

Iron (Fe) Removal from Peat Water using TiO₂-Decorated Hydroxyapatite (HAp): Effects of HAp Synthesis Temperature and Removal Kinetics

Dwiria Wahyuni*, Ya' Muhammad Arsyad, Bintoro Siswo Nugroho, Asifa Asri, and Zakia Sipana Herman

Department of Physics, Faculty of Mathematics and Natural Science, Universitas Tanjungpura, Pontianak, Indonesia; e-mail: dwiriawahyuni@physics.untan.ac.id

ABSTRAK

Air gambut, yang umum ditemukan di wilayah tropis seperti Indonesia, sering kali mengandung kadar besi (Fe) yang tinggi dan senyawa organik yang menyebabkan air berwarna gelap, serta memiliki tingkat keasaman dan kekeruhan tinggi. Kandungan Fe yang berlebih tidak hanya memengaruhi kualitas air tetapi juga menimbulkan masalah lingkungan dan kesehatan. Penelitian ini bertujuan untuk menurunkan kadar Fe dalam air gambut menggunakan komposit hidroksiapatit/titanium dioksida (HAp/TiO₂). HAp disintesis dari cangkang *Sulcospira testudinaria* melalui metode presipitasi dengan variasi suhu reaksi (30°C, 50°C, 70°C, dan 90°C), kemudian dilanjutkan dengan sintesis komposit HAp/TiO₂ menggunakan metode hidrotermal. Karakterisasi material dilakukan menggunakan Scanning Electron Microscopy (SEM) dan spektroskopi Energy Dispersive X-ray (EDX) untuk mengamati morfologi permukaan serta komposisi unsur HAp dan komposisinya. Analisis SEM-EDX mengonfirmasi keberhasilan penggabungan dan distribusi partikel TiO₂ pada permukaan HAp. Kinerja tiap variasi komposit HAp/TiO₂ kemudian dievaluasi dalam menurunkan kadar Fe pada air gambut. Hasil pengujian menunjukkan bahwa komposit HAp/TiO₂ yang dibuat menggunakan HAp hasil sintesis pada suhu 90°C memberikan kinerja terbaik, dengan tingkat penurunan Fe mencapai 82,4% dalam waktu 240 menit. Kinetika penurunan Fe dievaluasi menggunakan model kinetika orde nol, orde satu, dan orde dua. Hasilnya menunjukkan bahwa model orde dua memiliki kecocokan terbaik dengan data eksperimen ($R^2 = 0,98$) dan konstanta laju (K) sebesar $3,8 \times 10^{-3} \text{ L mg}^{-1} \text{ min}^{-1}$. Hasil ini mengindikasikan bahwa HAp/TiO₂, khususnya komposit yang dibuat menggunakan HAp hasil sintesis pada suhu 90°C, merupakan material yang menjanjikan untuk menurunkan kadar Fe dalam air gambut.

Kata Kunci: Besi (Fe), Air Gambut, Adsorpsi, Fotokatalitik, HAp/TiO₂

ABSTRACT

Peat water, commonly found in tropical regions such as Indonesia, often contains high concentrations of iron (Fe) and organic compounds that contribute to its dark color, acidity, and turbidity. The excessive Fe content not only affects the aesthetic quality of water but also poses environmental and health concerns. This study aims to reduce the Fe level in peat water using hydroxyapatite/titanium dioxide (HAp/TiO₂) composite. HAp was synthesized from *Sulcospira testudinaria* shells via the precipitation method with various temperature reactions (30°C, 50°C, 70°C, and 90°C), followed by the synthesis of HAp/TiO₂ composite using the hydrothermal method. The material characterizations were conducted using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) spectroscopy to examine the surface morphology and elemental composition of HAp and its composite. SEM-EDX and mapping analyses confirmed the successful incorporation and distribution of TiO₂ particles on the HAp surface. In its application, the HAp/TiO₂ composites were evaluated for Fe removal from peat water at different synthesis temperatures and treatment times. The experimental results showed that HAp/TiO₂ prepared using HAp synthesized at 90°C exhibited the best performance, achieving up to 82.4% Fe removal within 240 minutes. The Fe removal kinetics were evaluated using zero-, first-, and second-order kinetic models, with the second-order model providing the best fit to the experimental data ($R^2 = 0.98$), with a rate constant (K) of $3.8 \times 10^{-3} \text{ L mg}^{-1} \text{ min}^{-1}$. These results indicate that HAp/TiO₂, particularly the composite prepared using HAp synthesized at 90°C, is a promising candidate material for Fe removal from peat water.

Keywords: Iron (Fe), Peat water, Adsorption, Photocatalytic, HAp/TiO₂

Citation: Wahyuni, D., Arsyad, Y. M., Nugroho, B. S., Asri, A., dan Herman, Z. S. (2026). Iron (Fe) Removal from Peat Water using TiO₂-Decorated Hydroxyapatite (HAp): Effects of HAp Synthesis Temperature and Removal Kinetics. Jurnal Ilmu Lingkungan, 24(5), 1049-1058, doi:10.14710/jil.24.5.1049-1058

1. INTRODUCTION

Peat lands in Indonesia are spread over three major islands: Sumatra, Kalimantan, and Papua. These regions are rich in peatlands, which contribute to the abundance of peat water in these areas. Peat water, characterized by its high organic content and the presence of various dissolved minerals, has the potential to be processed and used as an alternative source of raw water for household needs (Ali et al., 2021). Given the geographical distribution of these peatlands, utilizing peat water can provide a reliable, local source of water, especially in remote or rural areas where access to clean water may be limited. Peat water is typically characterized by a reddish-brown hue, which results from the high levels of organic matter, such as humic substances, present in the water. It also exhibits low acidity (pH) and low oxygen levels, which are a consequence of the decomposition of organic material in the peatlands. Additionally, peat water contains high concentrations of iron (Fe), which is often in the form of soluble ferrous ions (Fe^{2+}) (Qadafi et al., 2023). The high concentration of Fe in peat water not only gives it an undesirable color and odor but also has the potential to cause staining and rusting of plumbing systems, as well as affect the taste and aesthetic quality of the water, making it unsuitable for direct use. Moreover, prolonged consumption of high-Fe water may lead to health concerns, such as Fe overload, which can result in various medical issues. Therefore, to ensure that peat water meets the standards for sanitation and consumption, it must undergo proper treatment to reduce its Fe concentration and improve its overall water quality.

