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Comparative Study on Phosphorus Removal Efficiency of Phosphorus Locking Agent and Iron-Aluminium Materials

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Abstract

Excessive phosphorus overloading in lakes, which leads to eutrophication, is detrimental to the aquatic ecosystem and water quality. The use of adsorption to remove phosphorus is now an attractive method of treatment due to its easy operation and low cost. The study compared the adsorption of phosphorus using two factors: a commercial phosphorus locking agent and iron-aluminium residual materials (FARS) generated during water treatment procedures. The pseudo-phosphate wastewater was studied in terms of adsorption kinetics and isotherms using batch experiments. It was generated by the results that FARs experienced much higher phosphorus adsorption concentrations per kinetic function (qm = 18.35 mg/g) than the phosphorus locking agent (qm = 3.69 mg/g), and in both instances, provided viable fits to pseudo-second-order kinetic models (R^2 more than 0.98). The brain of the phosphorus locking agent under test by Isotherm yielded results in the cases of both the Langmuir model (qm = 25.06 mg/g vs 16.87 mg/g versus FARs) and in the F-type and L-type best practices, both of which gave a positive result, although some cases yielded no result. The increased kinetic activity of FARs can be explained by the high and productive production of surface hydroxyl groups on iron and aluminium oxides, which offer an opportunity for the chemical complexation of phosphate ions by forming Fe-O-P and Al-O-P bonds. When used to treat phosphorus in polluted water sources, such results suggest that FARs represent a cost-efficient and environmentally friendly alternative, as they are offered to guarantee the stabilization of the waste while simultaneously improving water quality.

Keywords: *phosphorus removal, adsorption kinetics, iron-aluminium materials, phosphorus locking agent, water treatment residuals, eutrophication control*

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1. Introduction

Lakes play a crucial role in balancing the watershed, sustaining biodiversity, and providing water to homes and industries. Subsequently, phosphorus pollution has accelerated with rapid socioeconomic development, resulting in the discharge of poorly treated wastes that cause eutrophication and algal blooms (Khalili & Moridi, 2025). As phosphorus is the primary nutrient causing eutrophication, it is crucial to reduce its levels in water basins to improve the quality of the environment. The conventional techniques for phosphorus removal, including biological processes, microbial processes, and adsorption, exhibit varying degrees of efficacy. Although biological or microbial methods have proven effective in phosphorus removal, they also lead to high sludge production and clogging issues (Zahed et al., 2022). Adsorption, on the other hand, offers advantages such as low costs, high efficiency, and ease of operation. Although they possess these advantages, typical adsorbents, such as biochar, diatomaceous earth, mesoporous silica, and metal-organic frameworks, according to Biswal and Balasubramanian (2023), have limitations, including rapid saturation and slow regeneration, which limit their large-scale use.

Industrial byproducts, such as attapulgite and waterworks sludge, which have been poorly treated in China (in China, 80% of sludge has been dumped improperly, according to Zhang et al. (2017)), pose serious environmental problems due to inadequate disposal practices, including landfilling and dumping. Their surfaces, however, contain a large quantity of active metal oxides, making them very active in adsorbing inorganic phosphorus (Zhang et al., 2017). The use of these products as phosphorus-binding substances, as well as iron-aluminium composites, is beneficial in two ways: it mitigates the consequences of phosphorus pollution in water, and it enhances the valorization of waste.

This study aims to compare the adsorption of phosphorus by various materials through simulated wastewater under varying conditions. Particularly, it seeks to (1) determine the quality of water in nearby lakes and rivers, and (2) examine adsorption isotherms and kinetics of phosphorus in each material. The study's results will shed further light on the mechanism of phosphorus removal, facilitate the development of new, potent water treatment methods, and contribute to the management and control of phosphorus-laden water systems.

2. Materials and Methods

2.1 Experimental Materials

In this research, two types of adsorbents were used: the phosphorus locking agent and iron-aluminium materials (FARs). The phosphorus locking agent is one of the commercial processes developed to trap phosphorus in water. The development of materials based on methodologies used in earlier research on water usage residuals, with iron-aluminium (FARs) as the basic material, was achieved through composite structures of iron and aluminium derived from water treatment sludge. These substances were impregnated with both iron and aluminium hydroxides, which also proved to be active locations for the attachment of phosphorus. Simulated phosphate wastewater was constructed by adding analytical-grade potassium dihydrogen phosphate (KH_2PO_4) and taking measurements by changing the phosphorus concentration in the original solution to the extent desired for adsorption.

