Alginate-Immobilized Nopal-Chitosan Beads for Adsorptive Treatment of Pharmaceutical Pollution

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:

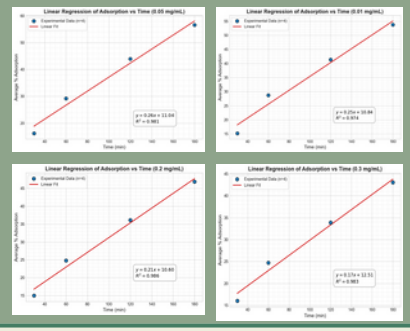
1. Can the micro-encapsulated nopal mucilage remove pharmaceuticals from water?
2. Will the micro-encapsulated nopal mucilage become saturated eventually?

Hypothesis

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

https://www.chemistryworld.com/news/extent-of-pharmaceutical-pollution-on-every-continent-on-earth-revealed/4015238.article

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.
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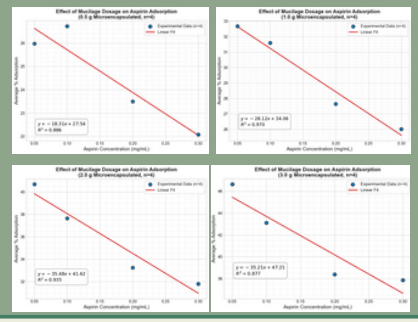
Results: Effect of Mucilage Dosage



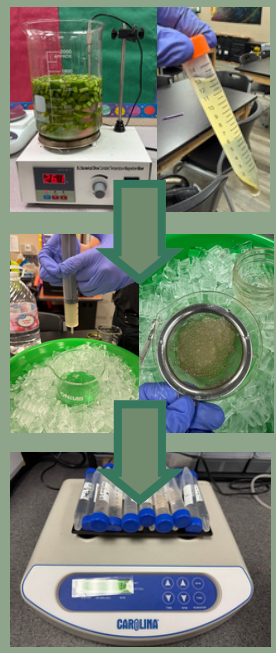
- The adsorption of aspirin decreased as the aspirin concentration increased across all mucilage dosages.
- Higher mucilage dosages (2.0-3.0 g) showed greater overall adsorption compared to lower dosages (0.5-1.0 g).
- The negative slope in each regression indicates that adsorption sites become saturated 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.

Methodology

Goal #1: Extracting the mucilage

Goal #2: Micro Encapsulation of the Mucilage

Goal #3: Adsorption Analysis of Aspirin Using UV-Vis Spectrophotometry



Discussion, Conclusion and Future Directions

What I found out

The longer the contact time, the higher the removal rate of aspirin.

The higher the dosage of microencapsulated beads, the greater the adsorption efficiency.

The adsorption followed a pseudo-second-order kinetic model and fit best with the Freundlich isotherm, indicating chemisorption on a heterogeneous surface.

Conclusion

- 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

- Test the microencapsulated beads on other pharmaceutical pollutants to evaluate their versatility.
- Perform a regeneration test to determine their reusability and long-term performance.
- Optimize pH and temperature conditions to enhance adsorption efficiency and stability.

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Chemistry

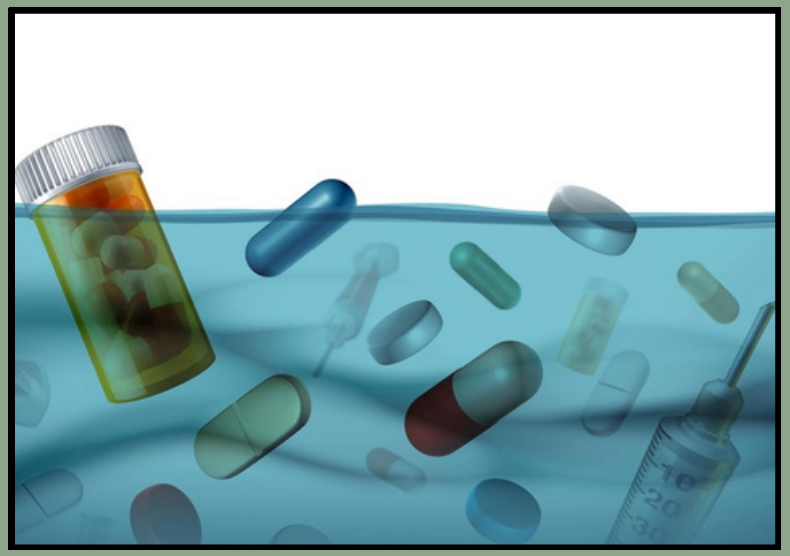
https://www.istockphoto.com/photos/nopal

All photos and graphs were taken by the student researcher unless otherwise noted.

When Medicine Becomes a Pollutant:

Why is pharmaceutical pollution concerning?

