



Terbit online pada laman web jurnal :<http://jurnaldampak.ft.unand.ac.id/>

Dampak: Jurnal Teknik Lingkungan Universitas Andalas

| ISSN (Print) 1829-6084 |ISSN (Online) 2597-5129|



Artikel Penelitian

Adsorption of Low-Phosphate Concentration in Water Using Commercial Fe-based Adsorbents

Salman Faris¹, Ervin Nurhayati^{1*}, Welly Herumurti¹

Department of Environmental Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia,

* Corresponding author: ervin@its.ac.id

Diterima: 5 Mei 2025

Diperbaiki: 23 Juni 2025

Disetujui: 7 Juli 2025

ABSTRACT

Phosphate contamination in aquatic environments has become a serious issue due to its role in eutrophication, leading to excessive algal growth and degraded ecosystems. Anthropogenic activities such as agricultural runoff and wastewater discharge significantly increase phosphate concentrations. Among treatment technologies, adsorption using iron-based adsorbents has shown high efficiency, especially at low concentrations. However, performance is influenced by adsorbent type, particle size, and hydrodynamic conditions.

This study evaluated the phosphate adsorption performance of Granular Ferric Hydroxide (GFH) and Bayoxide E33 with particle sizes of 74–149 μm , 37–74 μm , and <37 μm . Batch experiments were conducted with 0.3 mg P/L phosphate solution. The isotherm study was performed over 180 minutes, and the kinetics study extended to 240 minutes. Surface morphology was characterized by SEM, and specific surface area was analyzed using BET, which confirmed that smaller particles exhibited higher surface areas.

Results showed that GFH <37 μm achieved the highest adsorption capacity of 7.5 mg/g, while Bayoxide <37 μm reached 6.18 mg/g. The Langmuir model best described the isotherm data, and the Pseudo Second-Order model indicated chemisorption as the dominant mechanism. These findings underscore the importance of optimizing particle size to enhance phosphate removal.

Keyword: Adsorption, Bayoxide, GFH, Particle Size, Phosphate

1. INTRODUCTION

Phosphate is an essential nutrient commonly found in natural aquatic systems, as well as in domestic and industrial wastewater. While it plays a vital role in supporting aquatic life, excessive phosphate concentrations can lead to eutrophication, a condition characterized by the overgrowth of algae that disrupts aquatic ecosystems and deteriorates water quality (Smith et al., 1999).

The consequences of eutrophication include reduced dissolved oxygen levels, mass mortality of aquatic organisms, and the degradation of the ecological and aesthetic functions of water bodies (Chislock et al., 2013). In recent years, increasing attention has been directed toward phosphate control due to its significant environmental impact (Lalley et al., 2015). In Indonesia, studies have reported that rivers such as the Jagir, Musi, and Cikaniki have experienced phosphate levels that exceed environmental quality thresholds, largely attributed to anthropogenic activities such as agriculture, domestic discharge, and industrial effluents (Afifudin et al., 2025; Rahutami et al., 2023; Rosilla et al., 2015).

Among various treatment approaches, adsorption has emerged as a promising method for phosphate removal due to its operational flexibility and high efficiency (Kavand & Kazemian, 2025). Iron-based adsorbents such as Granular Ferric Hydroxide (GFH) and Bayoxide have demonstrated effectiveness under diverse environmental

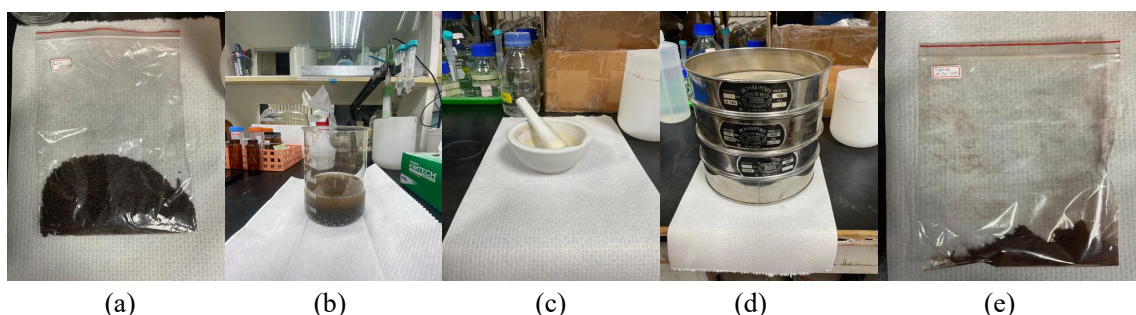
conditions (Kunaschk et al., 2015). However, the adsorption performance is strongly influenced by parameters such as particle size, agitation speed, and adsorbent dosage (Rapo & Tonk, 2021). Smaller particle sizes generally enhance adsorption capacity due to their larger specific surface area, although they may present challenges in terms of post-treatment separation (Zeng et al., 2004).

This study aims to evaluate phosphate adsorption performance at low concentrations using two commercially available iron-based adsorbents (GFH and Bayoxide) with three different particle size ranges (74–149 μm , 37–74 μm , and <37 μm), under a fixed dose of 20 mg in 500 mL solution and a constant agitation speed of 200 rpm. The primary focus is to assess the applicability of adsorption isotherm models (Langmuir and Freundlich) and kinetic models (Pseudo First-Order and Pseudo Second-Order) based on the experimental data. The findings are expected to offer practical insights for selecting suitable adsorbents and optimizing operational parameters for phosphate mitigation in low-concentration but ecologically sensitive environments.