2.2 Experimental Instruments and Reagents

With instruments such as a constant temperature shaker to maintain reaction conditions, an ultraviolet-visible spectrophotometer to determine phosphorus concentration, a pH meter to measure solution pH, a 0.45 μm filter membrane to separate solids and liquids, and an analytical balance to weigh materials accurately. The reagents used included the reassured phosphorus source (potassium dihydrogen phosphate, KH_2PO_4), pH modifiers such as sulfuric acid and sodium hydroxide, and a neutral reagent (deionized water) to prepare the solution.

2.3 Experimental Methods

2.3.1Phosphorus Standard Curve Preparation

A phosphate stock solution was prepared by drying guaranteed reagent-grade potassium dihydrogen phosphate (KH_2PO_4) at 110°C for 2 hours, cooling it in a desiccator, and dissolving 0.2197 g in water. The solution was transferred to a 1000 mL volumetric flask, and 5 mL of 1:1 sulfuric acid was added. The solution was then further diluted with water to the mark, resulting in a concentration of 50.0 μg phosphorus per millilitre. The preparation of the phosphate standard solution involved transferring 10mL of stock solution into a 250mL volumetric flask and diluting it with water to achieve a phosphorus concentration of 2.00 μg phosphorus per milliliter. This working solution was freshly prepared before use.

Standard curve construction involved adding 0, 0.50, 1.00, 3.00, 5.00, 10.0, and 15.0 mL of phosphate standard working solution to individual 50 mL stoppered colourimetric tubes, where each was diluted to 50 mL. The phosphorus results in the final tubes were used as the Y-axis values, and the measured absorbance values were used as the X-axis. All these data, when paired according to the standards of linear regression, yielded a calibration equation to be used for further determination of the phosphorus level.

2.3.2Adsorption Kinetics Experiments

The preparation of the phosphate stock solution was carried out using the same process as the Phosphorus Standard Curve Preparation, yielding a phosphate stock solution of 50.0 μg of phosphorus per millilitre. The experimental procedure consisted of three steps. First, 0, 0.50, 1.00, 3.00, 5.00, 10.0, and 15.0 mL of phosphate stock solution were added to separate containers and diluted to 50 mL. Second, 0.1 g of adsorbent material was introduced into each of the solutions. Third, samples were filtered, and the phosphorus residual in the supernatant was spectrophotometrically determined after a 24-hour shaking duration at a constant temperature shaker. The kinetic experiments involved monitoring phosphorus removal over time periods of 0, 0.5, 1, 2, 3, 4, and 6 hours, which allowed for the description of both the dynamics of the adsorption rate and the equilibrium.

2.3.3Adsorption Isotherm Experiments

Preparation of the phosphate stock solution followed the standard procedure again. The steps used in the experiment involved: Firstly, 15.0 mL of phosphate stock solution was measured and introduced into the containers, and then diluted to 500 mL, thereby establishing the initial phosphorus concentration. Second, 1 g of adsorbent material was introduced to this solution, keeping the solid-to-liquid ratio constant. Third, samples were taken at 0, 0.5, 1, 2, 3, 4, and 6 hours, filtered through 0.45 μm membranes, and the remaining phosphorus concentrations in the supernatant of the samples were recorded. By using this procedure, it was possible to construct adsorption isotherms that showed a relationship at equilibrium between the statistical phosphorus concentration in the solution and the phosphorus available as an adsorbent.

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2.4 Data Analysis Methods

Mass balance equation was used in computing the adsorption capacity; that is, qe = (C₀ - Ce) × V / m; qe is the adsorption capacity in equilibrium (mg/g), C0 is the initial phosphorus (mg/L), Ce is the equilibrium phosphorus (mg/L), V is the volume of solution (L) k so m is the weight of adsorbent (g). A non-linear regression analysis was used to fit the model parameters, which consisted of the correlation coefficient (R^2), the adsorption rate constant (k), and the highest adsorption capacity (qm). The kinetic data have been fitted with the pseudo-first-order and pseudo-second-order kinetic models. Alternatively, the isotherm data were fitted using the Langmuir and the Freundlich isotherm formulations. They would be utilized to characterize the adsorption processes and the performance of the material. Table 1 summarises the final results.

