due to its cost-effectiveness and environmentally friendly approach to reducing pollutant concentrations (Pang et al., 2023). Phytoremediation refers to a green technology that employs plants, often in partnership with beneficial bacteria or fungi (microorganisms), to absorb, accumulate, and detoxify (remove the harmful effects of) contaminants from polluted water (Oktaviani et al., 2020).

Several studies have demonstrated the effectiveness of aquatic plants such as water lettuce (*Pistia stratiotes* L.), water hyacinth (*Eichhornia crassipes*), and duckweed (*Lemna minor*) in reducing heavy metal concentrations in wastewater (Al-Baldawi et al., 2022; Haeril et al., 2024; Ntakiyiruta et al., 2022; Tang et al., 2020). In the present study, *Pistia stratiotes* L. is selected as the phytoremediation agent due to its promising capacity for heavy metal uptake. Kiambang (*Pistia stratiotes* L.) is an aquatic macrophyte widely found in tropical and subtropical freshwaters (Tang et al., 2020; Zou et al., 2018).

Kiambang (*Pistia stratiotes* L.) has been reported to effectively remove a broad spectrum of heavy metals, including iron (Fe), manganese (Mn), chromium (Cr), zinc (Zn), lead (Pb), and copper (Cu), particularly from wastewater streams and contaminated water bodies (Ergönül et al., 2020; Haeril et al., 2024; Rodrigues et al., 2020; Tang et al., 2020). Previous studies have demonstrated its capacity to reduce Fe concentrations in bauxite tailings wastewater, with Fe removal efficiencies of 37.3%, 53.1%, and 64.0% when using *Pistia stratiotes* with root lengths of 10 cm, 15 cm, and 20 cm, respectively (Ayani, 2022). Furthermore, recent research has shown that *Pistia stratiotes* L. can remove up to 89% of Fe and Mn, and significantly reduce other water quality parameters such as BOD, COD, phosphate, DO, ammonia, nitrite, and nitrate, achieving removal efficiencies of up to 99% (Wibowo et al., 2023).

Several studies have reported the potential of *Pistia stratiotes* L. as an effective phytoremediation agent for removing various heavy metals from contaminated water, including iron. However, most previous studies have mainly emphasized removal efficiency under specific conditions or focused on individual operational parameters (such as only changing the number of plants or only adjusting contact time), while paying limited attention to how key operational variables collectively influence the removal behavior and kinetic characteristics (how quickly and in what manner the removal happens) of the phytoremediation process. Therefore, this study aims to systematically investigate the phytoremediation of Fe(III) using *Pistia stratiotes* L. by evaluating the combined effects of contact time (how long the plants are in the water) and plant number on removal efficiency and kinetic behavior (the way and speed at which Fe(III) is removed). The novelty of this work lies in integrating operational parameter analysis (studying several variables at once) with kinetic modeling (predicting how the removal happens over time) to provide mechanistic insight into Fe(III) uptake (understanding the scientific processes involved), which is essential for improving process understanding and supporting the design and optimization of phytoremediation systems for wastewater treatment. Based on these findings, this study uses *Pistia stratiotes* L. to reduce Fe(III) in wastewater. The experimental design varies the number of plants and contact time to evaluate phytoremediation effectiveness under different conditions.

2. EXPRIMENTAL SECTION

2.1 Materials

In addition to distilled water and Kiambang (*Pistia stratiotes* L.), a phytoremediation plant from Makarti Jaya District, Morowali, Central Sulawesi, this research used Pro-Analyst chemicals from Merck (Germany): Ferro Ammonium Sulfate (FAS), Iron (III) Chloride ($FeCl_3$), Hydrochloric Acid (HCl), Sulfuric Acid (H_2SO_4), Potassium Thiocyanate (KSCN), Potassium Permanganate ($KMnO_4$), and Oxalic Acid ($C_2H_2O_4$). Fe (III) levels were measured only with a Visible Spectrophotometer (ICEN IN-B046, China).

