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# Recovery of Aluminum and Iron from Coal Fly Ash Waste Using Microwave Assisted Extraction (MAE) for Coagulant

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## ABSTRACT

Coal fly ash is an industrial waste containing aluminium and iron with potential for reuse as coagulant materials. This study aimed to recover aluminium and iron from coal fly ash using Microwave-Assisted Extraction (MAE) with hydrochloric acid and to evaluate their application in textile wastewater treatment. Variations in HCL concentration (1-5 M) and extraction time (30-50 minutes) were examined to determine optimal conditions. The result showed that the highest recovery was achieved at 5 M HCl for 40 minutes, with aluminium and iron recoveries of 48.4% and 78%, respectively. The extracted aluminium and iron were successfully used as coagulants in textile wastewater treatment, resulting in significant reductions in colour to 30 Pt-Co, turbidity to 26.9 NTU, and TSS to 46 mg/L, while maintaining a stable pH of 6. All treated wastewater parameters complied with the applicable discharge standards. These findings demonstrate that MAE is an effective and promising approach for recovering aluminium and iron from coal fly ash and producing sustainable coagulant for industrial wastewater treatment.

### Contribution to Sustainable Development Goals (SDGs):

SDG 6: Clean Water and Sanitation

SDG 9: Industry, Innovation, and Infrastructure

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

SDG 15: Life on Land

## 1. INTRODUCTION

### 1.1. Research Background

The urgency of addressing coal fly ash waste stems from its significant environmental and health impacts. Indonesia, as one of the largest coal producers in Southeast Asia, generates approximately 750 tons of fly ash annually from power plant operations, much of which is improperly disposed of, leading to soil and water contamination, air pollution, and potential health risks, including respiratory issues [1]. This waste, rich in valuable oxides such as aluminium and iron, represents a missed opportunity for resource recovery. Moreover, the growing demand for clean water, exacerbated by industrial activities such

as textile manufacturing, underscores the need for sustainable coagulants in wastewater treatment. Traditional coagulants like alum are costly and environmentally taxing. At the same time, fly ash-based alternatives offer a low-cost, eco-friendly solution that aligns with global efforts to reduce waste and promote circular economy principles.

The problem formulation centers on the inefficiencies of conventional extraction methods for recovering aluminium and iron from fly ash. Traditional techniques, such as heat-assisted leaching, are energy-intensive, time-consuming, and yield low recovery rates, often below 30% for aluminium and iron oxides [2]. This limits the scalability and economic viability of using fly ash as a coagulant source. Additionally, textile wastewater, characterized by high turbidity, color, and suspended solids,



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poses challenges for treatment, as it often exceeds regulatory standards and contributes to water scarcity. The lack of optimized, rapid extraction methods hinders the valorization of fly ash, perpetuating environmental degradation and increasing reliance on synthetic chemicals.

The clear objectives of this study are to optimise the recovery of aluminium and iron cations from coal fly ash using Microwave Assisted Extraction (MAE) with hydrochloric acid by varying acid concentration and extraction time, and to evaluate the effectiveness of the extracted coagulants in treating textile wastewater. Specifically, the study aims to determine the optimal conditions for maximum cation recovery and to assess reductions in key wastewater parameters, including colour, turbidity, and total suspended solids (TSS).

This research is highly relevant to environmental engineering and sustainable chemistry, particularly in the context of waste management and water treatment. It addresses the pressing need for innovative technologies in developing countries like Indonesia, where industrial waste and water pollution are critical issues. By focusing on MAE, a green extraction technique, the study contributes to advancements in resource recovery from industrial byproducts, supporting initiatives under the United Nations Sustainable Development Goals (SDGs), including SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Furthermore, it has practical implications for industries, offering a cost-effective alternative to conventional coagulants and promoting sustainable practices in textile manufacturing.

The scientific contribution of this study lies in providing empirical data on MAE optimisation for fly ash, demonstrating higher recovery efficiencies than traditional methods, and validating the use of recovered cations as effective coagulants. It fills a gap in the literature by integrating extraction optimisation into real-world wastewater treatment, potentially influencing policy and industry standards for waste valorisation. This work advances knowledge in microwave-assisted processes for mineral recovery, offering a foundation for further research into scalable, energy-efficient technologies for environmental remediation.

