Alginate Immobilized Nopal Mucilage Beads for Adsorptive Treatment of Pharmaceutical Pollution

A Research Paper Presented to

SARSEF Science and Engineering Fair

As a Partial Fulfillment of Requirements for

Advanced Research Methods

by

[redacted]

Chemistry

January 2026

Abstract

Every year over 100,000 tons of pharmaceutical products are consumed globally. Many of these products are often thrown into the environment with no eco-friendly treatment resulting in secondary pollutants. For this reason, this research aimed to synthesize alginate-immobilized nopal-chitosan beads to adsorb pharmaceuticals and prevent further contamination.

To test the bead's adsorption, I prepared aspirin solutions of 0.05 mg/ml, 0.1 mg/ml, 0.2 mg/ml, 0.3 mg/ml, in 10 ml test tubes and added different amounts of microencapsulated beads (0.5 g, 1g, 2g, 3g) then placed the tubes into an orbital shaker. Water samples were collected from each tube during 30-minute, 1-hour, 2-hour, and 3-hour periods, and the absorbance was measured at 274 nm using a Vernier UV-vis spectrophotometer.

My results indicated that the longer the contact time, the higher the removal rate of aspirin is. The higher the dosage of beads, the greater the adsorption efficiency. The beads worked through chemisorption on a heterogeneous surface.

The nopal–chitosan microencapsulated beads effectively removed aspirin from water through adsorption. Their biodegradability makes them a promising eco-friendly material for pharmaceutical wastewater treatment.

Rationale

In recent decades, the presence of pharmaceuticals in the environment has become a growing global concern, as excessive medication use continues to elevate. Some residues of common medications such as acetaminophen, ibuprofen, and other antibiotics are often found in surface, ground, and even drinking water sources. Their toxicity and persistence threaten aquatic

life and human health. Conventional methods of removing these pollutants like activated carbon and ozonation are often costly, energy-intensive, and generate secondary pollutants. Therefore, there is a desperate need for a sustainable, low-cost, and effective way to mitigate these pollutants in contaminated water. This project investigated how to efficiently remove drugs and medication from water using a natural polymer made of nopal and alginate as compared to traditional methods.

Background Research

Pharmaceutical Pollution and Its Environmental Impact

Pharmaceutical pollution, the contamination of the environment, especially in aquatic ecosystems, with the presence of pharmaceutical compounds like antibiotics, hormones, and painkillers. These compounds often derive from improper disposal, landfill leaching, and wastewater treatment systems underequipped to remove these compounds (U.S Environmental Protection Agency [EPA], 2023). The recent increased use of pharmaceuticals has led to concentrations of these substances to significantly increase in lakes, rivers, and groundwater sources (Ortúzar et al., 2022). Once within the environment, pharmaceuticals can cause severe ecological effects such as altered behavior, growth, organ damage, and genotoxicity in aquatic organisms (EPA, 2023). For example, antibiotics and endocrine-disrupting compounds are some identified pollutants currently affecting the Colorado River water quality (Central Arizona Project, n.d.).

The Potential of Nopal Mucilage for Water Remediation

Our current solutions to this problem generate secondary waste and do not fully remove specific pharmaceuticals. Consequently, the use of natural biosorbents to remove pharmaceutical residues in water has begun to be researched. With a promising material being nopal mucilage, a

polysaccharide rich substance derived from the Opuntia ficus-indica cactus. This mucilage contains pectin, cellulose, and hemicellulose, whose functional groups can bind pollutants and heavy metals (Ortíz-Hernández et al., 2022). Even though previous research has focused on the removal of dyes and heavy metals, the similar chemical nature of pharmaceuticals indicates potential for adsorption. This is shown in a recent study in which hydrogels made with nopal mucilage demonstrated high adsorption capacities for organic dyes (Rodríguez-Hernández et al., 2024). Moreover, adding chitosan to nopal mucilage has shown to further improve its adsorption capacity due to the additional functional groups it provides.