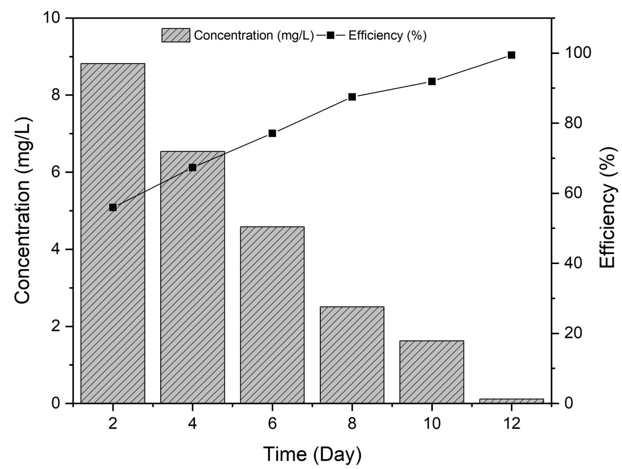

Figure 1. Effect of Contact Time & Efficiency (%) on Iron (III) Removal

2.2 Methods

This research begins with the basic stages and proceeds to the analysis and use of kinetic models in the phytoremediation process. The stages included Plant Species Selection, Plant Acclimatization, Iron Removal via Phytoremediation, Experimental Analysis, and Kinetics of the Phytoremediation Process.

2.2.1 Plant Species Selection

The phytoremediation plant (Hyperaccumulator Plant) used is kiambang (*Pistia stratiotes* L.), which meets several criteria, such as growing well in its natural habitat and having a plant size of 5-15 cm with 8-12 petals.

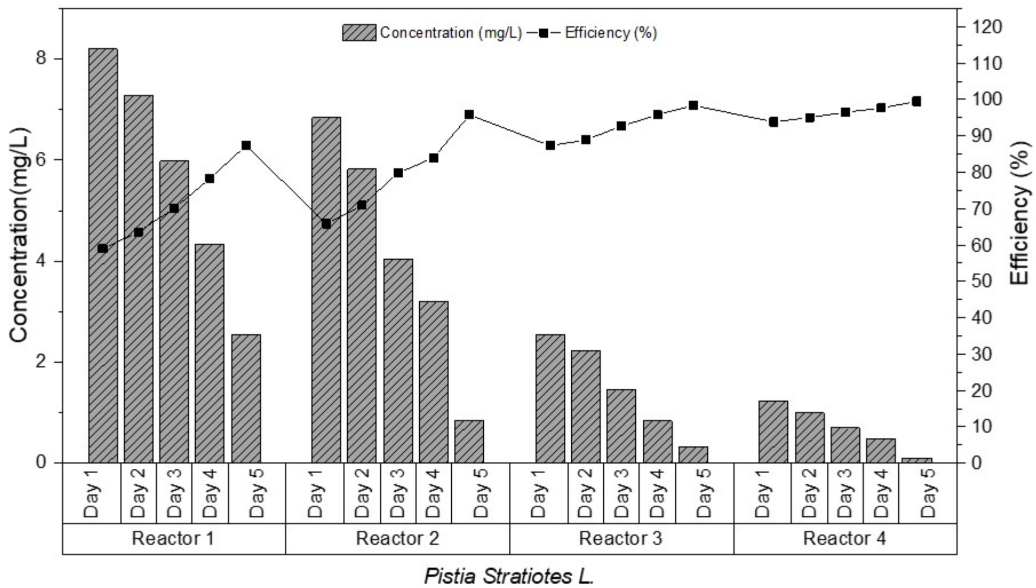

Figure 2. Effect of Number of Plants & Efficiency (%) on Iron (III) Removal

2.2.2 Plants Acclimatization

A total of reactors were prepared for batch operation using a pre-customized reactor model. The plastic reactor is 140 × 110 × 50 mm, as shown in Figure 1, with a single zone. However, the reactors were filled with a mixture of plant-origin habitat water and tap water for 7 days, until the plants had new shoots and non-yellowing petals.

