Utilization of Blast Furnace Slag for Phosphate Elimination from Aqueous Solution

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Abstract

This study explores the application of Blast Furnace Slag (BFS), a high-volume by-product of the iron & steel industry, as a cost effective sorbent for inorganic phosphate removal from aqueous sol^n. Batch adsorption experiments were performed to examine the influence of key operational parameters, including sorbent dosage, contact time, initial phosphate concentration, pH, and agitation speed. Under optimized conditions (15 g/L BFS, 120 min contact time, 150 rpm agitation, pH 7, and 20 mg/L initial phosphate concentration), a maximum phosphate removal efficiency of 88.8% was obtained. The equilibrium data were most accurately represented by the Langmuir isotherm ($R^2 = 0.985$), indicating mono-layer adsorption. while the Freundlich model ($R^2 = 0.905$) suggested some degree of surface heterogeneity. Kinetic analysis showed strong agreement to the pseudo 2nd order model ($R^2 = 0.996$), signifying that chemisorption was the dominant removal mechanism. The results demonstrate that BFS possesses promising sorptive properties and represents a sustainable and low-cost alternative for phosphate remediation in wastewater treatment, contributing to industrial waste valorization and circular economy practices.

Keywords: *Aqueous Solution, Phosphate, Industrial waste, Blast Furnace Slag (BFS), Batch Study.*

1. Introduction

Eutrophication, driven by excessive phosphate concentrations in aquatic ecosystems, poses a significant environmental challenge, disrupting ecological balance and threatening water quality [1]. Elevated levels of phosphorus, stemming from agricultural runoff, industrial discharge, and domestic wastewater, can trigger algal blooms, oxygen depletion, and a decline in aquatic biodiversity [2]. Consequently, effective phosphate removal strategies are crucial for mitigating eutrophication and safeguarding water resources [3].

Conventional methods for phosphate removal, like chemical precipitation, biological treatment & membrane filtration, often face limitations related to high operational costs, incomplete removal efficiency, sludge generation, and secondary pollution, which restrict their large-scale applicability [4]. Adsorption, utilizing cost-effective and readily available materials, has emerged as a promising alternative for phosphate removal from aqueous solutions. This approach offers several advantages, including high removal efficiency, ease of operation, and the potential for resource recovery. The looming depletion of accessible phosphorus reserves by approximately 2300 highlights the urgent need for innovative phosphorus recovery technologies to ensure a sustainable supply for future generations [5].

Recovering phosphorus from wastewater through technologies like struvite crystallization not only addresses environmental pollution but also reduces the agricultural sector's reliance on artificial phosphorus fertilizers [6]. Exploring the use of waste materials as bio-adsorbents aligns with the principles of sustainable development, transforming industrial byproducts into valuable resources for environmental remediation.

Blast furnace slag (BFS) is generated during the manufacturing of iron in blast furnaces, representing a significant industrial byproduct with substantial environmental and economic implications. It consists mostly of silica, alumina, calcium oxide, magnesium oxide. The utilization of blast furnace slag as an adsorbent for phosphate removal presents a sustainable and economically viable approach to wastewater treatment [7-10].

The chemical composition and mineralogical phases present in BFS play a crucial role in its adsorption capacity for phosphate ions [11]. The adsorption capacity of blast furnace slag is influenced by its structural and compositional characteristics, which can be enhanced through physical and chemical modifications [12].

The use of metallurgical slag as a sorbent offers a dual benefit: it mitigates the environmental challenges associated with slag disposal while contributing to the purification of natural water bodies [13]. Globally, large volumes of slag are produced each year, including approximately 20 million tons in the USA & 44 million tons in Europe [14]. The use of industrial byproducts is a significant move towards a "green" future for concrete and greatly improves waste management worldwide [15].

This investigation evaluates the capability of BFS as an efficient adsorbent for the elimination of phosphate from aqueous sol^n. The uptake capacity of BFS was evaluated under various experimental conditions, including different pH levels, adsorbent dosages, initial phosphate concentrations, and contact times.

2. Materials and Methods

2.1 Materials

2.1.1 Reagents

Phosphate sol^n of 50 ppm was synthetically prepared by adding 0.2195 grams of anhydrous monobasic potassium phosphate (KH_2PO_4) in 1 liter of distilled water. Desired concentrations in the range of 2.5–50 mg/L were then obtained through serial dilution. This synthetically prepared phosphate solution was used in batch experiments to optimize various sorption parameters.

2.1.2 Preparation of Adsorbent

BFS was sourced from a nearby industry located in Odisha, already in an extremely fine powdered form. Initially, it was cleaned with tap water and sun-dried for over four days. Subsequently, it was rinsed again with distilled water and subsequently dried overnight at 104 °C.