Several methods for peat water treatment have been studied and developed. One promising method is photocatalytic process, which is known to be capable of reducing Fe metal in peat water (Lubis et al., 2022). An advanced material, such as hydroxyapatite (HAp), a form of calcium phosphate, has garnered considerable attention as an adsorbent (Hariyanto et al., 2020), and have been demonstrated to be capable for treating peat water (Alif et al., 2024). The purification of peat water using HAp from biogenic source has been explored from *Corbicula moulkiana* shell waste (Alif et al., 2018). The use of HAp as an adsorbent continues to be investigated, with various new biogenic sources being explored to obtain HAp material. One such promising source from the freshwater snail shell is *Sulcospira testudinaria*, which contains 99.6% calcium carbonate (CaCO_3) (Nugroho, Wahyuni, et al., 2023). The advantage of utilizing biogenic sources for HAp synthesis is the abundance of raw materials, offering opportunities for sustainable production methods (Arsyad et al., 2026). However, due to relatively low adsorption of HAp, it often needs to be combined with other techniques, such as photocatalysis.

Photocatalysis is an advanced oxidation process (AOP) that is generally used to remove various pollutants, including metal ions, by utilizing

photocatalytic materials that generate reactive species under light irradiation (Gao & Meng, 2021). Photocatalytic materials, such as titanium dioxide (TiO_2), exhibit vigorous photocatalytic activity due to their band gap energy of approximately 3.2 eV (Al-Oubidy & Kadhim, 2019), which enables them to react with sunlight. The unique properties of TiO_2 , including its system stability and non-toxic nature, as well as its strong oxidizing ability under UV light, make it as photocatalyst agent for degrading pollutants in water. Our previous study, which used a TiO_2 photocatalyst deposited on polypropylene as a peat water purification agent, found that it can reduce Fe by up to 89.85% (Nugroho, Asri, et al., 2023). This result demonstrates that the photocatalytic activity of TiO_2 has the potential to enhance the properties of HAp. Modification of TiO_2 onto HAp can significantly improve the light absorption capacity of HAp in both the UV and blue light regions, making it a promising for photocatalytic material (Kato et al., 2022).

Despite the well-established potential of HAp and TiO_2 as functional materials, their combination as an HAp/ TiO_2 composite has been predominantly explored for dye and gas treatment, while its application for heavy metal removal remains largely unexplored. Previous studies have mainly investigated HAp/ TiO_2 -based composites for dye removal, such as methyl orange (Sheng et al., 2011), and methylene blue using erbium (Er)-co-doped HAp/ TiO_2 (Rocha et al., 2025), as well as for the photocatalytic removal of nitric oxide (NO) gas (Yao et al., 2017). Therefore, extending the application of HAp/ TiO_2 composites to heavy metal removal from aqueous solutions represents a promising research direction. In this study, the application of HAp/ TiO_2 for Fe removal from peat water provides a novel approach by demonstrating its potential for treating a real-world water matrix. Furthermore, the use of a biogenic source for HAp synthesis adds value to the proposed adsorbent by promoting the utilization of naturally available resources and supporting a more sustainable approach to adsorbent production.

Herein, this study aims to investigate Fe removal from peat water using an HAp/ TiO_2 composite and to elucidate the effects of HAp synthesis temperature on the morphology, elemental composition, and Fe removal performance of the composite. Furthermore, removal kinetic analysis is conducted to evaluate the Fe removal behavior and determine the kinetic parameters under different HAp synthesis conditions. It is hypothesized that variations in HAp synthesis temperature influence the morphology and elemental composition of HAp, thereby affecting the Fe removal performance and kinetic behavior of the HAp/ TiO_2 composite.

2. METHODOLOGY

2.1. Preparation of Biogenic HAp

Snail shells were initially washed thoroughly and then boiled for 1 hour to remove any impurities and organic matter. Following this, the shells were soaked

in a 5% (w/v) sodium hydroxide (NaOH, Technical grade) solution for 24 hours to further clean and demineralize the shells, which is essential for enhancing the subsequent chemical reactions. After soaking, the shells were oven-dried at 100°C to eliminate any residual water content (Arsyad et al., 2026), ensuring they were fully dried before further processing. The dried snail shells were then pulverized into a fine powder using a 200-mesh sieve. This fine powder was subsequently subjected to a calcination process at 1000°C for 4 hours (Arsyad et al., 2025). The high temperature during calcination serves to remove any remaining volatile compounds. It facilitates the conversion of CaCO₃ in the snail shells into calcium oxide (CaO) (Nugroho, Wahyuni, et al., 2023).

The synthesis of HAp using the precipitation method in this study is based on and modified from a previous study (Sari & Yusuf, 2018). A suspension of snail shell powder was prepared by adding 6 grams of the calcined powder into 150 mL of deionized water. To this, 8.4855 grams of ammonium hydrogen phosphate ((NH₄)₂ HPO₄, 99%, Riedel-de Haen) were dissolved in an additional 150 mL of deionized water to prepare the phosphate solution. The phosphate solution was then added slowly to the calcium suspension at a controlled rate of 3 mL/min using a syringe. At the same time, the mixture was continuously stirred on a hot plate set at a stirring velocity of 300 rpm. The reaction was carried out at different temperatures (30°C, 50°C, 70°C, and 90°C) for a duration of 60 minutes to investigate the effects of temperature on the formation of HAp.

To maintain the desired conditions for HAp synthesis, the pH of the solution was adjusted to 10 using a 3M ammonium hydroxide (NH₄OH) solution (25%, Merck) for a period of 50 minutes, while maintaining a constant stirring velocity and temperature. After the pH adjustment, the solution was continuously agitated for 24 hours to ensure thorough mixing and reaction completion. The resulting HAp solution was then dried at 100°C for 2 hours to remove any remaining water content. Finally, the dried product was subjected to a calcination process at 950°C for 3 hours to promote the crystallization of HAp and further enhance its structural properties.

2.2. Preparation of HAp/TiO₂ Composite

After the HAp was successfully synthesized, a total of 3 grams of HAp was mixed with 25% (w/v) of high-purity TiO₂ (99%, Merck) (Vemulapalli et al., 2020). This mixture was then combined with 15 mL of deionized water under continuous stirring for 2 hours to facilitate the homogeneous dispersion of the TiO₂ particles within the HAp. The paste that formed after this stirring process was then transferred into a 25 mL hydrothermal vessel, which was subsequently sealed. This vessel was placed in an oven, where it was subjected to a reaction at a temperature of 150°C for

24 hours. The high temperature facilitated the formation of the desired composite material. In the final stage of the process, the HAp/TiO₂ composite was carefully filtered to separate excess liquid. The filtered composite was then subjected to a second drying process at 110°C for 2 hours further to ensure the complete removal of any remaining moisture. This final dried composite was then ready for further characterization and application.

