Development and Characterization of a Citric Acid-crosslinked Cassava Starch Hydrogel Functionalized with Aloe vera for Potential Tissue Repair Applications

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Master of Science in Biomedical Engineering
Graduate Project EXPO, May 2026

Abstract

Bio-based hydrogels composed of cassava starch, citric acid, and *Aloe vera* powder were synthesized through a thermally induced process and characterized by swelling analysis, pH measurements, FT-IR spectroscopy, electrical characterization, and qualitative antibacterial assessment against *Escherichia coli*. FT-IR results suggested starch–citric acid crosslinking, while swelling and pH analyses revealed formulation-dependent aqueous stability and residual acidity. Electrical measurements showed differences in ionic transport behavior, with S3 and S9 exhibiting enhanced conductance. Selected formulations also demonstrated localized reduction in bacterial growth. These findings demonstrate the potential of formulation engineering to modulate the structural, electrical, and antibacterial properties of starch-based hydrogel systems for future biofunctional applications.

Introduction

- ❑ Hydrogels mimic extracellular matrix (ECM) behavior.
- ❑ Natural polymer hydrogels are biodegradable and sustainable.
- ❑ Cassava starch is an inexpensive biopolymer with limited aqueous stability.
- ❑ Citric acid can improve structural integrity through crosslinking.
- ❑ *Aloe vera* may enhance physicochemical and biofunctional properties.

Problem

Research Gap

The influence of formulation composition on the physicochemical, electrical, and antibacterial behavior of starch-based hydrogels remains insufficiently understood. In particular, the combined effects of citric acid crosslinking and Aloe vera incorporation have not been extensively investigated.

Objective

To develop and characterize cassava starch-based hydrogels with varying concentrations of citric acid, *Aloe vera* powder, and cassava starch in order to evaluate swelling behavior, surface pH, electrical conductance, and qualitative antibacterial response against *Escherichia coli*.

Methodology

Cassava starch-based hydrogels were synthesized through thermally induced esterification using citric acid as a crosslinking agent and *Aloe vera* powder (AVP) as a bioactive additive. Ten formulations (S1–S10) were prepared by varying formulation composition and characterized through physicochemical, electrical, and antibacterial analyses (Figure 1).

