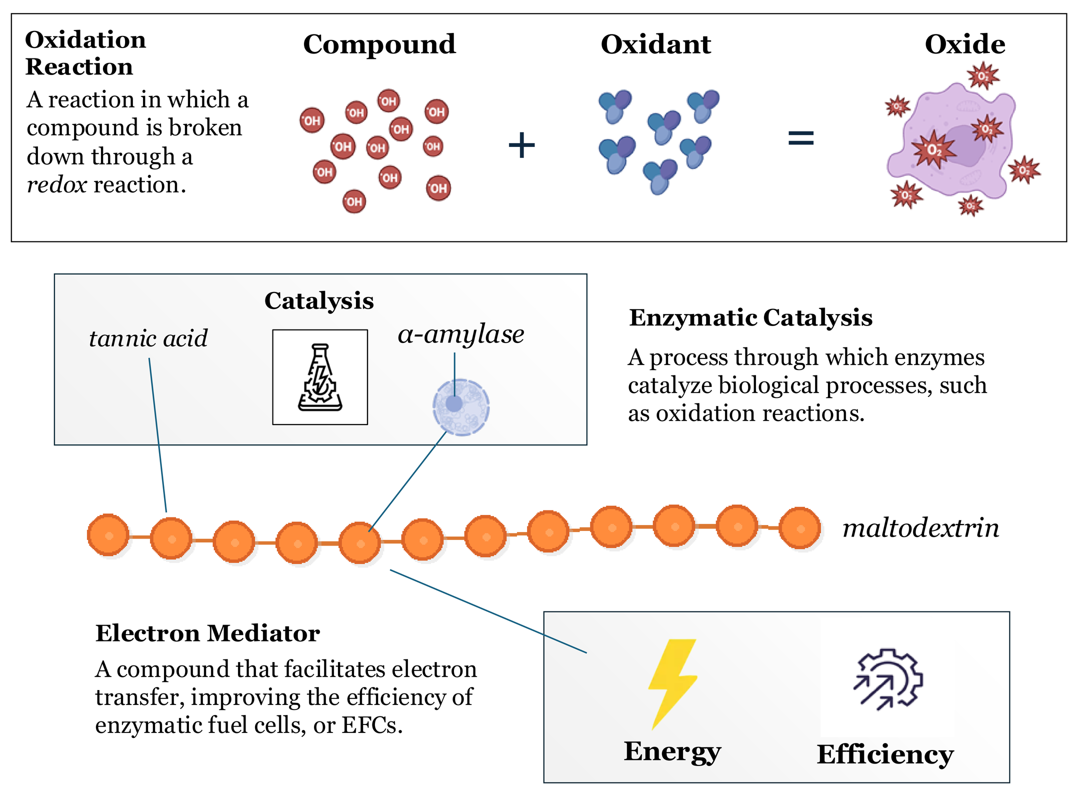
DEVELOPING SUSTAINABLE ENERGY ALTERNATIVES

Engineering a Novel Battery Using Biological Methods

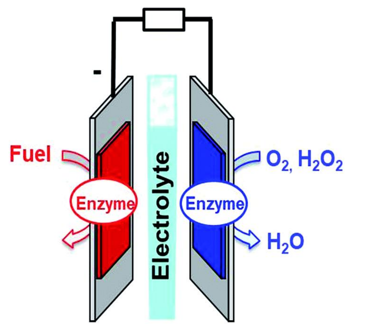
Researcher: Abhiruph Seetha Raman, Advisor: Kevin Crowthers, PhD.

GRAPHICAL ABSTRACT



INTRODUCTION

- Lithium-ion batteries (LIBs) are the primary form of energy storage globally
- One kg of LIB produced causes 17.63 kg-CO_2-eq. emissions (Clemente et al., 2025)
- Fuel cells are a promising LIB alternative
  - However, they are under-researched
- Enzymatic fuel cells have higher theoretical energy densities than LIBs (Oyarce et al., 2013)
- Developing efficient EFCs provides a sustainable, long-term LIB alternative



(Le Goff & Holzinger, 2018)

RESEARCH OBJECTIVES

ENGINEERING NEED: Lithium-ion batteries are the main form of global energy storage, but cause water pollution and accelerating climate change during mining.

