Logbook

*Please refer to the following link for the comprehensive logbook, which will be utilized for upcoming presentations: Final Logbook

Sept 9, 2025:

Today was the science fair kickoff meeting. During the session, the teachers introduced the overall expectations for the science fair this year, including timelines, important details, and examples of the types of projects I could do. These included innovative, experimental, and research projects. After listening to the descriptions, I want to create a project that combines both innovation and experimental design. I want to create something new, something that solves a real-world problem while still being feasible to perform.

Sept 16, 2025:

Today we had our second science fair meeting, where the teachers explained the proposal form in detail. We were given the official Science Fair Proposal Form, including my research question and safety considerations. I learned that my full proposal is due on October 1, 2025, which means I need to finalize my project topic soon so I can begin background research and planning. In this meeting we also went over the importance of keeping a logbook to record every idea, step, obstacle, and solution that we encounter.

Sept 20, 2025:

Today I began to brainstorm ideas for my science fair. I already knew I wanted to work on something in biology and chemistry because those fields interest me the most. I still don't know exactly what direction I want to go in. I started by writing things that came to mind when I thought about these subjects. I wrote the following words on my page:

- Bacteria
- Chemical Reactions
- Environmental Problems
- Materials Science
- Water Purification
- Energy
- Medical Diagnostics
- Biodegradation
- Polymers

At first none of these connected to each other, and I didn't get any topic ideas. But it did help me understand what I'm interested in.

Sept 22, 2025:

Today I spent most of my time researching broad science fair categories and reading summaries of past ISEF (International Science and Engineering Fair) winning projects. Many of the award-winning projects have solved global problems such as pollution, medical diagnostics, or sustainable energy. This made me want to do a topic with real-world relevance, not just a lab experiment. I made a list of world problems: plastic pollution, electronic waste, climate change, water contamination, unsustainable energy, food shortages, energy shortages, and lack of biodegradable materials. I noticed that my problems were centered around environmental sustainability, natural systems, and replacing harmful materials with biological ones. I tried to think of ways in which natural biological systems could be utilized to solve environmental issues around the world.

Resources used:

[1] ISEF. (2025). Isef.net. https://isef.net/categories

[2] Abstract Search Utility. (n.d.). Abstracts.societyforscience.org. Retrieved September 22, 2025, from https://abstracts.societyforscience.org/

Sept 23, 2025:

Today I began researching biological systems that could prove to be helpful to solve other problems. I began to read articles about how bacteria behave in nature, how they grow, how they form communities, and how they survive harsh environments. The articles I visited were mostly about using bacteria to capture methane and other unwanted gases in the atmosphere. This was an overused topic that I didn't want to do. I kept researching until I stumbled across article [3]. This article was titled "Could Microbes Help Create Sustainable Electronics," which immediately drew my attention, and I continued to read. The article talked about how electronic waste was a major problem contributing to many environmental issues. It explained electroactive microbes, which can generate electricity. It talked about bacterial species such as *Shewanella* and *Geobacter* utilizing the transfer of electrons to survive in areas where there is a lack of oxygen. The article read "…they transfer electrons out of their cells onto conductive terminal electron acceptors like minerals. Essentially, they can "breathe" metals instead of oxygen, and in doing so, they generate electricity." [3] I am already interested in doing a topic that uses bacteria to generate electricity. I will continue researching this field. I still have a lot of experience to gain before choosing my final topic.

Resources used:

[1] Burckhardt, R. (2023). *Climate Change Experts Tap Microbes to Protect the Planet*. ASM.org. https://asm.org/Magazine/2023/Spring/Climate-Change-Experts-Microbes-to-Protect-Planet

[2] Maglione, G., Zinno, P., Tropea, A., Mussagy, C. U., Dufossé, L., Giuffrida, D., & Mondello, A. (2024). Microbes' role in environmental pollution and remediation: a bioeconomy focus approach. *AIMS Microbiology*, *10*(3), 723–755. https://doi.org/10.3934/microbiol.2024033

[3] *Could Microbes Help Create Sustainable Electronics? | ASM.org*. (2024). ASM.org. https://asm.org/articles/2024/november/could-microbes-help-create-sustainable-electronics

Sept 24, 2025

I spent more time researching what makes a project "innovative." Several sources said that a project should either: Develop a completely new idea, improve an existing idea significantly, or combine fields in a new way. I am increasingly interested in the third option: combining biology and materials science. I started looking into biofilms, bacterial conductivity, and natural materials that carry electrical currents. I learned that some bacteria naturally form conductive structures, without any genetic engineering. That surprised me and made me think that this is the foundation for my project.