2. METHODOLOGY

2.1. Adsorbent Preparation

This study employed two commercially available iron-based adsorbents: Bayoxide® E33 (LANXESS Deutschland GmbH, Germany) and Granular Ferric Hydroxide (GFH) (GEH Wasserchemie GmbH & Co. KG, Germany). Prior to use, the adsorbents were pretreated to eliminate potential surface impurities. Each adsorbent was thoroughly rinsed with deionized water, oven-dried for five hours, and subsequently ground manually using a mortar and pestle to obtain uniform granules. The ground materials were then sieved using standard laboratory test sieves with mesh sizes ranging from 100 to 400 mesh, corresponding to particle size ranges of 74–149 μm , 37–74 μm , and <37 μm . These fractions were selected to assess the effect of particle size and thus surface area on phosphate adsorption efficiency. A phosphate stock solution was prepared by dissolving analytical-grade sodium dihydrogen phosphate (NaH_2PO_4) in deionized water and subsequently diluted to the required working concentration. The complete adsorbent preparation workflow is illustrated in **Figure 1**.



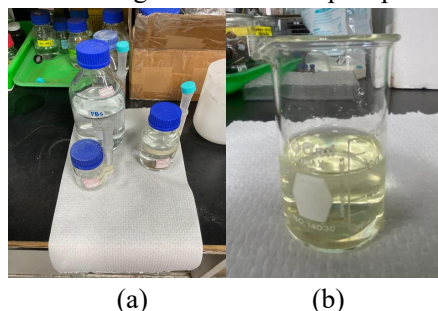
Figures 1. Adsorbent Preparation Process: (a) Raw Adsorbent, (b) Washing with Deionized Water, (c) Manual Grinding, (d) Particle Size Sieving, (e) Fine Adsorbent Fractions

2.2. Phosphate Concentration Analysis, Scanning Electron Microscopy, Brunauer–Emmett–Teller (BET) Surface Area

Phosphate concentrations in water samples were determined using the Standard Method 4500-P E (Ascorbic Acid Method). This colorimetric technique involves the reaction of phosphate with a reagent mixture containing 5N sulfuric acid, potassium antimonyl tartrate, ammonium molybdate, and ascorbic acid to produce a blue-colored complex, the intensity of which is measured spectrophotometrically.

Surface characterization of the adsorbents was conducted using a Scanning Electron Microscope (SEM) to observe surface morphology and elemental composition. SEM imaging was performed with a Hitachi SU8000 high-resolution instrument, specific surface area of the sample was determined using the Brunauer–Emmett–Teller (BET) method, performed on a Micromeritics ASAP 2020 surface area and porosity analyzer (Version 4.04). Nitrogen gas (N_2) was used as the adsorptive at a bath temperature of -195.81°C (77 K). Prior to analysis, the sample was automatically degassed to remove any physically adsorbed contaminants. A sample mass of 0.1139 g was used, and measurements were taken at 10-second equilibration intervals. The BET analysis provided

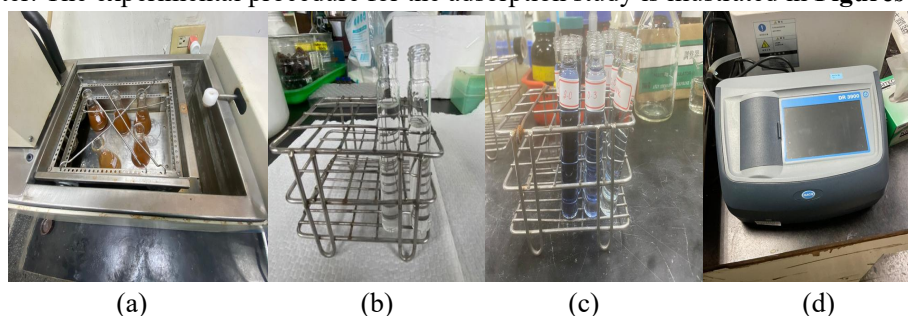
detailed information on the specific surface area based on nitrogen adsorption isotherms at cryogenic temperature conditions. The preparation procedure for the reagents used in the phosphate analysis is illustrated in **Figure 2**.



Figures 2. Reagent Preparation (a) Chemicals Used, (b) Prepared Reagent Solution

2.3. Adsorption Study

The adsorption experiments were conducted in two main phases. For the isotherm study, 500 mL phosphate solutions were used with a fixed adsorbent dose of 20 mg. The initial phosphate concentrations (C_0) were varied from 0.075 to 1.5 mg P/L, and the contact time was maintained at 180 minutes. The kinetic study was conducted using the same adsorbent dosage and volume, with a fixed phosphate concentration of 0.3 mg P/L. Samples were collected at various time intervals ranging from 0 to 240 minutes. All adsorption experiments were performed at a constant agitation speed of 200 rpm using a rotational shaker to ensure homogeneous mixing. The experimental conditions are summarized in **Tables 1**. After the designated contact time, the solutions were filtered through 0.45 μm syringe filters prior to phosphate analysis. Phosphate concentrations were then measured using a DR3900 spectrophotometer. The experimental procedure for the adsorption study is illustrated in **Figures 3**.