2.3. Characterization of HAp/TiO₂ Composite

The characterization of the material was conducted using JEOL JSM-6510LA Scanning Electron Microscopy-Energy Dispersive X-ray (SEM-EDX). SEM provides detailed images of the surface structure, which are essential for understanding the physical characteristics of the material and measuring particle morphology and size. At the same time, EDX is employed to analyze the elemental composition of the sample, particularly calcium (Ca) and phosphorus (P) for HAp, as well as titanium (Ti) and oxygen (O) for TiO₂. To evaluate the distribution of TiO₂ within the HAp matrix, HAp/TiO₂ mapping conducted on the most representative sample. This mapping helps visualize how TiO₂ is dispersed throughout HAp, which is crucial for understanding the interactions between the two materials and their impact on the composite's properties.

2.4. Experimental Procedure for Fe Removal

The peat water sample used in this study was collected from Rasau Jaya, Kubu Raya Regency, West Kalimantan. For peat water treatment, the performance of the HAp/TiO₂ composite was evaluated under direct sunlight for 240 min. During the treatment, solar irradiation intensity and ambient temperature were simultaneously monitored using a digital light meter (LUTRON YK35UV). Measurements were recorded at 0, 60, 120, 180, and 240 min to monitor the solar irradiation conditions throughout the treatment period. The measured solar irradiation intensity and ambient temperature remained relatively consistent throughout the treatment period, as shown in Table 1.

Table 1. Solar Irradiation and Temperature Conditions During Peat Water Treatment

Time (min)	Light Intensity (mW/cm ²)	Temperature (°C)
0	1.41	32.4
60	1.54	32
120	1.31	32.4
180	1.11	30.4
240	1.04	29.6

For each experimental variation, a total of 0.5 g of the composite was immersed in 200 mL of peat water, and 20 mL samples were withdrawn from the same beaker at 60-min intervals to monitor the progress of the treatment. Consequently, the solution volume decreased progressively from the initial 200 mL

throughout the experiment, with no volume replacement performed. The samples were analyzed to determine changes in the Fe concentration and turbidity levels, which are key indicators of the treatment's effectiveness. The Fe concentration of the peat water samples before and after treatment was measured using a HANNA HI721 iron checker instrument. The Fe concentration of the peat water samples before and after treatment was measured using a HANNA HI721 Iron Checker.

Prior to sample measurement, the instrument was calibrated in two steps using the solutions provided with the instrument: distilled water in vial 1 and Fe reagent in vial 2. For Fe determination, the peat water sample was first transferred into an empty vial, followed by the addition of the Fe reagent powder according to the manufacturer's procedure. The vial was then shaken for approximately 2 min until the sample was homogeneous. The vial containing the peat water sample and Fe reagent was subsequently introduced into the instrument, and the Fe concentration was determined from the displayed reading. The same procedure was applied to all peat water samples before and after treatment.

The turbidity levels of the peat water samples were measured using a PCE-TUM 50 turbidity meter. Prior to sample measurement, the instrument was calibrated using four standard calibration solutions with different turbidity levels provided by the manufacturer. After calibration, the peat water samples were directly introduced into the measurement vial, and the turbidity values were recorded in NTU. To evaluate the efficiency of the HAp/TiO₂ composite in reducing Fe content, the removal efficiency and adsorption capacity were calculated using Equations (1) and (2), respectively.

$$\text{Removal (\%)} = \frac{(C_i - C_t)}{C_i} \times 100\% \quad (1)$$

$$Q = \frac{(C_i - C_t)}{m} V \quad (2)$$

Where Q is the amount of Fe adsorbed onto the HAp/TiO₂ (mg/g), C_i and C_t are the initial and final concentrations of Fe (mg/L), V is the volume of peat water (L), and m is the mass of the HAp/TiO₂ (g).

2.5. Kinetic Models of Fe Removal

To provide a quantitative comparison of Fe removal among the samples, the removal kinetics were evaluated using zero-, first-, and second-order kinetic models. These models were applied to describe the rate of Fe removal during the irradiation process. The kinetic analysis provides the rate constants (k), which represent the Fe removal rate and enable quantitative comparison of the HAp/TiO₂ composites, determining from the slopes of the corresponding linear regression plots. The kinetic behavior was further evaluated to determine the most suitable model based on the coefficient of determination (R²). The corresponding equations for

the zero-, first-, and second-order kinetic models are given in Equations (3), (4), and (5), respectively.

$$C_t = C_0 - K_0 t \quad (3)$$

$$\ln C_t = \ln C_0 - K_1 t \quad (4)$$

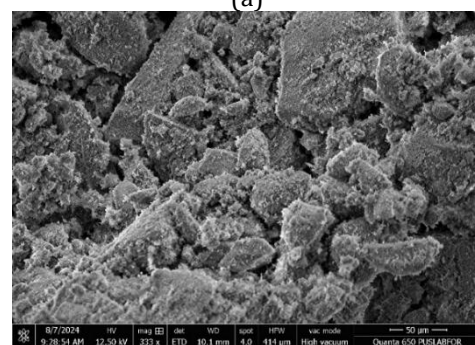
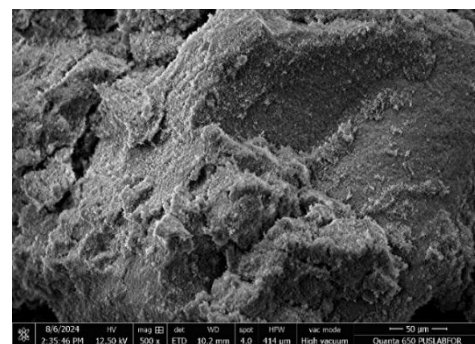
$$\frac{1}{C_t} = \frac{1}{C_0} + K_2 t \quad (5)$$

Where C_t is the level of Fe at time t, and C₀ is the initial level of Fe. k₀, k₁, and k₂ are the rate constants for the zero-, first-, and second-order kinetic models, respectively, and t is the time during irradiation.

3. RESULT AND DISCUSSION

3.1. Morphological and Elemental Analysis

The morphological observation of HAp adsorbent (Figure 1) at various synthesis temperatures showed significant changes with increasing temperature. At 30°C (Figure 1(a)), large aggregates with relatively smooth and dense surfaces were observed, and no visible pores appeared, indicating that this temperature was insufficient to develop a porous structure, making it less suitable for use as an adsorbent. Figure 1(b) shows the HAp variation at 50°C. The particles became rougher and less homogeneous, with the appearance of cracks, pores, and more distinct voids, accompanied by variations in particle shape and size. Similarly, at 70°C (Figure 1(c)), the surface remained rough. Still, the particles appeared smaller and layered, suggesting that higher temperatures promote particle agglomeration, although the size distribution was still not completely uniform. Finally, at 90°C (Figure 1(d)), the HAp exhibited more uniform particles with a more consistent size distribution, resulting in a well-ordered structure with a more exposed surface.