2.1.3 Preparation of Adsorbate

The concentration was measured using the Stannous Chloride method [16]. In this method, Ammonium Molybdate reagent, Stannous Chloride reagent, and the filtered sample were combined into a single solution. The analysis was performed using a UV spectrophotometer. Specifically, 25 mL of the treated sample was mixed with 1 mL of Ammonium Molybdate and 0.125 mL of Stannous Chloride reagent. The absorbance of the sol^n was observed at 690 nm between 10 and 12 minutes after reagent addition.

2.2 Methods

Batch experiments were conducted to optimize key parameters affecting the sorption process. Phosphate removal was investigated under varying operational parameters, including sorbent dose (1–20 g/L), contact time (15–150 min), initial pH (2–11), initial phosphate concentration (C_0: 2.5–50 mg/L), and agitation speed (25–200 rpm), while maintaining a cons^t temp of 25±2 °C. Batch investigation were executed out in a temp-controlled rotary-shaker using

0.250 L flasks containing 0.1 L of phosphate solution at the desired concentrations. The solution pH was adjusted with HCl and NaOH as required. Prior to analysis, all samples were filtered through Whatman filter paper & the phosphate conc was quantified using a UV-Vis spectrophotometer.

The amount of phosphate uptake per unit weight of adsorbent was estimated according to the following equation:

$$(Q_t) = \frac{(Co-Ce)V}{M} \qquad (1)$$

$$\text{The percentage sorption (\%)} = \frac{(Co-Ce)}{Ce} \times 100 \qquad (2)$$

Where, C_o is the initial conc. of phosphate in mg L^{-1}, C_e is the equilibrium conc. of phosphate in mg L^{-1}, V is the vol. of phosphate sol^n in L, M is the weight of sorbent dose in g

3. Results and Discussions

3.1 Sorbent Dose

The outcome of sorbent dose on phosphate sorption was investigated by adjusting the BFS dosage in the range of 1–20 g/L in a synthetic aqueous solution containing 20 mg/L of phosphate, while holding other parameters fixed—agitation speed at 150 rpm, solution volume at 50 mL, and room temperature. The results indicated that phosphate removal efficiency increased from 58% to 88% as the sorbent dose was elevated from 1 to 15 g/L. However, as shown in Fig. 1, upon extending the dose range from 15 to 20 g/L produced only a negligible change in removal efficiency, suggesting that the sorption capacity had reached a plateau. In general, an increase in sorbent dose enhances phosphate removal efficiency up to an optimal threshold, beyond which additional dosage does not significantly improve performance [17,18].

3.2 Initial Concentration

The influence of phosphate concentration on the adsorption of BFS was evaluated by varying C_0 from 2.5 to 50 mg/L, while keeping other parameters constant. This approach enabled assessment of how initial concentration influences the adsorption capacity of BFS.Results indicated that phosphate removal efficiency was highest at lower initial concentrations and decreased progressively as the concentration increased (Fig. 2). This inverse relationship is consistent with previous findings in wastewater treatment, where lower initial concentrations enable more effective utilization of available adsorption sites or enhanced activity of phosphate-accumulating organisms [19, 20].

3.3 Period of Contact

The outcome of contact period on phosphate sorption by the sorbent was evaluated by altering the duration from 15 to 150 minutes, while keeping other parameters constant. As revealed in Fig. 3, phosphate removal efficiency increased with contact time, indicating enhanced sorption. However, beyond 120 minutes, further increases in contact time resulted in minimal changes in removal efficiency, suggesting the system had reached equilibrium. This behavior can be ascribed to the progressive saturation of active sorption sites; as the sites become increasingly occupied, the rate of adsorption declines and eventually reaches equilibrium with the desorption rate [21].