OBJECTIVE: The engineering goal of this project is to engineer a low-cost enzymatic fuel cell (EFC) that can produce sustainable electricity.

GOAL 1

This project aims to study how fuel sources affect EFC performance.

GOAL 2

This project aims to study how an electron mediator affects EFC performance.

GOAL 3

This project aims to test novel fuel sources and system design.

ENGINEERING CRITERIA

- The engineering criteria for this project were evaluated in four parts: performance, cost, safety, and usability
- Many existing EFCs focus heavily on some, but not all, of these parts
- This project tests a model focused on maximizing performance across all criteria types
- Future EFC research can draw inspiration from the framework proposed in this project

METHODOLOGY

1

STEP 1: The first technique used in this project was preparing the cells. Petri dishes filled with agar were combined with the electron mediator, fuel source, and enzymes for each group. The concentrations of reagents chosen were 0.5 mM tannic acid, 25 mM sorbitol, 50 mM galacturonic acid, and 0.2 mM maltodextrin.

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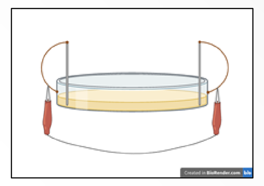
STEP 2: The next technique used was establishing the circuit. Graphite rods were chosen for electrodes, connected to a *5.6k-Ω* resistor by copper wires. Voltage was measured using a multimeter and used to calculate current.



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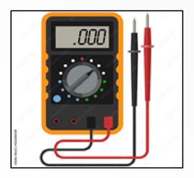
STEP 3: The third technique used was collecting data, which was read from the multimeter five times per cell over a total time interval of 20 minutes. Ohm's Law was used to relate voltage to current and current density.



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STEP 4: The final technique used in the project involved statistical analysis after taking the mean voltage for each cell and calculating current metrics. Tests include Student's *t*-test and one-way ANOVA.

PROJECT SIGNIFICANCE

- Current EFCs are **highly limited** in the **fuels** that they use and are **rigid** in their designs due to **bulky** membranes and **electrode materials**
- This project proposes a **membraneless** design for **enhanced cellular flexibility**, along with **lower production costs**
- This project also explores the use of **novel fuel sources**, namely **sorbitol** and **galacturonic acid**, that have **higher theoretical energy densities** than those used in current designs, like maltodextrin and glucose
- **Electron mediators** are used to **control** electrode interactions and **electron transfer**, but are **underutilized** in **EFC research**
- This project uses **tannic acid** as a **novel electron mediator** to provide a **higher peak energy production capability**, despite less advanced surrounding infrastructure compared to current models
- This project **successfully provides** a **framework** for developing **low-cost EFCs** with comparable performance to those on the market
- **Galacturonic acid** was deemed to be **more effective** as a fuel source in mediated EFCs due to **higher energy density** and improved enzyme interactions **compared to maltodextrin**
- This project determines the **optimal approach** for engineering EFCs in a manner that has **not yet been adopted** in formal research

RESULTS

[1]