2.2.3 Fe (III) Removal with Phytoremediation Process

Artificial wastewater is produced by dissolving various iron (III) chloride ($FeCl_3$) materials at a concentration of 20 mg/L. A total of 5 liters of wastewater samples were poured into each reactor. Moreover, the procedure for adding *Pistia stratiotes* L. to the reactor and contacting it with wastewater samples is carried out slowly to account for variations in the number of plants; for variations in contact time, plants are placed until they cover the entire surface of the sample. Wastewater samples are collected over 10 days and analyzed for Fe(III) removal. The method uses six reactors, divided into two distinct groups. This study was designed to evaluate the effects of contact time (the time plants remain in contact with wastewater) and plant number on Fe(III) removal using identical batch reactors. All reactors were operated under the same conditions, including initial Fe(III) concentration, solution volume, and reactor material, to ensure that observed differences were primarily related to the presence and quantity of plants.

A control reactor without plants was not included in this experiment. Therefore, the contribution of physicochemical processes, such as precipitation or adsorption at reactor surfaces, cannot be ruled out entirely. However, the clear dependence of Fe(III) removal on contact time and plant number suggests that plant-mediated uptake by *Pistia stratiotes* L. played a major role in the removal process. This limitation is acknowledged, and future studies will include control reactors to better distinguish phytoremediation effects from abiotic removal mechanisms.

2.2.4 Experimental Analysis

Total iron content in wastewater samples was analyzed using procedures described by Sirotiak et al. (2014). The iron content of wastewater removed by plants through roots and leaves will then be analyzed using a visible spectrophotometer at 500 nm. The Fe(III) removal efficiency was calculated by comparing the initial and final concentrations, as expressed in the Equation (1).

$$\%\ \text{efficiency} = \frac{C_0 - C_t}{C_0} \times 100\% \tag{1}$$

C_0 is the initial concentration of Fe (III) in wastewater samples. C_t is the final concentration of iron in the sample.

2.2.5 Study Kinetics

The phytoremediation process utilizing *P. stratiotes* L. was assessed by a kinetic model. The application of kinetic models in this process is a fundamental element for understanding the behavior observable within a system (López-Luna et al., 2019). The examination of the kinetics of heavy metal removal from water is a crucial endeavor for predicting the efficacy of the employed technology. The proposed kinetic model includes three basic models commonly used in previous studies, and its model-matching results are consistent with those presented by Samal and Trivedi (2020). This study has validated it with experimental data. Three basic

Table 1. Plant Condition Changes with Contact Time

Day	Plant Condition	Description
2		Discoloration in the petals; some areas appear yellow and dry.
4		The petals turn yellow, and decay begins in some areas. The roots begin to fall off.
6		Decay and drying of petals; root detachment observed.
8		Conditions tend to be similar to the previous day.
10		Growth begins to improve, characterised by new petal formation. However, rotting of older petals continues.
12		New petal growth improves further, while some old petals continue decaying.

kinetics models, namely zero-order, first-order, and second-order, were formulated to describe the process of heavy metal uptake and evaluate the behavior of the Floating Vegetated System process, followed by complete degradation through plant enzymes. The use of differential equations is advised, as demonstrated in Equations (2),(3), and (4).
Zero-Order Kinetic Model :

$$C_{Out} - C_{In} = kt \tag{2}$$

First-Order Kinetic Model:

$$\frac{C_{Out}}{C_{In}} = -k.t \tag{3}$$

Second-Order Kinetic Model:

$$\frac{1}{C_{Out}} = k.t + \frac{1}{C_{In}} \tag{4}$$

Where,

C_{In} = Influent heavy metals concentration at time t, mg/L
C_{Out} = Effluent heavy metals concentration at time t, mg/L
k = kinetic rate constant, day^{-1}
t = sampling time, day

Additionally, a sum-of-squares error (SSE) analysis was performed to assess the appropriate kinetic model for this system. The appropriate kinetic model is identified by the minimum sum of squared errors (SSE), which serves as a criterion for the optimal model because it yields the lowest error relative to the experimental data (Haeril et al., 2024). The sum of squared errors (SSE) is a statistical method used to quantify the overall discrepancy between the observed and attained values (Nainggolan et al., 2019). This function can be expressed by the subsequent Equation (5):

$$SSE = \sum_{i=1}^{n} (qt_{experiment} - qt_{prediction})^2 \quad (5)$$

Where, qt experimental is the concentration of Fe (III) resulting from the experiment. While qt prediction is the Fe (III) concentration calculated using the previously proposed kinetics model.