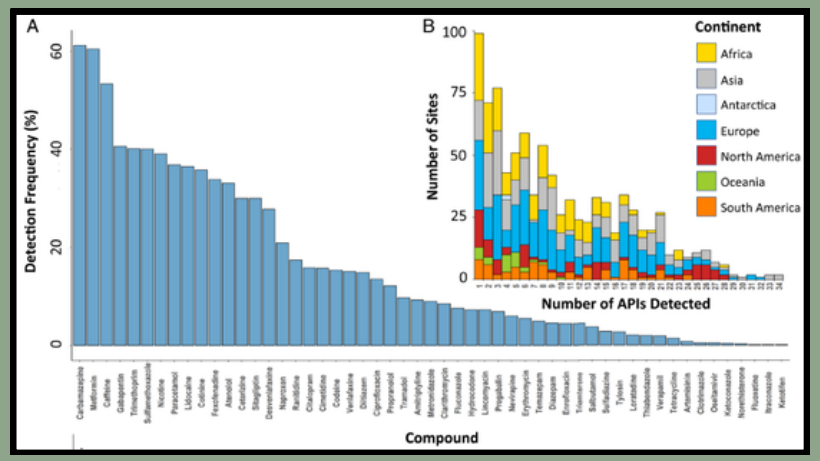
- Pharmaceutical pollution impacts humans, wildlife, and ecosystems by disrupting wildlife behaviors and contaminating water and soil for food sources.
- It contributes to the rise of antimicrobial resistance, threatening public health by making infections harder to treat.



https://watersecuritynewswire.com/treatment-security/2022/06/22/how-is-pharmaceutical-pollution-affecting-the-worlds-rivers/

How prevalent is pharmaceutical pollution in the world?

- According to a global study from 2022, of the more than 1,000 sampling sites across 258 rivers and 104 countries, only a handful were not contaminated.
- More than a quarter of the sampling sites had at least one pharmaceutical above concentrations considered safe for aquatic life or for selection of antimicrobial resistance.



https://www.pnas.org/doi/10.1073/pnas.2113947119

My Culture Offers a Solution

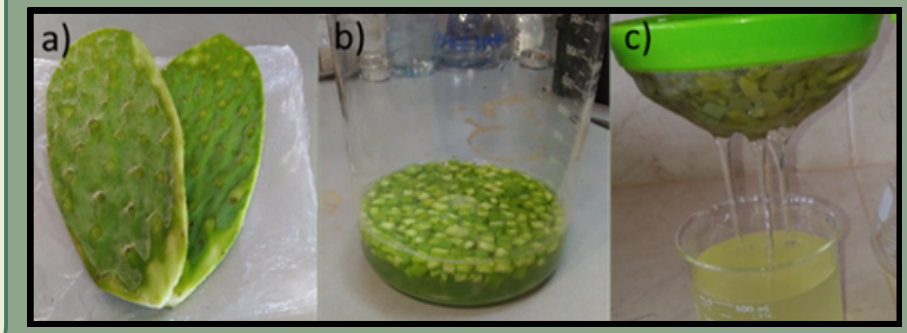
Nopal Mucilage: An effective Adsorbent

- 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 in water.

https://us.kiwilimon.com/recipe/easy-recipes/2-ways-to-remove-the-slime-from-nopales

Adsorption Efficiency of Nopal Mucilage

- Previous research has focused on the removal of dyes and heavy metals, therefore, 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.



https://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-68352019000300260

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Independent Variable
Micro-encapsulated nopal mucilage

Dependent Variable
Adsorption rate of pharmaceuticals

Constant Variables
Type of pharmaceutical in water

https://www.chemistryworld.com/news/extent-of-pharmaceutical-pollution-on-every-continent-on-earth-revealed/4015238.article

Extracting the Mucilage:

Clean and cut nopal pads into small cubes.

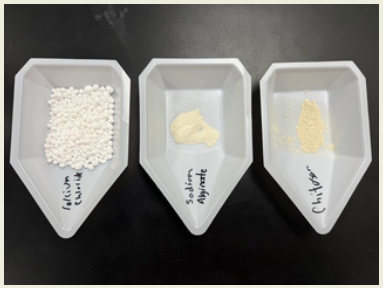
Boil the chopped nopal in distilled water at 90°C for 30 or 40 minutes.

Blend lightly to release the mucilage.

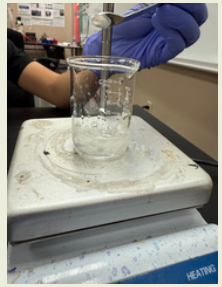
Pass the mixture through a strainer to remove solids from the mucilage.

Transfer mucilage into centrifuge tubes and spin at 3000 rpm for 10 minutes. Decant the clear mucilage from the residue.