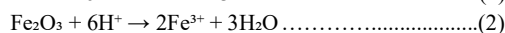
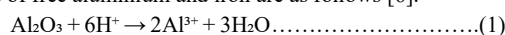
## 1.2. Literature Review

Coal fly ash, a byproduct of coal combustion, is characterised by its high silica, alumina, and iron oxide content, making it a potential source of coagulants for water treatment applications. Studies have highlighted the environmental challenges posed by improper fly ash disposal in Indonesia, where annual production reaches 750 tons, leading to contamination of soil and water resources [1]. Research by Safutra et al. (2017) emphasizes the potential of fly ash as a low-cost alternative to synthetic coagulants, noting its ability to bind colloidal particles and pollutants due to its oxide composition [2]. Furthermore, Utami et al. (2020) have explored the use of fly ash in wastewater treatment, demonstrating reductions in turbidity and colour. However, the recovery of specific cations, such as aluminium and iron, remains underexplored [3].

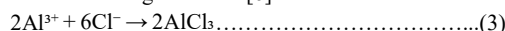
Conventional extraction methods for recovering aluminium and iron from fly ash, such as acid leaching with sulfuric acid, typically yield low recoveries, with reported values of 30.8% for aluminium and 16.96% for iron, due to prolonged processing times and high energy consumption. In contrast, Microwave Assisted Extraction (MAE) has emerged as a more efficient

technique, achieving up to 82.4% alumina recovery in just 30 minutes, as demonstrated by Ma et al. (2021) [4]. Daniswara et al. (2017) explain the mechanism of MAE, in which microwave energy induces ionic conduction and dipole rotation in the solvent, thereby enhancing mass transfer and the dissolution of metal oxides from the matrix [5]. This method not only reduces extraction time but also improves selectivity and energy efficiency compared to traditional heating methods.

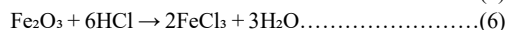
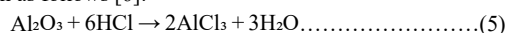
The mechanism of aluminium and iron extraction from coal fly ash using hydrochloric acid as a solvent is governed by heterogeneous reactions between the acid and oxide minerals that form the coal fly ash particle structure. The extraction process begins with the diffusion of  $H^+$  ions toward the particle surface, followed by reactions with metal oxides ( $Al_2O_3$  and  $Fe_2O_3$ ). The extraction reactions proceed irreversibly and are non-catalytic, in which metal compounds transfer from the solid phase to the liquid phase, forming dissolved metal ions ( $Al^{3+}$  and  $Fe^{3+}$ ). The release reactions of free aluminium and iron are as follows [6]:



Chloride ions stabilize the dissolved metal ion products in the form of soluble complexes such as  $AlCl_3$  and  $FeCl_3$  in solution, as shown in the following reactions [6]:



The overall reactions for the extraction process of aluminium and iron from coal fly ash using hydrochloric acid can be written as follows [6]:



The extraction reactions produce aluminium chloride and iron chloride, which can be utilized as coagulants in water treatment processes [6].

The recovered aluminum and iron cations, often in the form of chlorides, function effectively as coagulants by hydrolyzing in water to form hydroxide flocs that destabilize and aggregate suspended particles. Bolto and Gregory (2007) provide a comprehensive review of coagulation mechanisms, noting that iron-based coagulants are particularly effective in treating industrial wastewater with high organic content, such as textile effluents [7]. Recent studies, including Shi et al. (2024), have investigated the effects of acid concentration and extraction time on recovery rates, showing that higher concentrations and optimised durations yield better yields, with implications for scaling up the process [8]. Additionally, Ouadrhiri et al. (2025) have validated the use of fly ash-derived coagulants in real wastewater scenarios, achieving significant reductions in turbidity, colour, and total suspended solids, thereby aligning with regulatory standards [9].