3. RESULT AND DISCUSSION

3.1 Interpretation of Plant Condition Changes in the Phytoremediation Process

The phytoremediation procedure using *P. stratiotes* L. demonstrated significant effects on plant visual and physical condition, depending on contact time and the number of plants used. Before the observation method was carried out, a plant species selection and acclimatization process were performed, which took 7 days. The acclimatization process was terminated because the plants had adjusted to the environment, as demonstrated by blossoming leaves and the absence of yellowing. This acclimatization method is intended to help plants adjust to the new environment and to re-strengthen the roots cut and wounded during the plant-collecting process (Ayani, 2022). Then, observations were conducted for 12 (Twelve) Days by documenting visual changes in the petals and roots of plants exposed to the wastewater. Based on observations of changes in plant conditions, Tables 1 and 2 are provided.

Based on Table 1, observations were done in a phytoremediation tank, including 2 (Two) plants with the same relative size of 15 cm and the number of petals 8-12, and a contact duration of 12 days. The goal of this research was to assess the influence of plant number and contact duration on reducing the concentration of the heavy metal Fe(III) in wastewater. The findings obtained were that the plants had considerable physical changes, where on days 2-8, it was noted that certain plant petals suffered yellowing and drying slowly. Even some petals deteriorated within 8 days. However, on days 10 & 12, there were indications of recovery, especially the development of new petals that formed slowly, demonstrating the plants' capacity to adjust to liquid waste beyond the first crucial period. Table 2 presents observations of variations in the number of plants in contact, collected over 5 days in 4 reactors. Each reactor comprises 4 plants, 6 plants, 8 plants & 10 plants, with plant diameters ranging from 5 to 15 cm, and 8 to 12 petals. Observations indicated that physical changes were not particularly noticeable. This implies that plants' initial reaction to wastewater tends to be steady, as evidenced by their remaining green and healthy. However, on days 4 & 5, visible changes were detected in plants that started to turn yellow on the petals in virtually all reactors, demonstrating that, despite the number of plants, which might mitigate the detrimental impacts of waste, medium-term exposure can still induce physiological stress. The data obtained for all variables indicate that *P. stratiotes* L. has potential as a hyperaccumulator plant for phytoremediation, but additional studies are required to determine optimal contact time and plant density to assess its efficacy.

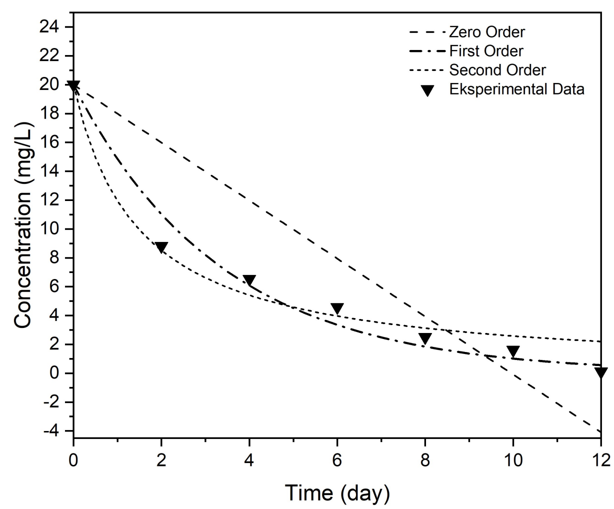

Figure 3. Kinetics Model of Zero, First, & Second Order on Variation of Contact Time