Statement of The Problem

General Problem:

This research aims to investigate the adsorption of pharmaceuticals using micro-encapsulated nopal mucilage in contaminated water.

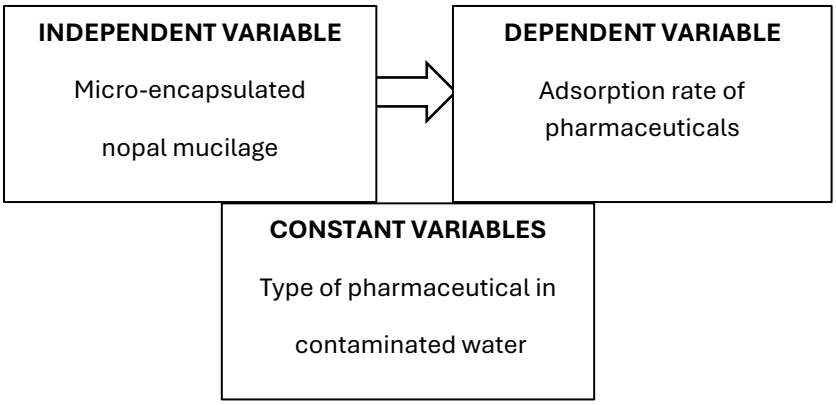
Specific Problems:

1. Can micro-encapsulated nopal mucilage remove pharmaceuticals from water?
2. Will the micro-encapsulated nopal mucilage become saturated eventually?

Hypothesis

If I introduce micro-encapsulated nopal mucilage into pharmaceutically polluted water, then the pharmaceutical particles will be absorbed into the mucilage due to its complex chemical structure that allows for hydrogen bonding and electrostatic attraction.

Variables



Methods

Extracting the Mucilage

To extract the mucilage, the nopal pads (Opuntia ficus-indica) were rinsed with water and cut into small cubes. Then, 300 grams of the diced nopal were measured then boiled in 1,000 ml of distilled water at 90°C for 50 minutes. They were then blended and strained to release the mucilage. For further purity, the mucilage was centrifuged at 3000 rpm for 10 minutes then decanted.

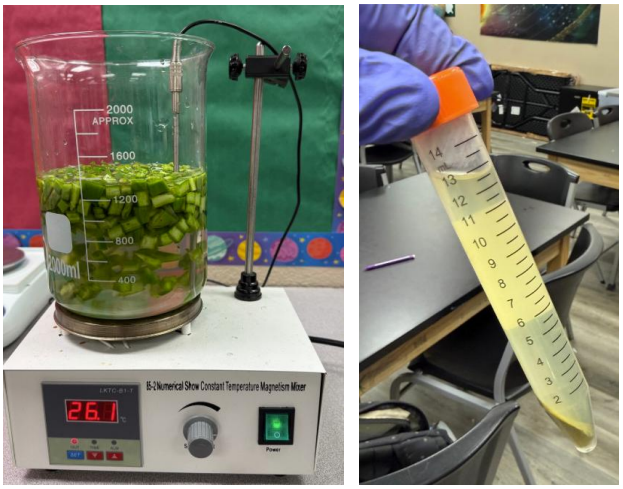


Figure 1: Boiling of nopal in a magnetic mixer (Left) Figure 2: Collected nopal mucilage in a test tube (Right) (Images taken by student researcher, 2025)

Microencapsulation of the Mucilage

The weight of calcium chloride (0.75 grams), sodium alginate (20 grams), and chitosan (0.75 grams) was measured. The sodium alginate and chitosan were mixed at low heat with 150 ml of nopal mucilage. Then, in a separate container, the calcium chloride was dissolved in 600 ml of distilled water and placed in ice to cool. Using a syringe, the alginate-nopal-chitosan solution was slowly dropped into the cold CaCl2 solution to form small beads, then they were collected and stored for later use.