Figures 3. Adsorption Experiment Procedure ; (a) Adsorption Process, (b) Collected Solution Sample, (c) Reagent and Sample Mixing, (d) DR3900 Spectrophotometer

Tables 1. Experimental Conditions

Condition	Isotherms	Kinetics
C_0	0.075 mg/L - 1.5 mg/L	0.3 mg/L
Dosage	20 mg	20 mg
Volume	500 mL	500 mL
pH	7,6	7,6
Temperature	21°C	21°C
Agitation Speed	200 rpm	200 rpm

The adsorption capacity (q_e) can be calculated using the following equation, as proposed by Hameed and El-Khaiary (2008):

$$Q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

The suitability of the isotherm and kinetic models was evaluated based on the coefficient of determination (R^2) of each model. An isotherm model is considered appropriate when it exhibits an R^2 value close to 1 (Neolaka et al., 2020). **Tables 2** and **Tables 3** present the mathematical expressions of the adsorption isotherm models and kinetic models applied in this study.

Tables 2. Equations of Adsorption Isotherm Models

Isotherm Model	Equation	Graphics Plot
Freundlich	$q_e = KF C_e^{1/n}$	Log Q_e vs Log C_e
Langmuir	$\frac{C_e}{Q_e} = \frac{C_e}{Q_0} + \frac{1}{kQ_0C_e}$	C_e/Q_e vs C_e

Source: Freundlich, 1906 ; Langmuir, 1916

Tables 3. Equations of Adsorption Kinetics Models

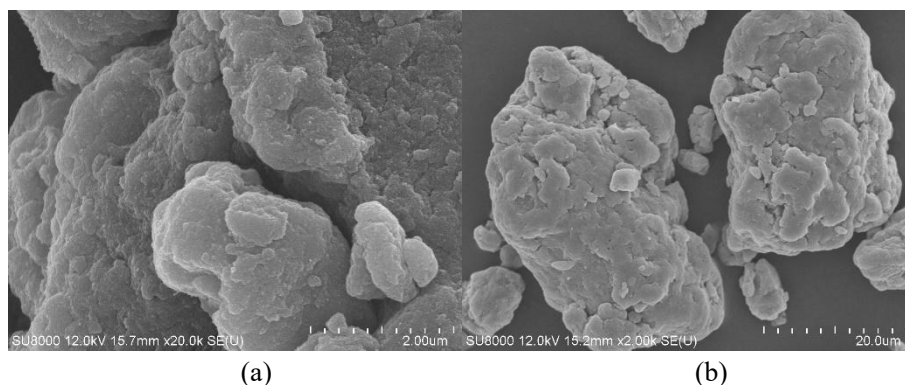
Kinetics Model	Equation	Graphics Plot
<i>Pseudo-First-Order</i> (PFO)	$\ln (q_e - q_t) = \ln q_e - k_1 t$	$\ln (q_e - q_t)$ vs t
<i>Pseudo-Second-Order</i> (PSO)	$\frac{t}{qt} = \frac{1}{K_2 qe^2} + \frac{t}{qe}$	t/qt vs t

Source: Lagergren, 1898 ; Ho & McKay, 1999

3. RESULTS AND DISCUSSION

3.1. Scanning Electrone Microscope and Brunauer–Emmett–Teller (BET) Surface Area

Figures 4 displays the surface morphology of GFH and Bayoxide E33 adsorbents based on SEM images taken at 20,000× magnification. The surface of GFH exhibits a highly porous and irregular structure, indicating the potential for a large active surface area suitable for adsorption processes. This rough and amorphous morphology is consistent with the characteristics of $Fe(OH)_3$, which is known to possess numerous active hydroxyl groups capable of binding phosphate ions. In contrast, the surface of Bayoxide E33 appears more compact and orderly, reflecting the crystalline nature of α - $FeOOH$. This structured morphology suggests fewer but more specific adsorption sites, which may lead to selective phosphate binding.



Figures 4. Surface Morfology Of Adsorbents, (a) GFH, (b) Bayoxide E33

Using the Brunauer–Emmett–Teller (BET) analysis method described in Chapter 2, the specific surface area values of each adsorbent were obtained, as presented in **Tables 4** and **Tables 5**.

Tables 4. BET Surface Area of Bayoxide E33

Particle Size	BET Surface Area (m ² /g)
74-149 μm	137.4937
37- 74 μm	139.5261
<37 μm	139.9988