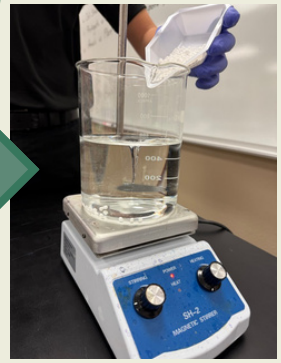
Microencapsulation of the Mucilage



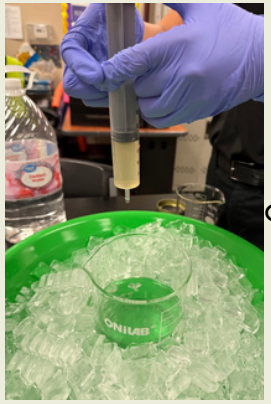
Measure the weight of calcium chloride (0.75 grams), sodium alginate (20 grams), and chitosan (0.75 grams)



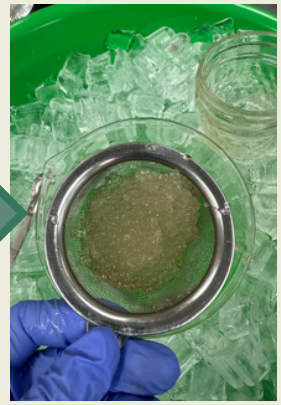
Mix and heat the sodium alginate and chitosan in 150 mL of nopal mucilage



Prepare the Calcium chloride solution by dissolving the CaCl2 in 600 mL of distilled water



Using a syringe drop the alginate-nopal-chitosan solution in the cold CaCl2 solution



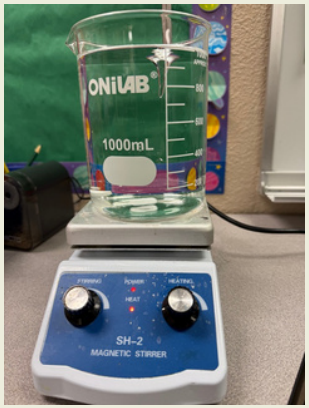
Collect the microencapsulated chitosan-nopal mucilage

The chemistry behind my project

- Nopal mucilage provided natural polysaccharides that increased the surface area and formed a porous network, helping trap and flocculate aspirin molecules.
- Chitosan offered positively charged amino groups that electrostatically attracted the negatively charged aspirin at pH 4-5.
- Together, they created a biodegradable hydrogel composite with improved adsorption efficiency, stability, and reusability.

Adsorption Analysis of Aspirin Using UV-Vis Spectrophotometry

Aspirin Preparation



- Prepare the aspirin concentrations of 0.05 mg/ml, 0.1 mg/ml, 0.2 mg/ml, 0.3 mg/ml, in 10 ml and place them in test tubes. (Four of each concentration, 16 total)

Adding the Adsorbent

- Add 0.5 g, 1g, 2g, 3g of the microencapsulated beads in each test tubes containing varying concentrations of aspirin
- Place the samples in an orbital shaker to constantly agitate the solution and the beads.

Measurement

- Collect water samples from each tube during 30-minute, 1-hour, 2-hour, and 3-hour periods.
- Measure the absorbance at 274 nm using a Vernier UV-vis spectrophotometer.

