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Modelling of phosphate removal from water by an eco-friendly material

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Abstract: Phosphate is a prevalent chemical element in the Earth's crust, and its presence in water can lead to eutrophication. To address this issue, researchers have explored various methods for removing phosphate from water and wastewater. Filtration methods have been shown to be effective, but they can be costly due to the materials used. Recent studies have focused on finding more cost-effective alternatives. In this context, this study aims firstly at examining the potential of using furnace bottom ashes (FBAs) from the iron industry to remove phosphate from synthetic water and secondly at the modelling of the adsorption of phosphate on this material. The modelling process will be conducted using the Box–Behnken design methodology (BBD). The study considers different operational conditions, such as detention times, FBA doses, and phosphate concentrations, to identify the most effective and affordable removal approach. The results indicate that FBAs can be a highly efficient alternative for phosphate removal, with an optimum removal of 97.1% at 120 minutes retention time, 10 mg/L phosphate concentration, 10 mg/L FBA doses, and pH of 7.5. The findings are used to develop a highly reliable model with an R^2 value of 0.97.

Keywords: Phosphate, FBA, water.

1. Introduction

Water is a critical resource for life on Earth, and with the global population increasing rapidly, demand for clean water is continuously rising. However, limited freshwater resources and insufficient water treatment infrastructure mean that much of the wastewater generated by human activities is not adequately treated before being discharged into the environment [1].

This has significant negative consequences for the health of aquatic ecosystems, as well as for human health, agriculture, and industry. For example, when wastewater containing nutrients like phosphates is discharged into freshwater bodies, it can lead to the growth of algae, which can have a range of negative effects.

Algal blooms can deplete oxygen levels in the water, leading to the death of fish and other aquatic organisms. They can also block sunlight, preventing other plants and organisms from growing, and can alter the chemical composition of the water, making it less suitable for human use. Additionally, some species of algae produce toxins that can be harmful to humans and animals, leading to illness or even death [2].

To address these issues, environmental regulations have been put in place to limit the concentrations of pollutants in wastewater, including nutrients like phosphates. However, traditional methods for removing phosphates from wastewater can be complex and expensive, requiring specialized equipment and materials. One potential solution to this problem is to explore alternative, more affordable adsorbent materials as adsorbents for removing phosphates from wastewater.

Adsorption is the process of molecules or particles adhering to the surface of a solid or liquid substance. The substance that the molecules or particles adhere to is known as the adsorbent, while the substance being adsorbed is called the adsorbate [3]. Adsorption occurs due to intermolecular forces, such as van der Waals forces or electrostatic forces, between the adsorbent and the adsorbate. These forces can be strong enough to hold the adsorbate in place, but weak enough that the adsorbate can be released from the adsorbent with relative ease. Adsorption is commonly used in a variety of applications, such as purification of gases and liquids, separation of components in mixtures, and removal of pollutants from air and water. Additionally, adsorption plays a critical role in many biological processes, such as the binding of enzymes to substrates and the adsorption of nutrients by cells. There are two main types of adsorption: physisorption and chemisorption. Physisorption, also known as physical adsorption, occurs when the adsorbate is held to the adsorbent by weak intermolecular forces. Chemisorption, on the other hand, involves the formation of chemical bonds between the adsorbate and the adsorbent [4]. This type of adsorption is typically stronger than physisorption and can be used to catalyze chemical reactions.

Although there are natural rocks that can be used as adsorbents, the use of by-products as adsorbents in water treatment offers several advantages over traditional adsorbents, such as activated carbon [5]. By-products are often low-cost or even free, and their use can help to reduce waste and promote sustainability. Additionally, the use of by-products can provide an alternative source of revenue for industries that produce these materials. However, it is important to carefully evaluate the properties and effectiveness of these materials for specific water treatment applications to ensure that they are safe and effective.

One such material that has shown promise in recent studies is furnace bottom ashes (FABs) from the iron industry. By studying the efficiency of using FABs for removing phosphates from synthetic water, this study aims to determine whether this material could be a viable alternative to traditional phosphate removal methods. The study examined several operational conditions, including detention times, FABs doses, and phosphate concentrations, to determine the best conditions for maximizing removal rates while minimizing operational costs.

2. Technologies for phosphate removal

The paragraph discusses various methods for removing phosphorus from water, which is typically achieved by converting phosphorus ions into solid fractions and removing them from the solution. This can be done through various methods, including chemical additives, wetlands, biological digestion, and adsorption on a solid surface. Each method has its advantages and disadvantages.

