Engineering a Novel Battery Using Biological Methods

Grant Proposal

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Author Note

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Executive Summary

With global electricity demand projected to steadily increase for the foreseeable future, dependence on lithium-ion batteries as primary energy storage technologies continues to rise. However, like other metal-based energy storage systems, these batteries pose many environmental harms, ranging from ecosystem disruption from mining processes to pollution during material extraction. These issues, along with concerns over future metal scarcity, make developing sustainable energy storage solutions crucial. Therefore, the objective of this proposal is to engineer a battery built exclusively from bio-derived compounds with performance and efficiency comparable to traditional models. The proposed model for this project is an enzymatic fuel cell utilizing catalysts and electron mediators to oxidize polysaccharide fuel sources, namely maltodextrin, galacturonic acid, and sorbitol. Previous research has demonstrated the use of maltodextrins as the primary fuel source in biobatteries with nearly optimal output efficiencies and higher power densities than traditional batteries. Therefore, maltodextrin will be used as a control group to determine the effectiveness of sorbitol and galacturonic acid as potentially effective novel fuel sources for future fuel cells. The engineering criteria for this project include achieving an output efficiency of at least 80%, producing consistent energy output for an extended period, and displaying a comparable energy density to traditional battery models. This proposal aims to mitigate the environmental impact of traditional metal-ion batteries by offering a sustainable biological solution to growing energy storage issues.

Keywords: enzymatic fuel cells, biobattery, oxidation, biological catalysis, sustainable energy

Engineering a Novel Battery Using Biological Methods

As global energy demand rises, the need for developing sustainable energy storage solutions is becoming paramount. The current energy storage market is dominated by lithium-ion batteries (LIBs), comprising over 70% of all batteries sold in the world (International Energy Agency, 2023). LIBs consist of a lithium-metal oxide cathode, graphite anode, lithium salt electrolyte, and dielectric separator (Koech et al., 2024). The electrolyte is a chemical solution that allows lithium ions to move between the cathode and anode at the ends of the battery, while the separator ensures that the anode and cathode are never in direct contact, to prevent short-circuiting. This design is widely replicated in other models, including LIB alternatives, such as nickel-cadmium and solid-state batteries.

Environmental Effects of Mining Processes

To source the lithium necessary to mass-produce LIBs, global mining processes have been refined for improved efficiency and reduced environmental impact through technologies like Direct Lithium Extraction. These procedures allow for the selective extraction of lithium from underground brine, though the environmental outcomes are still far from ideal. The evaporation ponds from which lithium is extracted require immensely large plots of land, which directly harms the biodiversity of native microbes, trees, and insects (Gajardo & Redón, 2019; Gutiérrez et al., 2022). Therefore, there is a critical need for a sustainable alternative to LIBs that does not pose these risks in the material sourcing process.

Current Alternatives

Currently proposed LIB alternatives include nickel-cadmium, nickel-metal hydride, and solid-state models. These designs have similar system-level compositions to LIBs but differ in the exact compounds used in the electrolyte and electrodes. For example, the cathode, anode, and electrolyte in nickel-cadmium batteries are composed of nickel oxide hydroxide, cadmium, and a potassium hydroxide solution, respectively. These models have shown potential to be more environmentally sustainable alternatives to LIBs but have largely stayed in developmental stages due to safety concerns, such as potential flammability and chemical toxicity (Phogat et al., 2025). Additionally, the manufacturing processes of these models are not yet optimized for maximum production, leading to inefficiencies and suboptimal output (Vedhanarayanan & Seetha Lakshmi, 2024). Mechanical stress experienced by these models also exceeds that of LIBs, primarily due to poor material-hardware compatibility, meaning that manufacturing processes require specialized machinery that come with higher production costs.

Biological Solutions

Despite the intensive work being done within the field of sustainable energy to address these concerns, relatively little research has been done on finding biological approaches to optimizing battery function. As a result, large-scale use and development of these solutions has been hindered. However, the potential of these models, or “biobatteries,” to increase battery efficiency, improve safety, and minimize biological waste, makes them a crucial technology to explore in the pursuit of sustainable energy generation.