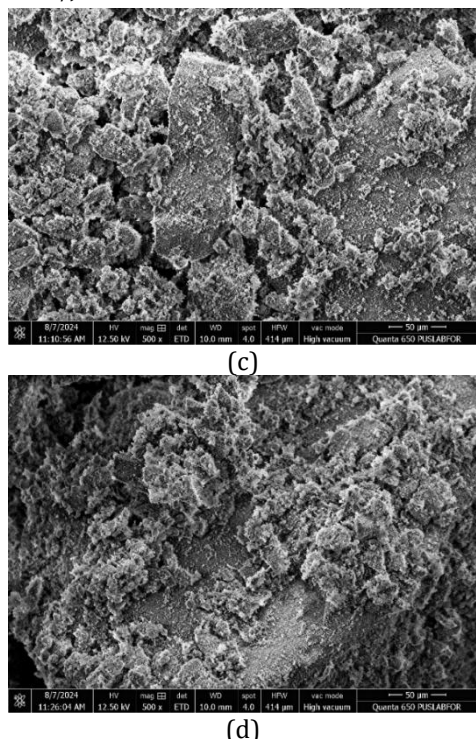


Figure 1. Micrograph (500× mag) of HAp with Various Temperature: (a) 30°C, (b) 50°C, (c) 70°C, and (d) 90°C

Figure 2(a) presents the surface morphology of the hydrothermally synthesized $\text{HAp}(90^\circ\text{C})/\text{TiO}_2$ composite, which was selected based on its highest Fe removal performance among the investigated synthesis temperatures, as further discussed in the following section. As shown in the image, the HAp particles indicated by the yellow arrows exhibit irregular shapes and non-uniform particle sizes. This result is consistent with our previous study, which reported that calcium phosphate from snail shell raw materials generally possess non-uniform morphologies (Nugroho et al., 2025). The use of a 200-mesh size resulted in HAp particles match the suitable surface for TiO_2 attachment, offering a large surface area for pollutant adsorption (Nurhanisa et al., 2025). Figure 2(b) displays the elemental mapping of the $\text{HAp}(90^\circ\text{C})/\text{TiO}_2$ composites. The elemental mapping results indicate that calcium (Ca), phosphorus (P), oxygen (O), and titanium (Ti) are uniformly distributed throughout the composite. Furthermore, the homogeneous dispersion of TiO_2 particles on the HAp surface suggests a strong potential for photocatalytic applications. Such intimate contact is beneficial for charge transfer during irradiation processes, potentially improving electron-hole separation and enhancing the photocatalytic performance of the composite (Shafiq et al., 2024).

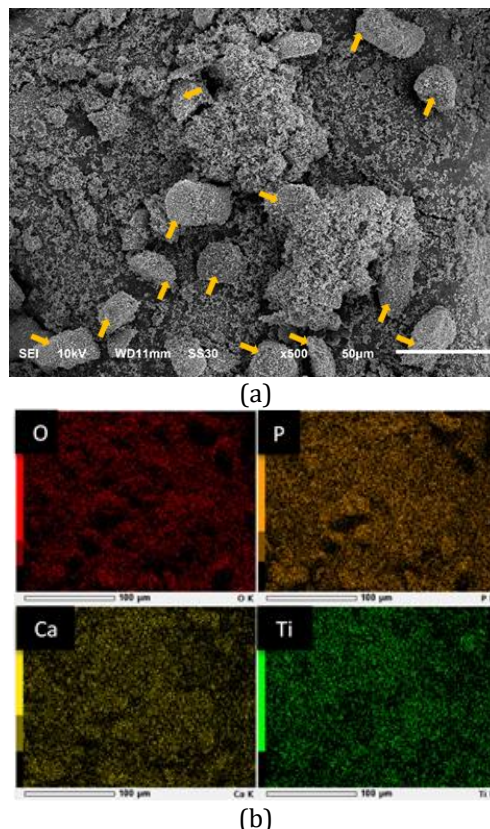


Figure 2. SEM-EDX Analysis (500× mag) of $\text{HAp}(90^\circ\text{C})/\text{TiO}_2$ Composite: (a) Morphological Features and (b) Distribution of the Elements Through Mapping Analysis

The chemical composition analysis obtained from EDX characterization is presented in Table 2. The data revealed an increase in the Ca element by 4.85%, which may result from the stirring process during the preparation of the HAp/TiO_2 composite, promoting the redistribution or reorientation of Ca ions on the HAp surface. Conversely, a reduction in the P element by 31.17% was observed from pure HAp to the HAp/TiO_2 composite, subsequently increasing the Ca/P ratio of HAp/TiO_2 to 2.73, higher than that of the pure HAp synthesized at 90°C (1.78). This phenomenon could be attributed to the heat treatment during the hydrothermal process, as phosphorus elements may disengage from the HAp surface and volatilize in the form of oxides during heating (Xie et al., 2013).

Table 2. Elemental composition at 500x magnification of HAp and HAp/TiO_2 at 90°C

Element	Mass (wt. %)	
	HAp	HAp/TiO_2
Calcium (Ca)	39.1	41.00
Phosphate (P)	17.0	11.61
Oxygen (O)	43.9	36.56
Titanium (Ti)	-	10.83

3.2. Fe Levels Relative to Quality Standards

The Fe concentration of the peat water decreased progressively with increasing treatment time under all HAp synthesis temperature conditions (Table 3). At

240 min, the Fe concentration decreased from the initial value of 5.00 mg/L to 3.08, 1.17, 1.53, and 0.88 mg/L for HAp synthesized at 30, 50, 70, and 90°C, respectively. Among the investigated conditions, the HAp/TiO₂ composite prepared at 90°C exhibited the lowest Fe concentration, indicating the highest Fe removal performance. According to the Indonesian Ministry of Health Regulation No. 2 of 2023, the maximum permissible concentration of Fe for water intended for hygiene and sanitation purposes is 0.2 mg/L. Therefore, although the treatment at 90°C resulted in the lowest Fe concentration, the obtained value of 0.88 mg/L remained above the applicable quality standard. This finding suggests that the synthesis temperature of HAp plays an important role in determining the Fe removal performance of the HAp/TiO₂ composite, with 90°C providing the most favorable condition among the investigated temperatures. Nevertheless, the residual Fe concentration indicates that further optimization of the treatment conditions is required to achieve the applicable water quality standard. These results demonstrate the potential of the HAp/TiO₂ composite for Fe reduction in peat water, while also highlighting the need for optimization of the material synthesis and treatment parameters for practical application.

