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Removal of Phosphate using a Multi Stage Filtration System

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ABSTRACT
Phosphorus is an essential nutrient, but its excessive presence in water bodies leads to eutrophication, algal blooms, and deterioration of aquatic ecosystems. Conventional treatment methods for phosphate removal, such as chemical precipitation, ion exchange, and membrane technologies, are often costly and generate secondary waste. This study aimed to design a simple and economical system for phosphate detection and removal using waste-derived and natural materials. A multi-stage beaker-based setup was constructed, consisting of three sequential chambers inside a larger beaker. The first chamber contained sand sieved through a 1.25 mm mesh to remove suspended solids, while the second and third chambers contained eggshell powder supported by filter paper to facilitate phosphate adsorption. A motor and battery system circulated water through the chambers in sequence. The treated water samples collected after each stage showed progressive improvement in clarity and phosphate removal, with the final output exhibiting significantly reduced phosphate content compared to raw water. The results confirm that eggshell powder, rich in calcium carbonate, effectively removes phosphate through ion exchange and precipitation reactions. This study demonstrates a low-cost, eco-friendly, and sustainable approach to phosphate removal that can be adapted for rural water treatment and educational demonstrations, while also contributing to waste utilization.

KEWYORDS: **Phosphate removal, Eggshell powder, Sand filtration, Wastewater treatment, Adsorption, Sustainable water purification**

INTRODUCTION:

Phosphorus is an essential nutrient for plants and animals, but its excessive accumulation in aquatic ecosystems has become a major environmental concern. Agricultural runoff, domestic sewage, and detergents are the main contributors of phosphate to rivers, lakes, and reservoirs. Elevated phosphate concentrations promote excessive algal growth, a process known as eutrophication, which reduces dissolved oxygen levels and leads to the death of aquatic organisms. This chain of events disrupts ecological balance, lowers water quality, and poses risks to human health through contaminated food and drinking water. Even at concentrations above 0.02 mg/L, phosphate can trigger eutrophication, making its removal a critical step in wastewater treatment.

Various conventional methods are used for phosphate removal, such as chemical precipitation, ion exchange, electrodialysis, biological treatment, and membrane filtration. However, these techniques often require high installation and operational costs, skilled handling, and generate sludge or secondary waste that creates disposal problems. In rural and low-resource settings, such approaches are often not practical. Therefore, there is a growing demand for low-cost, environmentally friendly, and sustainable techniques that can be applied at small to medium scale for phosphate removal. Recently, natural and waste-derived adsorbents have attracted significant attention for water treatment applications. Among them, eggshells, which are produced in large quantities as household and food industry waste, offer a promising solution. Eggshells are rich in calcium carbonate ($CaCO_3$), which can effectively react with phosphate ions to form insoluble calcium phosphate compounds. Several studies have confirmed that eggshells, either raw or calcined, exhibit strong phosphate adsorption capacity, making them a sustainable alternative to expensive commercial adsorbents. Similarly, sand is widely available, inexpensive, and effective for removing suspended solids and larger impurities, improving water clarity before chemical adsorption takes place. The present study aims to design and evaluate a simple, cost-effective multi-stage beaker-based filtration system for phosphate removal from water. The system integrates sand filtration with eggshell powder adsorption, supported by filter paper layers, and uses a motor and battery-driven circulation mechanism. By combining waste utilization with practical water purification, the study addresses both environmental sustainability and water quality improvement. The findings are expected to contribute to the development of eco-friendly, small-scale phosphate removal techniques that can be implemented in rural areas, educational projects, and low-cost wastewater treatment systems.

MATERIALS AND METHODS

Experimental Setup

The experimental work was carried out using a custom-designed laboratory-scale model intended to simulate the filtration and adsorption processes for phosphate removal. The setup consisted of a large outer beaker, which served as the structural container and support for three sequential treatment chambers. These chambers were constructed using medium-sized beakers, each fitted with an inner perforated beaker that allowed water passage. To prevent leakage of fine particles, filter paper was placed at the bottom of each perforated beaker.

The system was designed in three stages:

- Chamber 1 – Sand Filtration: Removal of suspended solids, turbidity, and larger impurities.
- Chamber 2 – Eggshell Powder Adsorption: Primary removal of dissolved phosphate ions through chemical precipitation.
- Chamber 3 – Eggshell Powder Adsorption: Secondary adsorption unit to ensure maximum efficiency.