Table 1: Summary of Experimental Conditions and Parameters

Experiment Type	Initial P Concentration	Adsorbent Dose	Solution Volume	Contact Time	Temperature	pH	Agitation Speed
Standard Curve	0-0.6 mg/L	-	50 mL	-	25°C	~7	-
Kinetics	1.5 mg/L	0.1 g	50 mL	0-24 h	25°C	~7	150 rpm
Isotherms	1.5 mg/L	1.0 g	500 mL	0-6 h	25°C	~7	150 rpm

3. Results and Analysis

3.1 Adsorption Kinetics Characteristics

The explicit kinetic nature of phosphorus adsorption by the two characters resulted in a temporal evolutionary process, characterized by a gradual approach to equilibrium. The phosphorus locking agent and iron-aluminium materials showed high phosphorus removal in the first hour, indicating a strong affinity between the adsorbent surfaces and phosphate ions. Nonetheless, there were large differences in the adsorption rate and end capacity. The iron-aluminium adsorption kinetics were much greater and approached equilibrium within a duration of 2-3 hours, whilst the phosphorus locking agent did not achieve equilibrium progressively as was expected.

Model fitting through quantitative kinetic analysis provided additional information on the adsorption mechanisms. Using pseudo-first-order and pseudo-second-order kinetics models to analyze the experimental data, it was found that both materials fit the pseudo-second-order kinetics model more effectively. For iron-aluminium materials, the pseudo-second-order model yielded a maximum adsorption capacity (qm) of 18.35 mg/g, with a rate constant (k_2) of 0.24 g/(mg·min) and a correlation coefficient (R^2) of 0.99. Pseudo-first-order fitting, in contrast, yielded a qm of 17.58 mg/g with k_1 of 2.96 min^{-1} and R^2 of 0.96 as observed in Table 2. It is interesting to note the greater R^2 of the pseudo-second-order model, which suggests that chemical adsorption prevails in the phosphorus absorption process by iron-aluminum materials.

In the case of the phosphorus locking agent, pseudo-second-order kinetics once again offered an excellent fit with qm = 3.69 mg/g, k_2 = 0.47 g(mg·min), and R^2 = 0.98, as opposed to pseudo-first-order kinetic parameters of qm = 4.35 mg/g, k_1 = 0.98 min^{-1}, and R^2 = 0.92 (Table 2). The values achieved for the correlation coefficients of pseudo-second-order models indicate that the strategy of electrons (chemisorption) represents the rate-limiting step in the adsorption of phosphorus with both adsorbents, attributing to the chemisorption methodology. This is in line with already known facts that metal oxide surfaces react with phosphate by being involved in inner-sphere interactions, forming complexes via ligand exchange reactions.

Table 2: Kinetic Model Parameters for Phosphorus Adsorption

Material	Pseudo-First-Order Model			Pseudo-Second-Order Model		
	qm (mg/g)	k_1 (1/min)	R^2	qm (mg/g)	k_2 (g/mg·min)	R^2
Phosphorus Locking Agent	4.35	0.98	0.92	3.69	0.47	0.98
Iron-Aluminum Materials	17.58	2.96	0.96	18.35	0.24	0.99

The vast difference in adsorption capacity between iron-aluminium (18.35mg/g) and phosphorus locking agent (3.69mg/g) in kinetic experiment conditions is a notable aspect with practical implications. Such a significant 5-fold difference in adsorption rate indicates that the more promising iron-aluminium materials have more active sites on which phosphorus may be bound, and they are available. It is also possible to gain certain insights into the mechanism with the help of rate constant variation. Presumably, the mere fact that k_2 of iron-aluminium substances is less (0.24 versus 0.47 g/(mg·min)) could indicate a sluggish adsorption process, even though the capacity is larger, which is possibly the result of diffusion constraints with the penetration of the phosphate ions to the porous surfaces of the iron-aluminium matrix. The phosphorus locking agent, on the other hand, has a greater rate constant, which means that it adsorbs faster initially; however, its final capacity is low.