Conceptual Diagram of my Model

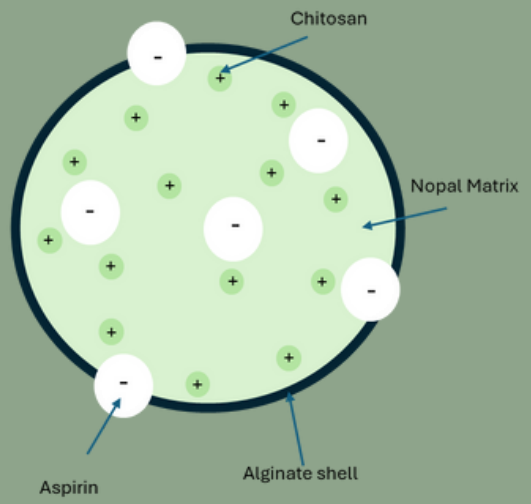
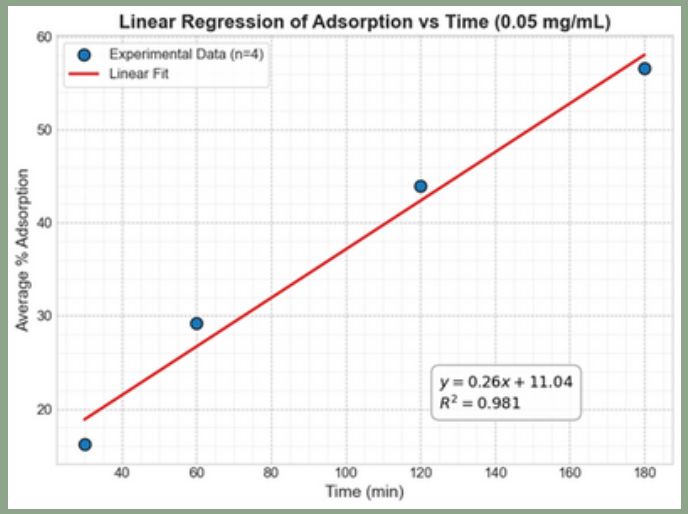
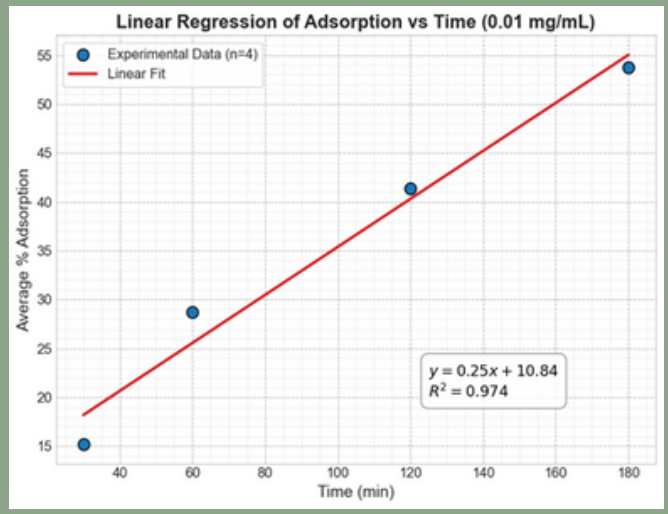


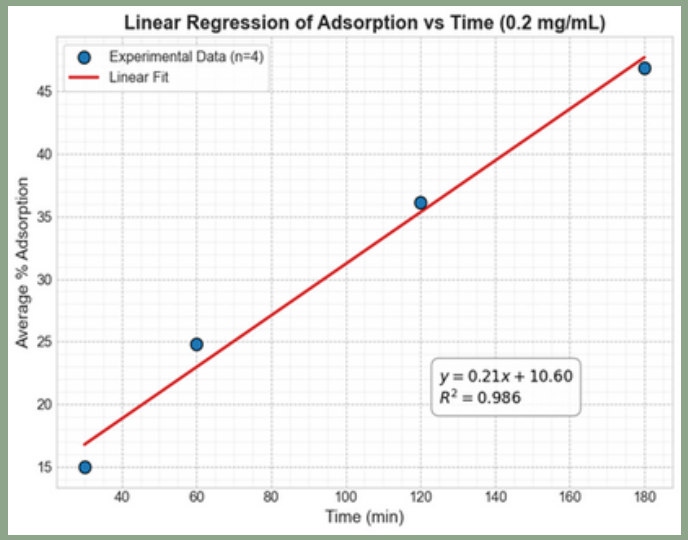
Image created by the student researcher using MS Powerpoint, 2025

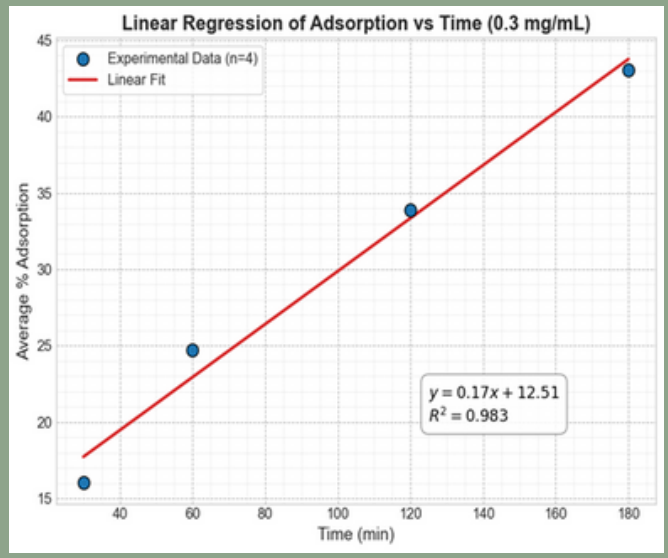
The microencapsulated bead consists of a calcium alginate shell enclosing a nopal mucilage matrix with dispersed chitosan. The positively charged chitosan binds the negatively charged aspirin molecules through electrostatic attraction, enhancing adsorption efficiency.