Overall, the literature underscores the need for innovative extraction techniques, such as MAE, to maximise resource recovery from fly ash while addressing environmental concerns. However, gaps remain in optimising MAE parameters specifically for aluminium and iron recovery and in evaluating their coagulant performance across diverse wastewater types, such as textile effluents. This study builds on these findings by integrating MAE optimization with practical application, contributing to sustainable waste management and water treatment technologies

## 2. MATERIALS AND METHODS

### 2.1. Materials and Tools

Materials included coal fly ash from PT Sinar Indogreen Kencana Sidoarjo, textile wastewater from PT Pabrik Textil Kasrie Pasuruan, hydrochloric acid 37% and aquadest from CV Chemical Indonesia Multisentosa. The equipment system for the microwave-assisted extraction process is shown in Figure 1.

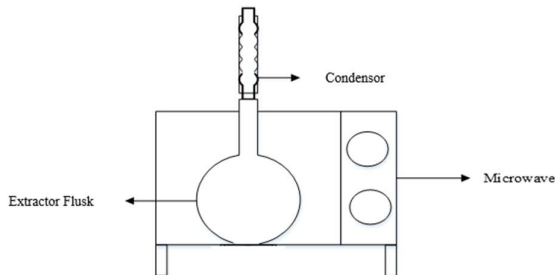


Fig. 1 Microwave Assisted Extraction Tool Series

### 2.2. Methods

#### 2.2.1. Extraction process of aluminium and iron from coal fly ash using microwave-assisted extraction (MAE)

The coal fly ash was first dried in an oven at 100°C until a constant weight was achieved to remove residual moisture. The dried material was then ground and sieved to obtain particles passing through a 200-mesh sieve. A total of 50 g of the prepared fly ash was mixed with 250 ml of HCl solution and subjected to a solid-liquid extraction process using microwave assistance at 300 W. After the extraction, the slurry was filtered using filter paper to separate the liquid filtrate from the solid residue. The filtrate was subsequently concentrated by evaporation on a hot plate stirrer until a concentrated product was obtained. The concentrated solution was then filtered again to remove any remaining solids, and the resulting residue was dried in an oven to a constant weight. The dried residue was analysed by X-ray fluorescence (XRF) to determine the aluminium and iron contents, and the percentage recovery of each metal was calculated from the analytical results.

#### 2.2.2. Coagulation process

The coagulation experiment was conducted using textile wastewater, with initial pH, color, turbidity, and TSS measured to obtain baseline data. A volume of 300 ml of textile wastewater was placed in a beaker, and the coagulant obtained from extraction process was added at a dosage of 150 mg/L. The mixture was subjected to rapid mixing at a stirring speed of 150 rpm for 3 minutes, followed by slow mixing at 100 rpm for 2 minutes to promote floc formation. The treated wastewater was then allowed to settle for 15 minutes to enable the formed flocs to sediment. After the settling period, the supernatant was collected, and the final pH, colour, turbidity, and TSS were analysed to evaluate coagulation performance.

## 3. RESULT AND DISCUSSION

### 3.1. Fly Ash Characterization

Coal fly ash waste was analyzed using XRF (X-Ray Fluorescence) at the Energy and Environment Laboratory, DKPU ITS, to determine the initial levels of aluminium and iron in the coal fly ash waste. Based on XRF analysis, coal fly ash has three main components: iron (46.05%), silica (28%), and aluminium (6.2%). XRF analysis showed initial compositions in Table 1.

Table 1: Fly Ash Composition using XRF analysis

Component	Initial Weight Content (%)
Aluminum	6.2
Iron	46.05
Silica	28
Sulfur	3.7
Potassium	3.69
Calcium	7.31
Titanium	1.6
Vanadium	0.079
Chromium	0.046
Manganese	0.14
Nickel	0.4
Copper	0.27
Zinc	0.15
Strontium	0.72
Barium	0.76
Rhenium	0.68