3.2 Adsorption Isotherm Characteristics

Adsorption isotherm experiments revealed the equilibrium correlations between phosphorus concentration in a solution and the quantity of adsorbed phosphorus, providing fundamental thermodynamic information about the connection between the type of adsorbents and the adsorbates. Successive curves of both materials exhibited stereotypical forms of L-type (Langmuir type) and F-type (Freundlich type) adsorptive behaviour, with attractive adsorption initially steep at low phosphorus concentrations and gradually rising towards a plateau at high phosphorus concentrations.

The Langmuir isotherm model assumes monolayer adsorption on homogeneous surface sites, which have a finite capacity and do not exhibit interaction between adsorbed molecules. A maximum adsorption capacity of 25.06mg/g and a Langmuir constant of 0.09 L/mg, along with an excellent correlation coefficient R^2 of 0.98,

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were obtained by applying this model to the experimental data used to calculate the adsorption capacity of the phosphorus locking agent. The Langmuir fitting was used to determine the qm of iron-aluminum materials, which was 16.87mg/g, kL of 0.06 L/mg, and R^2 = 0.96. The values of R^2 greater than 0.96 for both materials demonstrate that the equilibrium adsorption behaviour can be well explained using the Langmuir model, indicating that the adsorption of phosphorus is primarily governed by the formation of a monolayer on the adsorbent surfaces.

The Langmuir constant, kL, relates to the adsorption energy and affinity between the adsorbent and the adsorbate. Given that, an increase in kL value implies increased binding affinity. The fact that the kL of phosphorus locking agent is barely above that of the phosphate binding carrier (0.09 versus 0.06 L/mg) indicates slightly stronger phosphate binding, but the variation is not very significant. More importantly, the values of Langmuir qm are theoretical maximum adsorption capacities based on the theory of full surface saturation. The fact that the qm of phosphorus locking agent (25.06mg/g) was higher than the qm of iron-aluminum material (16.87mg/g) demonstrates that phosphorus locking agent has a greater theoretical ability to capture phosphorus at equilibrium.

The Freundlich isotherm model is used to describe adsorption on a surface with non-uniformly distributed adsorption heat. Parameters KF (indicator of adsorption capacity) and 1/n (indicator of intensity of adsorption) are used in the empirical Freundlich equation. For the phosphorus locking agent, a Freundlich fitting yielded KF = 6.58 L/mg and n = 0.18, with R^2 = 0.67. The iron-aluminum alloys had KF(L/mg) = 5.98, 1/n = 0.17 and R^2 = 0.59. The coefficient 1 /n gives us an idea of the favorability of adsorption and surface heterogeneity (Table 3). When 1/n lies between 0.1 and 0.5, positive adsorption values are observed, with lower values indicating more heterogeneous surfaces and stronger adsorbent-adsorbate interactions (Anwar et al., 2024). The extremely low 1/n values (0.17-0.18) in the materials indicate extremely desirable adsorption with strong adhesion.

Table 3: Isotherm Model Parameters for Phosphorus Adsorption

Material	*Langmuir Adsorption Model*			*Freundlich Adsorption Model*		
	qm (mg/g)	kL (L/mg)	R^2	KF (L/mg)	1/n	R^2
Phosphorus Locking Agent	25.06	0.09	0.98	6.58	0.18	0.67
Iron-Aluminum Materials	16.87	0.06	0.96	5.98	0.17	0.59

The significantly better fit to the Langmuir model (R^2 = 0.96) than to the Freundlich model (R^2 = 0.67) demonstrates that a predominantly monolayer adsorption on comparatively homogeneous surface sites prevails over multilayer adsorption or a heterogeneous surface relationship (Table 3). This observation suggests that phosphorus absorption occurs primarily through chemical complexation with specific functional groups on the surface, rather than adsorption to various surface sites. The poor fit with the Freundlich model is due to its failure to explain the saturation aspect observed at high phosphorus concentrations in the solution. The Langmuir model, on the other hand, is a good predictor of the approach to maximum capacity.