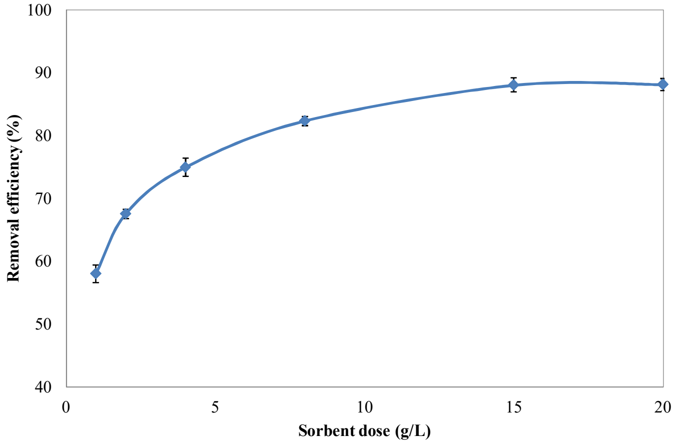

Fig. 1 Phosphate removal (%) at different sorbent dose

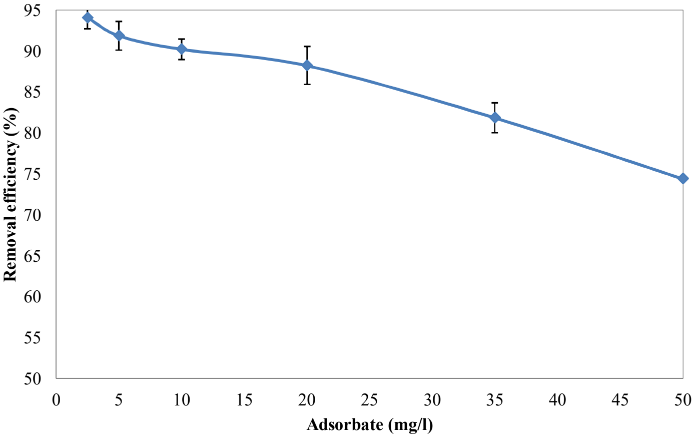

Fig. 2 Phosphate removal (%) at different phosphate concentration

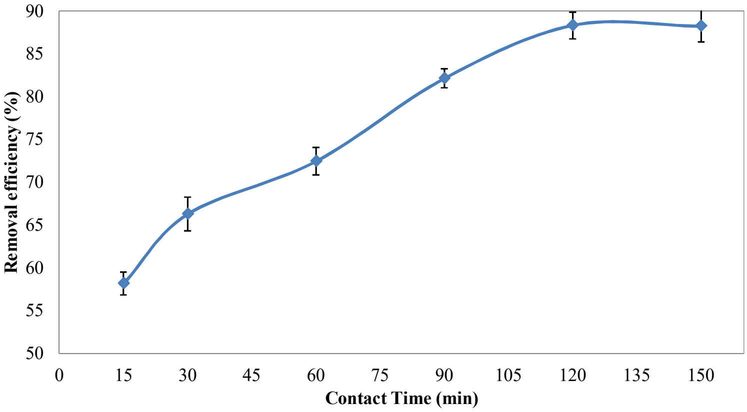

Fig. 3 Phosphate removal (%) at different contact time

3.4 Agitation Speed

The agitation speed was varied in increasing order from 25 revolution per minute to 200 revolution per minute. As shown in Fig. 4, phosphate removal efficiency increased with increasing agitation speed. Initially, an increase in agitation speed often correlates with an enhanced rate of phosphate removal, but this positive correlation typically plateaus and can even reverse beyond an optimal agitation threshold [22].

3.5 pH

To analyze the effect of pH on the adsorption capacity of BFS, the solution pH was altered across a range from acidic to alkaline conditions. That is from pH 2 to pH 11. Maximum adsorption of phosphate occurred as the solution pH rose from 2 to 7, while a decline in adsorption occurred when the pH was further raised to 11. The enhanced adsorption at lower to neutral pH values can be linked to the greater availability of negatively charged functional groups on the BFS surface, which facilitates electrostatic interactions with phosphate species [23]. However, as the pH breaches the neutral threshold and ventures into alkaline realms, the adsorbent surface tends to acquire a negative charge, engendering an electrostatic repulsion that curtails phosphate adsorption [23, 24].