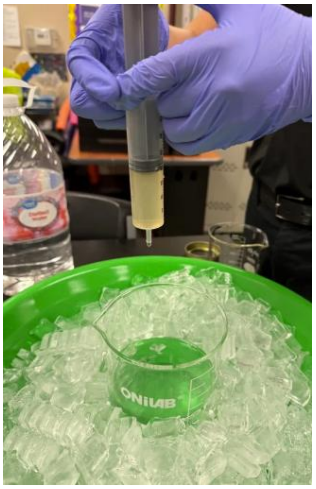


Figure 3: Dropping the a-n-c solution into the CACl2 (Left) Figure 4: The resulting microencapsulated mucilage beads (Right)

(Images taken by student researcher, 2025)

Adsorption Analysis of Aspirin Using UV-Vis Spectrophotometry

To test the adsorption of the beads, aspirin solutions were prepared at four concentrations (0.05 mg/ml, 0.1 mg/ml, 0.2 mg/ml, 0.3 mg/ml) in 10 ml test tubes, with 4 samples for each concentration. Then, 0.5 g, 1g, 2g, and 3g of the microencapsulated beads were added into each test tube containing varying concentrations of aspirin. To constantly agitate the beads and aspirin solutions, the test tubes were placed in an orbital shaker. Water samples from each tube were collected during 30-minute, 1-hour, 2-hour, and 3-hour periods and had the absorbance measured at 274 nm using a Vernier UV-vis spectrophotometer.

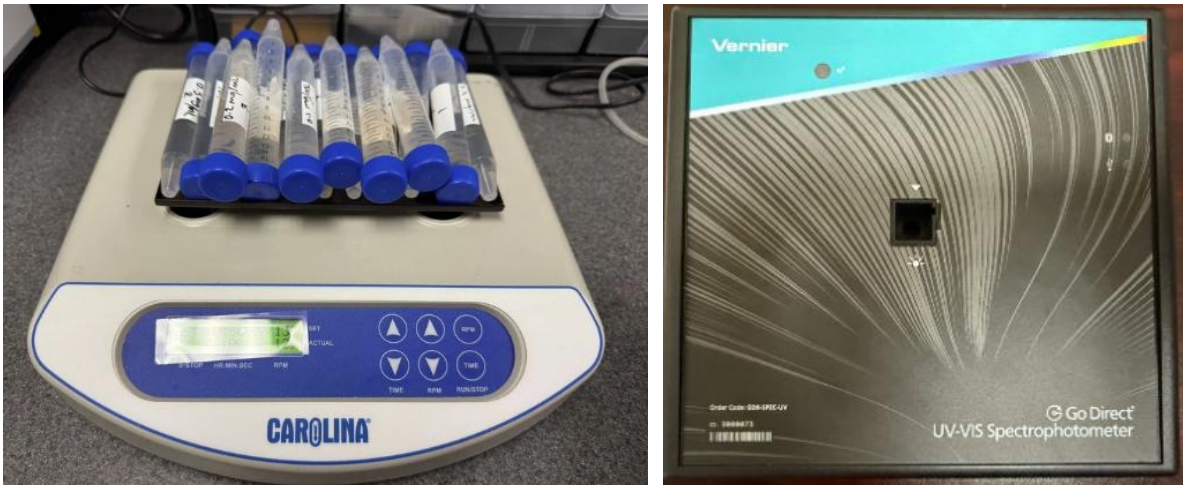
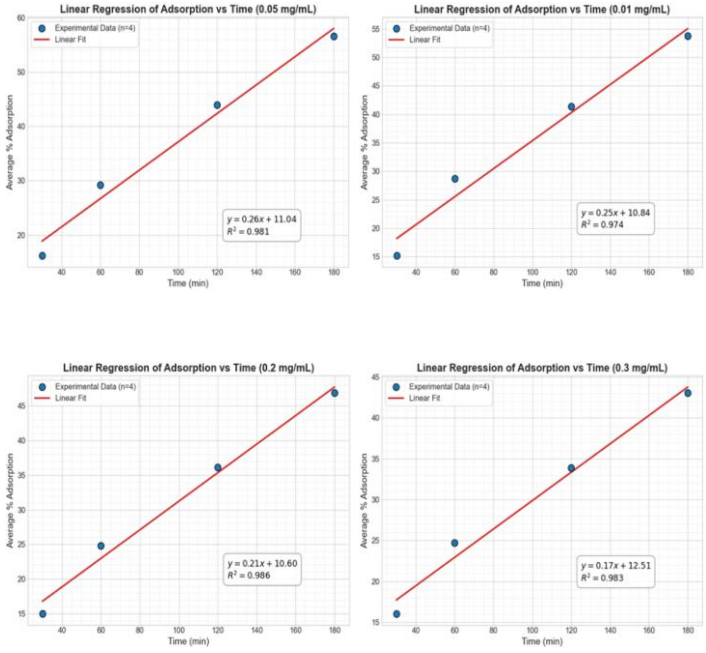