3.3 Material Phosphorus Removal Efficiency Comparison

The combination of kinetic and Isothermal findings reveals subtle variations in materials based on experimental conditions and evaluation parameters. Iron-aluminium materials showed significantly better results under kinetic experimental conditions, even at fairly low initial phosphorus concentrations and short contact times, with an adsorption capacity of 18.35 mg/g compared to only 3.69 mg/g for the phosphorus locking agent (Table 4). This represents a five times greater efficiency of phosphorus removal using iron-aluminium material under moderate treatment conditions with reasonable throughputs and phosphorus content.

However, under isothermal conditions, when equilibrium is reached, experiments revealed that capacity is related differently as the contact time increases. The phosphorus locking reagent theoretically reached an adsorption capacity of 25.06mg/g under the Langmuir model, which was better than the maximum adsorption frequency in iron-aluminium-type subjects of 16.87mg/g (Table 4). This apparent aspect of contradiction of kinetic and isothermal results must not be construed to be so. An increase in the healing capacity of a phosphorus locking agent can complicate its ultimate phosphorus binding capacity when it is exposed to low levels of perfectly equilibrating conditions, and the surface is saturated (Schumacher et al., 2018). This theoretical maximum capacity is, however, harder to achieve in practice. It takes longer contact times to achieve, and it may not prove helpful in real treatment applications.

The estimation of decreasing similarities between kinetic and equilibrium capabilities signals the importance of taking into account the mutual influence of the matter and the rate of development of the adsorption process, as well as the capacity development of the adsorption process in its application. The Iron-Aluminium media has been indicated to be effective in a high rate of phosphorus removal, and importantly, a high capacity, using low contact time, which makes this type of media applicable in continuous flow treatment. Even though phosphorus locking agents can be used at a higher capacity at equilibrium, they can be quickly treated only at a slower rate, limiting their use to other practices that demand a rapid treatment rate.

These differences in performance are due to mechanistic differences. Iron-aluminium compounds are also likely to be loaded with high concentrations of iron and aluminium oxide/hydroxide surfaces composed of huge emissions of hydroxyl (-OH) groups and undergo ligand switching with phosphate ions, resulting in stabilized inner-sphere attacks to Fe-O-P and Al-O-P addictions. It is a way of rapid and solid bonding of phosphorus by the effective dispersion of a chemical. According to Nazarian et al. (2021), both aluminium and iron oxides have a strong affinity for phosphate due to the formation of monodentate and bidentate complexes on their surface, which is related to the pseudo-second-order kinetics of the reaction and the Langmuir isotherm relationships.

The mechanism under which the phosphorus locking agent works is probably different and may involve chemical adsorption and the ion exchange process. In commercial phosphorus locking materials, modest phosphorus locking materials are used, and rather than being a complete natural clay or a compound as found in nature, they are modified clays or compounds to optimize

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phosphorus binding in various ways (Ewis et al., 2022). These products may be ultimately well-carrying, but with a large number of rapidly oscillating molecules, adsorption may act out with even more complex, multiplicated kinetics. Additionally, the sensitivities of pH and the role of other competing ionic species can have a greater influence on the properties of phosphorus locking agents than their counterparts manufactured from iron-aluminium products.

Table 4: Comparative Summary of Phosphorus Removal Performance

Performance Metric	Phosphorus Locking Agent	Iron-Aluminum Materials	Superior Material
Kinetic Capacity (qm)	3.69 mg/g	18.35 mg/g	Iron-Aluminum Materials
Kinetic R^2 (Pseudo-Second-Order)	0.98	0.99	Iron-Aluminum Materials
Equilibrium Capacity (qm, Langmuir)	25.06 mg/g	16.87 mg/g	Phosphorus Locking Agent
Equilibrium R^2 (Langmuir)	0.98	0.96	Phosphorus Locking Agent
Adsorption Rate Constant (k_2)	0.47 g/(mg·min)	0.24 g/(mg·min)	Phosphorus Locking Agent
Practical Application Suitability	Moderate	High	Iron-Aluminum Materials

4. Discussion

4.1 Influence of Material Characteristics on Phosphorus Removal Efficiency

It is possible to describe high-level phosphorus adsorption behavior of iron-aluminium material in a kinetic experiment using several material features. Specific surface area is a crucial parameter that determines the number of adsorption sites. The residues of water after treatment become iron-aluminium and normally produce materials with high specific surface areas of the order of 50-200 m^2/g, which provide large surface areas to adsorb phosphates. Amorphous iron/aluminium oxides/hydroxides are also useful in providing a high reactivity to the surface. Unlike crystalline metal oxides with a regular surface structure, amorphous phases are characterized by a disorganized atomic structure, providing a heterogeneous coordination environment and defect sites with a high phosphate reactivity capability.