Fuel Sources and Enzymatic Catalysis

The most widely used fuels in biobatteries are polysaccharides, such as glucose, due to the high density of energy stored within their covalent bonds. Through oxidation, these compounds are broken down, resulting in carbon dioxide as the final product. As oxidation occurs, electrons are released, stored as energy within the biobattery’s anode. A biobattery that implements enzymes to catalyze the oxidation process is defined as an enzymatic fuel cell (EFC). EFCs are preferred over alternative designs, such as microbial fuel cells, due to the innate catalytic abilities of enzymes. Furthermore, the inexpensive nature of biological catalysts makes them ideal for low-cost energy storage solutions. The most widely researched fuel sources for EFCs are glucose and maltodextrin, with the latter providing higher energy density, energy output, and Faraday efficiency (Zhu et al., 2014). In EFC research, Faraday efficiency is used to evaluate performance by dividing the moles of the experimental product by the moles of the theoretical product. In an EFC model implementing enzymatic catalysis using alpha-glucan phosphorylase (α-GP) and phosphoglucomutase (PGM), tests for Faraday efficiency resulted in 97.6% for a single test and 92.3% over a period of 60 hours. Additionally, the power density of an EFC containing an enzymatic pathway consisting of 13 enzymes was measured to be 0.026 mW cm^{-2}, compared to 0.011 mW cm^{-2} for a cell with only one enzyme (Zhu et al., 2014).

Limitations of Previous Models

Despite these advantages, existing EFC designs exhibit key limitations. One of the main disadvantages of previous designs is the decline in model performance over extended periods of time, which is crucial to improve before widespread use. In the context of EFCs, this primarily occurs due to the inactivity of enzymes over extended periods, which can be partially addressed through enzyme immobilization methods. However, due to the physical or chemical limitations that enzymes undergo within these processes, total energy output decreases.

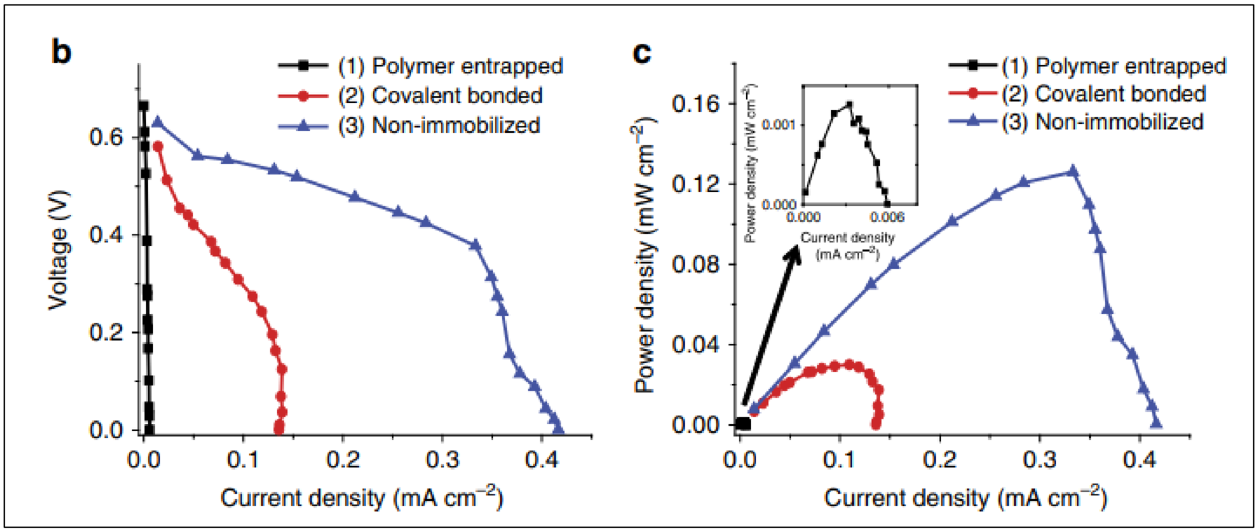

Figure 1: Comparison of electrodes based on immobilized and non-immobilized enzymes. An analysis of varying current densities, voltages, and power densities based on the state of the enzymes being used in the EFC, immobilized versus non-immobilized (Zhu et al., 2014, Figs. 1b and 1c).

This proposal aims to address this issue by testing novel fuel sources and improving the stability of the enzymes and compounds used.