Biological treatment methods rely on the activity of microorganisms such as microalgae, bacteria, and fungi to remove phosphorus [6]. However, these methods require sufficient biodegradable carbon quantities and careful control of the nutrient concentration and pH to avoid rapid microorganism growth, which can reduce treatment efficiency. Chemical treatment methods involve adding divalent or trivalent metallic salts to precipitate phosphates, which are then separated from the solution. While chemical methods are relatively simple and cost-effective, they can produce toxic sludge and are not as environmentally friendly as other methods [7].

Physical treatment methods, such as filtration and membrane methods, do not alter the chemical composition of the water and are reversible [8]. Filtration utilizes porous materials to remove pollutants from the water, and the cost of the process depends on the price of the materials used. Membrane methods, such as reverse osmosis, use semipermeable membranes to separate pollutants from water through pressure but can be expensive and require specific equipment and expertise.

Recent studies have focused on using industrial by-products or natural materials as cost-effective and efficient alternatives for phosphorus removal. For example, calcined paper mill sludge and fly ash have been used for ammonium nitrogen and phosphate removal and have demonstrated high efficiency at a neutral pH and temperature. This is particularly important given the increase in rainfall due to global warming, which can result in more phosphorus washing into water sources.

3. Materials and Methods

The focus of this investigation was to explore the potential of using furnace bottom ashes (FABs) as a cost-effective adsorbent material for the removal of phosphates from wastewater. The physical characteristics of the FABs, such as particle size, specific gravity, porosity, and surface area, were studied to assess their suitability for this purpose. The particle size test was conducted using sieve analysis with six different sieves (numbers 4, 6, 10, 16, 30, and 50), and the mass retained on each sieve was measured to determine the particle size distribution. The particle size of the FABs is a crucial factor in determining the total surface area, which is directly proportional to the adsorption capacity per unit mass. Therefore, understanding the particle size distribution of the FABs is essential for assessing their effectiveness as an adsorbent material for phosphate removal.

The next step was to analyze the chemical composition of the FAB sample using an X-ray fluorescence analyzer to identify its components. This analysis was crucial in determining the efficiency of phosphate removal as materials containing iron, calcium, aluminium, or magnesium were found to be suitable for adsorbing phosphate. Synthetic water samples were then prepared and used for water treatment experiments. The Box–Behnken design (BBD) was employed to optimize the process with regard to the temperature of the water, the dosage of FABs, and the retention time. The adsorption experiments were conducted using analytical chemicals provided by Sigma-Aldrich, UK, with a phosphate concentration of 10 mg/L. The polluted water and FABs were mixed in a 0.5 L container for different times, from 20 to 120 minutes.

The operational factors were kept within ranges studied in the literature, with FABs doses of 1 to 10 mg per 1000 mL, pH values ranging between 4 and 11 a constant temperature of 20±2 ^{o}C. The concentrations of phosphate were measured using a Hach Lange spectrophotometer (Model: DR 2800). To achieve optimum water treatment, the BBD was employed to design a simulation model. The main variable in this experiment was phosphate removal, while the other factors (FABs dose, pH and retention time) were treated as independent variables. Minitab 19.2 was used to design the matrix. The ranges of the independent variables used in the experiment are outlined in Table 1.

Table 1. The studied ranges of parameters.

Independent variables	Values

	Minimum	Maximum
pH	4	11
FBAs dose (DO), mg/L	1	10
Time, minutes	20	120

4. Results and discussion

4.1. Physical properties

Based on the results, it was found that most of the particles in the FBAs were caught in sieves 4 through 16. This suggests that the majority of the FBAs sample was made up of particles with a small diameter (between 1.180 and 4.750 mm). The uniformity coefficient (UC) and gradation coefficient (CC) were calculated based on the passing rate of particles at different sizes, with D10, D30, and D60 representing specific particle sizes. A sample is considered well-graded if the UC is greater than 4.0 and the CC falls between 1.0 and 3.0. The sieve analysis revealed that the D10, D30, and D60 values were 0.59, 1.48, and 3.09, respectively. Using equations (3) and (4), the UC value was calculated to be 5.237, and the CC value was 1.201. Therefore, the FBAs sample is considered well-graded.

The gradation level was calculated using the sieve analysis results as shown:

$$UC = \frac{D_{60}}{D_{10}} \tag{3}$$

$$CC = \frac{D_{30}^2}{D_{10} \times D_{60}} \tag{4}$$

The specific gravity of FBAs was calculated and found to be 1.28, which is greater than that of water, indicating that they will not float. The FBAs were also found to have a porosity of 0.66 m^2/g and a surface area of 6.8 m^2/g. Based on these physical properties, the FBAs are suitable for use in phosphate treatment, as they have a high surface area and acceptable porosity, and their specific gravity is greater than that of water.

4.2. Chemical composition

The results of the chemical composition test indicated that over 20% of the FBAs' composition consisted of oxides of iron, magnesium, aluminum, and calcium. This composition aligns with the literature, which suggests that FBAs are suitable for use in phosphate treatment based on their chemical composition.