Results: Effect of Contact Time









Graphs created by the student researcher using Jupyter notebook, 2025

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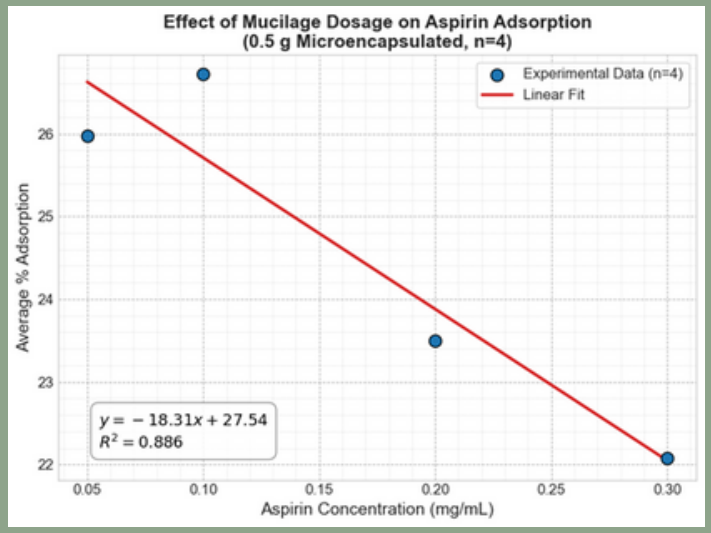