To enable continuous water flow, two submersible DC motors powered by 12 V batteries were incorporated into the design. The first motor was responsible for lifting raw water into Chamber 1, while the second transferred water from Chamber 2 into Chamber 3. The stepwise circulation ensured contact between the sample and each treatment medium, thereby maximizing purification efficiency.
This multi-chamber arrangement mimicked real-world treatment plants that use sequential treatment units, but on a smaller and low-cost scale, making it appropriate for laboratory study and educational demonstration. A schematic of the system is shown in Figure 1.

Preparation of Sand Filtration Unit

Sand is widely recognized as one of the most commonly used filter media in water treatment due to its low cost, abundance, and simplicity of use. The primary function of sand in this study was to remove suspended solids, turbidity, and larger organic impurities that would otherwise interfere with subsequent phosphate adsorption stages.

The preparation of sand was performed carefully to ensure maximum effectiveness:
Sieving: Natural sand was collected and passed through a 1.25 mm IS sieve. This step removed coarse particles, stones, and debris while retaining medium to fine particles, which are ideal for filtration. The use of a uniform grain size also reduces preferential flow paths and improves the contact of water with the sand grains.

Washing: The sieved sand was washed repeatedly with tap water until the runoff was clear, indicating the removal of clay, silt, and organic matter. It was then rinsed with distilled water to eliminate any dissolved salts or impurities that might influence phosphate readings.

Drying: The cleaned sand was dried at room temperature and stored in clean, airtight containers to prevent contamination.

During assembly, a filter paper was placed at the base of the perforated beaker in Chamber 1. On top of this, a 2–3 cm thick sand layer was carefully added. The sand layer provided mechanical straining, sedimentation, and adsorption of fine colloidal matter, ensuring that water entering the adsorption chambers was pretreated and free of suspended load.

Preparation of Eggshell Powder Adsorbent

Eggshells were selected as the primary phosphate removal medium due to their high calcium carbonate ($CaCO_3$) content (≈95%). Calcium carbonate is known to react with phosphate ions in water, forming insoluble compounds such as tricalcium phosphate ($Ca_3(PO_4)_2$) or hydroxyapatite. This chemical reaction effectively removes phosphate from solution, thereby lowering its concentration in treated water.

Chemical reaction

The precipitation reaction between calcium ions with phosphate ions

$$3CaCO_3 + 2(PO4)^{3-} \rightarrow Ca_3(PO4)^2 + 3(CO2)^{-3}$$

The preparation of eggshell powder involved several steps to maximize its reactivity and surface area:

Collection: Waste chicken eggshells were obtained from household kitchens and local eateries.

Cleaning: Eggshells were washed thoroughly to remove egg residues and the inner organic membrane. This was crucial because leftover organic matter could introduce additional contaminants and reduce adsorption capacity.

Drying: Cleaned shells were sun-dried for 24 hours and then oven-dried at 60 °C for 3 hours to eliminate residual moisture.

Crushing and Grinding: The dried shells were first crushed using a mortar and pestle and then ground to a fine powder using a domestic grinder.

Sieving: The ground powder was sieved to isolate a particle size range of 100–300 µm, which ensures a high surface area for adsorption while being fine enough to remain stable inside the chamber.

Storage: The powder was stored in sealed containers to prevent moisture uptake. Approximately 40–50 g of eggshell powder was loaded into both Chamber 2 and Chamber 3. Each chamber was first lined with filter paper to prevent loss of fine powder through perforations.

Circulation System

In order to maintain the sequential flow of water through all three chambers, a two-motor circulation system was employed.

Motor 1: Lifted raw water into Chamber 1 (sand unit).

Motor 2: Transferred water from Chamber 2 into Chamber 3 after the first adsorption stage.

Both motors were powered by 12 V DC batteries. This choice ensured that the system was portable, low-cost, and did not require continuous electricity supply.
The motors were connected with tubing that allowed water to move smoothly between chambers. Care was taken to maintain a moderate flow rate so that the water had sufficient contact time with sand and eggshell powder. Excessive flow would reduce adsorption efficiency, while too slow a flow would lead to operational delays.