Resources used:

[1] *What Makes an Idea Innovative? 6 Characteristics to Consider | Arizona Alumni*. (n.d.). Alumni.arizona.edu. Retrieved September 24, 2025, from https://alumni.arizona.edu/career-lab/resources/what-makes-idea-innovative-6-characteristics-consider

[2] *Biofilms*. (n.d.). Quadram Institute. Retrieved September 24, 2025, from https://quadram.ac.uk/targets/biofilms/

Sept 28, 2025

Today I continued researching. I found out that different bacteria build different types of biofilms with different strengths and materials. What surprised me the most was that some bacteria can conduct electricity through their structures. Not precisely like a metal wire, but through special protein chains or nanowires. I also investigated eco-friendly materials and sustainable electronics. I learned that modern electronics rely heavily on mining. plastics, and metals that harm the environment. Many scientists are trying to create new forms of "green

materials" that are biodegradable, affordable, and safe for the environment. This made me think once again about using natural biological systems to create functional materials. I asked myself a few questions:

- Could bacteria create a type of eco-friendly conductor
- Could biofilms act like "living wires"?
- Is there a way to measure conductivity in living systems?
- Can living materials replace harmful ones?

I wanted to combine this idea of biofilms, sustainability, and materials science.

Resources used:

[1] Starr, M. (2025b, May 8). *Scientists Discover New Bacteria That Conduct Electricity Like a Wire*. ScienceAlert. https://www.sciencealert.com/scientists-discover-new-bacteria-that-conduct-electricity-like-a-wire

[2] *Researchers find new species of electricity-conducting organism, name it after Tribe | Newsroom*. (2025, April 22). Newsroom. https://news.oregonstate.edu/news/researchers-find-new-species-electricity-conducting-organism-name-it-after-tribe

Sept 30, 2025

Today I began to evaluate the possibility of this idea. I researched safe bacterial strains and discovered species like Bacillus are non-pathogenic, school-safe, and known for forming rigid biofilms. More importantly, they don't require any genetic modifications, which is crucial as I do not plan on doing genetic engineering. I also explored whether conductive materials can be integrated into natural structures. I found out that simple items like

- graphite,
- iron oxides,
- carbon cloth,
- hydrogels

are inexpensive and accessible, and many of them can transport electrons. I began constructing the framework for my problem statement:

"Exploring how to create or improve conductivity in biofilms using natural bacterial species and simple materials."

Resources used:

[1] Lyu, X., Cui, F., Zhou, H., Cao, B., Zhang, X., Cai, M., Yang, S., Sun, B., & Li, G. (2023). 3D co-culture of macrophages and fibroblasts in a sessile drop array for unveiling the role of macrophages in skin wound-healing. *Biosensors & Bioelectronics/Biosensors*

& Bioelectronics (Online), *225*, 115111–115111. https://doi.org/10.1016/j.bios.2023.115111

[2] Yuk, H., Lu, B., & Zhao, X. (2025). Hydrogel bioelectronics. *Chemical Society Reviews*, *48*(6), 1642–1667. https://doi.org/10.1039/c8cs00595h

Oct 1, 2025

Today I submitted my final project proposal. The title I chose is:

"Programmable Living Conductors: Curli Protein-Fiber Assembly and Microbial/Graphite Mineralization in *Escherichia coli* K-12 and *Bacillus subtilis* for Sustainable Bioelectronic Circuits."

My idea is to use two separate pathways. Protein-fiber (curli) assembly and metal/graphite integration utilizing two different bacteria species.

How I got to the two pathways:

During the brainstorming stage I wanted a project that combined biology and materials science while remaining safe and doable. I explored naturally occurring biological structures and processes, focusing primarily on bacteria and their abilities to form complex materials. I came across two interesting mechanisms.

1. Curli protein-fiber assembly:
   Through research I learned that certain bacteria, such as *E. coli* K-12 and *Bacillus subtilis,* produce curli fibers as a part of their biofilms. These fibers form dense protein networks that add to their biofilm structure. What caught my attention is that these protein fibers are electrically conductive, meaning they could serve as natural wires within living systems.