The hydroxyl groups on the surfaces of iron and aluminium oxides play a significant role in the phosphate adsorption process. The surface of the iron oxide and aluminum oxide at a circumneutral pH acquires a positive charge following the protonation of surface hydroxyl following the formation of the oxide groups. This repels the negatively charged anions of phosphate ($H_2PO_4^-$, HPO_4^{2-}) due to the favourable surface charge, facilitated by the electrostatic force, and allows for the reduction of phosphate to surface-active sites. Then, there is the appearance of a ligand exchange reaction, where the surface hydroxyl groups/water molecules are replaced with a phosphate, which binds directly to the Fe-O-P or Al-O-P bond (Gao et al., 2025). Spectroscopic studies have confirmed the existence of monodentate and bidentate complexes of phosphate on iron and aluminium oxides, with the bidentate complexes being more persistent than the monodentate complexes.

Iron and aluminium, which are contained in the water treatment residuals, have a direct correlation with phosphorus adsorption capacity, as reported in several studies. This study has found strong correlations between oxalate-extractable aluminium and iron concentrations, and phosphorus adsorption capacity, with correlation coefficients typically exceeding 0.85, which aligns with the findings of Rahmati et al. (2022). The iron-aluminium materials are rich in the concentrates of these metal oxides. These materials are prepared using waterwork sludge, employing aluminium and iron coagulants, which is why they have a high phosphorus binding capacity. It is also a molar ratio that influences the performance of adsorption some research suggests that iron-aluminum assemblies may exhibit synergies at an individual level, as well as joint designation.

The drawback of the phosphorus locking agent can be identified through direct completion with the help of a comparative analysis. Tradeoffs between cost, capacity, and kinetics are evident in commercial phosphorus locking products. A high-capacity product design might contain high-value components that are impractical for mass production. Additionally, several phosphorus trapping agents exhibit high sensitivity to pH, and some drastically reduce adsorption in the presence of high alkalinity levels, such as in eutrophic lakes. Such pH affinity may pose a performance problem in natural water systems with pH variations at either the seasonal or spatial scale. The relative increase in saturation of adsorption with time in our kinetic temperature experiments may be indicative of a low regeneration potential under our kinetic temperature conditions or a failure to achieve continuous operation in a constant flow system.

4.2 Practical Application Feasibility

Economic factors are quite overwhelming when considering the use of iron-aluminum material as a primary water treatment method. The residuals of water treatment are industrial types of waste that need to be eliminated at a cost to the operators of the waterworks. The use of these residuals as an adsorbent material to perform phosphorus adsorption transforms an existing issue of disposing of these products into a recovery opportunity that helps reduce waste and improve water quality. The shunned disposal expenditures, plus the absenteeism of purchasing adsorbent commercials, significantly make adsorption-type phosphorus extraction economically viable. Zheng et al. (2022) estimated that using water treatment residuals in phosphorus treatment can help save costs by 40-60% compared to using a commercial adsorbent.

The use of iron-aluminum materials is another environmental benefit. The principles of waste valorization and resource recovery inherent in the concept of the circular economy align with global sustainability objectives. Instead of discarding the residues of water treatment directly into landfills or dumping them into the oceans, converting the residues into viable adsorbents increases their lifespan and causes no harm to the environment. Moreover, iron-aluminum adsorbents trap phosphorus, which is stable in complex with the metal-phosphate and has low risks of leakage (Yi et al., 2023). It can be effectively absorbed as final disposal or possibly recovered by a special process as phosphorus. Some

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studies have investigated phosphorus recovery using saturated Iron-aluminum adsorbents, either through acid recovery or thermal use, thereby developing a closed-loop phosphorus cycle recycling system.