4.3. Phosphate removal

A series of batch flow experiments were conducted to assess the effectiveness of FBAs for removing phosphate. In total, 20 experiments were carried out, with each experiment involving different operational factors. The goal was to identify the optimal conditions that would ensure a high removal rate while minimizing operational costs. The results of these experiments are presented in Table 2.

Table 2. Actual results and conditions of experiments for phosphate removal.

No.	pH	DO	Time	Removal %	No.	pH	DO	Time	Removal %
1	4	10	70	82.2	**9**	11	10	70	96.9
2	11	5.5	20	88.8	**10**	4	5.5	20	68.2
3	7.5	10	120	97.1	**11**	11	1	70	86.4
4	4	5.5	120	82.2	**12**	4	1	70	73.1
5	7.5	1	120	93.5	**13**	7.5	5.5	70	96.4
6	7.5	1	20	67.4	**14**	7.5	5.5	70	95.7
7	7.5	10	20	84.1	**15**	7.5	5.5	70	96.1
8	11	5.5	120	96.5	**16**	7.5	5.5	70	95.9

The study found that increasing both the dose and retention time of FBAs led to a higher removal efficiency, while higher phosphate concentrations had a negative impact on removal rates. This was likely because the available surface area on the FBAs was not sufficient to accommodate all the phosphate ions, resulting in lower removal rates. Using more FBAs provided a larger surface area for adsorption, and longer retention times increased the chance of contact between FBAs and phosphate ions, resulting in higher removal rates. For example, at a dose of 10 mg/L and pH of water of 7.5 with a retention time of 120 minutes, the removal rate was 97.1%, while at a dose of 10 mg/L and pH of water of 7.5 with a retention time of 20 minutes, the removal rate decreased to 67.4%.

The results were modelled and the model was applied to the real experiment conditions, and the obtained results of the model are shown in Table 3.

Table 3. Predicted results and conditions of experiments for phosphate removal.

No.	pH	DO	Time	Removal %	No.	pH	DO	Time	Removal %
1	4	10	70	83.2	**9**	11	10	70	97.5
2	11	5.5	20	86.5	**10**	4	5.5	20	68.4
3	7.5	10	120	95.4	**11**	11	1	70	87.8
4	4	5.5	120	84.5	**12**	4	1	70	73.1
5	7.5	1	120	91.2	**13**	7.5	5.5	70	96.3
6	7.5	1	20	71.4	**14**	7.5	5.5	70	96.3
7	7.5	10	20	84.5	**15**	7.5	5.5	70	96.3
8	11	5.5	120	99.1	**16**	7.5	5.5	70	96.3

It is very clear from these tables the real and predicted results are very closed that confirm the dependability of the results, as shown in Figure 1. Therefore, the FBAs is a good option for the removal of phosphate from water.

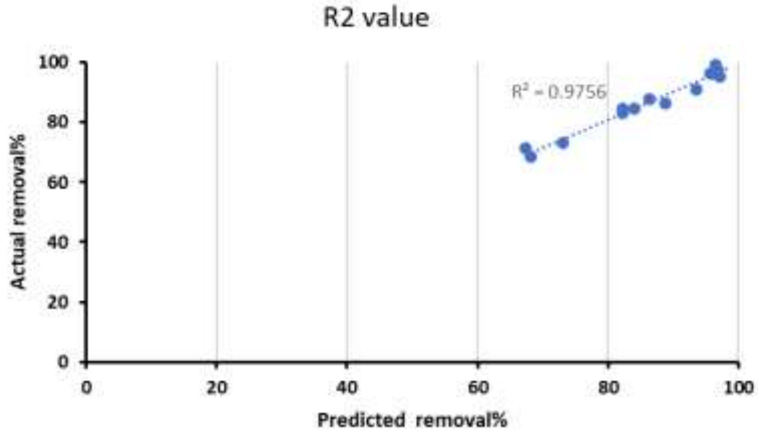

Figure 1. Relationships between actual and predicted removals of phosphate.

1. Conclusions

This study examined the use of FBAs to treat effluent containing phosphate and aimed to determine the optimal operational factors. The findings revealed that FBAs possess suitable chemical and physical properties for treating phosphate. By using a 550 mg/L FBAs dose, 5 mg/L phosphate concentration, and a retention time of 31 minutes, the removal efficiency was comparable to previous research with an 89% removal rate. The removal rate is directly proportional to both the FBAs dose and retention time, while it is inversely proportional to the phosphate concentration. Additionally, based on the suitable CCD value, it may be possible to develop a simulation model to predict phosphate removal under different FBAs doses, phosphate concentrations, and retention periods.

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