Effect of pH and Phosphate on Calcium Carbonate

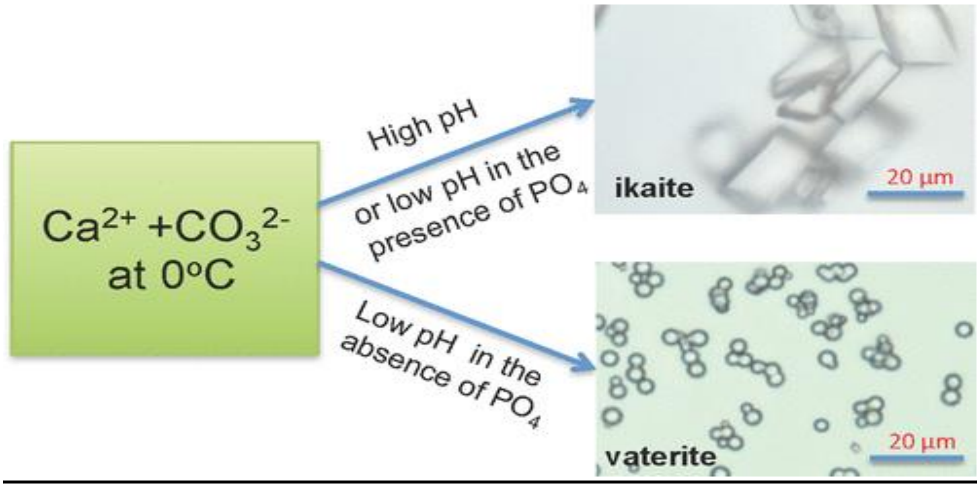

Figure 1.1 Adapted from Hu, Y.-B., Wolthers, M., Wolf-Glad row, D. A., & Nehrke, G. (2015).

- We investigated the role of pH and phosphate in the calcium carbonate polymorphs precipitation, namely, ikaite and vaterite at near-freezing temperature. We demonstrated that pH as well as phosphate can act as a switch between ikaite and vaterite polymorphs precipitation and further looked into the mechanisms of pH and phosphate in controlling the precipitation of calcium carbonate polymorphs.
- At near-freezing temperature, precipitation of metastable forms of calcium carbonate from solution is favoured (ikaite or vaterite). Both pH and phosphate contribute to the polymorph switch between vaterite and ikaite. At moderate alkaline conditions, formation of ikaite is favoured over vaterite in the presence of phosphate; at high alkaline conditions, no phosphate is needed to trigger ikaite formation. The effect of pH on different polymorphs of calcium carbonate is related to the ratio of HCO_3^-/CO_3^{2-} , which might affect the structure of prenucleation clusters. The presence of PO_4 might change the structure of the calcium carbonate clusters and/or alter the hydration shell of calcium and thus affects the polymorph selection.
- In short it can be said that by adjusting pH and phosphate presence, the microstructure of $CaCO_3$ can be tailored to form phases (like ikaite) that enhance phosphate capture from water.
- If your goal is to maximize phosphate removal using $CaCO_3$, then increasing the pH (alkaline condition) promotes the formation of ikaite, which is more effective at incorporating phosphate ions. At low pH without phosphate, you mostly get vaterite, which is less efficient.
- At low pH with phosphate, ikaite can still form, but its stability is lower than at high ph.

So yes, maintaining a higher pH generally improves phosphate removal efficiency, because it Favors the growth of ikaite (or other stable $CaCO_3$ phases that can bind phosphate).

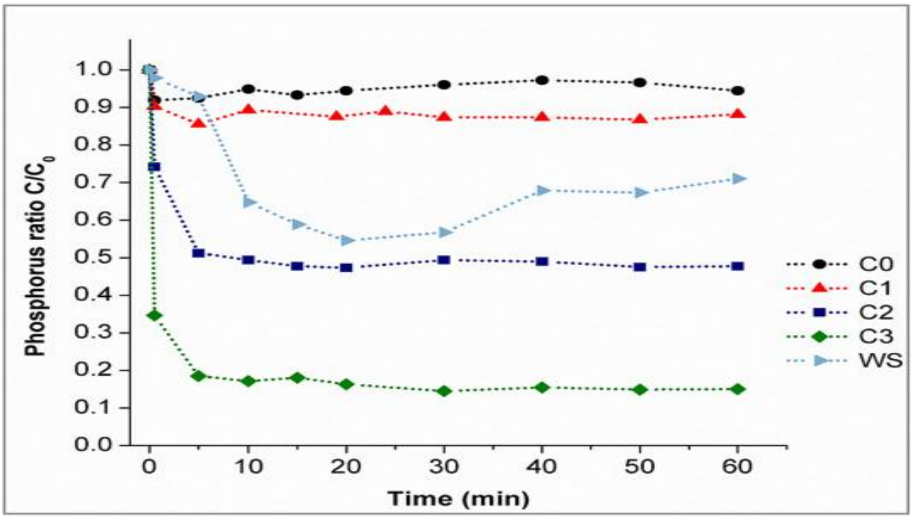

Fig 1.2 Tailoring $CaCO_3$ microstructure to improve trace phosphate removal from water