Table 3. Fe Concentration in Peat Water During Treatment using HAp/TiO₂ Composites

Time (min)	Fe level (mg/L)			
	30°C	50°C	70°C	90°C
0	5	5	5	5
60	3.57	1.76	2.36	1.81
120	3.21	1.46	2.1	1.36
180	3.20	1.07	1.82	1.04
240	3.08	1.17	1.53	0.88

To comprehensively analyze the performance of HAp/TiO₂, turbidity measurements were conducted at the end of water treatment to assess its ability to reduce turbidity in peat water. Turbidity is usually caused by suspended insoluble Fe particles (Filip et al., 1974). Consequently, measuring turbidity at post-treatment is necessary to assess the performance of HAp/TiO₂ in removing Fe from peat water. The pattern of variation observed in turbidity measurements matches the pattern of HAp/TiO₂ in reducing Fe metal, following the order 90°C > 50°C > 70°C > 30°C. This optimization suggests that higher synthesis temperatures, particularly at 90°C, significantly enhance the material's ability to adsorb Fe metal. This finding provides crucial guidance for improving the HAp/TiO₂ synthesis method.

Table 4 shows that the analysis of the results of reducing peat water turbidity using HAp/TiO₂ showed significant effectiveness in improving the quality of peat water. The HAp(90°C)/TiO₂ demonstrated the highest turbidity reduction, which aligns with the trend in Fe reduction performance. According to the Indonesian Ministry of Health Regulation No. 2 of 2023, the maximum permissible turbidity level for water intended for hygiene and sanitation purposes is

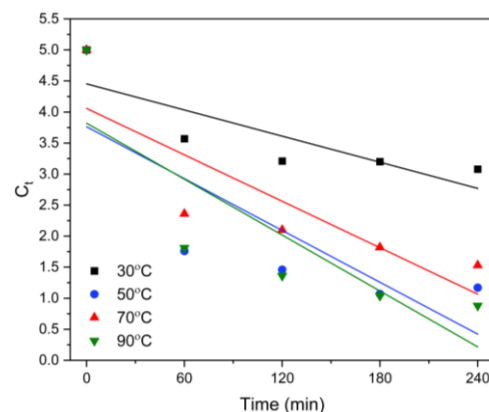
<3 NTU. However, the turbidity value obtained after treatment with HAp(90°C)/TiO₂ was 42.6 NTU, indicating that although HAp(90°C)/TiO₂ achieved the highest turbidity reduction, the treated peat water did not yet meet the applicable turbidity quality standard.

Table 4. Turbidity of Peat Water Contain HAp/TiO₂ Before and After Irradiation (240 min)

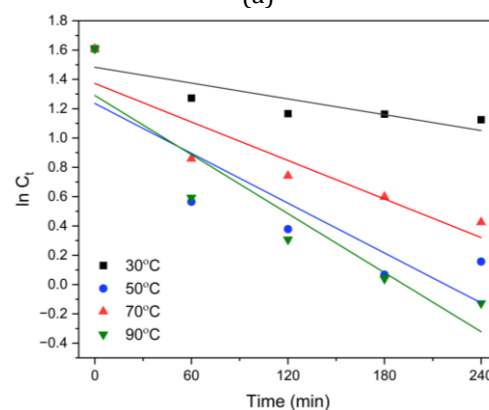
Variation	Turbidity (NTU)
Initial	603.9
HAp(30°C)/TiO ₂	444.9
HAp(50°C)/TiO ₂	80.5
HAp(70°C)/TiO ₂	310.3
HAp(90°C)/TiO ₂	42.6

3.3. Removal Kinetics Analysis of Fe

The Fe removal from peat water using the HAp/TiO₂ composite was evaluated over a treatment period of 240 min. The kinetic behavior was analyzed using zero-order, first-order, and second-order models, as presented in Figure 3(a), (b), and (c), respectively. Figure 3(a) shows a decreasing linear relationship between C_t and treatment time, while Figure 3(b) presents a decreasing relationship between $\ln C_t$ and time. In contrast, Figure 3(c) shows an increasing relationship between $1/C_t$ and treatment time, corresponding to the respective linearized kinetic models.



(a)



(b)

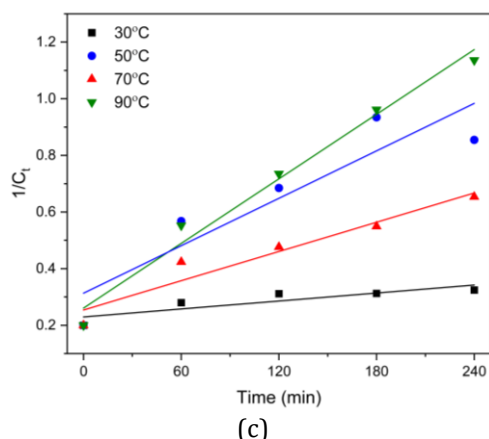


Figure 3. Removal Kinetics of Fe: (a) Zero-Order Kinetics, (b) First-Order Kinetics, and (c) Second-Order Kinetics

The differences in the linear fitting behavior among the synthesis temperatures indicate that the HAp synthesis temperature influences the Fe removal kinetics of the HAp/TiO₂ composite. The 50°C sample showed a higher Fe removal performance than the 70°C sample despite its lower synthesis temperature. This behavior may be associated with differences in surface morphology, as the 50°C sample exhibited a more porous surface than the 70°C sample based on the SEM analysis (Figure 1(b) and (c)), potentially providing more accessible sites for Fe ion uptake. Furthermore, the superhydrophilic nature of HAp may promote interactions between the material surface and Fe-containing species in aqueous media, facilitating Fe uptake (Wang et al., 2023). The incorporation of TiO₂ may further contribute to the removal process through enhanced contaminant adsorption and suppression of photogenerated electron-hole pair recombination, thereby supporting the photocatalytic process (Shafiq et al., 2024).