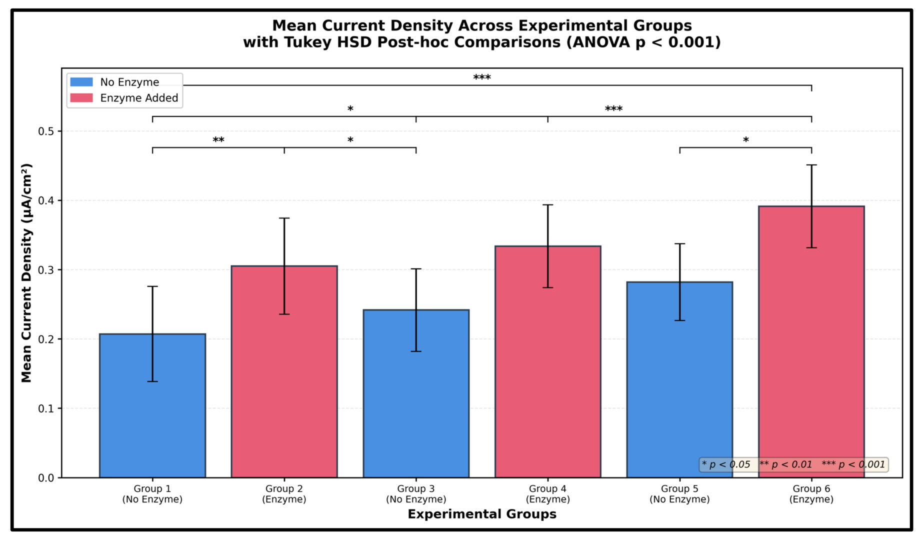

Figure 1 shows the results of Tukey's HSD analysis of differences in mean current density as shown from a One-Way ANOVA.

[2]

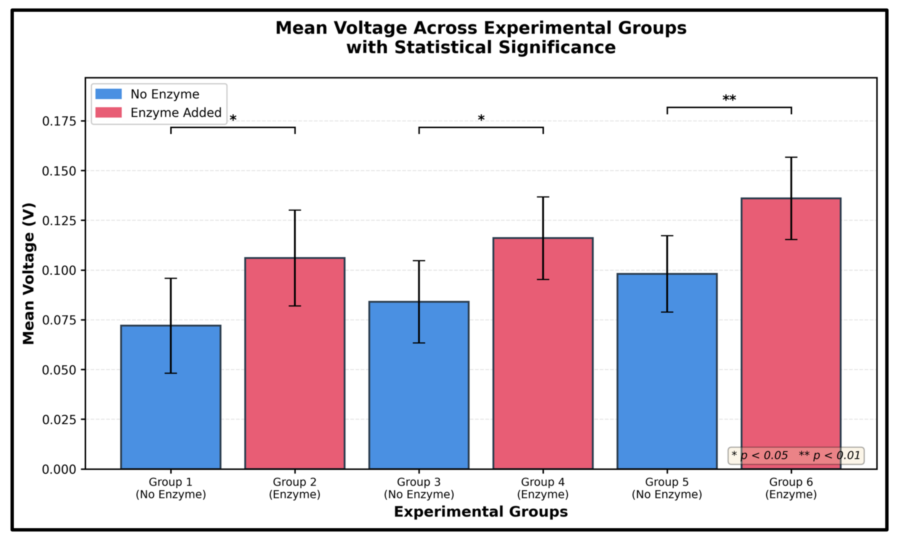

Figure 2 shows the results of Student's *t*-test for analysis of mean voltage across testing groups.

[3]

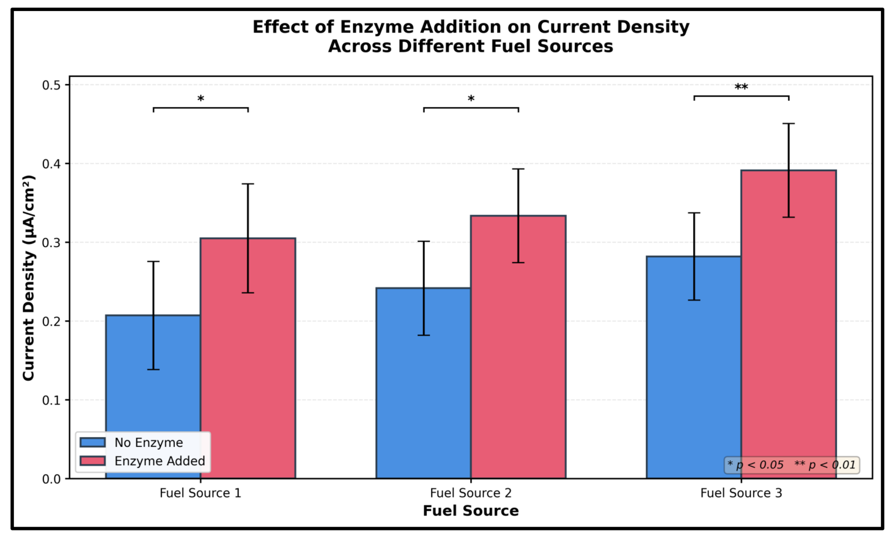

Figure 3 shows the results of Student's *t*-test for analysis of the effect on enzymes on mean current density grouped by fuel source.