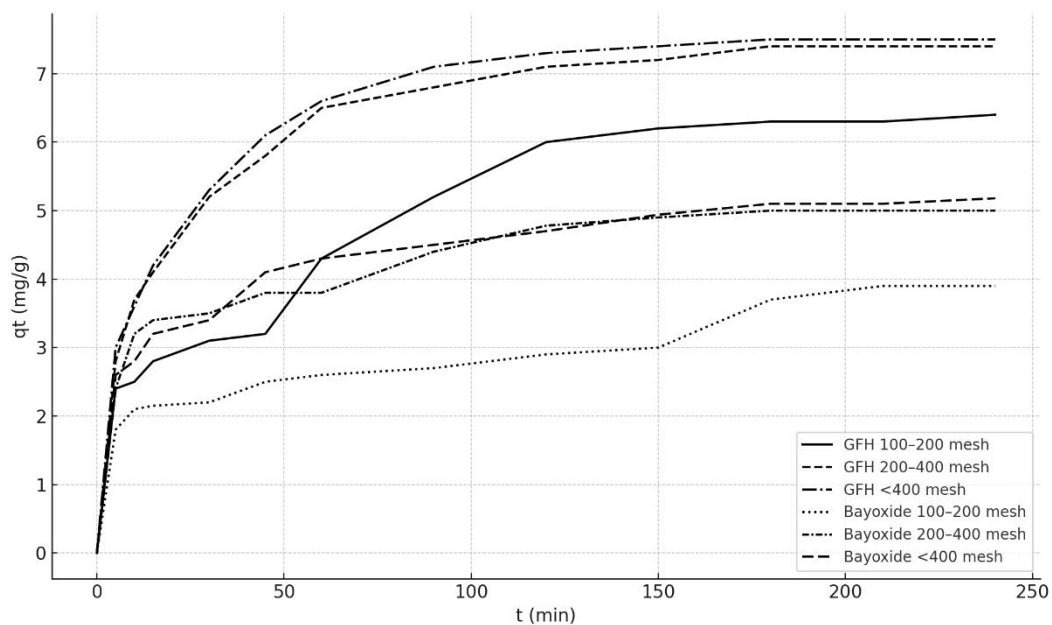
Tables 5. BET Surface Area of GFH

Particle Size	BET Surface Area (m ² /g)
74-149 μm	275.4427
37- 74 μm	276.8994
<37 μm	278.9657

The BET surface area analysis revealed a slight increase in surface area with decreasing particle size for both Bayoxide E33 and GFH adsorbents. For Bayoxide E33, the surface area ranged from 137.4937 m²/g (74–149 μm) to 139.9988 m²/g (<37 μm), indicating a relatively small variation. In contrast, GFH exhibited a significantly higher surface area overall, with values increasing from 275.4427 m²/g to 278.9657 m²/g as the particle size decreased. This trend confirms that smaller particle sizes tend to provide greater surface areas, potentially enhancing adsorption capacity.

3.2. Adsorption Capacity

Figures 5 illustrates the phosphate adsorption capacities of the tested adsorbents. Among the two iron-based adsorbents evaluated, GFH exhibited the highest phosphate adsorption capacity, with a maximum q_e value of 7.5 mg/g achieved at a particle size of <37 μm , under agitation at 200 rpm and an initial phosphate concentration of 0.3 mg P/L.



Figures 5. Adsorption Capacity Of Each Adsorbents

Although this value is considered moderate compared to those reported in the literature, it remains consistent with the characteristics of a low-concentration experimental system. For comparison, a previous study reported a maximum q_e of up to 17.3 mg/g using micron-sized GFH particles (0.1–2 μm) in phosphate solutions with initial concentrations (C_0) of 3 and 40 mg/L, highlighting the significant influence of smaller particle sizes and higher initial concentrations on adsorption performance (Martí et al., 2021). Furthermore, phosphate adsorption by GFH

has been reported to reach up to 24 mg/g under optimal conditions, particularly at pH 6 and an equilibrium phosphate concentration of 2 mg/L. That study also emphasized the enhancing effect of calcium ions, which promote phosphate removal through co-adsorption mechanisms. This suggests that higher adsorption capacities may be achievable in real water matrices such as wastewater or drinking water compared to synthetic laboratory media, due to the presence of ionic interactions that are not fully represented in simplified systems.

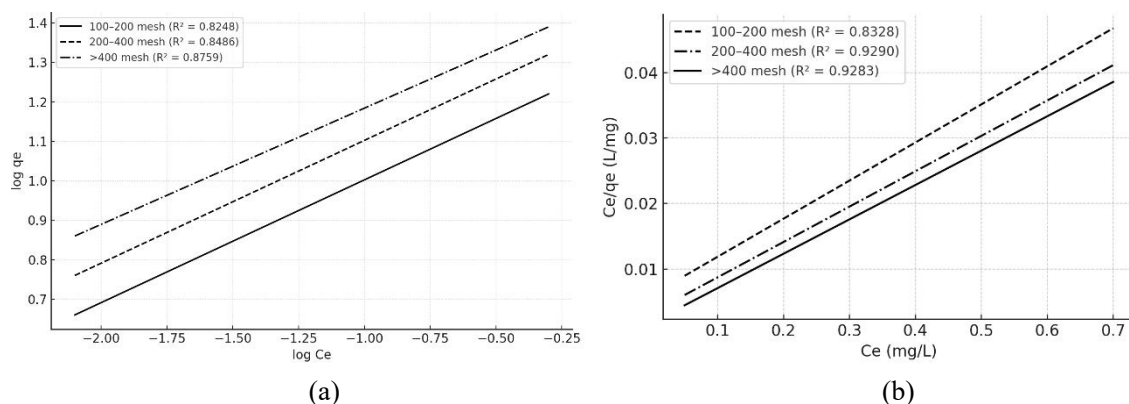
Meanwhile, Bayoxide E33 exhibited slightly lower adsorption performance compared to GFH, with a maximum adsorption capacity (q_e) of 5.18 mg/g for the <37 μm particle size under identical experimental conditions (C_0 = 0.3 mg P/L; 200 rpm; 240 minutes). This value remains consistent with previous findings under low-concentration experimental settings. For instance, earlier studies have reported q_e values of 26.8 mg/g for unmodified Bayoxide E33 and 28.0 mg/g for silver-modified E33 (E33/AgII), although these results were obtained at significantly higher phosphate concentrations (C_0 = 80 mg/L). The improved performance in such cases has been attributed to surface modifications that increase the number of active sites for phosphate binding (Lalley et al., 2015). Overall, although the adsorption capacities obtained in this study are lower than the optimal values reported in the literature, the results still demonstrate the potential of GFH and Bayoxide E33 as effective phosphate adsorbents, particularly in low-concentration water treatment scenarios. Adsorption efficiency is strongly influenced by operational factors such as particle size, contact time, and the characteristics of the solution matrix (Panjaitan et al., 2025).