Table 5 presents the coefficient of determination (R^2) obtained from the zero-, first-, and second-order kinetic models for Fe removal by the HAp/TiO₂ composites. Overall, the R^2 values increased from the zero-order to the second-order model for all samples. The second-order model exhibited the highest R^2 values, namely 0.77, 0.84, 0.93, and 0.98 for HAp(30°C)/TiO₂, HAp(50°C)/TiO₂, HAp(70°C)/TiO₂, and HAp(90°C)/TiO₂, respectively. These results indicate that the second-order kinetic model provided the best fit to the experimental Fe removal data. Among the samples, HAp(90°C)/TiO₂ exhibited the highest R^2 value (0.98), indicating the strongest agreement between the experimental data and the second-order kinetic model.

Table 5. Coefficient of Determination (R^2) of the Fe Removal Kinetic Models for HAp/TiO₂ Composites

Variation	Coefficient of determination (R^2)		
	Order 0	Order 1	Order 2
HAp(30°C)/TiO ₂	0.69	0.73	0.77
HAp(50°C)/TiO ₂	0.64	0.75	0.84
HAp(70°C)/TiO ₂	0.71	0.83	0.93
HAp(90°C)/TiO ₂	0.69	0.86	0.98

Table 6 summarizes the kinetic rate constants (k) obtained from the slopes of the corresponding linear regression plots. For the zero-order model, K_0 increased from 7.0×10^{-3} to 15.0×10^{-3} mg L⁻¹ min⁻¹ as the HAp synthesis temperature increased from 30 to 90°C. Similarly, the first-order rate constant (K_1) increased from 1.8×10^{-3} to 6.7×10^{-3} min⁻¹, while the second-order rate constant (K_2) increased from 0.4×10^{-3} to 3.8×10^{-3} L mg⁻¹ min⁻¹. The highest rate constant for each kinetic model was obtained for HAp(90°C)/TiO₂, indicating a higher Fe removal rate for this composite. However, because the three kinetic models have different units for their rate constants, the absolute values of K_0 , K_1 , and K_2 should not be directly compared with one another. Based on the R^2 values in Table 4, the second-order model was the most appropriate model for describing the Fe removal kinetics for this study. Therefore, K_2 is the most relevant kinetic parameter for comparing the Fe removal rate among the HAp/TiO₂ composites.

Table 6. Kinetic parameters for Different Kinetic Orders of Fe Removal using HAp/TiO₂ Composites

Variation	K_0 (mg L ⁻¹ min ⁻¹)	K_1 (min ⁻¹)	K_2 (L mg ⁻¹ min ⁻¹)
HAp(30°C)/TiO ₂	7.0×10^{-3}	1.8×10^{-3}	0.4×10^{-3}
HAp(50°C)/TiO ₂	13.9×10^{-3}	5.7×10^{-3}	2.8×10^{-3}
HAp(70°C)/TiO ₂	12.5×10^{-3}	4.4×10^{-3}	1.7×10^{-3}
HAp(90°C)/TiO ₂	15.0×10^{-3}	6.7×10^{-3}	3.8×10^{-3}

3.4. Performance Analysis of HAp/TiO₂ Composite

The Fe removal performance of the HAp/TiO₂ composites is presented in Figure 4, including the removal efficiency as a function of treatment time (Figure 4(a)) and the relationship between adsorption capacity (Q) and the kinetic rate constants (K_0 , K_1 , and K_2) (Figure 4(b)). Adsorption capacity represents the amount of adsorbate that can be retained by an adsorbent under specific conditions (Wahyuni et al., 2025). The higher K value indicates a faster polutan removal (Fe in this study) rate under the corresponding kinetic model (Arsyad & Wahyuni, 2024). As shown in Figure 4(a), the Fe removal efficiency increased with increasing treatment time for all synthesis temperatures, with the HAp/TiO₂ composite synthesized at 90°C exhibiting the highest removal efficiency throughout the treatment period. At 240 min, the removal efficiencies at 30, 50, 70, and 90°C were approximately 38%, 77%, 70%, and 82%, respectively. Figure 4(b) further shows that the 90°C composite exhibited the highest adsorption capacity (Q) and the highest kinetic rate constants across the investigated kinetic models, followed by the 50°C, 70°C, and 30°C composites. In particular, the K_1 values increased from approximately 1.8 min⁻¹ for 30°C to 6.7 min⁻¹ for 90°C, indicating faster Fe removal kinetics at the higher HAp synthesis temperature. The simultaneous increase in Q and K values (K_0 , K_1 , and K_2) suggests that the HAp synthesis temperature influences both the Fe uptake capacity and the

removal rate of the HAp/TiO₂ composite. Therefore, the composite synthesized at 90°C exhibited the most favorable Fe removal performance among the investigated synthesis conditions.

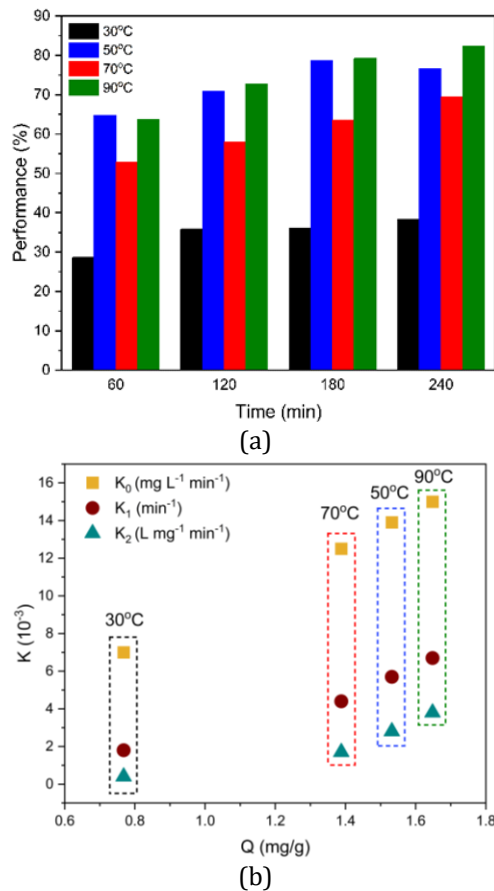


Figure 4. Performance of HAp/TiO₂ in Reducing of Fe Ions
(a) Effectivity and (b) Relationship Q and K

Table 7. Comparison of Various Materials for Fe Metal Removal from Peat Water

Materials	Performance	Reference
Chitosan from Shrimp Shell	92.20%	(Lubis et al., 2022)
Activated Carbon from Bamboo	73.03%	(Wahyuni et al., 2022)
Activated Carbon from OPEFB	91.00%	(Sumila et al., 2023)
TiO ₂ -coated Polypropylene	89.85%	(Nugroho, Asri, et al., 2023)
Bentonite-Chitosan	68.60%	(Permana et al., 2025)
Nanocomposite TiO ₂ -Decorated HAp from Snail Shell	82.4%	This Study

As shown in Table 7, the Fe ion removal performance obtained in this study is comparable to or even higher than those reported in previous works. While other studies utilizing materials such as chitosan, bentonite-chitosan, activated carbon, and TiO₂-coated substrates also demonstrated relatively high efficiencies (ranging from approximately 68% to 92%), the present study achieves a competitive removal percentage (82.4%), indicating the

effectiveness of HAp synthesized at various temperatures decorated with TiO₂ material in treating Fe-contaminated peat water.