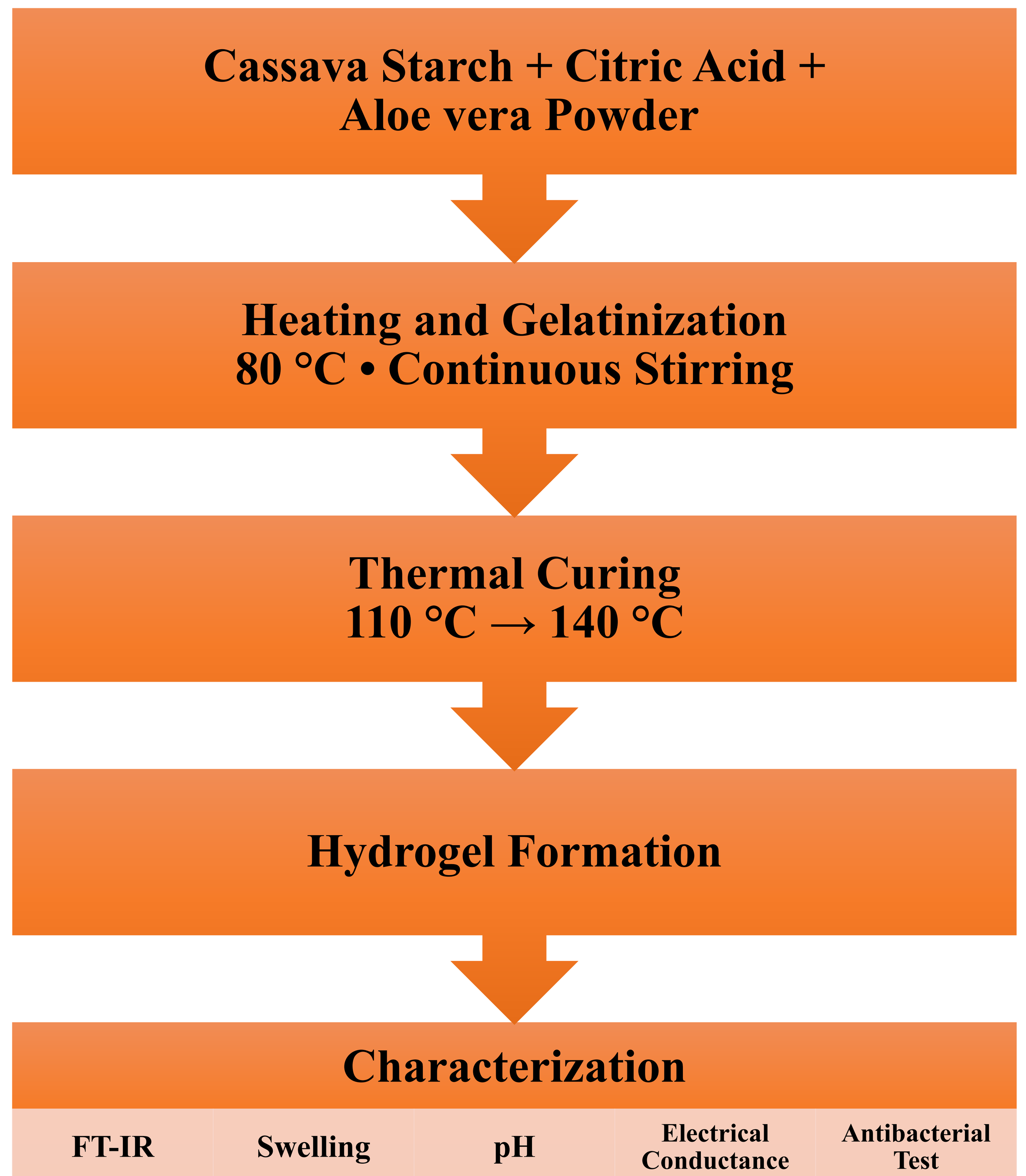


Figure 1
Schematic representation of hydrogel synthesis and characterization workflow.

Results and Discussion

FT-IR Analysis

- ❑ FT-IR spectra revealed characteristic bands associated with the starch-based hydrogel matrix (Figure 3).
- ❑ A carbonyl-related peak suggested possible esterification between cassava starch and citric acid.
- ❑ Broad O–H stretching bands indicated hydrophilic behavior and hydrogen-bonding interactions.