The superior phosphate adsorption capacity of GFH, compared to Bayoxide E33 and Ferrolox, is primarily attributed to its mixed composition of $\beta\text{-FeOOH}$ and amorphous $\text{Fe}(\text{OH})_3$. The amorphous phase provides a high density of surface hydroxyl groups ($\equiv\text{Fe}-\text{OH}$), which enhances the availability of active binding sites and facilitates phosphate complexation. In contrast, Bayoxide E33 is composed of crystalline $\alpha\text{-FeOOH}$ (goethite). Although Bayoxide possesses a relatively high surface area (approximately 400 m^2/g), the ordered lattice structure of its crystalline phase results in a lower number of reactive sites (Chitrakar et al., 2006).

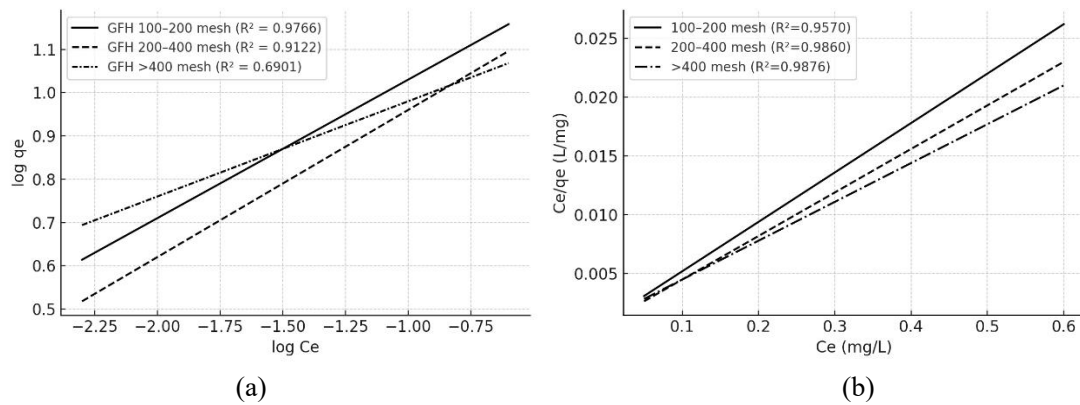
In this study, a consistent trend was observed in which smaller particle sizes yielded higher phosphate adsorption capacities (q_e) across all adsorbents. This enhancement is commonly attributed to the increased specific surface area and shorter diffusion paths, which directly offer more accessible active sites for phosphate binding. These findings suggest that particle size reduction can increase the external surface area while minimizing internal mass transfer resistance—both of which contribute to faster and more efficient adsorption processes. This observation is consistent with the findings of Xiao et al. (2013), and further supported by the BET surface area results in **Tables 4** and **Tables 5**, which confirm that smaller particle sizes exhibited higher specific surface areas

3.3. Adsorption Isotherms and Kinetics

Based on the equations provided in Table 1, the corresponding isotherm model plots are presented in **Figures 5** and **Figures 6**.



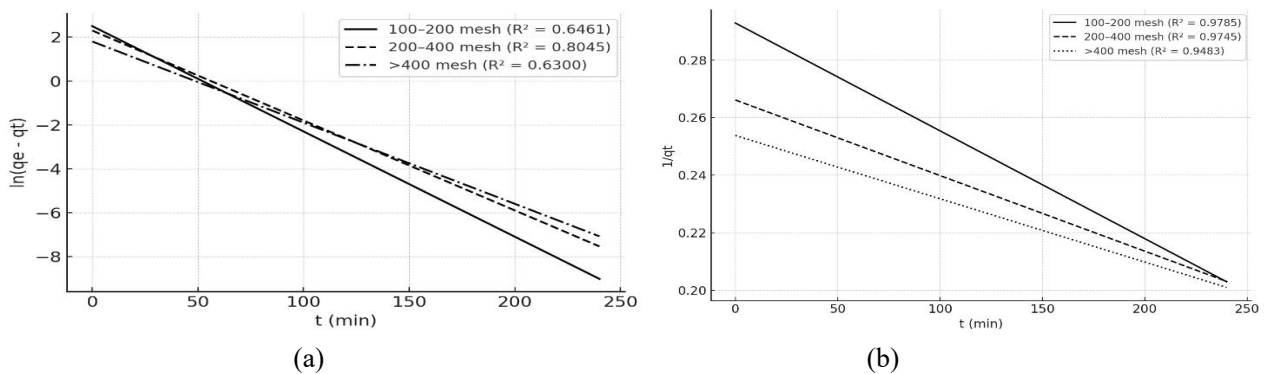
Figures 6. Adsorption Isotherm Model for Bayoxide E33 E33, (a) Freundlich, (b) Langmuir