Figure 3: Test tubes with aspirin concentrations and adsorbent in an orbital shaker (Image taken by student researcher, 2025) and UV-vis Spectrophotometer used to measure absorbance (Image taken by student researcher, 2025)

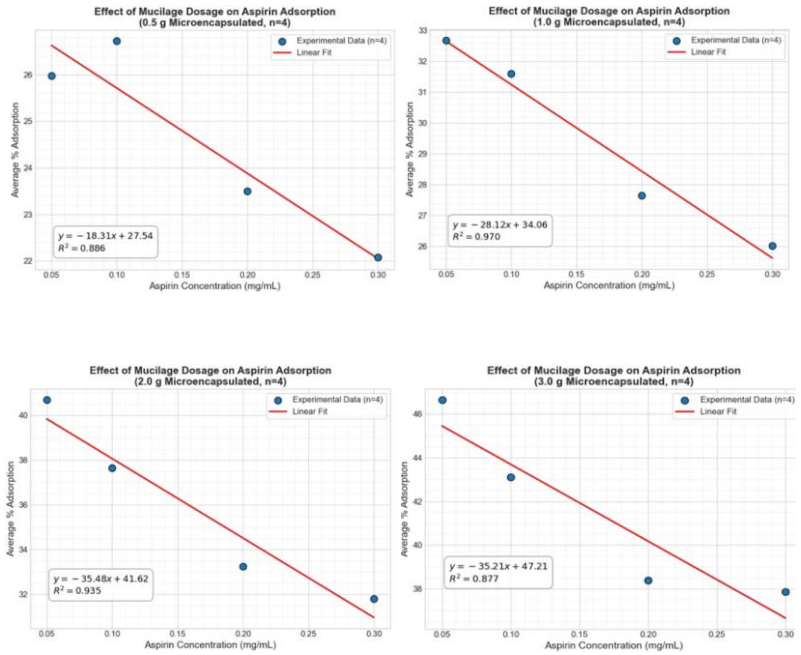
Results

Effect of Contact Time



Adsorption of aspirin increased linearly with contact time for all concentrations. The high R2 values (0.97–0.99) indicate a strong correlation between time and adsorption efficiency. Lower concentrations (0.05–0.1 mg/mL) showed slightly faster adsorption rates due to more available active sites. The microencapsulated nopal–chitosan beads maintained steady adsorption until approaching saturation over time.