3.2 Effect of Contact Time on Fe (III) Removal

This study aims to examine the influence of contact time on the effectiveness of *Pistia stratiotes* L. in removing heavy metals from wastewater and to identify the optimal contact duration for this phytoremediation process. The experiment was conducted over 12 days, with sampling carried out every 2 days, using two *P. stratiotes* L. plants of identical size and characteristics. These plants were exposed to wastewater with an initial Fe(III) concentration of 20 mg/L in a reactor containing 5 L of liquid. The data indicate that the reduction in Fe(III) levels began at the start of the phytoremediation process and gradually decreased through day 12. On day 2, the concentration of Fe(III) had dropped to 8.81 mg/L, reaching a low of 0.11 mg/L on day 12-marking the most

Table 2. Plant Condition Changes with Number of Plants

Day	Plant Condition	Description
1		Plant growth is good and green across all petals.
2		The condition of the plants is still similar to the previous day.
3		Visually, the plant condition still appears good.
4		The plants begin to turn yellow in some parts of the petals.
5		Plant growth begins to decline, characterised by increased yellowing of the petals.

effective point of metal absorption by the plants. The absorption efficiency increased with increasing contact time; the longer the exposure, the more heavy metals were absorbed by the plant roots. However, this efficiency also depends on factors such as plant size and quantity, as well as the wastewater's initial concentration and volume. The process by which plants degrade pollutants in wastewater is called rhizofiltration. Rhizofiltration is one of the mechanisms of pollutant absorption in the phytoremediation method (Ali et al., 2020).

The method The method *P. stratiotes* L. plants remove heavy metal Fe (III) via the roots, where the roots will absorb all pollutants and transmit these contaminants to other sections of the stem and finish up in the leaves (Ali et al., 2020; Haeril et al., 2024; Khan et al., 2025). It contains a long, hanging root-biofilm network that serves as a naturally active surface for chemical and physical processes, such as filtration and trapping (Ali et al., 2024). Previous research by Coelho et al. (2023) provides additional insight into the life cycle and degradation processes of contaminants in wastewater, carried out by *P. stratiotes* L. The study shows that iron accumulation in root tissue reaches a significant level and that plants can continue to grow in an environment with high heavy-metal exposure. In contrast to previous studies, this study focuses on the ability of *P. stratiotes* L. plants to absorb heavy metal Fe (III) by examining the effect of the number of plants and the duration of contact time on the effectiveness of the phytoremediation process, then evaluating these operational parameters and taking a quantitative approach with kinetics model analysis as practical information in designing phytoremediation process systems for industrial wastewater treatment.

3.3 Effect of Number of Plants on Fe (III) Removal

The number of plants significantly affects the reduction of Fe (III) levels in nickel industrial waste, as a greater number increases the root surface area available for heavy metal absorption, thereby accelerating the phytoremediation process. This research comprised four reactors, each containing 4, 6, 8, and 10 plants with comparable specifications. Sampling for analysis was conducted daily for a period of five days, maintaining identical conditions throughout each reactor, such as an effluent concentration of 20 mg/L and an effluent volume of 5 liters in each reactor. The study's findings indicated a considerable reduction in waste concentration throughout the reactor over time. On the first day, the waste concentration decreased from 8.20 mg/L to 1.23 mg/L across the whole reactor. fluent content decreased significantly, from 2.53 mg/L to 0.106 mg/L. The best reduction in waste concentration is observed in reactor 4, with each drop occurring sequentially over 5 days: 1.23 mg/L, 0.99 mg/L, 0.69 mg/L, 0.48 mg/L, and 0.106 mg/L. The overall results for this variable are shown in Figure 2. The substantial drop in Fe (III) waste content is because