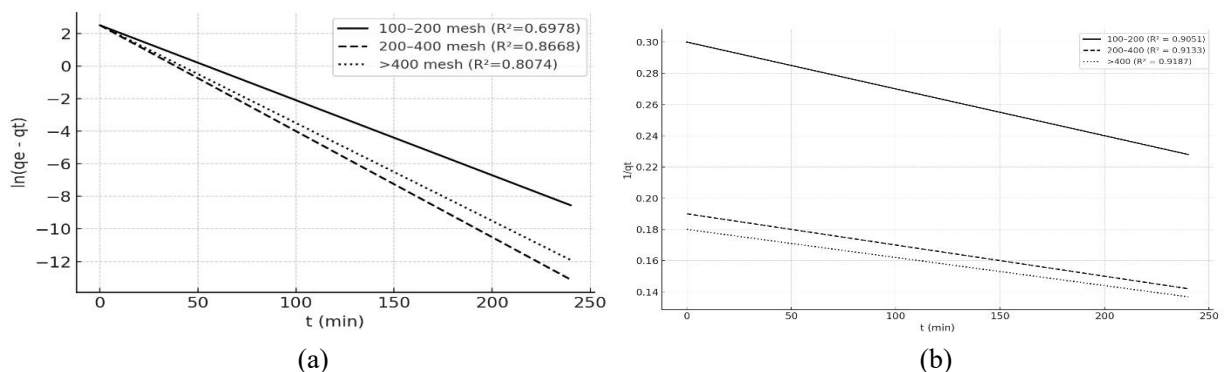
Figures 7. Adsorption Isotherm Model for GFH, (a) Freundlich, (b) Langmuir

The isotherm study results, summarized in Figures 6 and 7, reveal clear trends in phosphate adsorption behavior for each adsorbent across different particle size ranges. For GFH, the Langmuir maximum adsorption capacity (q_{max}) increased with decreasing particle size, reaching up to 28.76 mg/g for particles $<37 \mu\text{m}$. This was accompanied by high coefficients of determination (r^2) indicating a strong fit with the monolayer adsorption model. A similar pattern was observed for Bayoxide E33, with a q_{max} of 23.80 mg/g at the $<37 \mu\text{m}$ size fraction, also supported by a high r^2 value in the Langmuir model. Overall, the Langmuir model provided a better fit than the Freundlich model, as consistently indicated by higher r^2 values. This suggests that the adsorption mechanism is predominantly governed by monolayer formation on a homogeneous adsorbent surface. In contrast, the Freundlich model generally yielded lower r^2 values, further supporting the notion that the surface characteristics of the adsorbents in this system align more closely with the assumptions of the Langmuir model.

The Langmuir isotherm model is based on several fundamental assumptions: adsorption occurs on a surface with uniformly distributed energy and identical binding sites, where each site can accommodate only one molecule of adsorbate, forming a monolayer. The model further assumes that there are no lateral interactions between adsorbed molecules, and that the adsorption-desorption process is dynamic and reversible. Once all active sites are occupied, no further adsorption takes place, and the interaction energy remains constant throughout the process. These conditions are characteristic of systems governed by chemisorption mechanisms (Langmuir, 1918), as frequently reported in phosphate adsorption studies involving iron-based.



Figures 8. Adsorption Kinetics Model for Bayoxide E33, (a) PFO, (b) PSO



Figures 9. Adsorption Kinetics Model for GFH, (a) PFO, (b) PSO

Figures 8 and **Figures 9** illustrate that the adsorption kinetics are best described by the Pseudo Second-Order (PSO) model for both types of adsorbents used in this study, GFH and Bayoxide E33. The coefficient of determination (R^2) values obtained from the PSO model fitting show a consistently high trend, with values approaching unity. This indicates that the PSO model accurately captures the phosphate adsorption rate across all particle size variations, particularly for GFH, which exhibited near-perfect conformity.

The PSO model assumes that the adsorption rate is proportional to the square of the number of unoccupied active sites and proceeds via a chemisorption mechanism, involving chemical interactions between phosphate ions and the functional groups on the adsorbent surface. This process is typically irreversible and occurs gradually until equilibrium is reached. Unlike physical diffusion-based models, the PSO model accounts for adsorption through covalent bond formation or electron transfer. As the particle size decreases, the external surface area increases and internal diffusion resistance decreases, thereby enhancing adsorption efficiency, reflected in the improved R^2 values (Ho & McKay, 1999). These findings reinforce that chemisorption is the dominant mechanism governing phosphate removal by iron-based adsorbents, especially GFH and Bayoxide E33, under low-concentration conditions as investigated in this study.