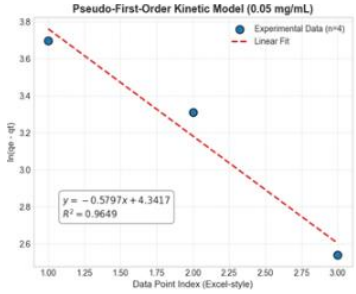
Effect of Mucilage Dosage

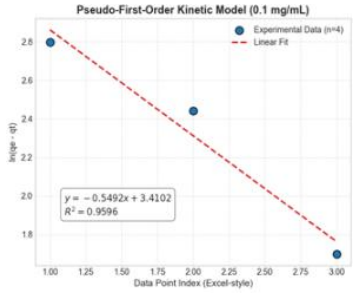


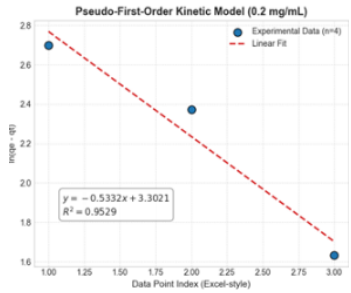
The adsorption of aspirin decreased as the aspirin concentration increased across all mucilage dosages. Higher mucilage dosages (2.0–3.0 g) showed greater overall adsorption compared to lower dosages (0.5–1.0 g). The negative slope in each regression indicates that adsorption sites become saturated at higher aspirin concentrations. High R2 values (0.88–0.97) confirm a strong linear relationship between aspirin concentration and adsorption efficiency. This suggests that increasing the mucilage amount enhances the binding capacity of the microencapsulated beads up to a certain limit.

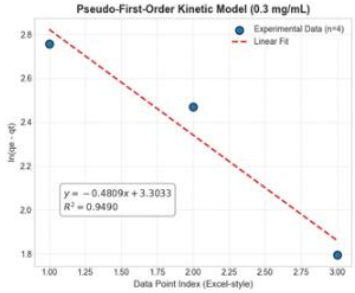
Kinetic Models

Pseudo first kinetic models

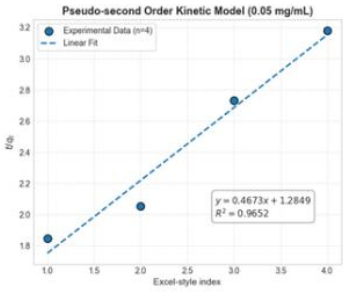


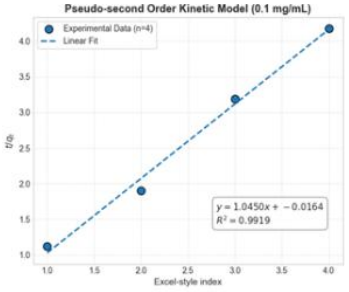


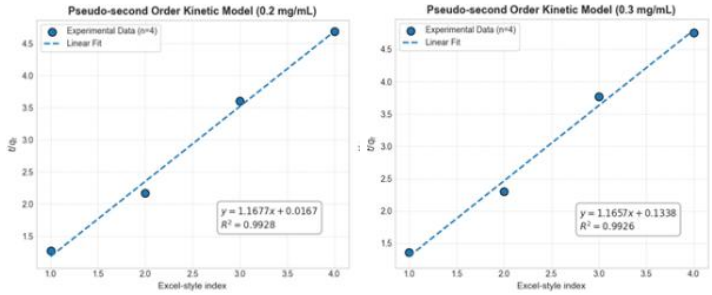




Pseudo second kinetic models







The pseudo-second-order model (R^2 = 0.96–0.99) consistently showed a better correlation compared to the pseudo-first-order model (R^2 = 0.94–0.96). This suggests that the adsorption of aspirin onto the nopal–chitosan beads follow a chemisorption process, involving electron sharing or electrostatic attraction between aspirin and chitosan's amino groups. The model implies that reaction rate depends on the availability of active sites rather than only on the aspirin concentration.

Adsorption Isotherm Models

Langmuir Adsorption Isotherm **Freundlich Adsorption Isotherm**

yThe Freundlich isotherm (R^2 = 0.9739) provided a better fit than the Langmuir isotherm (R^2 = 0.7760). This indicates that aspirin adsorption occurs on a heterogeneous surface with multiple active sites rather than forming a single uniform layer. The adsorption process is likely multilayered and non-ideal, consistent with the natural variability of the nopal–chitosan composite.