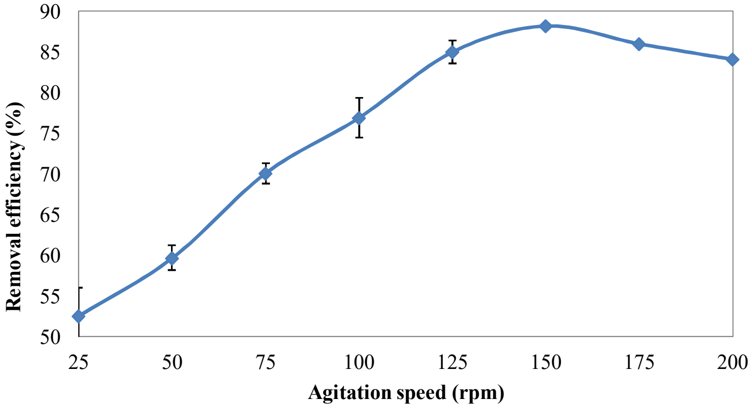

Fig. 4 Phosphate removal (%) at different agitation speeds

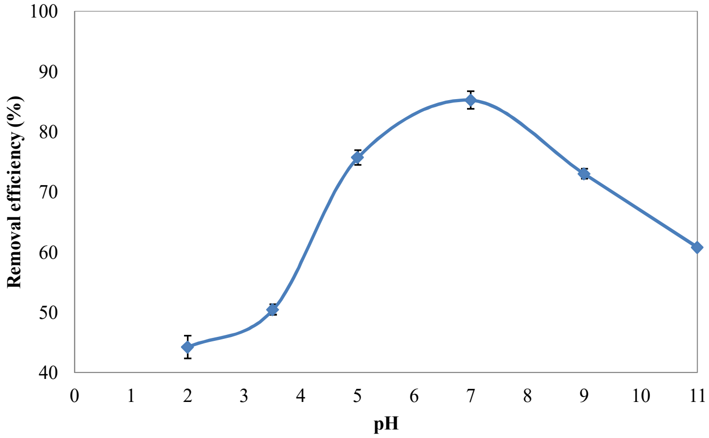

Fig. 5 Phosphate removal (%) at different pH

3.6 Modeling of Adsorption Isotherms and its Studies

3.6.1 Langmuir isotherm (LI)

LI model presupposes monolayer adsorption on a homogeneous surface with minimal interaction between adsorbed molecules. Data fitting was performed using the Langmuir isotherm & the resulting isotherm (Fig. 6) showed good linearity. Langmuir constants were found to be 2.04 mg/g for maximum adsorption capacity (Q_0) & 0.54 for the adsorption affinity constant (b). The high correlation coefficient ($R^2 = 0.985$) indicates an excellent fit, confirming monolayer adsorption behavior. Additionally, the dimensionless separation factor (R^L) was calculated to be 0.085, indicating that the sorption process is favorable and spontaneous.

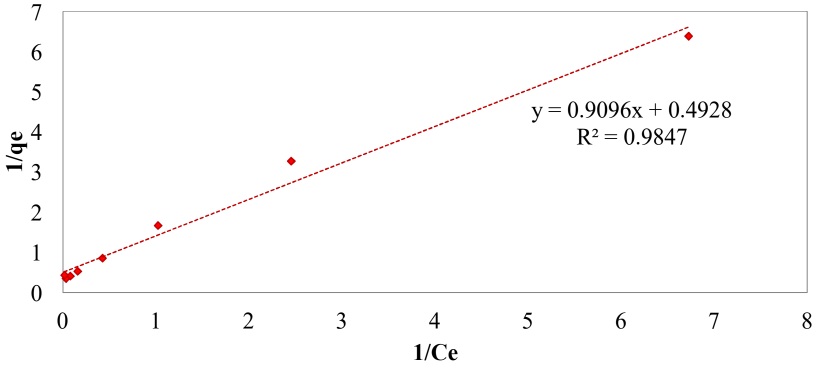

Fig. 6 LI plots of phosphate adsorption

3.6.2 Freundlich isotherm (FI)

FI model is commonly invoked to explain adsorption on heterogeneous surfaces, accounting for differences in adsorption site energies and permitting multilayer adsorption. This model was applied to fit the observed data, as presented in Fig. 7. The FI constants n & K_F have values of 2.07 and 0.55 mg/g, respectively. The correlation coefficient ($R^2 = 0.905$) suggests a good fit, supporting the occurrence of multilayer adsorption on a non-uniform surface.

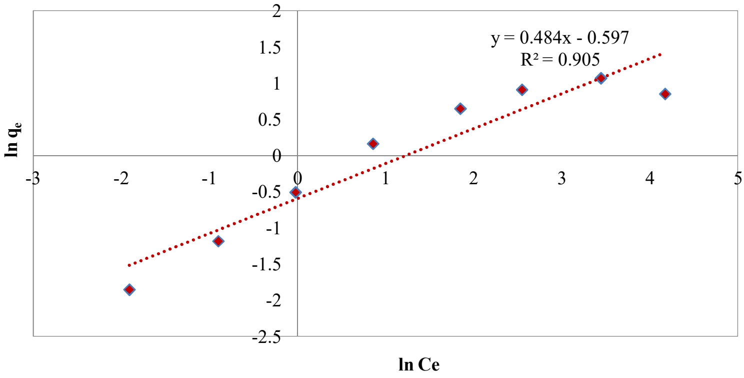

Fig. 7 FI plots of phosphate adsorption

3.7 Adsorption kinetics

3.7.1 Pseudo first order model (PFO)

The PFO model was evaluated by charting $\log(q_e - q_t)$ versus time (t). A linear correlation was observed, with the slope corresponding to $-K_1$ & the intercept representing $\log q_e$, as depicted in Fig. 8. The PFO kinetic model yielded a rate constant (K_1) of 2.3×10^{-2} min^{-1} and a calculated equilibrium adsorption capacity (q_e) of 5.16 mg/g. The correlation coefficient

($R^2 = 0.958$) reveals a reasonably good correspondence of the data to this model, suggesting that physisorption is likely the predominant mechanism.