Novel Fuel Sources and Electron Mediator

While glucose and maltodextrin remain the primary fuel sources used in EFCs, a variety of other fuels have been tested in isolation, displaying potential for further research. The main characteristic of fuel sources in EFCs is high amounts of energy stored within chemical bonds, meaning that certain polysaccharide-adjacent compounds, such as sugar alcohols and fibers, may also function as effective fuels. One of these compounds with immense potential for use in EFCs is pectin, a soluble fiber that naturally occurs in the cell walls of plants. Pectin has many desirable chemical properties, such as ionic conductivity, that make it a viable option for EFC electrolytes (Sultana, 2023; Muthukrishnan et al., 2023). Pectin is also water-soluble, meaning it can be formed into hydrogels that can facilitate electron transfer when paired with conductive materials, such as carbon nanotubes (Xu et al., 2024). Furthermore, when hydrolyzed, pectin can be converted into galacturonic acid, an oxidized form of galactose. In EFCs, galacturonic acid can be used directly as a fuel source or converted into galactaric acid, a highly oxidized platform chemical rich in carboxyl and hydroxyl groups (Nakagawa et al., 2022).

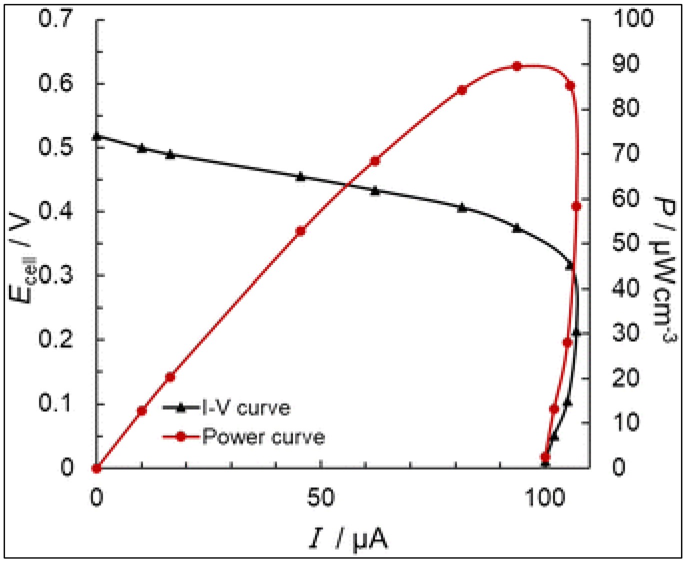

Figure 2: The polarization and power curves of an EFC using galacturonate as fuel vs. an Ag/AgCl reference under an O_2 atmosphere. A comparison of the power and polarization of an EFC utilizing oxidation of a galacturonate fuel with a 0.1 mol dm^{-3} galacturonic acid buffer (Nakagawa et al., 2022, Fig. 4).

Galactaric acid's polarity means that it has few high-energy chemical bonds. Therefore, converting from galacturonic acid to galactaric acid releases an abundance of electrons that can be stored in an EFC's anode as electricity. Sugar alcohols have also shown potential for being effective fuel sources in EFCs. Sugar alcohols are often derived from traditional polysaccharides that have been fermented. This results in sugar alcohols being highly reduced chemical compounds. One of the most well-researched sugar alcohols is sorbitol, which has a theoretically higher energy density compared to glucose, due to its level of hydrogenation (Oyarce et al., 2013). In the context of EFCs, each mole of sorbitol has a theoretical yield of 26 moles of electrons, while glucose is limited to 24 moles (Torres-Pacheco et al., 2019). Therefore, sorbitol has the potential to not only replicate the energy output of glucose-based EFCs but even exceed it.

A crucial component of EFCs is the electron mediator, which facilitates the transfer of electrons between electrodes, thereby allowing electricity production to occur. For a mediator to be successful, several criteria must be met. Firstly, the redox potential of the mediator, or its tendency to change its electron structure, must match the redox potentials of the interaction sites, or the electrodes. It must also resist chemical, physical, and biological degradation within the testing environment, and be membrane permeable (Gemünde et al., 2022). Various compounds meet these criteria, including tannins. Tannins are a class of polyphenols present in a variety of organic compounds, such as fruit, legumes, and leaves. Tannins are responsible for antimicrobial defense and thus have strong binding capabilities to electrode materials (Cosme et al., 2025). Tannic acid is the most common hydrolyzable tannin and has strong chelating abilities, which allow it to rigidly bind to metal ions. In EFCs, this provides enhanced stability and a viable approach to ensuring long-term high-level performance.