The adsorption performance of GFH and Bayoxide E33 was evaluated across three particle size ranges based on isotherm and kinetic model parameters. For GFH, the Freundlich constant K_f decreased with decreasing particle size, from 39.81 (mg/g)(L/mg) at 74-149 μm mesh to 11.12 at $<37 \mu\text{m}$, while the adsorption intensity n increased from 2.50 to 4.33, indicating increasingly favorable adsorption onto finer particles. Consistent with this, the Langmuir maximum adsorption capacity q_{max} also increased, reaching up to 28.76 mg/g for particles $<37 \mu\text{m}$. Kinetic modeling showed that the pseudo second order rate constant k_2 increased slightly from 0.00021 to 0.00038 g/mg·min as particle size decreased, suggesting improved chemisorption dynamics due to enhanced surface accessibility.

Bayoxide E33 followed a similar trend, with K_f ranging from 24.71 to 14.96 and n values consistently around 2.67–2.80. Its Langmuir capacity q_{max} also rose with decreasing particle size, reaching 23.80 mg/g at $<37 \mu\text{m}$. The k_2 values for Bayoxide varied between 0.00029 and 0.00039 g/mg·min, while pseudo first order constants k_1 remained constant at 0.00667 min^{-1} across all particle sizes for both adsorbents. These results confirm that finer particles enhance adsorption kinetics and capacity, with both GFH and Bayoxide demonstrating favorable phosphate adsorption governed predominantly by chemisorption mechanisms.

The adsorption capacity and kinetic performance observed in this study were compared to those reported in the literature using similar iron-based adsorbents. A study by Lalley et al. (2015) investigated phosphate removal using modified iron oxide media and reported a Langmuir maximum adsorption capacity q_{max} of 25.71 mg/g and a pseudo second-order rate constant (k_2) of 0.0641 g/mg·min under comparable conditions. In the present study, the highest q_{max} value obtained was 28.76 mg/g for the smallest particle size fraction, which slightly exceeds the literature value. This improvement is likely due to the use of finer adsorbent particles ($<37 \mu\text{m}$), which provide increased surface area which proved by BET surface area analyze and reduced diffusion resistance, enhancing phosphate uptake. In contrast, the k_2 values observed in this study ranged from 0.00021 to 0.00039 g/mg·min, significantly lower than those reported by Lalley et al (2015). This discrepancy may stem from differences in surface modification, pore structure, or chemical functionality, as Lalley et al. used a specially treated media designed to enhance phosphate affinity. Furthermore, variations in pH, ionic strength, or adsorbent dosage between the two studies could have contributed to the observed differences. Despite this, the overall trend confirms that decreasing particle size leads to increased adsorption capacity and improved kinetics, consistent with chemisorption dominated mechanisms (Rapo & Tonk, 2021).

The suitability of the Langmuir model and PSO model in this study is consistent with previous research, which reported that phosphate adsorption onto micron-sized GFH follows the Langmuir isotherm model. This behavior has been attributed to homogeneous surface interactions and the saturation of active binding sites (Martí et al., 2021). Prior studies have also demonstrated that Bayoxide E33 follows Langmuir type adsorption, supported by the formation of inner-sphere complexes on the relatively uniform goethite based surface. Overall, these findings reinforce the relevance of the Langmuir model in describing the phosphate adsorption mechanism on iron based media such as GFH and Bayoxide E33 (Lalley et al., 2015).

4. CONCLUSION

This study evaluated the phosphate adsorption performance at low concentrations using two commercially available iron-based adsorbents, namely GFH and Bayoxide E33, across three particle size ranges (74–149 μm , 37–74 μm , and <37 μm). The results demonstrated that smaller particle sizes consistently yielded higher adsorption capacities for both adsorbents. GFH with a particle size of <37 μm exhibited the highest experimental adsorption capacity (q_e) of 7.5 mg/g, along with a Langmuir maximum capacity (q_{max}) of 28.76 mg/g. In comparison, Bayoxide E33 with the same particle size achieved a q_e of 5.18 mg/g and a q_{max} of 23.80 mg/g.

The Langmuir isotherm model provided the best fit to the experimental data, suggesting that phosphate adsorption occurred via monolayer formation on a homogeneous surface. Meanwhile, the Pseudo Second-Order (PSO) kinetic model most accurately described the adsorption rates for all particle sizes and adsorbent types, indicating that chemisorption is the dominant mechanism.

Overall, this study confirms that optimizing particle size and utilizing iron-based media such as GFH and Bayoxide E33 are effective strategies for phosphate removal in low-concentration water environments. These findings provide a solid scientific foundation for further development toward practical-scale applications.