#### 3.2. Effect of HCl Concentration and Extraction Time on the Aluminium Recovery Percentage

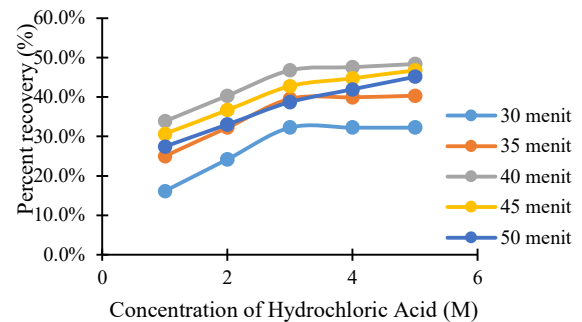


Fig. 2 Graph of the Effect of Hydrochloric Acid Concentration on the Percentage of Aluminium Recovery at Various Times

Figure 2 shows that increasing the hydrochloric acid concentration enhances aluminium recovery at extraction times of 30, 35, 40, and 50 minutes. A significant increase in aluminium recovery is observed as the HCl concentration rises from 1 M to 3 M. However, further increases to 4–5 M result in slower recovery. This trend indicates that higher acid concentrations provide more  $H^+$  ions to react with aluminium in readily soluble phases, thereby increasing the extraction rate. Once most of the amorphous aluminium has dissolved, further increases in acid concentration become ineffective due to diffusion limitations and the reduced reactivity of the remaining solid phases [10].

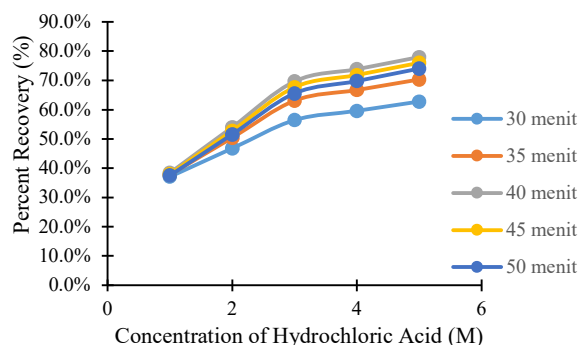
Extending the extraction time increases the contact between the solid material and the solvent, promoting the diffusion of  $H^+$

ions to break metal–oxide bonds and release  $\text{Al}^{3+}$  ions into the solution. During the initial extraction stage, the process is controlled by surface chemical reactions, resulting in a high dissolution rate due to the presence of open pores on coal fly ash particles.  $\text{H}^+$  ions can readily attack the Al–O bonds in the amorphous phase, whereas the acid-resistant mullite phase remains on the particle surface and gradually restricts ion diffusion. As the extraction proceeds, the dissolution rate decreases and becomes controlled by ion diffusion through the surface layer and particle pores. At this stage, the extraction rate is independent of solvent concentration and extraction time and is governed by diffusion kinetics [11].

The mineralogical form of aluminium is the main factor limiting recovery. Aluminium in the amorphous phase has unstable, disordered Al–O bonds, making it highly reactive toward acidic solvents. In contrast, crystalline aluminium in coal fly ash mainly exists as mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ), which possesses a highly stable aluminosilicate structure and strong resistance to acid attack. The dense Al–O–Si network in mullite hinders acid penetration, leaving a substantial portion of aluminium in the solid residue even under high acid concentrations and prolonged extraction times. Mullite is the most acid-resistant phase, and pretreatment methods such as thermal activation are required to enhance its reactivity toward acidic solvents [12].

In this study, the extraction process was conducted using the Microwave-Assisted Extraction (MAE) method at an HCl concentration of 5 M and an extraction time of 40 minutes, yielding aluminum recoveries of 48.4%, respectively. In comparison, [2] reported lower recovery values of 38.57% for aluminum using conventional leaching with 6 M HCl and an extraction time of 80 minutes. The improved extraction efficiency achieved by MAE can be explained by the application of microwave energy, which induces ionic conduction and dipole rotation. These mechanisms generate uniform internal heating, promote particle disintegration, open surface pores, and enhance mass transfer between the solvent and solid matrix. As stated by [13], microwave heating reduces diffusion resistance and increases solvent molecular mobility, thereby accelerating metal extraction and shortening extraction time by approximately 30–50% compared to conventional heating methods.