2. Microbial/Graphite Mineralization:
   I also explored the possibility of improving conductivity by including metal or graphite particles within the bacterial mix. This idea came from reading research papers on microbial mineralization. By combining bacteria with conductive materials, I could create a system in which the mineral or graphite particles would stay above the living biofilm to create a stronger conductive network.

Submitting this proposal gave me a clear direction. The next steps will focus on creating deep background research for each pathway, material selection, and experimental design that allows me to safely measure conductivity and biofilm structures in both the protein fiber and mineralized systems.

Resources used:

[1] Bhavdip Anavadiya, Acharya, D., Saraf, M., & Goswami, D. (2023). Multispecies metabolomics interactions resulting in the development of resistance. *Elsevier EBooks*, 133–150. https://doi.org/10.1016/b978-0-323-95715-1.00016-9

[2] Oh, Y., Cui, Y., Kim, H., Li, Y., Hinterdorfer, P., & Park, S. (2012). Characterization of Curli A Production on Living Bacterial Surfaces by Scanning Probe Microscopy. *Biophysical Journal*, *103*(8), 1666–1671. https://doi.org/10.1016/j.bpj.2012.09.004

Nov 16, 2025:

Today I began brainstorming keywords for my project that I will define to gain a

Nov 23, 2025:

Today I focused on creating the background research section of my project. I created a new document and organized the main headings so that the structure is organized before I begin researching. I created the document and began working on it. I began my document as such: 1. Introduction and objective, followed by 1.1 Project title and scope statement. Today I completed the following in the document:

1.1 Project Title and Scope Statement

Project Title:

"Programmable Living Conductors: Curli Protein-Fiber Assembly and Microbial Graphite Mineralization in *Escherichia coli* K-12 and *Bacillus subtilis* for Sustainable Bioelectronic Circuits."

Scope Statement:

This Background Research aims to review the biological, chemical, materials science, and theoretical principles required to design and create programmable living conductors formed by protein fibers and by microbial templating or mineralization of conductive substances (including metal nanoparticles and graphite) in *Escherichia coli* K12 and *Bacillus subtilis.* This section will be tailored towards guiding microbial construction into circuits, utilizing patterned hydrogels, and on the foundations of electron transfer models, nucleation/mineralization chemistry, hydrogel-biofilm interactions, curli biogenesis, and theoretical theories that determine conductivity, stability, and experimental performance. The purpose of this section is to revise previous research and theoretical frameworks to aid in the development of the experimental procedure.

Nov 24, 2025

Today I began the real researching portion of my project. I began by creating a new section, which I titled 1.2 motivation and global issue. This was followed by 1.2.1 which was titled "Scale and growth of the e-waste problem." I used trustworthy resources for this portion, and I cited them appropriately in APA 7 format. Here's what I completed today:

1.2 Motivation and Global Issue

The growing problem of electronic waste (e-waste), environmental demand for a more ecological, sustainable conductor, and the urgent global need for a low-cost, biodegradable circuit led to the motivation for this project.

1.2.1 Scale and growth of the e-waste problem

Electronic waste, commonly known as "e-waste," is becoming a fast-growing, global issue contributing a large amount to the worldwide waste stream. This prevalent, environmentally damaging problem is dangerous, difficult to handle, and expensive to get rid of [1]. Recent data indicate that e-waste production reached a record of approximately 62 million metric tons in 2022, an 82% increase from 2010 expected to rise by an additional 32% to 82 million tons in 2030. Substantial resources worth billions of dollars were wasted and disposed of; E-waste recycling only provides 1% of the demand for rare earth metals. In addition, less than a quarter (22.3%) of 2022's e-waste was recorded to be appropriately collected and recycled. This raises hazards of contamination to communities throughout the world and leaves the US $62 billion worth of recoverable natural resources all left unaccounted for [2]. The majority of this waste, however, is dumped, burned, or processed in unregulated areas where hazardous metals like lead, cadmium, and mercury pollute the land, water, and soil [3]. This waste is extremely toxic to all forms of life, with children being the most vulnerable. According to the World Health Organization (WHO, 2024), "E-waste contains several known neurotoxicants, including lead and mercury, that may disrupt the development of the central nervous system during pregnancy, infancy, childhood and adolescence... may also impact the structural development and function of the lungs... may cause irreparable harm and affect them for the rest of their lives."