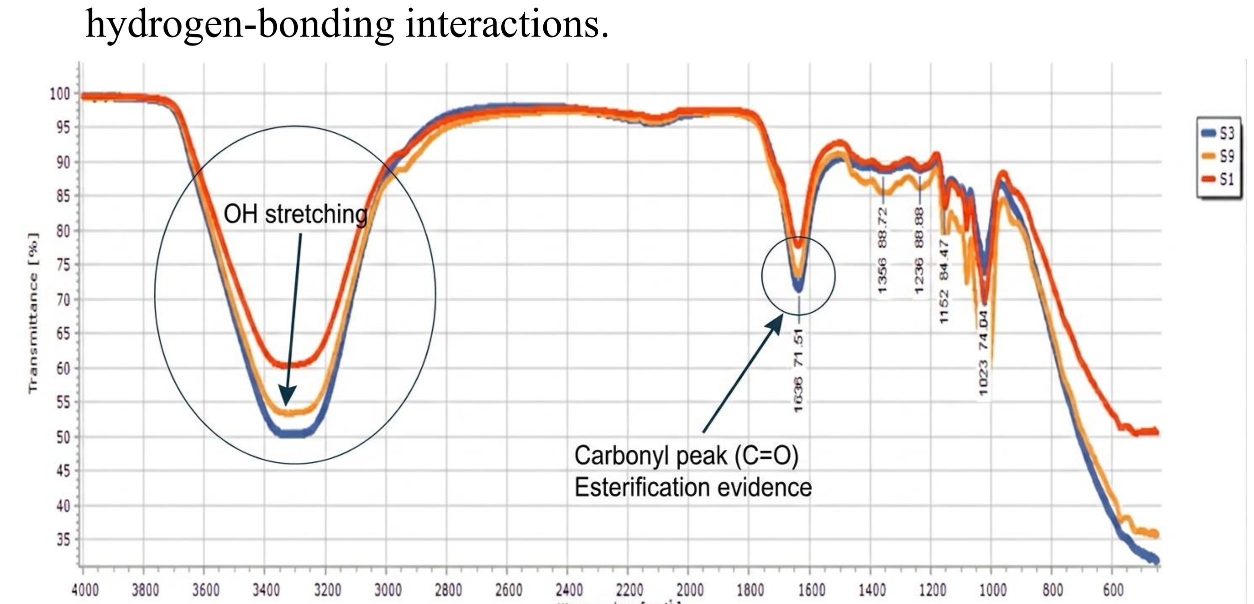
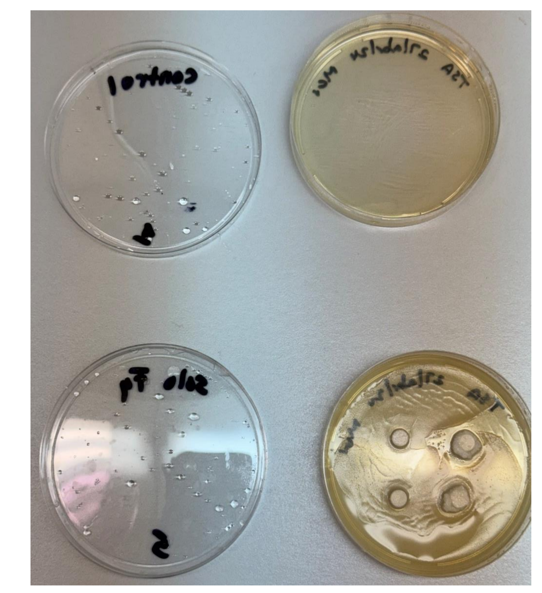


Figure 2
FT-IR spectra of hydrogel formulations S1, S3, and S9 showing characteristic absorption bands of the starch-based hydrogel system.

Antibacterial Analysis

- ❑ **Method:** Qualitative disk diffusion evaluation against *E. coli*.
- ❑ **Results:** All formulations showed reduced bacterial growth compared to the untreated control.
- ❑ **Categorization:** A semi-quantitative scale was established based on visual density reduction (Figure 4):
  - ❑ (+) Minimal: Localized reduction at the interface
  - ❑ (++) Moderate: Noticeable thinning of the bacterial lawn
  - ❑ (+++) Pronounced: Significant reduction in bacterial coverage



Formulation	Relative inhibition
S1	+
S2	+
S3	++
S4	++
S5	++
S6	++
S7	+++
S8	+++
S9	+++
S10	+++

Figure 3
Representative qualitative antibacterial evaluation of hydrogel formulations against *Escherichia coli* using disk diffusion analysis and semi-quantitative inhibition categorization.

pH Analysis

- ❑ Surface pH ranged from 2.02–3.55, indicating acidic behavior across all formulations.
- ❑ Residual citric acid likely contributed to formulation acidity.