Section II: Specific Aims

This proposal's objective is to develop a sustainable and efficient biobattery using novel fuel sources and an electron mediator. The long-term goal of this project is to determine the effectiveness of sorbitol and galacturonic acid as potentially new fuel sources for future biobattery research. The central hypothesis of this proposal is that, given the theoretically higher energy densities of the fuel sources mentioned, the biobattery should exhibit high Faraday efficiency, with capabilities of sustaining high-level energy output over extended periods of time (Torres-Pacheco et al., 2019). The specific aims for this proposal are intended to guide the engineering objective, with clear testing strategies to evaluate the battery's performance.

Specific Aim 1: Determine the optimal fuel source for high energy output in an enzymatic fuel cell under controlled conditions

Specific Aim 2: Evaluate the impact of enzyme catalysis on the oxidation of polysaccharide-adjacent compounds

The expected outcome of this work is an independent biobattery system capable of functioning at an elevated level over an extended period. The potential implications of this proposal include a deeper understanding of oxidation processes on a molecular level for a variety of fuel sources and determining the feasibility of a biological system to replicate LIB function.

Section III: Project Goals and Methodology

Relevance/Significance

This proposal directly addresses growing environmental concerns surrounding LIBs by proposing a sustainable alternative with significantly lower environmental impact. Additionally, the process of constructing an EFC is considerably cheaper than the material sourcing and manufacturing processes necessary for mass-producing LIBs. With global electricity demand growing at an unprecedented rate, there is a substantial need for sustainable energy storage solutions. Given that this project centers around biological agents and bioderived compounds that are naturally more disposable and sustainable than chemical agents, there is preliminary evidence to suggest the final model that this proposal offers will attain the engineering objective.

Innovation

The novel fuel sources and electron mediator proposed in this project have not yet been studied within the same design. Therefore, there is no conclusive evidence as to whether they can efficiently function in the same battery model. However, in isolation, they have shown immense potential for further research, which this proposal aims to conduct. Sorbitol and galacturonic acid have been shown to have higher energy thresholds than those attainable by strictly glucose-based EFCs, displaying a core area of research crucial for future developments in biobatteries (Nakagawa et al., 2022; Torres-Pacheco et al., 2019). Furthermore, the proposed electron mediator within this design, tannic acid, has distinct properties analyzed in past studies showcasing its potential within an EFC (Cosme et al., 2025). Likewise, pectin has many desirable properties for an EFC electrolyte but has not been extensively researched in past studies. These compounds have shown extensive potential in isolation but have not yet been unified into one design. This proposal aims to engineer a system implementing these compounds into a cohesive design that can display tangible evidence of their theoretical potential. The final model aims to serve as a guide for future research and development into the field of sustainable energy by displaying the potential of biological systems to solve growing energy storage concerns.

Methodology

Specific Aim #1: Determine the optimal fuel source for high energy output in an enzymatic fuel cell under controlled conditions.

The goal of this aim is to identify the optimal fuel source for energy output in a polysaccharide-based EFC. Prior research has shown the theoretical capabilities and efficiencies of the fuel sources studied within this project, but innovation for these fuels has been done in isolation (Oyarce et al., 2013; Torres-Pacheco et al., 2019). This project proposes engineering a design involving all fuels with a novel electron mediator to determine the optimal system configuration for long-term energy output.

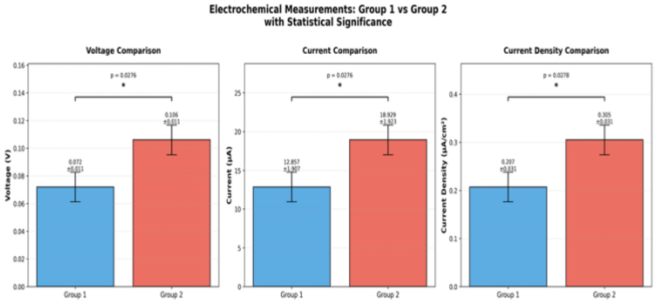

Figure 1: Control group data obtained from lab trials with a non-enzyme treated and enzyme-treated maltodextrin cell.