Resources I cited today:

[1] *Tackling informality in e-waste management: The potential of cooperative enterprises*. (2025, August 30). International Labour Organization. Retrieved November 24, 2025, from https://www.ilo.org/publications/tackling-informality-e-waste-management-potential-cooperative-enterprises

[2] E-Waste Monitor. (2024, December 12). *The Global E-Waste Monitor 2024 - E-Waste Monitor*. Retrieved November 24, 2025, from https://ewastemonitor.info/the-global-e-waste-monitor-2024/

[3] World Health Organization: WHO. (2024, October 1). *Electronic waste (e-waste)*. Retrieved November 24, 2025, from https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste)

Nov 26, 2025

Today I completed the final introduction paragraph, which I titled 1.2.2 Environmental costs for metal conductors and the need for sustainable alternatives. I talked about the e-waste problem and how copper mining plays an essential role in CO_2 emissions. Today I completed the following:

1.2.2 Environmental costs for metal conductors and the need for sustainable alternatives

The environmental demand for electronics is not just about disposal and recycling methods but rather the water-intensive energy required to mine copper. These mining processes largely contribute to greenhouse gas emissions and immense pollution [4]. Copper extraction alone has an extremely significant CO_2 footprint and could possibly lead to scarcity of resources such as water, along with heavy-metal contamination, and acid mining and tailings lead to environmental depletion [5], [6], [7]. These are the primary reasons that demand biological approaches, including microbial biofilms, curli-based nanofibers, and engineered living materials. The majority of these pathways, however, remain largely unexplored at the level of patterned-like conductors.

Resources I cited today:

[4] Recycling, G. A. (2025, November 18). The Environmental Impact of Mining vs. Recycling Electronics - Global Ardour Recycling. *My WordPress*. Retrieved November 26, 2025, from https://globalardour.co.uk/the-environmental-impact-of-mining-vs-recycling-electronics/

[5] *Sustainable Copper*. (n.d.). International Copper Association. Retrieved November 26, 2025, from https://internationalcopper.org/sustainable-copper/

[6] Federal Metals Inc. (2022, August 11). *How does copper mining affect the environment? | Calgary*. Federal Metals Inc. | Federal Metals Inc. Retrieved November 26, 2025, from https://federalmetals.ca/how-does-copper-mining-affect-the-environment/

[7] Recycling, G. A. (2025b, November 18). The Environmental Impact of Mining vs. Recycling Electronics - Global Ardour Recycling. *My WordPress*. Retrieved November 26, 2025, from https://globalardour.co.uk/the-environmental-impact-of-mining-vs-recycling-electronics/

Nov 27, 2025

Today I completed section 2 of my background research which was titled "Historical Context." I added the two subsections, 2.1 Evolution of bioelectronics and biologically derived conductors and 2.2 comparison of inorganic conductors and biomaterials. Here is what I completed:

Historical Context

2.1 Evolution of bioelectronics and biologically derived conductors

The idea that living organisms, particularly microbes, could play a vital role in electrical systems and bioelectronics (the study of biological systems for electronic functions) has transformed from a theoretical idea to experimental reality. In 1911, M.C. Potter first reported that microbial metabolism reacted with organic compound degradation could yield measurable electricity, highlighting that microorganisms could generate electricity under specific conditions [8]. However, for many decades research on bioelectric conductors remained vastly untouched. It wasn't until the second half of the 20th century that materials science and bioelectronics began to emerge. The demonstration of metallic-like conductivity in iodine-doped polyacetylene in the late 1970s by Alan J. Heeger, Alan MacDiarmid, and Hideki Shirakawa, research that would eventually earn them the 2000 Nobel Prize in Chemistry, opened the possibility that organic materials might outdo metals and semiconductors in terms of electrical conductance [9].