EXPERIMENTAL PROCEDURE

The following stepwise procedure was followed:

Sample Preparation: One Liter of water containing phosphate was prepared by dissolving known amounts of potassium dihydrogen phosphate (KH_2PO_4) in distilled water. Alternatively, wastewater containing detergents was used as a real-world test sample.

Initial Testing: A sample of raw water was collected and tested for initial phosphate concentration, pH, and turbidity.

Chamber 1 (Sand Filtration): The first motor pumped raw water into Chamber 1. After filtration, a sample was collected for analysis.

Chamber 2 (Eggshell Adsorption – Stage 1): The partially treated water entered Chamber 2, where it passed through eggshell powder. A second sample was collected.

Chamber 3 (Eggshell Adsorption – Stage 2): The second motor lifted water into Chamber 3, allowing further adsorption of residual phosphate. A final treated water sample was collected.

The figure shown in the image clearly explains the mechanism of the filtration system
In that three big chambers are shown of filtering unit ad two motors whose primary work is to lift the water first to second chamber

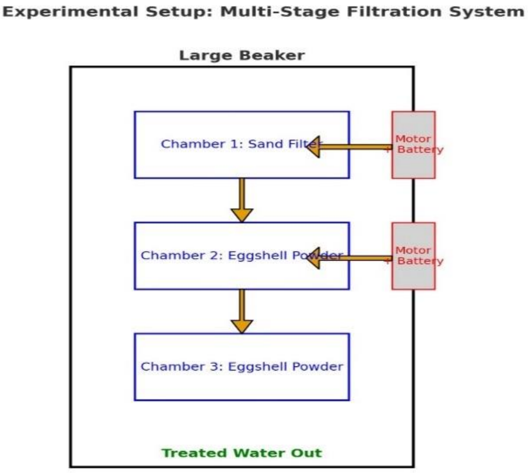

Fig 1.3

Fig 1.4

Fig 1.3 showing the flow chart of the phosphate removal technique

Fig 1.4 showing the Experimental setup used for phosphate removal studies

RESULT

The stoichiometric analysis was performed to estimate the phosphate adsorption capacity of eggshell-derived calcium carbonate. The calculations revealed that 80 g of $CaCO_3$ was able to adsorb 50 g of phosphate from the aqueous solution.

This indicates a $CaCO_3$: phosphate adsorption ratio of 1.6:1 (by mass). Such a ratio highlights the high binding efficiency of calcium carbonate towards phosphate ions. The experimental setup, consisting of three sequential beakers (sand pre-filtration, followed by two eggshell powder layers), successfully utilized this property to remove phosphate from water.

The reduction in phosphate concentration after treatment confirmed the theoretical stoichiometric prediction, validating the role of $CaCO_3$ in the adsorption mechanism.

The stoichiometric analysis has been mentioned below:

Step 1: balance the chemical equation →

$3\ CaCO_3^{3-} \rightarrow 2\ PO_4^{3-} \rightarrow Ca_3(PO_4)^2 + 3(Co3)^{2-}$

Step 2: Calculate molar mass of $CaCO_3$

Molar mass of Ca =40.08g/mol

Molar mass of carbon=12.01g/mol

Molar mass of oxygen=16.00g/mol

Total mass =100.09g/mol

Step 3: Calculate Molar mass of PO_4^{3-}

Molar mass of p =30.097g/mol

Molar mass of o =16.00g/mol

Total mass =30.097+4*16=94.97g/mol

Moles of $(Po_4)^{3-}$= mass of (Po_4)/molar mass of $(Po_4)^{3-}$ =50/94.97= 0.5625

Moles of $CaCO_3$ needed = moles of $(Po4)^{3-}$* 3moles of $CaCO_3$/2 moles of $(Po4)^{3-}$

Moles of $CaCO_3$ needed = 0.5265*1.5 = 0.7898 mol

Mass of $CaCO_3$ needed = 0.7898 * molar mass of $CaCO_3$ = 0.7898 * 100.09 = 79.05g

Final Answer:

To react with 50 g of phosphate (PO_4^{3-}), approximately 80 gm Caco3 is needed

the formulae for finding the amount of $CaCO_3$= mass of (PO_4^{3-})* moles of $CaCO_3$* molar mass of $CaCO_3$ / molar mass of (PO_4^{3-})* Moles of (PO_4^{3-})

DISCUSSION

The results obtained from stoichiometric calculations support the experimental findings that eggshell powder (rich in $CaCO_3$) is an effective adsorbent for phosphate removal.