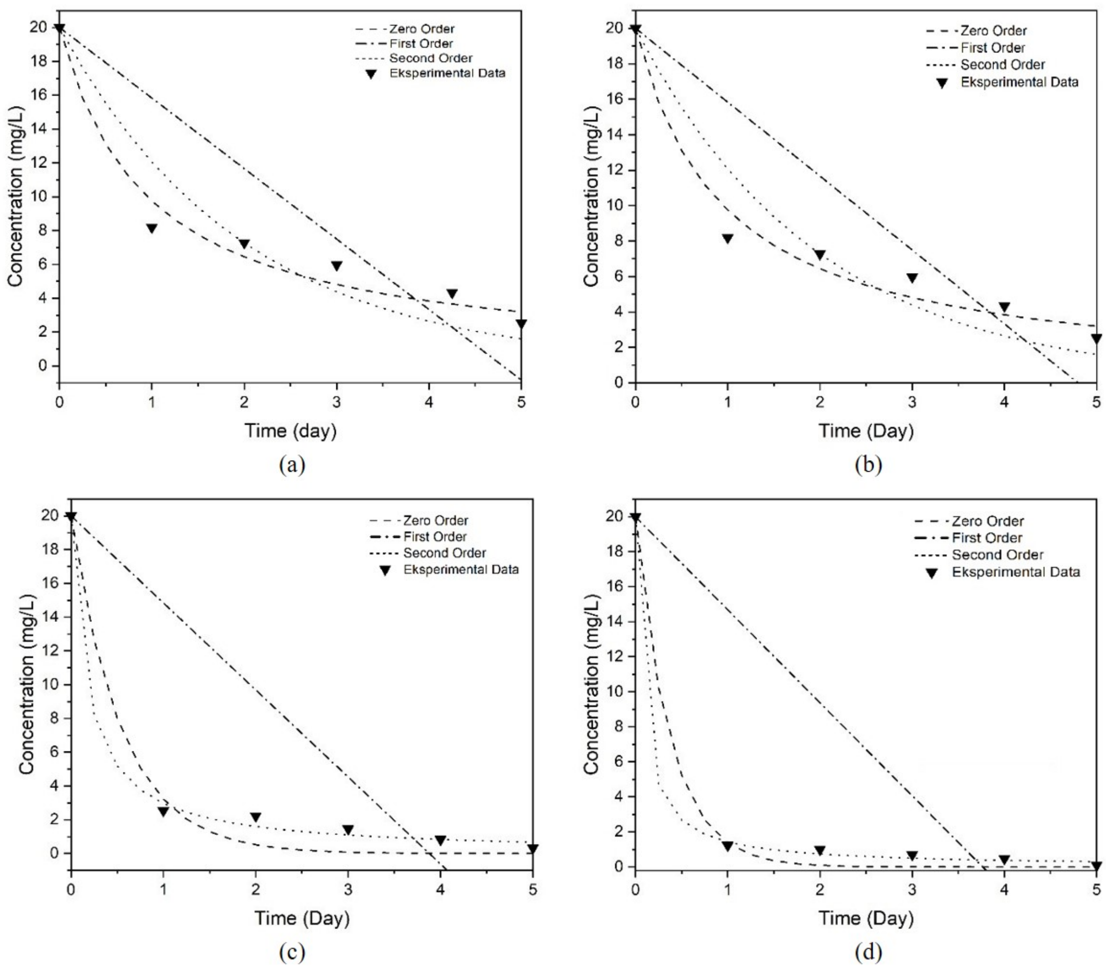

Figure 4. Kinetics model of Zero, First, & Second Order on Variation the Number of Plants

Table 3. Kinetic Parameters of Variation Contact Time

Parameter	Kinetic Models		
	Zero Order	First Order	Second Order
k (day^{-1})	2.0085	0.2977	0.0337
SSE	114.96	7.5960	7.3881

reactor 4 comprises 10 plants that enable the absorption process of heavy metals to run considerably quicker than other reactors, so that the phytoremediation process runs faster (Khan et al., 2025; Ratna and Slamet, 2020; Samal and Dash, 2024). *P. stratiotes* L. demonstrates the capacity for growth at elevated heavy metal concentrations of up to 3 mg/L, and the associated relative treatment efficiency indices (RTEI) indicate that the plant is appropriate for phytoremediation applications (Zahari et al., 2021). The hypertolerant characteristics of these plants facilitate the natural absorption of contaminants via phytoextraction and rhizofiltration (Oktaviani et al., 2020).