2.2 Comparison of inorganic conductors and biomaterials

In modern electronics, metals such as copper or silver and carbon-based conductors (e.g., graphite, graphene, and carbon nanotubes) are extremely popular because of their extremely high conductivity, copper's conductivity being around 5.8001×

107*107*
S/m (siemens per meter) under standard conditions [10]. Graphite also conducts electricity due to the covalent bonds that exist between three carbon atoms, resulting in layers of hexagonal patterns in its atomic structure (its conductivity being around
103to 104*103to 104*
S/m) [11]. In contrast, biologically derived conductors such as protein-based fibers and microbial nanowires are renewable, potentially biodegradable, and can self-assemble under specific conditions. These biological conductors do have major flaws, including much lower conductivity, being more sensitive to environmental conditions (moisture, pH, ionic strength, etc.), and often having poor structural weaknesses. For example, according to research led by Malvankar et al., in 2011, report "...metallic-like conductivity in films of the bacterium Geobacter sulfurreducens and also in pilin nanofilaments (known as microbial nanowires) extracted from these bacteria. These materials have electronic conductivities of ~5 mS cm(-1)..." [12]. Thus, although traditional materials offer high performance and stability, bioelectronics offer new kinds of electronics, ones that are flexible, biodegradable, self-assembling, and more sustainable. The following table summarizes advantages, limitations, usages, and conductivity of different conductors

Conductor type	Typical Conductivity (S/m)	Key advantages	Key limitations	Uses
Metals (e.g., copper, silver)	~ 5.8001× 107*107* S/m	- High conductivity - Durable - Mass-produced	- Nonbiodegradable - Requires mining - Limited flexibility	- Standard wiring - PCBs - Power transmission
Carbon-based conductors (e.g., graphite, graphene, and CNTs)	~ 103− 105*103− 105* (graphite/carbon mats) to about ~ 106− 107*106− 107* (CNT/ graphene film) [13]	- High strength-to-weight ratio - Chemical stability - Resistance to corrosion - Potential for flexible electronics	- Conductivity lower than metals - Complex production - High costs to produce and manufacture	- Flexible electronics - Sensors - Composite materials
Biomaterials (e.g., protein fibers microbial nanowires)	~ 10−2− 100*10−2− 100* S/cm, e.g., microbial nanowires 5× 10−2*10−2*	- Renewable - Sustainable - Self-Assembly - Biodegradability - Patternable using biology	- Lower conductivity - Environmental sensitivity - Weaker durability	- Biodegradable electronics - Biosensors - Environmental sensing

*Conductivity values vary widely depending on material quality, processing, and structure; listed values represent typical values under standard conditions.

Resources I cited today:

[8] Potter, M. C., & Waller, A. D. (1911). Electrical effects accompanying the decomposition of organic compounds. *Proceedings of the Royal Society of London Series B Containing Papers of a Biological Character*, *84*(571), 260–276. https://doi.org/10.1098/rspb.1911.0073

[9] *Nobel Prize in Chemistry 2000*. (n.d.). NobelPrize.org. Retrieved November 27, 2025, from https://www.nobelprize.org/prizes/chemistry/2000/popular-information/

[10] *Nondestructive Evaluation Physics : Materials*. (n.d.). Www.nde-Ed.org. Retrieved November 27, 2025, from https://www.nde-ed.org/Physics/Materials/Physical_Chemical/Electrical.xhtml

[11] Carbon, E. (2024, September 30). *Graphite Electrical Conductivity –A Complete Guide*. East Carbon. Retrieved November 27, 2025, from https://www.eastcarb.com/graphite-electrical-conductivity/?

[12] Malvankar, N. S., Vargas, M., Nevin, K. P., Franks, A. E., Leang, C., Kim, B., Inoue, K., Mester, T., Covalla, S. F., Johnson, J. P., Rotello, V. M., Tuominen, M. T., & Lovley, D. R. (2011). Tunable metallic-like conductivity in microbial nanowire networks. *Nature Nanotechnology*, *6*(9), 573–579. https://doi.org/10.1038/nnano.2011.119

[13] Cesano, F., Uddin, M. J., Lozano, K., Zanetti, M., & Scarano, D. (2020). All-Carbon conductors for electronic and electrical wiring applications. *Frontiers in Materials*, *7*. https://doi.org/10.3389/fmats.2020.00219

Nov 28, 2025

Today I researched bacterial cell biology, which was the next section for my research. I also learned while researching and completed a very small part of this section. This is primarily because I was learning through the process to ensure I could grab ahold of the topics I will discuss. Here is what I researched today:

3. Bacterial Cell Biology

3.1 Prokaryotic cell envelopes

3.1.1 Structural overview and definitions

To understand how bacteria can build materials outside of their cells, we first need to understand how bacterial cells are built internally with different structures and their functions. The “cell envelope” is a term that refers to the outermost layer of the bacterial cell, and its functions include protecting the cell, communicating with the environment, maintaining the cell’s shape and structure, and permitting the proper metabolism, growth, and replication of the cell [14]. Major structures include:

1. Inner (Plasma/cytoplasmic) membrane
    - **Phospholipids** and embedded proteins make up the prokaryotic cell’s innermost lipid bilayer. This membrane surrounds the cytoplasm and controls the movement of small molecules, ions, and proteins between the cytosol and the periplasm [15].
        - **Phospholipids** play a vital role in the plasma membrane. Since lipids are fats, they are composed of fatty acid chains attached to a glycerol backbone. [15]
2. Peptidoglycan Layer (Cell Wall)
3. Periplasmic Space
4. Outer membrane (in Gram-negative bacteria)

Resources I cited today:

[14] *Cell Envelope - an overview | ScienceDirect Topics*. (n.d.). Www.sciencedirect.com. Retrieved November 28, 2025, from https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/cell-envelope

[15] Libretexts. (2024, November 23). *3.5: lipid molecules - phospholipids*. Biology LibreTexts. Retrieved November 28, 2025, from https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/General_Biology_(Boundless)/03%3A_Biological_Macromolecules/3.05%3A_Lipid_Molecules_-_Phospholipids

Nov 29-30, 2025

I continued to research these days to help gain context into the bacterial cell envelope. Here is what I researched today:

- **Phospholipids** play a vital role in the plasma membrane. Since lipids are fats, they are composed of fatty acid chains attached to a glycerol backbone. [15] As illustrated in figure 3.1.1.1 a lipid is composed of a hydrophilic head and hydrophobic tails. The tails contain saturated and unsaturated fatty acids. Saturated fatty acids only contain single carbon to carbon bonds leading to a straight and uniform chain. Whereas unsaturated fatty acids are more kinked or bent due to one or more carbon-carbon double bonds [16].

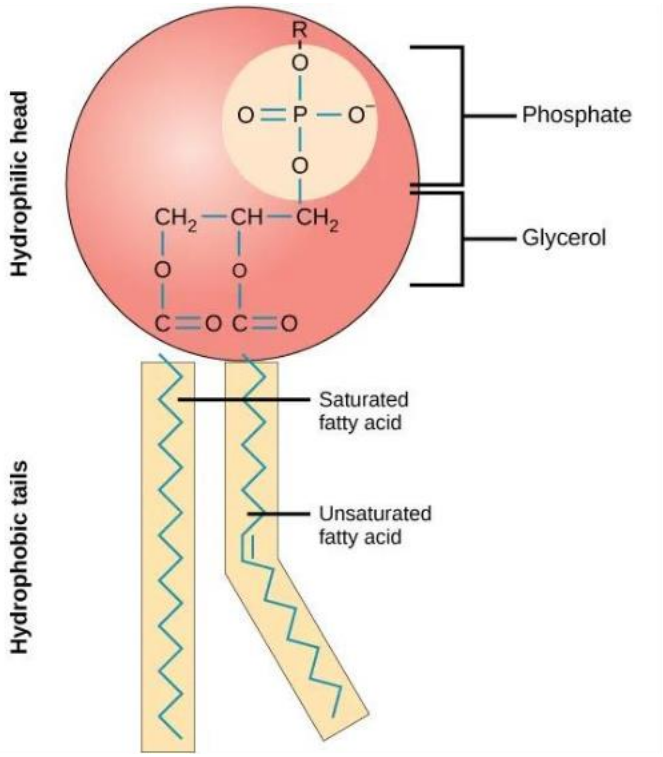


Figure 3.1.1.1: A diagram of a phospholipid (Image credit: OpenStax Biology) [17]

- The inner membrane is present in both gram positive and gram-negative bacteria. It is a fundamental component of the prokaryotic cell as it separates internal metabolic parts from the external environment. Figure 3.1.1.2 reinforces the structure of the components in the inner membrane.