[4]

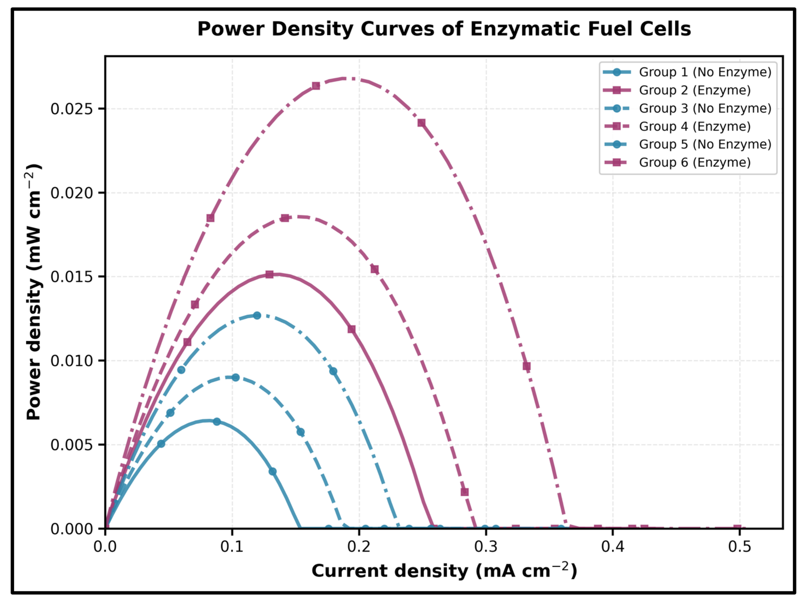

Figure 4 shows the results of polynomial regression methods used to create power density curves for each group.

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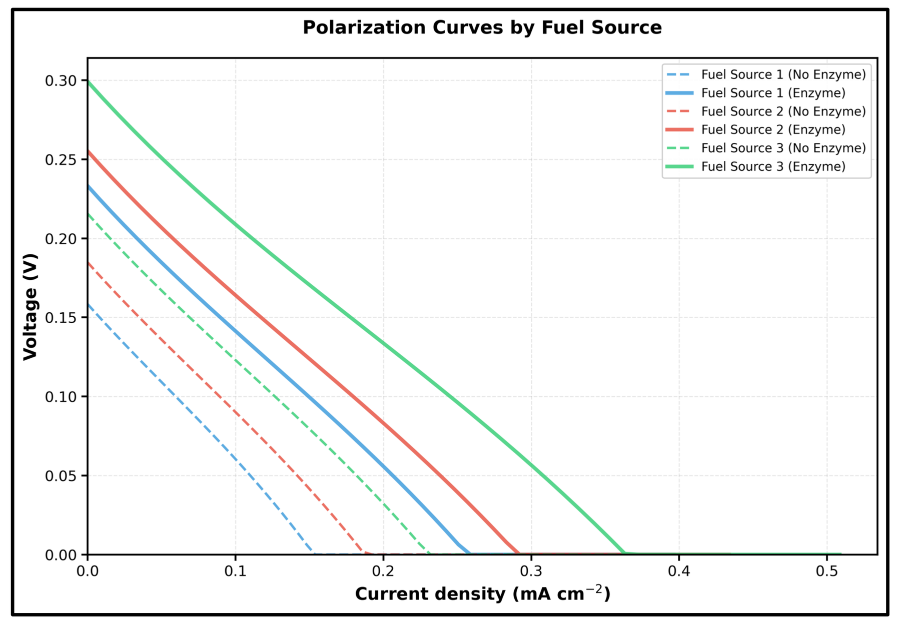

Figure 5 shows the linear relationship between voltage and current.