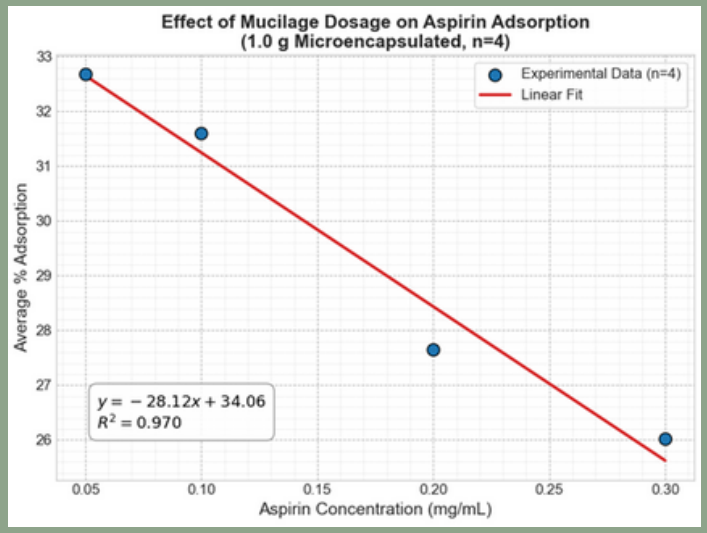

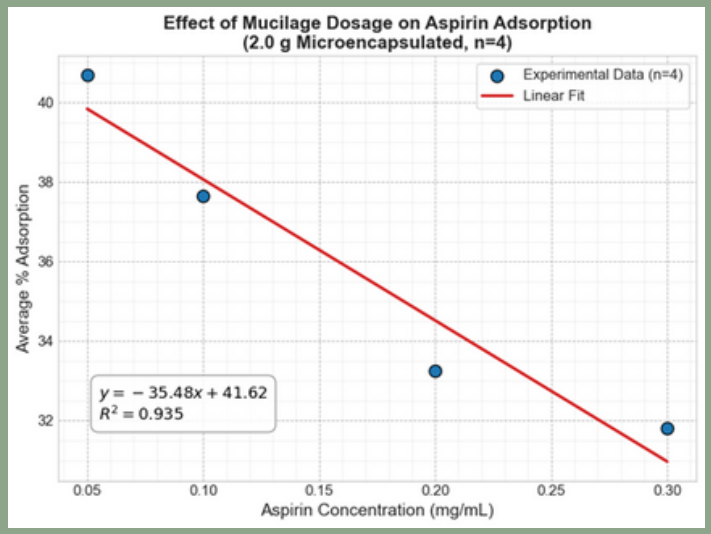

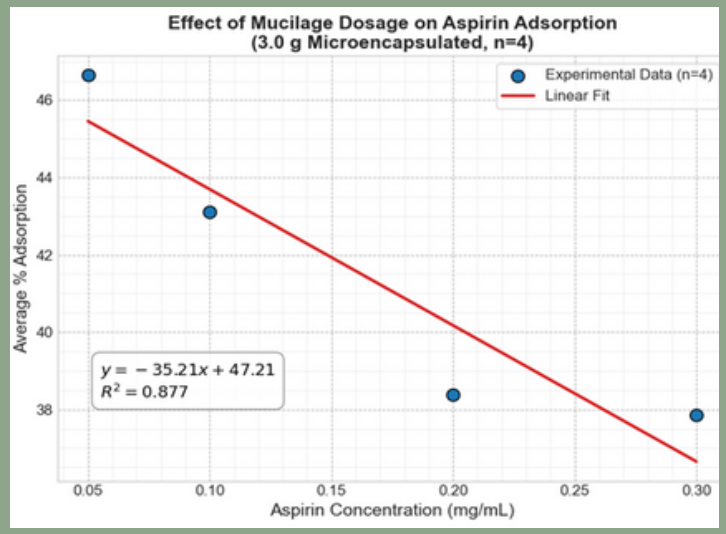

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- The adsorption of aspirin decreased as the aspirin concentration increased across all mucilage dosages.
- Higher mucilage dosages (2.0–3.0 g) showed greater overall adsorption compared to lower dosages (0.5–1.0 g).
- The negative slope in each regression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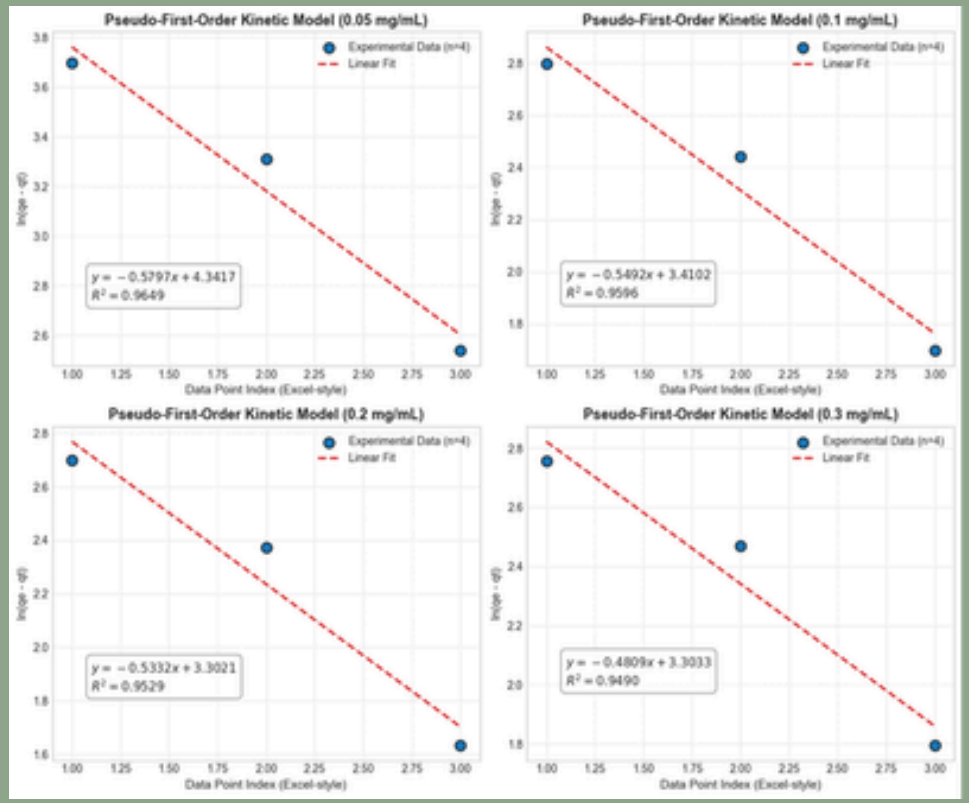
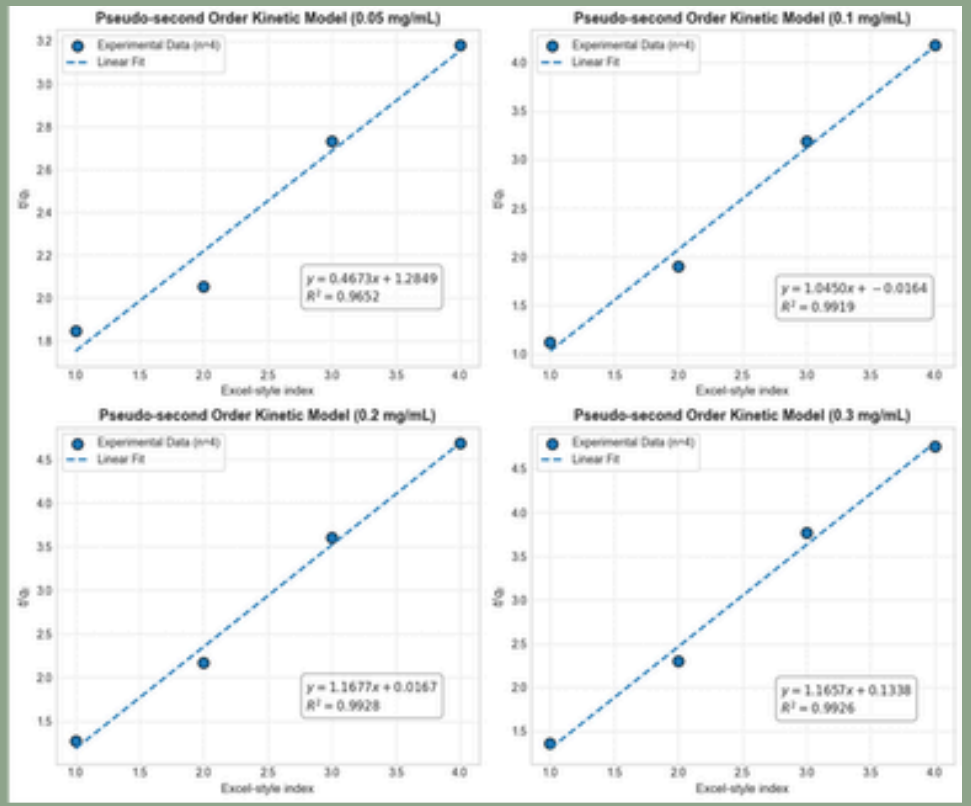
- This suggests that increasing the mucilage amount enhances the binding capacity of the microencapsulated beads up to a certain limit.