### 3.3. Effect of HCl Concentration and Extraction Time on the Iron Recovery Percentage



**Fig. 3** Graph of the Effect of Hydrochloric Acid Concentration on the Percentage of Aluminum Recovery at Various Times

Figure 3 presents the effect of hydrochloric acid concentration on iron recovery at extraction times of 30, 35, 40, and 50 minutes.

As with aluminium, an increase in hydrochloric acid concentration results in a higher iron recovery percentage. This trend indicates that higher acid concentrations provide a greater availability of  $\text{H}^+$  ions to react with iron-bearing phases, thereby enhancing the extraction rate. However, once most of the iron has been dissolved, further increases in HCl concentration no longer produce a significant improvement in recovery. Under these conditions, the extraction process becomes limited by ion diffusion and the reactivity of the remaining solid phases. This behaviour is consistent with the findings, which observed that increasing the acid concentration beyond the optimal condition does not further enhance iron recovery [10].

The effect of extraction time on iron recovery also follows a trend comparable to that observed for aluminium. Increasing extraction time initially enhances iron recovery by extending the contact between the solid particles and the acidic solvent. During this early stage, the extraction process is controlled by surface chemical reactions between  $\text{H}^+$  ions and iron oxides on the particle surface. As the system approaches equilibrium, the iron recovery percentage decreases, indicating a transition from surface reaction control to diffusion-controlled kinetics. In the later stage, ion diffusion through the product layer becomes the rate-limiting step, resulting in a reduced extraction rate. This two-stage kinetic behaviour is consistent with the model proposed by [14], in which the initial stage is governed by surface dissolution. In contrast, the final stage is controlled by diffusion through the formed product layer.

A direct comparison of aluminium and iron recovery highlights the influence of mineralogical characteristics on extraction behaviour. Iron exhibits a higher recovery percentage than aluminium due to its dominant mineralogical forms in coal fly ash, which are magnetite ( $\text{Fe}_3\text{O}_4$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ). These iron oxide phases possess relatively simple crystal structures and Fe–O bonds that are more easily protonated than the Al–O–Si bonds in mullite ( $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ), the primary crystalline aluminium phase. Hematite has a simple rhombohedral structure, while magnetite exhibits an inverse spinel structure, both of which are more reactive toward acidic solvents. As a result,  $\text{H}^+$  ions from HCl can readily attack and break Fe–O bonds, forming soluble species such as  $\text{FeCl}_2$  and  $\text{FeCl}$ . Both hematite and magnetite exhibit high dissolution rates in strong acids at moderate temperatures, owing to their relatively low activation energies. Consequently, increasing the HCl concentration effectively accelerates iron dissolution to an optimal point, beyond which the extraction process is limited by the diffusion of iron ions from within the particle matrix [14].

In this study, the extraction process was conducted using the Microwave-Assisted Extraction (MAE) method at an HCl concentration of 5 M and an extraction time of 40 minutes, yielding iron recoveries of 78%, respectively. In comparison, [2] reported lower recovery values of 44.95% for iron using conventional leaching with 6 M HCl and an extraction time of 80 minutes. The improved extraction efficiency achieved by MAE can be explained by the application of microwave energy, which induces ionic conduction and dipole rotation. These mechanisms generate uniform internal heating, promote particle disintegration, open surface pores, and enhance mass transfer between the solvent and solid matrix. As stated by [13], microwave heating reduces diffusion resistance and increases solvent molecular mobility, thereby accelerating metal extraction

and shortening extraction time by approximately 30–50% compared to conventional heating methods.

#### 3.4. Application of Aluminium Chloride and Ferric Chloride as Coagulants in Textile Wastewater

A clear difference is observed between the textile wastewater before and after coagulation. Before coagulation, the wastewater exhibited a deep bluish colour, indicating a high concentration of dye compounds. After coagulation with aluminium- and iron-based coagulants derived from fly ash extraction, the wastewater colour faded significantly and became clearer. In addition, a large number of relatively large flocs formed and settled to the bottom of the container, indicating successful destabilisation and aggregation of suspended particles and colloidal compounds through metal hydroxide floc formation during the coagulation–flocculation process.