In general, both HAp and TiO₂ based composite systems have demonstrated effectiveness in removing Fe ions. However, adsorptive materials (HAp) are more widely utilized due to their stable performance under various environmental conditions. In contrast, the efficiency of photocatalyst material (TiO₂) can be limited in complex matrices, such as peat water, where high organic content and turbidity reduce light penetration, subsequently hindering photocatalytic activity. Thus, in this study, the developed material exhibits excellent combined adsorption-photocatalytic capabilities. The combination of the two functional materials creates a synergistic effect that enhances overall removal efficiency compared to single-component materials (Arsyad & Wahyuni, 2024), making it a promising candidate for practical water purification applications, particularly under peat water conditions.

4. CONCLUSION

This study investigated the potential of HAp/TiO₂ composites for Fe removal from peat water. Among the investigated synthesis temperatures, HAp(90°C)/TiO₂ exhibited the highest Fe removal performance, achieving up to 82.4% within 240 min. The kinetic analysis showed that the Fe removal process was best described by the second-order kinetic model, which exhibited the highest R² of 0.98 indicating a strong fit between the experimental data and the model. Although HAp(90°C)/TiO₂ demonstrated the highest removal performance, the treated peat water did not yet meet the applicable quality standards for either Fe concentration or turbidity level specified by the Indonesian Ministry of Health Regulation No. 2 of 2023. Therefore, HAp/TiO₂ can be considered a promising candidate material for Fe removal from peat water, rather than a material that can be directly applied to produce water meeting the required quality standard. Further optimization of the treatment process and/or integration with additional treatment steps is required to achieve the applicable water quality standards. Future studies should investigate the long-term stability and reusability of HAp/TiO₂ composites, as well as their performance under different operating conditions and toward other water pollutants.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Pusat Laboratorium Forensik (PUSLABFOR) Bogor for providing SEM characterization and to the Advanced Physics Laboratory, Department of Physics, Universitas Tanjungpura for supporting the application for peat water treatment.

REFERENCES

Al-Oubidy, E. A., & Kadhim, F. J. (2019). Photocatalytic

Wahyuni, D., Arsyad, Y. M., Nugroho, B. S., Asri, A., dan Herman, Z. S. (2026). Iron (Fe) Removal from Peat Water using TiO₂-Decorated Hydroxyapatite (HAP): Effects of HAP Synthesis Temperature and Removal Kinetics. *Jurnal Ilmu Lingkungan*, 24(5), 1049-1058, doi:10.14710/jil.24.5.1049-1058