3.4 Efficiency of Fe (III) Removal

The efficiency reached 99.41% on day 12, while the variation in the number of plants was 99.46% on day 5 (reactor 4), resulting in the largest increase in efficiency. This is due to a drop in effluent concentration from 20 mg/L to 0.106 mg/L on day 5, with 10 plants. The substantial decline in levels demonstrates that the phytoremediation process is functioning extremely efficiently, with an efficiency exceeding 99%. The determination of efficiency in the phytoremediation process using *P. stratiotes* L. as a hyperaccumulator plant aims to evaluate the capacity of *P. stratiotes* L. plants to remove heavy metals from contaminated sites, such as wastewater from the nickel manufacturing process. Through the effi-

Table 4. Kinetic Parameters of Variation the Number of Plants

Parameter	Zero Order	First Order	Second Order
Reactor 1			
k (day^{-1})	4.1682	0.5058	0.0526
SSE	92.169	21.184	5.1232
Reactor 2			
k (day^{-1})	4.5878	0.6991	0.0800
SSE	120.08	16.920	4.3550
Reactor 3			
k (day^{-1})	5.1565	6.0507	0.2866
SSE	255.83	1.8268	0.8121
Reactor 4			
k (day^{-1})	5.3129	2.6810	0.6488
SSE	309.92	1.5593	0.1929

Table 5. Comparison of Fe Removal Performance Using *Pistia stratiotes* L. with Previous Studies

Study	Target Metal	Initial Concentration (mg/L)	Key Operational Parameters	Removal Efficiency (%)	Kinetic Model
(Ayani, 2022)	Fe	–	Root length variation	37–64	Not reported
(Wibowo et al., 2023)	Fe, Mn	–	Batch system	Up to 89	Not reported
(Haeril et al., 2024)	Cr(VI)	50	Contact time	Up to 54	Second-order
This study	Fe(III)	20	Contact time and plant number	>99	Second-order

ciency value, the plant's performance as a phytoremediation agent can be directly assessed and used as an indicator of success and a starting point for evaluating the feasibility of scaling up the phytoremediation process.

3.5 Kinetics of the Phytoremediation Process

The kinetics model of a process plays an important role in the initial concentration of Fe(III). Consistently, reductions in contaminant levels decrease as reaction time increases (Samal and Dash, 2024; Samal and Trivedi, 2020). The aim of using the kinetic model in this research is to determine the mechanism by which a plant removes heavy metals from wastewater. This section also examines the rate and mechanism of plant phytoremediation. Both objectives may serve asa basis for determining the most acceptable model for developing a more effective and efficient phytoremediation system. To better understand the mechanism governing Fe(III) removal, the influence of operational parameters on the system's kinetic behavior is discussed. The removal of Fe(III) by *Pistia stratiotes* L. was clearly influenced by both contact time and plant number. Increasing contact time enhanced removal efficiency due to continuous rhizofiltration and gradual bioaccumulation of Fe(III) on root surfaces. At the early stage, metal uptake occurred rapidly due to the availability of active binding sites, whereas prolonged exposure led to a slower uptake rate as these sites became partially saturated. Similarly, higher Fe(III) removal observed with an increasing number of plants can be attributed to the larger total root surface area available for metal binding. A higher plant density provides more adsorption and absorption sites and distributes the metal load more evenly, thereby improving phytoremediation performance. Visual changes in plant condition during the experiments further indicate active metal uptake and physiological stress associated with Fe(III) accumulation.