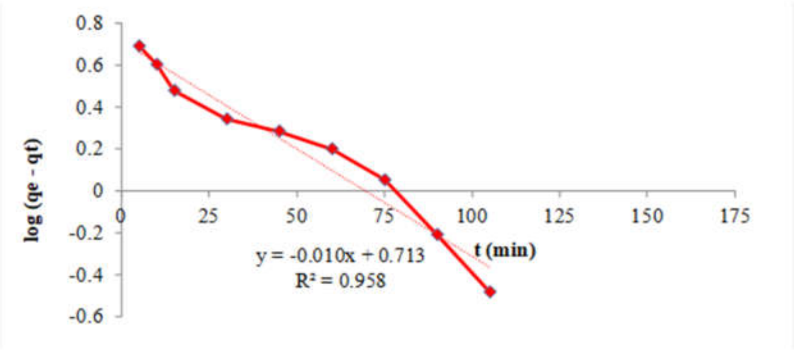

Fig. 8 PFO kinetic model of phosphate adsorption

3.7.2 Pseudo second order model (PSO)

The PSO model was assessed by plotting t/q_t versus time (t), as shown in Fig. 9. PSO rate constant (K_2) & the theoretical adsorption capacity (q_e) were determined as 0.452×10^{-2} min^{-1} and 9.69 mg/g. The strong consistency between the experimental and predicted q_e values, together with the strong linearity of the plot, confirms that the adsorption process is satisfactorily interpreted by the PSO model, indicating chemisorption as the dominant rate-controlling mechanism.

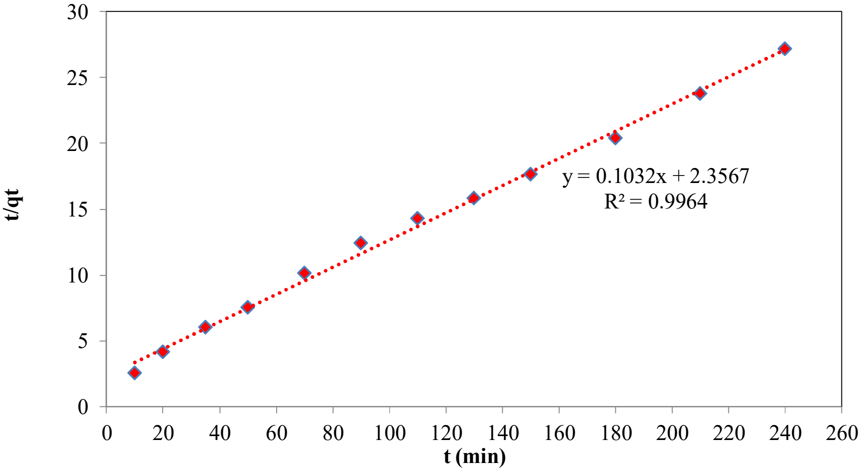

Fig. 9 PSO kinetic model of phosphate adsorption

4. Conclusion

The investigation presented here highlights the potential of BFS, an abundant industrial byproduct, as an economical and efficient adsorbent for eliminating phosphate from aqueous sol^n. Batch experiments systematically evaluated the consequence of key operational parameters, including sorbent dosage, contact time, pH, agitation speed, & initial phosphate concentration. Maximum removal efficiency (~88.8%) was achieved under optimized conditions (15 g/L BFS dose, pH 7, 150 rpm, 120 min contact time, and 20 mg/L initial phosphate concentration).

Equilibrium adsorption behavior was best explained by the LI model ($R^2 = 0.985$), representing monolayer adsorption. The FI model also provided a equitable fit ($R^2 = 0.905$), reflecting surface heterogeneity. Kinetic analysis revealed that PSO model ($R^2 = 0.996$) most accurately described the adsorption process, confirming chemisorption as the dominant rate-limiting mechanism.

Overall, BFS exhibited promising adsorption capacity and removal efficiency, positioning it as a viable and sustainable alternative for phosphate remediation in wastewater treatment. The application of such metallurgical waste materials not only offers an economical solution for environmental management but also contributes to the principles of circular economy and industrial waste valorization.

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