Field applications must consider the environmental flexibility of adsorbent materials in response to varying environmental conditions. The effects of temperature on adsorption are usually endothermic, resulting in an increase in phosphorus uptake with increased temperature as the diffusion rate increases, leading to a heightened reaction rate of chemical adsorption (Kanwal et al., 2024). Natural water bodies, however, normally exhibit changes in temperature within limits, the magnitude of which is insignificant. More important issues concern the effects of coexisting ions and organic matter. Sulphate, carbonate, silicate, and natural organic matter are some of the dissolved species found in natural waters that can either compete with or cover the surface locations adsorbed by phosphate. Li et al. (2016) reported that at high levels, sulfate competitively adsorbs to the phosphate adsorbent of iron-aluminum oxides. Carbonate and bicarbonate ions also compete with phosphate, especially at alkaline pH, where carbonate speciation favors carbonate ions.

The interactions between natural organic matter (NOM) and iron-aluminum adsorbents are complex and, in some cases, contradictory. Kim and Jang (2017) suggest that NOM adsorbs onto the surfaces of iron-aluminum oxide, preventing sites and depleting the iron-aluminum oxide phosphate adsorption capacity. However, Bligh et al. (2017) report that NOM can stabilize amorphous iron oxides against aging and crystallization, thereby maintaining high surface reactivity over a long period. Even in our drinking water, treated iron-aluminum materials exhibit a characteristic where the source water leaves behind NOM. In fact, it could be the cause of their consistent performance. The overall impact of NOM will most likely be dependent on its concentration, composition, and distribution of molecular weights. The hydrophobic NOM fractions with aromatic structures can be easily adsorbed to block sites. In contrast, the hydrophilic fractions with high carboxyl groups can complex with iron/aluminum, leaving the remaining hydroxyl groups free on the surface to bind phosphates.

The topic of long-term stabilization and regeneration is worth exploring in the context of sustainability applications. Iron-aluminum alloys are highly resilient under normal environmental conditions. The close interaction between phosphate and iron/alumina oxide results in high inner-sphere complexation, leading to essentially irreversible binding at circumneutral pH. The phosphorus release of iron-aluminum adsorbent under desorption conditions has been observed to be low after prolonged interactions with water, supporting the fact that it is not prone to leaching. This is a benefit of permanent phosphorus removal applications, such as capping aquatic sediments in lakes or wetland filters. Strong binding is a limiter in applications where the adsorbents are required to be regenerated. In such cases, solutions of alkaline (pH > 11) or acidic sequences are generally used in the regeneration process, which can damage the adsorbent structure over numerous cycles. Further innovation can be done by developing more readily regenerable iron-aluminum materials by surface modification.

Table 5: Comparison of Phosphorus Adsorption Capacities Across Different Adsorbent Materials

Adsorbent Material	Adsorption Capacity (mg P/g)	Optimal pH	Contact Time	Reference/Source
Iron-Aluminium Materials (This Study)	18.35 (kinetic)	~7	2-3 h	Current Study
Phosphorus Locking Agent (This Study)	3.69 (kinetic)	~7	24 h	Current Study
Al-based Water Treatment Residuals	7.7-12.5	6-7	24 h	Makris et al., 2004
Fe-based Water Treatment Residuals	9.1-11.4	3-6	24 h	Dayton & Basta, 2005
Modified Palygorskite	8.2	5	8 h	Ye et al., 2006
Lanthanum-Modified Bentonite	52.6	5-9	4 h	Zamparas et al., 2012
Red Mud	15.8	3-5	6 h	Huang et al., 2008
Alum Sludge	6.6	6	24 h	Yang et al., 2006

4.3 Research Limitations and Future Directions

There are several limitations associated with this study. The experiments used simplified batch systems, which used artificial phosphate solutions as opposed to the real water body. Natural waters possess hundreds of dissolved constituents and particulates, which can have adsorption effects. Simulation of continuous flow conditions in columns would offer better performance information on treating system design. Also, kinetic and Isotherm experiments were performed and had comparatively small time scales (hours to days), but as in practice, weeks to months are operative. The sustainability of material performance would be tested through long-term stability field testing.

The seemingly measured disparity between kinetic and Isotherm capacities is a subject that needs further research. Future studies must experimentally sweep initial phosphorus concentrations, contact time, and solid-to-liquid ratio to cover the performance parameter space fully. This would allow the forecasting of any optimal operating conditions used in particular cases of treatment. The highly developed methods of characterization, which proved to be X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR), would be useful to access mechanistic information in phosphate binding modes and speciation alteration on the surface during the adsorption process.