Justification and Feasibility. The methods in this section are relevant because it is important to identify the optimal fuel source within an EFC to determine further metrics, such as overall efficiency and potential for further work. Current and prior research have shown convincing evidence that the control group for this proposal, maltodextrin, is the optimal fuel source for an EFC (Zhu et al., 2014). However, other polysaccharide-adjacent compounds have been studied for their chemical properties, with indicators that they may also be viable solutions for EFC electricity generation.

Summary of Preliminary Data. The data for this specific aim was obtained from lab trials using control group fuel cells. The cells were prepared using petri dishes with agar. Lab trials were conducted over twenty-minute testing periods, with data collected one, five, ten, fifteen, and twenty minutes after the incorporation of fuel. Data was analyzed using statistical methods such as Student's *t*-test.

Expected Outcomes. The overall outcome of this specific aim is to select the optimal fuel source for a polysaccharide-adjacent fuel-based enzymatic fuel cell. The findings of this specific aim will be important in determining future steps for the project, along with further research into the field by providing a framework for optimal biobattery design and functionality.

Potential Pitfalls and Alternative Strategies. It is expected that the fuels used in this project will be in limited supply. Therefore, alternative lab strategies will involve strategically and diligently planning fuel source usage for each iteration of the model throughout the experimentation process.

Specific Aim #2: Evaluate the impact of enzyme catalysis on the oxidation of polysaccharide-adjacent compounds

The goal of this aim is to analyze the impact that enzyme catalysis has on the oxidation process of the proposed fuel sources. This will be done through trials involving three distinct groups: maltodextrin, sorbitol, and galacturonic acid. Each group will have trials conducted with and without enzyme catalysis for a categorical understanding of enzyme impact.

Justification and Feasibility. The methods in this section are relevant because the main component of EFCs are the enzymes used to catalyze oxidation reactions, making them distinct from other biological energy generation methods, like microbial fuel cells. However, an understanding of enzyme impact is crucial for ensuring that the model allows for high-level function including and in the absence of enzymes.

Expected Outcomes. The overall outcome of this specific aim is to quantify enzyme impact on the oxidation of fuel sources in an enzymatic fuel cell.

Potential Pitfalls and Alternative Strategies. It is expected that the enzymes used in this project will be in limited supply and prone to atmospheric changes. Therefore, lab strategies to mitigate these pitfalls will include strategically dividing enzymes based on the trial they are used in and implementing immobilization and stabilization techniques to ensure near-constant atmospheric conditions.

Section IV: Resources/Equipment

Materials

Cell Component	Material	Purpose
Electrodes	Tannin	Mediates electron transfer
	Graphite rods	Stable surface for anode
	Copper wires	Connects electrodes and circuit
Electrolyte	Chitin	Structural support
	Pectin	Stabilizes gel electrolyte
	Calcium chloride	Crosslinks pectin in gel matrix
	Water	Electrolyte solvent
	Petri dishes	Containers for experimentation
Fuel Sources	Maltodextrin	Control group fuel source
	Sorbitol	Experimental fuel source 1
	Galacturonic acid	Experimental fuel source 2
	α-amylase	Oxidizes maltodextrin
	Sorbitol dehydrogenase	Oxidizes sorbitol
	Pectinase	Oxidizes pectin

Equipment

Equipment	Purpose
Multimeter	Measures voltage output
Load resistors	Measures resisted current
Beakers	Containers for chemical solutions
Pipettes	Transferring liquids

Graduated cylinders	Measuring liquids
Fume hood	Secure environment for enzyme work
pH test strips	Controlling pH of electrolyte
Lab gloves	Protection for tester
Safety goggles	Protection for tester
Dust mask	Protection for tester

Section V: Ethical Considerations

All laboratory safety procedures will be assumed by the tester, including the use of safety equipment and careful handling of biological compounds. Safety goggles and dust masks will be worn when working with biological agents, and hands will be washed before and after any specific experimental procedure. All surfaces will be thoroughly sterilized using an ethanol solution before and after experimentation.