The coagulation process was conducted using 250 mL of textile wastewater and 0.045 g of coagulant obtained under optimal extraction conditions, followed by rapid mixing at 150 rpm for 3 minutes, flocculation at 100 rpm for 2 minutes, and a settling period of 15 minutes. The dominant mechanisms involved charge neutralization by  $Al^{3+}$  and  $Fe^{3+}$  ions and the formation of metal hydroxide flocs capable of adsorbing suspended solids, dyes, and colloidal substances.

**Table 2** Textile Wastewater Parameters Before and After the Coagulation Process

Parameter	Before Coagulation	After Coagulation	Quality Standar	Unit
pH	6	6	6-9	
Color	135.8	30	200	Pt-Co
Turbidity	76.9	26.9	30	NTU
TSS	183	46	50	Mg/L

Before coagulation–flocculation, the textile wastewater did not comply with the discharge standards specified in the Regulation of the Ministry of Environment and Forestry No. 12 of 2025, with color, turbidity, and TSS values of 135.8 Pt-Co, 76.9 NTU, and 88 mg/L, respectively. However, the pH remained within the acceptable range (pH 6). After treatment, substantial reductions were observed, with color decreasing to 30 Pt-Co, turbidity to 26.9 NTU, and TSS to 46 mg/L, while the pH remained stable at 6. These results demonstrate that the Al- and Fe-based coagulants derived from fly ash effectively reduced key pollutant parameters to levels that meet regulatory standards (colour  $\leq$  200 Pt-Co, TSS  $\leq$  50 mg/L, and pH 6–9).

The high coagulation performance is attributed to the significant presence of  $Fe^{3+}$  (78%) and  $Al^{3+}$  (48.4%) ions, which promote the formation of  $Fe(OH)_3$  and  $Al(OH)_3$  flocs. Hydrolysis of  $FeCl_3$  yields large, porous  $Fe(OH)_3$  flocs with high surface area, thereby enhancing dye adsorption and sweep flocculation. Meanwhile,  $AlCl_3$  hydrolysis generates  $Al(OH)_3$ , which destabilizes colloids through charge neutralization. These mechanisms operate synergistically, with  $Al(OH)_3$  reducing interparticle repulsion and  $Fe(OH)_3$  enhancing particle entrapment, thereby improving overall coagulation efficiency [9]. Consequently, aluminium- and iron-based coagulants derived from coal fly ash under optimal extraction conditions (5 M HCl for 40 minutes) effectively reduce textile wastewater pollutants, thereby complying with national discharge standards.

## 4. CONCLUSION

The recovery of aluminium and iron from coal fly ash using the Microwave-Assisted Extraction (MAE) method was strongly affected by hydrochloric acid concentration and extraction time. The optimal conditions were achieved at an HCl concentration of 5 M and an extraction time of 40 minutes, yielding aluminium and iron recoveries of 48.4% and 78%, respectively. This confirms that a high acid concentration combined with sufficient extraction time enhances metal dissolution and recovery efficiency. The aluminum and iron rich extracts obtained under optimal conditions were successfully applied as coagulants for textile wastewater treatment. Significant reductions in color (135.8 to 30 Pt-Co), turbidity (76.9 to 26.6 NTU), and TSS (183 to 46 mg/L) were achieved, while pH remained stable at 6. These values comply with the wastewater discharge standards stipulated in the Regulation of the Ministry of Environment and Forestry of Indonesia No. 12 of 2025. Overall, MAE combined with appropriate extraction conditions shows strong potential for producing aluminum- and iron-based coagulants from coal fly ash, offering an effective and sustainable alternative for textile wastewater treatment while promoting the valorization of industrial waste.