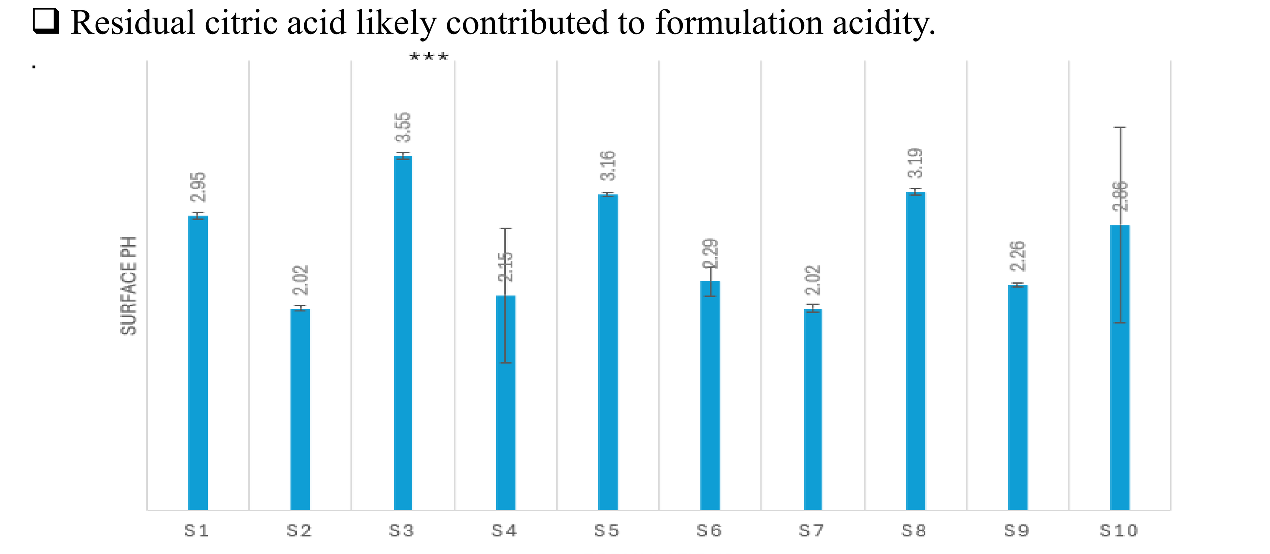


Figure 4
Surface pH values of hydrogel formulations S1–S10 showing consistently acidic behavior across all samples.

Electrical Characterization

- ❑ Frequency-dependent impedance and conductance behavior was observed among the hydrogel formulations.
- ❑ S3 and S9 exhibited enhanced conductance and lower impedance, suggesting improved ionic transport within the hydrated polymer matrix.

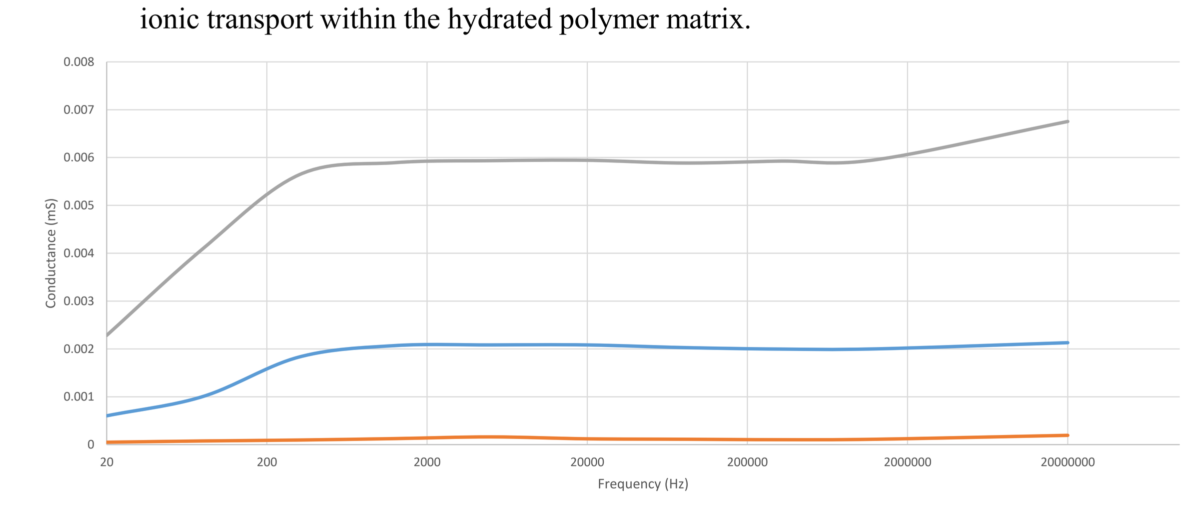


Figure 5
Frequency-dependent conductance behavior of selected hydrogel formulations (S1, S3, and S9).

Swelling Analysis.