The kinetic analysis supports these observations, as the second-order model best described the experimental data, suggesting that Fe(III) removal was governed by chemical interactions between metal ions and functional groups on the roots. Although the absence of a control reactor limits this study, the consistent dependence of Fe(III) removal on operational parameters indicates that plant-mediated uptake was the dominant removal mechanism. The acquired experimental data is input into the several suggested linear equations, as shown in Tables 3 and 4, which represent the kinetic parameters of each variation. After analyzing the suggested model, the rate constant (k) ranged from 0.037 day-1 to 6.05 day-1, while the SSE ranged from 0.192 to 309.92. Based on the data, the value of k for day variation is larger in the zero-order model, with a larger SSE, than in the other two models. This suggests that the model is insufficient to represent events in the phytoremediation process, even though the expected heavy metal removal rate is higher.

The acceptable model in this variation is second-order, with a k value of 0.033 day-1 and the least SSE of 7.388. Meanwhile, for changes in the number of plants, there is a similar pattern in the acquisition of k values across reactors: an increase in the number of plants in each reactor leads to larger k values for zero-order reactions. Similarly, the acquisition of k values for order 2, where the greatest k value is reached by reactor 4, which is 0.648 day-1. For the first order, the maximum k value is produced by reactor 3, namely 6.05 day-1. The least SSE value, averaged across the whole reactor, is obtained with the second-order kinetics model. This demonstrates that the most suitable kinetics model is second-order, even if the first-order kinetics model is quite excellent. However, the second order has greater accuracy, as indicated by the lowest SSE. The sum of Squared Errors (SSE) is a commonly used mathematical technique for quantifying the overall discrepancy between the actual and attained values.SSE can indeed be utilized to assess the efficacy of previously employed prediction models and serves as a research benchmark for identifying the ideal prediction model (Nainggolan et al., 2019). The value of the kinetic rate constant (k) represents the reaction rate of a system. From the results, it is clear that the zero-order value of k indicates that the rate of Fe(III) reduction is continuous, whereas the first-order value shows that the rate of decline remains proportional over time. Meanwhile, the second order shows that the kinetics in this process run relatively slowly per unit concentration. The second-order model indicates that Fe(III) binding is likely controlled by a chemical binding mechanism in the roots (Chemisorption) (Hubbe et al., 2019). The suitability of the second-order kinetic model suggests that Fe(III) uptake may involve chemical interactions between metal ions and functional groups on the root surface, a behavior commonly associated with chemisorption. However, direct confirmation of the binding mechanism would require further characterization analyses, such as FTIR or SEM–EDS.

In the meantime, a comparison can be made between the predicted concentration value per minute and the concentration derived from the experimental data. Figure 3 clearly shows the intermediate between the predicted values and the experimental data for the variation in contact time, indicating that the predicted concentration of Order 2 aligns more closely with the experimental data. Figures 4 (a-d) represent the kinetic fitting results for reactors containing 4,6,8, and 10 plants, respectively. These figures illustrate the relationship between predicted concentrations and experimental data concentrations across varying numbers of plants, revealing a consistent pattern between the two sets of values. The analysis indicates that the 2nd-order kinetics model most accurately represents the phytoremediation process, as evidenced by its smallest SSE. To further highlight the significance and positioning of the present study, a comparison with relevant previous studies on Fe removal using *Pistia stratiotes* L. is presented in Table 5. Based on the comparison presented in Table 5, this study adds value by correlating operational parameters with kinetic behavior, thereby strengthening the understanding of Fe(III) phytoremediation using *Pistia stratiotes* L.

4. CONCLUSIONS

The overall results of the study show that the phytoremediation process using *P. stratiotes* L. and plants can be used as an environmentally friendly alternative for removing heavy metal content from wastewater. This is evident from the removal of heavy metals, which reached 99.46% with 10 plants and a contact time of 5 days. The most suitable kinetic model for this process is the second-order model, with reaction rate constants ranging from 0.0337 day-1 to 0.6488 day-1 and an SSE of 0.1929.

5. ACKNOWLEDGEMENT

The authors express their deepest gratitude to Politeknik Industri Logam Morowali for providing access to facilities during the implementation of this research. Access in the form of laboratory facilities, instrument tools, and a conducive environment so that this research can be carried out without a significant impact.

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