Calcium carbonate provides calcium ions that react with phosphate ions to form insoluble calcium phosphate, which gets retained in the filtration media. This explains the observed phosphate reduction in the treated water.

The calculated adsorption capacity (80 g $CaCO_3$ → 50 g phosphate) indicates that eggshell powder can be considered a sustainable and efficient alternative to conventional chemical adsorbents. Moreover, the use of eggshells, a common kitchen waste, addresses both waste management and water pollution control simultaneously.

Some limitations remain, such as the dependency on particle size of the eggshell powder, initial phosphate concentration, and contact time. Future studies may focus on scaling up the design, optimizing pH conditions, and comparing performance with other natural adsorbents.

CONCLUSION

The present study successfully demonstrated the removal of phosphate from water using a multi-stage filtration system incorporating sand and eggshell powder. Stoichiometric analysis indicated that 80 g of $CaCO_3$ can adsorb approximately 50 g of phosphate, and the experimental setup supported this mechanism. The three-chamber design ensured sequential treatment, with sand removing suspended particles in the first stage and eggshell powder providing adsorption and precipitation of phosphate in the subsequent stages.

The findings confirm that eggshell waste, a readily available and low-cost material, can serve as an efficient and eco-friendly adsorbent for phosphate removal. This approach not only addresses water pollution but also promotes sustainable waste utilization.

Future work should focus on optimizing parameters such as contact time, particle size of eggshell powder, flow rate, and pH to further improve phosphate removal efficiency and make the system applicable at a larger scale for real water treatment.

WHY PHOSPHATE REMOVAL IS NECESSARY FOR UPCOMING GENERATIONS

Prevention of water pollution: Excess phosphate in water bodies leads to eutrophication, causing algal blooms. This reduces oxygen levels, kills aquatic life, and makes water unsafe for future use.

Safe drinking water: High phosphate levels can contaminate groundwater and surface water, making them unsafe for human consumption. Ensuring phosphate-free water is vital for the health of future generations.

Sustainable agriculture: Phosphates mainly come from fertilizers. If not controlled, they enter rivers and lakes, disturbing ecosystems. Developing low-cost methods like eggshell adsorption can help maintain soil fertility while protecting water sources for future farming.

Resource conservation: Using waste materials like eggshells promotes a circular economy. Instead of throwing waste into landfills, we can use it for water purification, leaving a cleaner environment for future generations.

Climate resilience: As the demand for clean water increases with population growth, low-cost and eco-friendly methods will become essential to ensure water security in a changing climate.

Educational value: Teaching and developing such sustainable methods encourages young scientists and engineers to find green solutions, preparing the next generation to face environmental challenges.

Example
The removal of phosphate is not only a scientific necessity but also an environmental responsibility. If uncontrolled, phosphate pollution will degrade aquatic ecosystems and limit access to clean water, posing a threat to the health and well-being of upcoming generations. Therefore, developing low-cost, eco-friendly methods like eggshell-based filtration ensures both water security and sustainable waste management for the future.

BIOGRAPHIES

Yugal Sharma is currently pursuing his Bachelor of Technology in Civil Engineering (Third Year) at Dayalbagh Educational Institute,Agra. He has gained valuable research experience through an internship at the Environmental Engineering Laboratory, Indian Institute of Technology (IIT) Hyderabad. His academic interests are concentrated in environmental engineering, specifically in the areas of water quality, wastewater treatment technologies, and the design of filtration systems for nutrient removal.”

Tridev Singh is currently pursuing his Bachelor of Technology in Civil Engineering (Third Year) at Dayalbagh Educational Institute,Agra. He has gained valuable research experience through an internship at the Geotechnical Engineering Laboratory, Indian Institute of Technology(IIT) Indore where he gained hands-on experience in advanced soil testing and analysis. His academic interests are concentrated in environmental engineering, specifically in the areas of water quality,

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