Discussion

Effect of Contact Time

The results from my experimentation indicated that the longer the contact time between the beads and the polluted water, the higher removal rate of aspirin. This confirms the bead's capabilities for adsorption, with greater adsorption over a greater period of time.

Effect of Mucilage Dosage

Further analysis of the data suggested that the higher the dosage of microencapsulated beads, the greater the adsorption efficiency. This means that by increasing the mucilage dosage in the beads, the binding capacity is improved to a certain limit. There was a strong correlation between aspirin concentration and adsorption efficiency, suggesting that the higher the concentration of aspirin, the greater the capability of the active sites to absorb.

Kinetic Models

Based on the kinetic models, the pseudo-second-order model demonstrated a stronger correlation compared to the pseudo-first-order model, suggesting that the adsorption of aspirin onto the beads follow a chemisorption process. This indicates that the reaction rate depends on the availability of active sites rather than only on the aspirin concentration.

Adsorption Isotherm Models

According to the adsorption isotherm models, the Freundlich isotherm gave a better fit as compared to the Langmuir isotherm, indicating that aspirin adsorption occurs on a heterogeneous surface with multiple active sites rather than forming a single uniform layer.

Conclusion

Key Outcomes

The nopal–chitosan microencapsulated beads effectively removed aspirin from water through adsorption. Their biodegradable and natural composition makes them a promising eco-friendly material for pharmaceutical wastewater treatment.

Cultural Significance

The use of nopal, a traditional Mexican plant, connects cultural heritage with sustainable science, showcasing how indigenous knowledge can inspire modern environmental solutions.

Future Directions

The future for this project includes Testing the microencapsulated beads on other pharmaceutical pollutants to evaluate their versatility. Performing a regeneration test to determine their reusability and long-term performance. Optimizing pH and temperature conditions to enhance adsorption efficiency and stability.

References:

Central Arizona Project. (n.d.). *Colorado River water quality*. https://www.cap-az.com/community/sustainability/colorado-river-water-quality/

EPA. (2023a). *How pharmaceuticals enter the environment*. U.S. Environmental Protection Agency. https://www.epa.gov/household-medication-disposal/how-pharmaceuticals-enter-environment

EPA. (2023b). *Impact of pharmaceuticals released into the environment*. U.S. Environmental Protection Agency. https://www.epa.gov/household-medication-disposal/impact-pharmaceuticals-released-environment

Ortúzar, M., Esterhuizen, M., Olicón-Hernández, D. R., González-López, J., & Aranda, E. (2022). Pharmaceutical pollution in aquatic environments: A concise review of environmental impacts and bioremediation systems. *Frontiers in Microbiology, 13*, 869332. https://doi.org/10.3389/fmicb.2022.869332

Ortíz-Hernández, M. L., Vázquez-Ovando, A., & Carrillo-Nieves, D. (2022). Use of *Opuntia ficus-indica* fruit peel as a novel source of mucilage with coagulant physicochemical/molecular characteristics. *Journal of Environmental Chemical Engineering, 10*(4), 14183832. https://doi.org/10.3390/polym14183832

Ovando Franco, M. (2013). *Modificación de biopolímeros extraídos de nopal (Opuntia ficus indica) y su aplicación para la remoción de metales pesados en agua* [Master's thesis, Instituto Potosino de Investigación Científica y Tecnológica]. IPICYT Institutional Repository. http://ipicyt.repositorioinstitucional.mx/jspui/handle/1010/556

Rodríguez-Hernández, A., Martínez-Padilla, L. P., & García-Valdez, M. A. (2024). Adsorption of methylene blue dye using an *Opuntia ficus-indica* mucilage–alginate hydrogel: Kinetic and isotherm study. *Environmental Technology & Innovation, 33*, 103121. https://doi.org/10.1016/j.eti.2023.103121