REFERENCES

- Afifudin, A. F. M., Pradiptaadi, B. P. A., Rizqiah, Z., Aini, H. Q., Rofiq, A. A., & Sari, I. K. (2025). Evaluasi satu tahun kualitas air Sungai Jagir, Wonokromo, Surabaya. *Envirotek: Jurnal Ilmiah Teknik Lingkungan*, 16(2), 97–103. <https://doi.org/10.33005/envirotek.v16i2.1926>
- Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: Causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge*, 4(4), 10. Retrieved from <https://www.nature.com/scitable/knowledge/library/eutrophication-causes-consequences-and-controls-in-aquatic-102364466>
- Chitrakar, R., Tezuka, S., Sonoda, A., Sakane, K., Ooi, K., & Hirotsu, T. (2006). Phosphate adsorption on synthetic goethite and akaganeite. *Journal of Colloid and Interface Science*, 298(2), 602–608. <https://doi.org/10.1016/j.jcis.2005.12.054>
- Freundlich, H. M. F. (1906). Über die Adsorption in Lösungen. *Zeitschrift für Physikalische Chemie*, 57, 385–470.
- Hameed, B.H., & El-Khaiary, M.I. (2008). Batch removal of Malachite Green from aqueous solutions by adsorption on oil palm tree trunk fibre: Equilibrium isotherms and kinetic studies. *Journal of Hazardous Materials*, 154, 237–244. <https://doi.org/10.1016/j.jhazmat.2007.10.017>
- Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process Biochemistry*, 34(5), 451–465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)
- Kavand, M., & Kazemian, H. (2025). Advancing phosphate batch adsorption: Comprehensive modeling and scalability with granulated clay adsorbent in single and binary systems. *Journal of Water Process Engineering*, 70, 106996. <https://doi.org/10.1016/j.jwpe.2025.106996>
- Kunaschk, M., Schmalz, V., Dietrich, N., Dittmar, T., & Worch, E. (2015). Novel regeneration method for phosphate loaded granular ferric (hydr)oxide – A contribution to phosphorus recycling. *Water Research*, 71, 219–226. <https://doi.org/10.1016/j.watres.2015.01.001>
- Lagergren, S. (1898). Zur Theorie der sogenannten Adsorption gelöster Stoffe. *Kungliga Svenska Vetenskapsakademiens Handlingar*, 24(4), 1–39.
- Lalley, J., Han, C., Mohan, G. R., Dionysiou, D. D., Speth, T. F., Garland, J., & Nadagouda, M. N. (2015). Phosphate removal using modified Bayoxide® E33 adsorption media. *Environmental Science: Water Research & Technology*, 1(1), 96–107. <https://doi.org/10.1039/c4ew00020j>
- Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361–1403. <https://doi.org/10.1021/ja02242a004>

- Martí, V., Jubany, I., Ribas, D., Benito, J. A., & Ferrer, B. (2021). Improvement of phosphate adsorption kinetics onto ferric hydroxide by size reduction. *Water*, 13(11), 1558. <https://doi.org/10.3390/w13111558>
- Neolaka, Y. A. B., Lawa, Y., Naat, J. N., Pau Riwu, A. A., Darmokoesoemo, H., Supriyanto, G., & Kusuma, H. S. (2020). A Cr(VI)-imprinted-poly(4-VP-co-EGDMA) sorbent prepared using precipitation polymerization and its application for selective adsorptive removal and solid phase extraction of Cr(VI) ions from electroplating industrial wastewater. *Reactive and Functional Polymers*, 147, 104451. <https://doi.org/10.1016/j.reactfunctpolym.2019.104451>
- Panjaitan, A. F., Sitanggang, E. E., Sitorus, H., Alexander, V., & Tambun, R. (2025). The effect of particle size, activation type and contact time of cocoa pod husk (*Theobroma cacao* L.) activated carbon on artificial waste chromium adsorption capability. *Environmental Research, Engineering and Management*, 81(1), 35–43. <https://doi.org/10.5755/j01.erem.81.1.37115>
- Rahutami, S., Said, M., Ibrahim, E., & Herpandi. (2022). Actual status assessment and prediction of the Musi River water quality, Palembang, South Sumatra, Indonesia. *Journal of Ecological Engineering*, 23(10), 68–79. <https://doi.org/10.12911/22998993/152284>
- Rapo, E., & Tonk, S. (2021). Dose optimization and adsorption efficiency of iron-based materials for phosphate removal from aqueous solutions. *Journal of Environmental Chemical Engineering*, 9(4), 105783. <https://doi.org/10.1016/j.jece.2021.105783>
- Rosilla, R., Azizah, M., & Setiawati, D. (2016). Kadar fosfat dalam air Sungai Cikaniki. *Jurnal Sains Natural Universitas Nusa Bangsa*, 5(2), 124–131. <https://doi.org/10.31938/jsn.v5i2.263>
- Smith, V. H., Tilman, G. D., & Nekola, J. C. (1999). Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, 100(1–3), 179–196. [https://doi.org/10.1016/S0269-7491\(99\)00091-3](https://doi.org/10.1016/S0269-7491(99)00091-3)
- Xiao, Y., Zhu, X. L., Cheng, H. K., Li, K. J., Lu, Q., & Liang, D. F. (2013). Characteristics of phosphorus adsorption by sediment mineral matrices with different particle sizes. *Water Science and Engineering*, 6(3), 262–271. <https://doi.org/10.3882/j.issn.1674-2370.2013.03.003>
- Zeng, L., Li, X., & Liu, J. (2004). Adsorptive removal of phosphate from aqueous solutions using iron oxide tailings. *Water Research*, 38(5), 1318–1326. <https://doi.org/10.1016/j.watres.2003.12.009>

NOMENCLATURE

Q _e	= Adsorption Capacity (mg/g)
C ₀	= Initial Concentration (mg/L)
C _e	= Equilibrium Concentration (mg/L)
V	= Volume (L)
M	= Adsorbent Mass (mg)
K ₁	= the Pseudo First Order Rate Constant (1/min)
k ₂	= the Pseudo Second Order Rate Constant (g/mg·min)
k	= Langmuir Constant (L/mg)
k _{max}	= Maximum Adsorption Capacity Constant (mg/g)
K _F	= Freundlich Constant
n	= Surface Heterogeneity