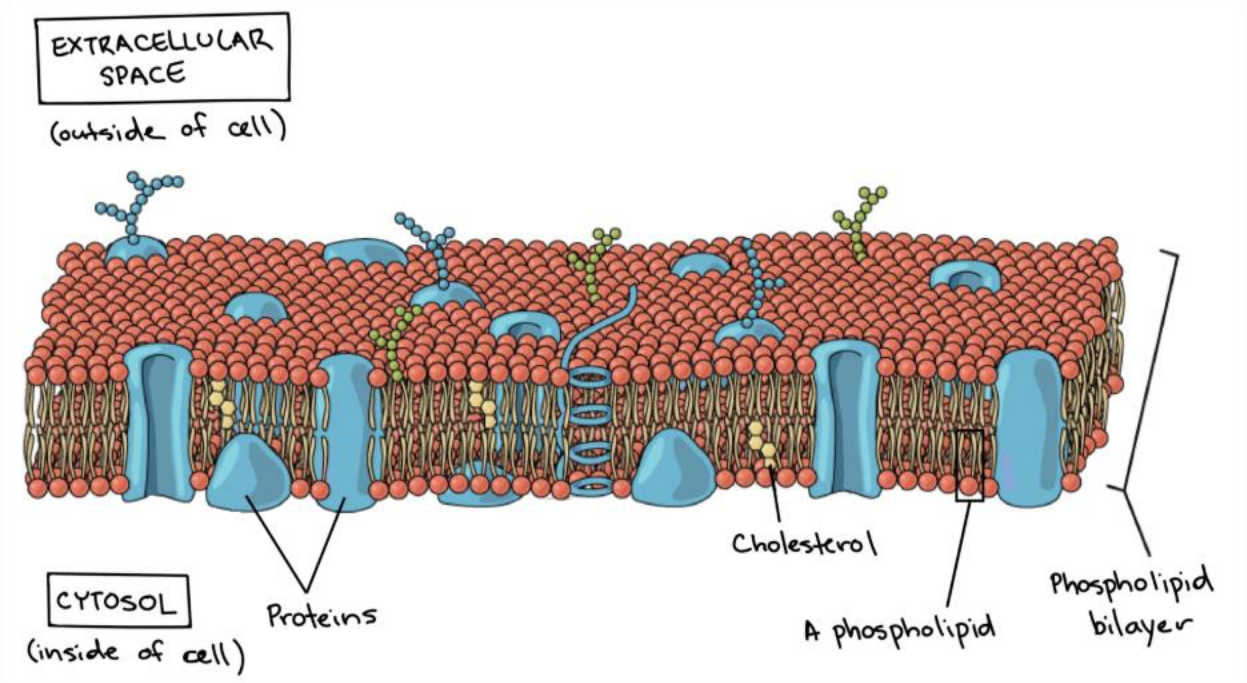
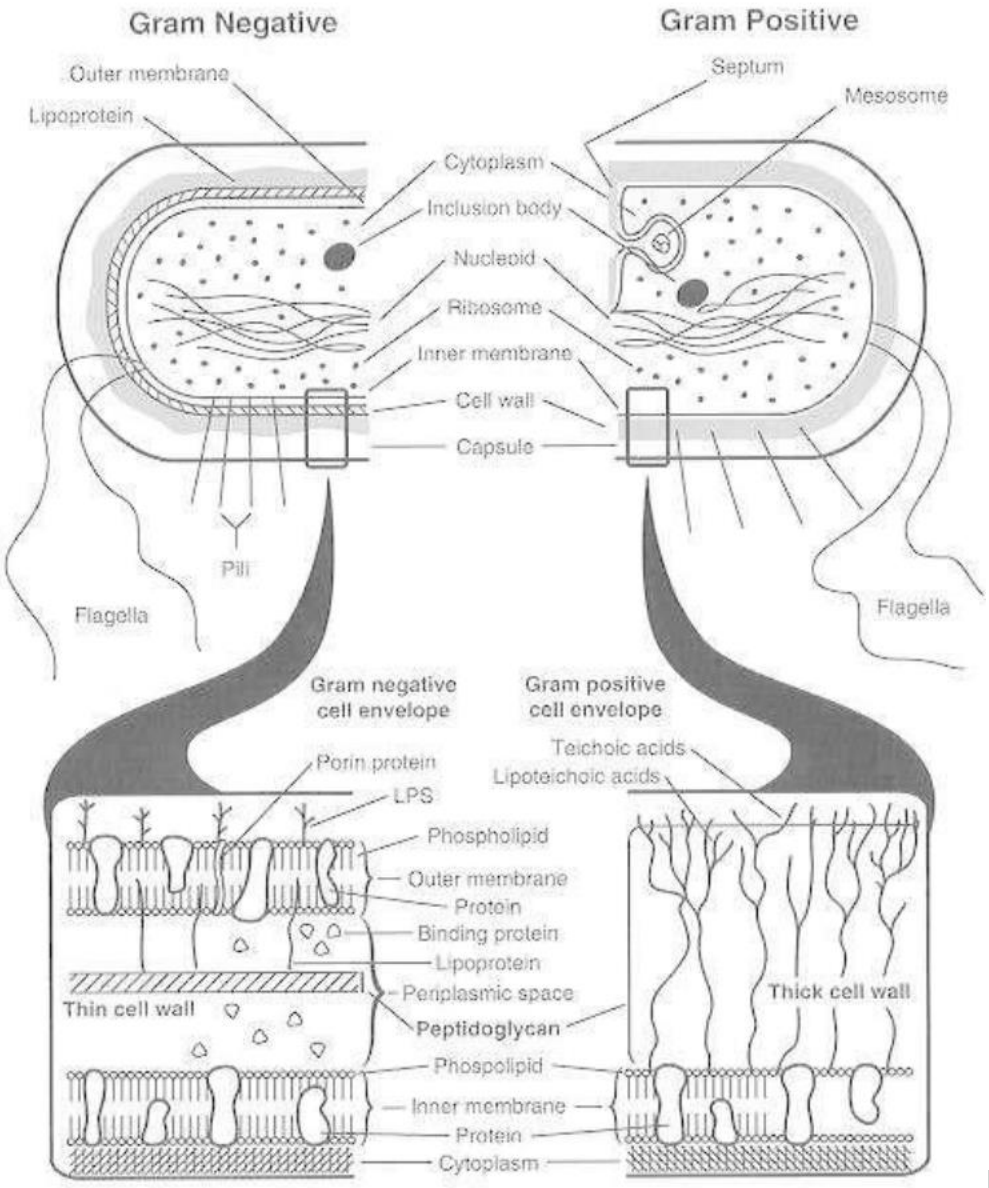