## REFERENCE

- [1] E. R. Aida, S. Y. Lisha, and Y. Puty, "Pemanfaatan Limbah Abu Terbang Batubara (Fly Ash) Di Pltu Ombilin Sebagai Bahan Koagulan," *J. Pendidik. Teknol. Kejur.*, vol. 1, no. 3, pp. 125–131, 2018, doi: 10.24036/jptk.v1i3.2223.
- [2] Y. Safutra, B. Amin, and S. Anita, "Potensi Limbah Abu Layang (Coal Fly Ash) Sebagai Koagulan Cair Dalam Pengolahan Air Gambut," *Din. Lingkung. Indones.*, vol. 4, no. 2, p. 99, 2017, doi: 10.31258/dli.4.2.p.99-108.
- [3] N. F. Utami, S. M. Nurdianty, Sutanto, and U. Suhendar, "Pengaruh Berbagai Metode Ekstraksi Pada Penentuan Kadar Flavonoid Ekstrak Etanol Daun Iler (*Plectranthus Scutellarioides*)," *J. Ilm. Farm. Fitofarmaka*, vol. 10, no. 1, pp. 76–83, 2014.
- [4] Y. Ma, S. Stopic, B. Xakalash, S. Ndlovu, K. Forsberg, and B. Friedrich, "A cleaner approach for recovering Al and Ti from coal fly ash via microwave-assisted baking, leaching, and precipitation," *Hydrometallurgy*, vol. 206, pp. 1–10, 2021, doi: 10.1016/j.hydromet.2021.105754.
- [5] E. F. Daniswara, T. I. Rohadi, and Mahfud, "Ekstraksi Minyak Akar Wangi dengan Metode Microwave Hydrodistillation dan Soxhlet Extraction," *J. Tek. ITS*, vol. 6, no. 2, pp. 380–383, 2017.
- [6] A. Seidel and Y. Zimmels, "Mechanism and kinetics of aluminum and iron leaching from coal fly ash by sulfuric acid," *Chem. Eng. Sci.*, vol. 53, no. 22, pp. 3835–3852, 1998, doi: 10.1016/S0009-2509(98)00201-2.
- [7] B. Bolto and J. Gregory, "Organic polyelectrolytes in water treatment," *Water Res.*, vol. 41, no. 11, pp. 2301–2324, 2007, doi: 10.1016/j.watres.2007.03.012.
- [8] Y. Shi, F. Jiang, R. Wang, S. Yang, X. Zhu, and Y. Shen, "A mini review on the separation of Al, Fe and Ti elements from coal fly ash leachate," *Int. J. Coal Sci. Technol.*, vol. 11, no. 1, pp. 1–15, 2024, doi: 10.1007/s40789-024-00683-z.
- [9] F. El Ouadrhiri, E. A. M. Saleh, and A. Lahkimi, "From Mineral Salts to Smart Hybrids: Coagulation–Flocculation at the Nexus of Water, Energy, and Resources—A Critical Review," *Processes*, vol. 13, no. 11, pp. 1–38, 2025, doi: 10.3390/pr13113405.

- [10] J. C. Mahecha-Rivas, E. Fuentes-Ordoñez, E. Epelde, and J. F. Saldarriaga, "Aluminum extraction from a metallurgical industry sludge and its application as adsorbent," *J. Clean. Prod.*, vol. 310, pp. 1–11, 2021, doi: 10.1016/j.jclepro.2021.127374.
- [11] B. Zhao, Y. Guo, W. Wang, X. Wan, S. He, and T. Wang, "Study on Experimental Parameters of Alkali-Assisted Extraction of Aluminum from Fly Ash," *Materials (Basel)*, vol. 18, no. 7, pp. 1–24, 2025, doi: 10.3390/ma18071568.
- [12] S. O. Lee, T. Tran, Y. Y. Park, S. J. Kim, and M. J. Kim, "Study on the kinetics of iron oxide leaching by oxalic acid," *Int. J. Miner. Process.*, vol. 80, no. 2–4, pp. 144–152, 2022, doi: 10.1016/j.minpro.2006.03.012.
- [13] R. Motte and W. De Waele, "An Overview of Estimations for the High-Cycle Fatigue Strength of Conventionally Manufactured Steels Based on Other Mechanical Properties," *Metals (Basel)*, vol. 14, no. 1, pp. 1–53, 2024, doi: 10.3390/met14010085.
- [14] Muhammad Saidur Rahman, "Advancements in solvent extraction of metal ions: Mechanisms, kinetics, and efficiency with diverse extractants," *Int. J. Sci. Res. Arch.*, vol. 12, no. 2, pp. 2374–2396, 2024, doi: 10.30574/ijsra.2024.12.2.1493.