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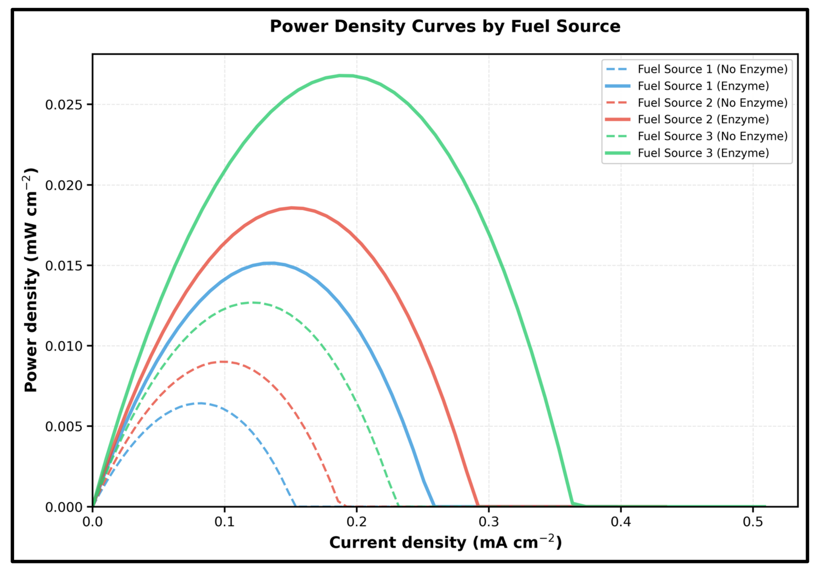


Figure 6 shows the parabolic relationship between power and current density.

STATISTICAL ANALYSIS

1 A two-sample *t*-test was conducted for each fuel source's enzyme-non-enzyme-group pair. The resulting *p*-values were 0.028, 0.020, and 0.0085, respectively. This shows strong evidence of enzymes significantly improving mean cellular voltage.

2 A one-way ANOVA test was performed to determine if there was a difference in current density across the six groups. The resulting *p*-value was 0.0035, showing strong evidence that one group had a significantly different current density.

3 To determine the cause of these differences, a Tukey's HSD test was performed. The test confirmed that the differences were caused by the presence of enzymes, as the *p*-values were around 0.001. This confirms the effect of enzymatic catalysis on cellular performance.

4 Finally, three two-sample *t*-tests were used to compare current density across enzyme-non-enzyme pairs for each fuel source. The results mirrored significance for voltage comparisons, showing the correlation between voltage and current density.

ANALYSIS

- The **addition** of fuel source-specific **enzymes** proved to be extremely important in improving **cellular performance** and **efficiency**
- Statistical testing showed **highly significant differences** between **enzyme** and **non-enzyme groups** for the **same fuel sources**
- **Galacturonic acid** and **sorbitol** provided **higher mean voltages** and **current densities** compared to the control
- This project provides a **framework** for testing **novel fuel sources**, thereby **accelerating** progress in **EFC research**
- Overall, this project **successfully determined** the **optimal system design** for non-energy-intensive **energy production** in an **EFC**

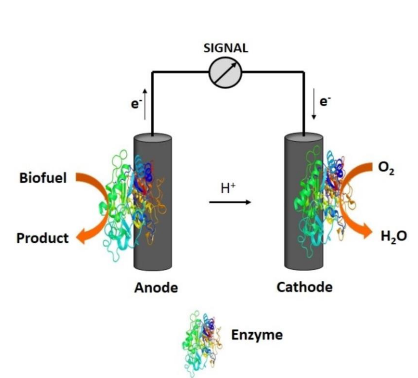
CONCLUSION

Developing EFCs with Novel Fuel Sources

- Expanding EFC research beyond current fuel sources can accelerate innovation and improve cellular efficiency long-term
- This project provides a framework for evaluating EFC performance using novel fuels

Accelerating Research into LIB Alternatives

- As lithium becomes scarce in the future, this project outlines methods to develop EFC alternatives
- Future EFC research can further explore galacturonic acid and sorbitol as effective fuel sources for long-term energy generation



(Aswathi et al., 2022)

KEY REFERENCES

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