Results: Kinetic Models

Pseudo-First Kinetic Model



Pseudo-Second Kinetic Model

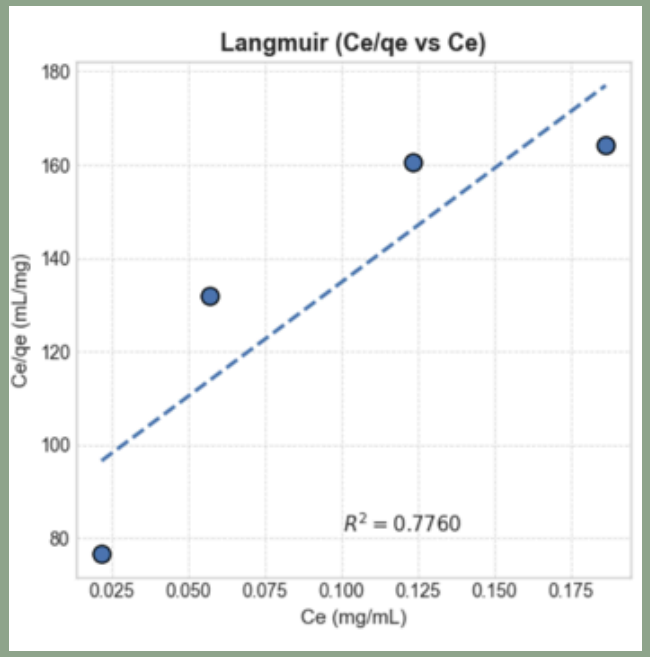


- The pseudo-second-order model (R^2 = 0.96–0.99) consistently showed a better correlation compared to the pseudo-first-order model (R^2 = 0.94–0.96).
- This suggests that the adsorption of aspirin onto the nopal-chitosan beads follows a chemisorption process, involving electron sharing or electrostatic 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.

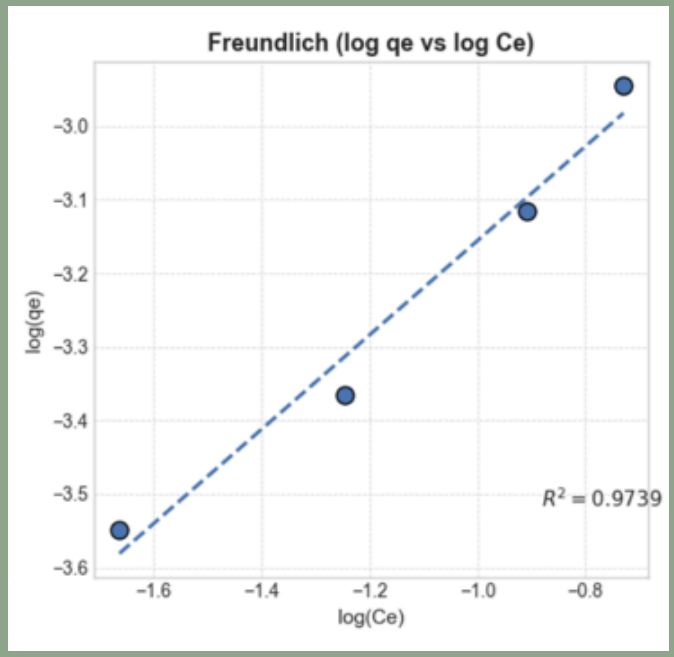
Graphs created by the student researcher using Jupyter notebook, 2025