- ❑ Higher citric acid content improved structural retention after immersion.
- ❑ Some formulations exhibited severe erosion or complete dissolution.
- ❑ Aloe vera incorporation may have increased hydrophilicity and mass loss.

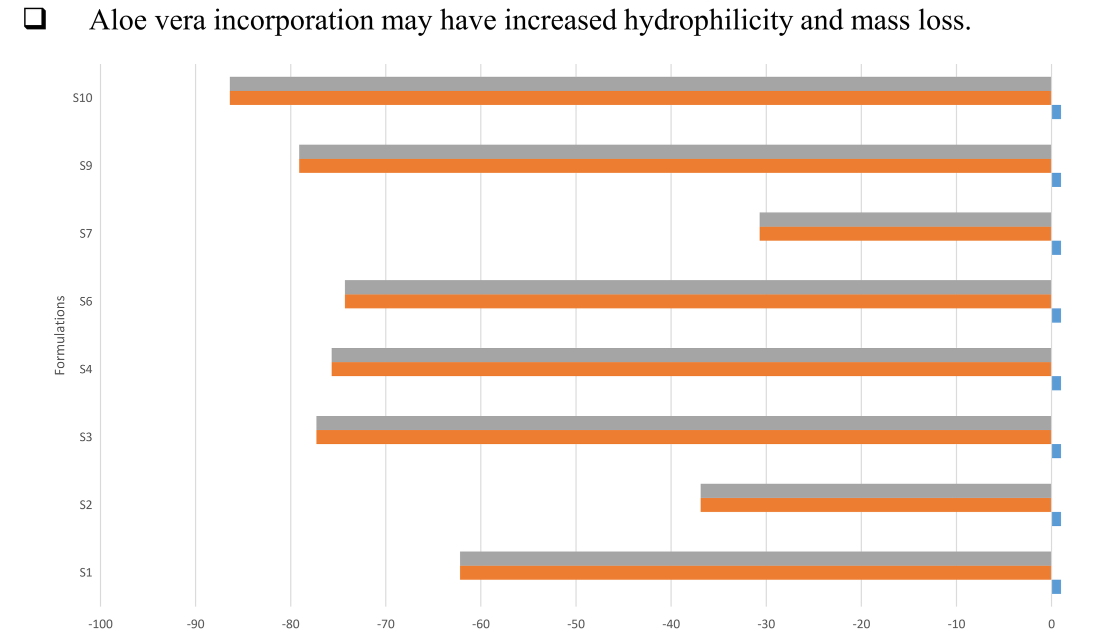


Figure 6
Swelling and stability behavior of hydrogel formulations after water immersion.

Conclusions

- ❑ Small compositional variations significantly affected hydrogel behavior.
- ❑ Increased citric acid content generally improved structural retention after immersion.
- ❑ Aloe vera incorporation influenced electrical and qualitative antibacterial behavior.
- ❑ Formulations S3 and S9 exhibited enhanced ionic transport behavior.
- ❑ Selected formulations showed localized reduction of *E. coli* growth.
- ❑ FT-IR analysis suggested partial starch–citric acid crosslinking.
- ❑ Additional studies involving quantitative antibacterial analysis, mechanical characterization, degradation, cytotoxicity, and biocompatibility are required.

Future Work

Future work should focus on improving fabrication and thermal curing conditions to obtain more uniform hydrogel samples. Additional studies involving quantitative antibacterial analysis against a broader range of microorganisms, mechanical characterization, controlled degradation, and evaluation of Aloe vera bioactive release are recommended. Furthermore, cytotoxicity and biocompatibility assessments are necessary before considering advanced biomedical-related applications

Acknowledgements

I would like to thank laboratory technicians Asheley Devestrez and Angel Lopez for their technical assistance and support during the experimental work of this project. I also express my appreciation to Professor Maria Garriga for her guidance throughout a part of the research.

Finally, and most importantly, I would like to express my sincere gratitude to my mentor and professor, Dr. Jairo Rondon, for his continuous support, guidance, and encouragement throughout this project. His constructive feedback and mentorship contributed significantly to the completion of this research.

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