Section VI: Timeline

Task	**Estimated Date of Completion/Resolution**
Begin physical prototyping	End December 2025
Select prototypes for further testing	Beginning of January 2026
Begin collecting experimental data	Beginning – Mid January 2026
Begin data analysis & prototype refining	Mid-January 2026
Select final model & begin further testing	End January – Beginning February 2026

Section VII: References

Cosme, F., Aires, A., Pinto, T., Oliveira, I., Vilela, A., & Gonçalves, B. (2025). A Comprehensive Review of Bioactive Tannins in Foods and Beverages: Functional Properties, Health Benefits, and Sensory Qualities. *Molecules*, *30*(4), 800. https://doi.org/10.3390/molecules30040800

Gajardo, G., & Redón, S. (2019). Andean hypersaline lakes in the Atacama Desert, northern Chile: Between lithium exploitation and unique biodiversity conservation. *Conservation Science and Practice*, *1*(9). https://doi.org/10.1111/csp2.94

Gemünde, A., Lai, B., Pause, L., Krömer, J., & Holtmann, D. (2022). Redox Mediators in Microbial Electrochemical Systems. *ChemElectroChem*, *9*(13). https://doi.org/10.1002/celc.202200216

Gutiérrez, J. S., Moore, J. N., Donnelly, J. P., Dorador, C., Navedo, J. G., & Senner, N. R. (2022). Climate change and lithium mining influence flamingo abundance in the Lithium Triangle. *Proceedings of the Royal Society B: Biological Sciences*, *289*(1970). https://doi.org/10.1098/rspb.2021.2388

International Energy Agency. (2023). *Batteries and secure energy transitions: Executive summary*. International Energy Agency. https://www.iea.org/reports/batteries-and-secure-energy-transitions/executive-summary

Koech, A. K., Mwandila, G., Mulolani, F., & Mwaanga, P. (2024). Lithium-ion Battery Fundamentals and Exploration of Cathode Materials: A Review. *South African Journal of Chemical Engineering*, *50*. https://doi.org/10.1016/j.sajce.2024.09.008

Muthukrishnan, M., Shanthi, C., Selvasekarapandian, S., & Premkumar, R. (2023). Biodegradable flexible proton conducting solid biopolymer membranes based on pectin and ammonium salt for electrochemical applications. *International Journal of Hydrogen Energy*, *48*(14), 5387–5401. https://doi.org/10.1016/j.ijhydene.2022.11.152

Nakagawa, T., Abe, H., Gessei, T., Takeda, K., Igarashi, K., & Nakamura, N. (2022). Biorefinery of galacturonic acid using a biofuel cell as a reactor. *Reaction Chemistry & Engineering*, *7*(12), 2629–2635. https://doi.org/10.1039/d2re00202g

Oyarce, A., Gonzalez, C., Lima, R. B., Lindström, R.W., Lagergren, C., & Lindbergh, G. (2013). Direct sorbitol proton exchange membrane fuel cell using moderate catalyst loadings. *Electrochimica Acta*, *116*, 379–387. https://doi.org/10.1016/j.electacta.2013.11.070

Phogat, P., Dey, S., & Wan, M. (2025). Powering the sustainable future: A review of emerging battery technologies and their environmental impact. *RSC Sustainability*, *3*(8), 3266–3306. https://doi.org/10.1039/D5SU00127G

Sultana, N. (2023). Biological Properties and Biomedical Applications of Pectin and Pectin-Based Composites: A Review. *Molecules*, *28*(24), 7974. https://doi.org/10.3390/molecules28247974

Torres-Pacheco, L. J., Álvarez-Contreras, L., Lair, V., Cassir, M., Ledesma-García, J., Guerra-Balcázar, M., & Arjona, N. (2019). Electrocatalytic evaluation of sorbitol oxidation as a promising fuel in energy conversion using Au/C, Pd/C and Au–Pd/C synthesized through ionic liquids. *Fuel*, *250*, 103–116. https://doi.org/10.1016/j.fuel.2019.03.149

Vedhanarayanan, B., & Seetha Lakshmi, K.C. (2024). Beyond lithium-ion: emerging frontiers in next-generation battery technologies. *Frontiers in Batteries and Electrochemistry*, *3*. https://doi.org/10.3389/fbael.2024.1377192

Xu, B., Li, S., Ding, W., Zhang, C., Rehman, M. U., Tareen, M. F., Wang, L., & Huang, S. (2024). From structure to function: A comprehensive overview of polysaccharide roles and applications. *Food Frontiers*. https://doi.org/10.1002/fft2.490

Zhu, Z., Tam, T., Sun, F., You, C., & Zhang, Y. (2014). A high-energy-density sugar biobattery based on a synthetic enzymatic pathway. *Nature Communications*, *5*(1). https://doi.org/10.1038/ncomms4026