- Activity of Anatase Titanium Dioxide Nanostructures Prepared by Reactive Magnetron Sputtering Technique. *Optical and Quantum Electronics*, 51(23), 1–11. <https://doi.org/10.1007/s11082-018-1738-z>
- Ali, F., Lestari, D. L., & Putri, M. D. (2021). Peat Water Treatment as an Alternative for Raw water in Peatlands Area. *IOP Conference Series: Materials Science and Engineering*, 1144(1), 012052. <https://doi.org/10.1088/1757-899X/1144/1/012052>
- Alif, M. F., Aprillia, W., & Arief, S. (2018). Peat Water Purification by Hydroxyapatite (HAP) Synthesized from Waste Pensi (*Corbicula moltkiana*) Shells. *IOP Conference Series: Materials Science and Engineering*, 299(1). <https://doi.org/DOI 10.1088/1757-899X/299/1/012002>
- Alif, M. F., Fitria, R. A., Arief, S., Triandini, S., Manawan, M., Purnama, P., & Goei, R. (2024). Peat water purification using nanohydroxyapatite synthesized from Carbon Negative Precipitated Calcium Carbonate precursor. *Sustainable Chemistry for the Environment*, 6(April), 100105. <https://doi.org/10.1016/j.scenv.2024.100105>
- Arsyad, Y. M., Nurhanisa, M., Narulita, E., Handayani, A. D., Barus, F. R., Maharani, R. F., Risla, H. A., Amanda, L. T., Amanda, D., & Siregar, Z. T. (2025). Dependence of Crystallinity and Crystallite Size of Hydroxyapatite from Chicken Eggshell on Calcination Time: A Comparative Study on Scherrer Approach. *Newton-Maxwell Journal of Physics*, 6(2), 79–86. <https://doi.org/10.33369/nmj.v6i2.43228>
- Arsyad, Y. M., Pragandi, A., Asri, A., Nugroho, B. S., & Wahyuni, D. (2026). The Role of Hydrothermal Time in Determining the Phase Purity and Compressive Strength of Biogenic Hydroxyapatite from *Meretrix meretrix* Clam Shell. *Risalah Fisika*, 6(2), 53–59. <https://doi.org/10.35895/rf.v6i2.90>
- Arsyad, Y. M., & Wahyuni, D. (2024). Deposition of Activated Carbon/TiO₂ on Polystyrene and Its Performance in Photodegradation of Methylene Blue. *Jurnal Teori Dan Aplikasi Fisika*, 12(02), 121–130. <https://doi.org/10.23960/jtaf.v12i02.373>
- Filip, A., Vuskovic, B., & Strundjalic, P. (1974). Correlation Between Turbidity and Iron Content of the Filter Effluent of Well Origin. *Journal (American Water Works Association)*, 66(3), 166–168. <https://doi.org/10.1002/j.1551-8833.1974.tb01995.x>
- Gao, X., & Meng, X. (2021). Photocatalysis for heavy metal treatment: A review. *Processes*, 9(10). <https://doi.org/10.3390/pr9101729>
- Hariyanto, S. D., Sriani, T., Mahardika, M., & Prihandana, G. S. (2020). Hydroxyapatite (HA) for wastewater treatment. *AIP Conference Proceedings*, 2314(December). <https://doi.org/10.1063/5.0034511>
- Kato, K., Kobayashi, F., Xin, Y., Nakagawa, S., Nishikawa, H., & Shirai, T. (2022). HAP / TiO₂ heterojunction catalyst towards low- temperature thermal oxidation of VOC. *Materials Research Express*, 9. <https://doi.org/10.1088/2053-1591/ac5350>
- Lubis, K. L., Elystia, S., Ermal, D. A. S., & Zultiniar, Z. (2022). Penyisihan Logam Fe Pada Air Gambut Menggunakan Membran Chitosan Sebagai Adsorben. *Jurnal Sains Teknologi & Lingkungan*, 8(1), 15–24. <https://doi.org/10.29303/jstl.v8i1.298>
- Nugroho, B. S., Asri, A., & Arman, Y. (2023). Exploring TiO₂-PP as a Reusable Floating Photocatalyst for Humic Acid and Iron Removal in Peat Water. *Indonesian Journal of Applied Physics*, 13(2), 171. <https://doi.org/10.13057/ijap.v13i2.60342>
- Nugroho, B. S., Wahyuni, D., Asri, A., & Lirawanto, A. (2025). Effects Of Calcination Temperature on Ca/P Ratio of Calcium Phosphate from Freshwater Snails (*Sulcospira Testudinaria*) Shells. *Journal of Physics: Conference Series*, 2945(1), 1–6. <https://doi.org/10.1088/1742-6596/2945/1/012032>
- Nugroho, B. S., Wahyuni, D., Asri, A., & Mustafa, U. (2023). Effect of Calcination Temperature on the Powder of Freshwater Snail Shells (*Sulcospira testudinaria*) Properties. *Positron*, 13(2), 158. <https://doi.org/10.26418/positron.v13i2.70055>
- Nurhanisa, M., Wahyuni, D., & Arsyad, Y. M. (2025). Study on the Performance of Activated Carbon / TiO₂ Composite in the Degradation of Methylene Blue Based on Particle Size of Carbon. *Jurnal Fisika Flux*, 22(1), 10–16. <https://doi.org/10.20527/flux.v21i3.17999>
- Permana, E., Naswir, M., Wijaya, D. E., Hidayat, A. N., Nurjamil, D. S., & Prayogi, A. S. (2025). Application of bentonite-chitosan nanocomposites for the adsorptive removal of iron and natural organic matter in peat water. *Journal of Degraded and Mining Lands Management*, 12(4), 8107–8116. <https://doi.org/10.15243/jdmlm.2025.124.8107>
- Qadafi, M., Wulan, D. R., Notodarmojo, S., & Zevi, Y. (2023). Characteristics and treatment methods for peat water as clean water sources: A mini review. *Water Cycle*, 4, 60–69. <https://doi.org/10.1016/j.watcyc.2023.02.005>
- Rocha, R. L. P., Alan, I., Morais, S., Araujo, F. P., Maria, L., Hon, C., Silva, M. P., Furtini, M. B., Vieira, E. G., Silva-filho, E. C., & Osajima, J. A. (2025). Enhanced Photocatalytic Performance of TiO₂@Er-Hydroxyapatite Composite for Cationic Dye and Drug Removal. *ACS Omega*, 10, 5351–5361. <https://doi.org/10.1021/acsomega.4c06314>
- Sari, M., & Yusuf, Y. (2018). Synthesis and characterization of hydroxyapatite based on green mussel shells (*perna viridis*) with Calcination Temperature Variation using the precipitation method. *International Journal of Nanoelectronics and Materials*, 11(3), 357–370. <https://doi.org/10.1088/1757-899X/432/1/012046>
- Shafiq, F., Yu, S., Pan, Y., & Qiao, W. (2024). Synthesis and Characterization of Titania-Coated Hollow Mesoporous Hydroxyapatite Composites for Photocatalytic Degradation of Methyl Red Dye in Water. *Coatings*, 14(8). <https://doi.org/10.3390/coatings14080921>
- Sheng, G., Qiao, L., & Mou, Y. (2011). Preparation of TiO₂/Hydroxyapatite Composite and Its Photocatalytic Degradation of Methyl Orange. *Journal of Environmental Engineering*, 137(7), 611–616. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000357](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000357)
- Sumila, Asri, A., Arsyad, Y. M., & Wahyuni, D. (2023). Uji Kinerja Karbon Aktif Tandan Kosong Kelapa Sawit (TKKS) Sebagai Reusable Adsorbent Logam Besi Pada Air Gambut. *Jurnal Fisika*, 8(2), 2657–1900. <https://doi.org/10.35508/fisa.v8i2.12894>
- Vemulapalli, A. K., Penmetsa, R. M. R., Nallu, R., & Siriyala, R.

- (2020). HAp/TiO₂ nanocomposites: Influence of TiO₂ on microstructure and mechanical properties. *Journal of Composite Materials*, 54(6), 765–772. <https://doi.org/10.1177/0021998319868517>
- Wahyuni, D., Nurhanisa, M., Bahtiar, A., & Rutdiyanti. (2022). Optimasi Sintesis Karbon Aktif dari Bambu Buluh (*Schizostachyum brachycladum*) dengan Variasi Suhu Karbonisasi untuk Penyerapan Besi pada Air Sumur Gambut. *Jurnal Fisika Unand*, 11(3), 292–298. <https://doi.org/10.25077/jfu.11.3.292-298.2022>
- Wahyuni, D., Nurhasanah, Arsyad, Y. M., & Mariani. (2025). Removal of mercury and iron in water using reduced graphene oxide/zinc oxide composite. *Journal of Physics: Conference Series*, 2945(1). <https://doi.org/10.1088/1742-6596/2945/1/012031>
- Wang, J., Yu, Z., Xiao, X., Chen, Z., Huang, J., & Liu, Y. (2023). A novel hydroxyapatite super-hydrophilic membrane for efficient separation of oil-water emulsions, desalting and removal of metal ions. *Desalination*, 565, 116864. <https://doi.org/10.1016/j.desal.2023.116864>
- Xie, J., Meng, X., Zhou, Z., Li, P., Yao, L., Bian, L., Gao, X., & Wei, Y. (2013). Preparation of titania/hydroxyapatite (TiO₂/HAp) composite photocatalyst with mosaic structure for degradation of pentachlorophenol. *Materials Letters*, 110, 57–60. <https://doi.org/10.1016/j.matlet.2013.07.108>
- Yao, J., Zhang, Y., Wang, Y., Chen, M., Huang, Y., Cao, J., Ho, W., & Lee, S. C. (2017). Enhanced photocatalytic removal of NO over titania/hydroxyapatite (TiO₂/HAp) composites with improved adsorption and charge mobility ability. *RSC Advances*, 7(40), 24683–24689. <https://doi.org/10.1039/C7RA02157G>