Results: Adsorption Isotherm Model

Langmuir Adsorption Isotherm



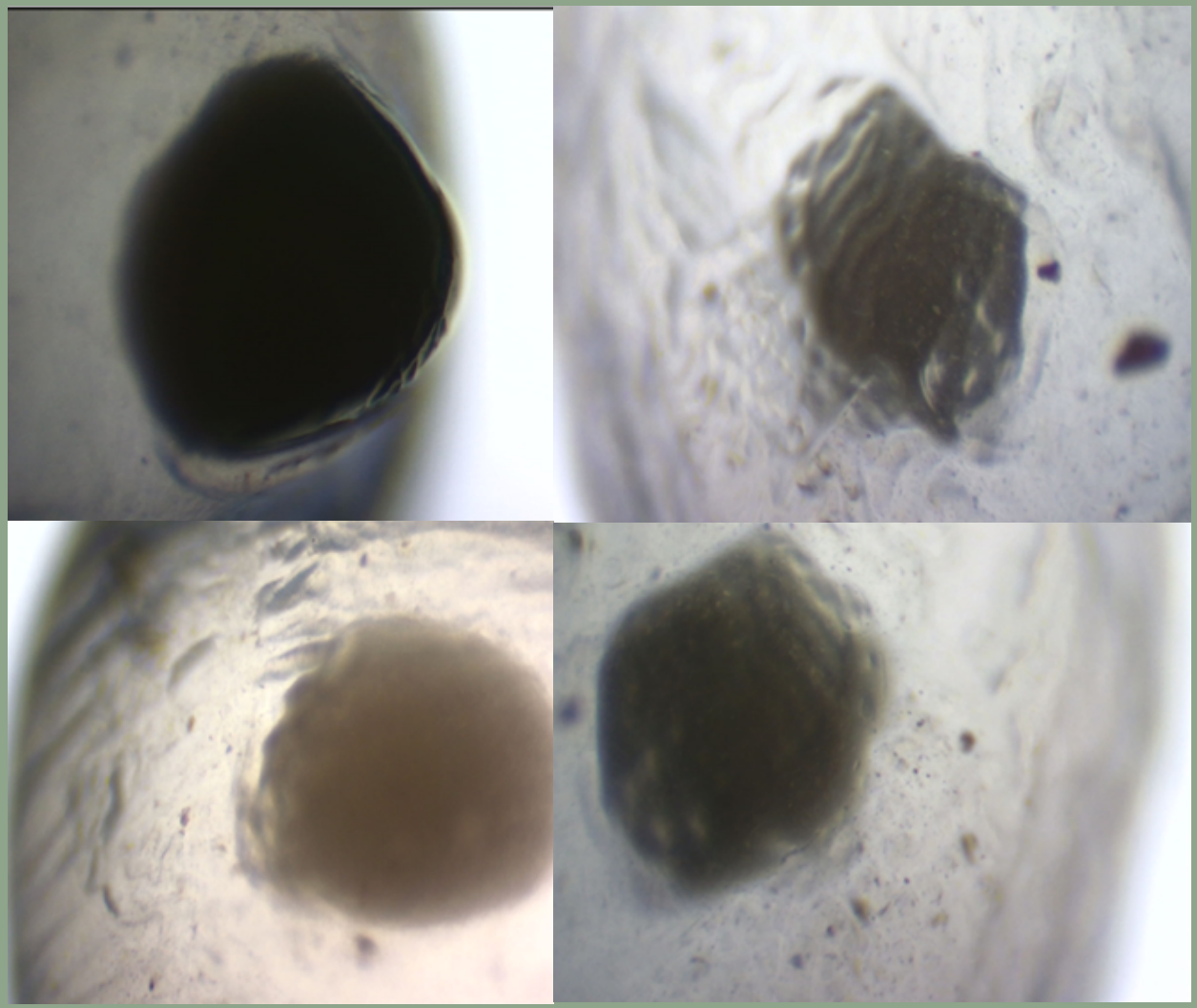
Freundlich Adsorption Isotherm



- The 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.

Graphs created by the student researcher using Jupyter notebook, 2025

Results: Microscopic Images



I was curious about how the microencapsulated beads and aspirin look at the microscopic level, so I decided to view them under a microscope. The darker region of the image represents aspirin and it shows that it was successfully adsorb by the nopal-chitosan beads confirming my results.

Images taken by the student researcher using an Amscopre Microscope, 2025

Discussion, Conclusion and Future Directions

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Slide was created by the researcher using Canva, 2025

References

- 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
- U.S. Environmental Protection Agency. (2025, February 11). How pharmaceuticals enter the environment.https://www.epa.gov/household-medication-disposal/how-pharmaceuticals-enter-environment
- Central Arizona Project. (n.d.). Colorado River water quality.https://www.cap-az.com/community/sustainability/colorado-river-water-quality/
- U.S. Environmental Protection Agency. (2025, October 29). Impact of pharmaceuticals released to the environment.https://www.epa.gov/household-medication-disposal/impact-pharmaceuticals-released-environment
- Fox, D. I., Pichler, T., Yeh, D. H., & Alcantar, N. A. (2012). Removing heavy metals in water: The interaction of cactus mucilage and arsenate (As V). Environmental Science & Technology, 46(8), 4553-4559. https://doi.org/10.1021/es2021999