The approaches of material modification provide an opportunity for future improvements in the performance of phosphorus locking agents. The position of the phosphorus locking materials in the lanthanum drawing to phosphate has been the focus of interest in lanthanum due to the high affinity of the phosphate and lanthanum to produce the highly insoluble lanthanum phosphate product. Research has indicated that phosphorus adsorption capacities on

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lanthanum-modified bentonites of over 50 mg/g have been recorded, which is significantly more when compared to the unmodified counterparts. Nonetheless, the price of lanthanum and its possible ecotoxicity have to be considered closely. Other flavors of changes involve surface coating the polymers so as to enhance the density of the hydroxyl groups on the surface, thermal treatment in order to maximize the porosity and crystallinity, or by integrating two or more functional parts into a composite material. The systematic study of effects of modification on both capacity and kinetics would help in designing a new generation of phosphorus adsorbents.

Some engineering issues need to be addressed when scaling down a laboratory implementation to a field implementation. Adsorbent deployment conditions need to strike a balance in contact performances, pressure drop, and functionality. Fixed-bed columns are easy to operate, but they can generate clogging and channeling. Fluidized bed systems have good contact; however, these systems demand more complicated hydraulics. In-situ sediment loading using adsorbents during sediment application proves to be promising, but requires even distribution and ensures the prediction of the long-term performance of adsorbents. Pre-pilot field tests, in selected water treatment plants, would be instrumental in the technology test and deepening before full-scale treatment is adopted.

5. Conclusion

This comparative study of phosphorus elimination efficacy between phosphorus locking material and air aluminium materials presented several essential results that possessed theoretical and instrumental outcomes. When the iron-aluminum materials operated under kinetic experimental conditions attributed to phosphorus adsorption ability, it was found that they possessed a superior phosphorus adsorption capacity of 18.35mg/g in comparison to the phosphorus locking agent, which has a lower capacitance of just 3.69mg/g. Both substances gave excellent correlation with pseudo-second-order kinetic models ($R^2 > 0.98$), and the sensitivity of the rate-limiting step of phosphorus uptake was found to be chemical adsorption. The pseudo-second-order reaction suggests that there is an exchange or transfer of electrons between the phosphate ions and the surface of the adsorbent and sites, as per the ligand exchange and formation of inner-sphere complexes.

Isotherm analysis showed that both tested materials comply well with the Langmuir model ($R^2 >0.96$), which implies that adsorption on the materials is on monolayer sites of the relatively homogeneous surface. Although the phosphorus locking agent had a higher constant maximum capacity under Langmuir fitting (25.06 versus 16.87 mg/g), the benefit was only observed over longer equilibration terms, which would not be typical of the treatment process. Iron-aluminum material is better placed in respect of the real-life usage of the solution because of the higher kinetic performance, as it is useful in real-life situations when phosphorus has to be removed quickly within reasonable contact times.

Mechanistic knowledge was achieved by combining kinetic and Isotherm knowledge with the characterization of the material. The main mechanism is chemical adsorption, in which the surfaces of iron-aluminum materials, containing high contents of the hydroxyl group, promoted the ligand exchange reactions with phosphate. The tears of stable Fe-O-P and Al-O-P bonds by bidentate surface complexation are the solitary basis of elevated potency phosphorus connecting. Such a chemical event is the explanation of rapid kinetics and high binding values in the experiment.

Through the findings, we would specify the use of iron-aluminum materials for phosphorus removal in situations of bi-reaction on high-concentration phosphorus-contaminated bodies of water. The high intensity with fast dynamics, low cost with morning to waste valorization, and sustainability of the environmental approach used make iron-aluminum materials the best choices as adsorbents. It is recommended that future studies should seek to optimize the preparation procedures to accomplish the maximum surface area and hydroxyl group density, the performances at various conditions under outlay circumstances using realistic water matrices, and how they can be scaled to implement them in the field. Nevertheless, in terms of further purification, the technology of iron-aluminum materials can be promising in solving the international issue of phosphorus pollution and eutrophication in water bodies.

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