Figure 3.1.1.2: The inner membrane illustrating the phospholipid bilayer (Image credit: Khan Academy) [18]

2. Peptidoglycan Layer (Cell Wall)
   - The peptidoglycan layer is a mesh-like area that is constructed by the covalent bonding of repeating **disaccharides** units, typically **N-acetylglucosamine** (NAG) and **N-acetylmuramic acid** (NAM) connected via **β-1, 4 glycosidic bonds**, with **peptide side chains** [24].
     - **Disaccharides** are simple sugars made of two monosaccharide units connected through a glycosidic bond.
     - **N-acetylglucosamine**


Gram Negative
Gram Positive
Outer membrane
Lipoprotein
Septum
Mesosome
Cytoplasm
Inclusion body
Nucleoid
Ribosome
Inner membrane
Cell wall
Capsule
Pili
Flagella
Flagella
Gram negative cell envelope
Gram positive cell envelope
Porin protein
LPS
Teichoic acids
Lipoteichoic acids
Phospholipid
Outer membrane
Protein
Binding protein
Lipoprotein
Periplasmic space
Thin cell wall
Peptidoglycan
Thick cell wall
Phospolipid
Inner membrane
Protein
Cytoplasm

[22]

3. Periplasmic Space (in gram-negative bacteria)
    - This space is a gel-like compartment that is located between the inner (cytoplasmic) membrane and the outer membrane. According to Michael S. Donnenberg the author of Principles and Practice of Infectious Diseases, "...the periplasm, an aqueous environment containing a high concentration of proteins and the peptidoglycan, which probably forms a hydrated gel." [19] This area contains the Peptidoglycan Layer (Cell Wall) and a numerous number of soluble proteins such as binding proteins (for nutrients and ions), enzymes (periplasmic enzymes), and other important functional proteins (transporters, etc.) [20].
    - This compartment is different depending on the type of bacteria. Gram-negative has a large, distinct periplasmic space between the inner and outer membranes, while gram-positive bacteria have a much smaller periplasmic space (or none at all) located between the inner membrane and the thick peptidoglycan cell wall [21]. This difference between the periplasmic space is depicted in Figure 3.1.1.4.

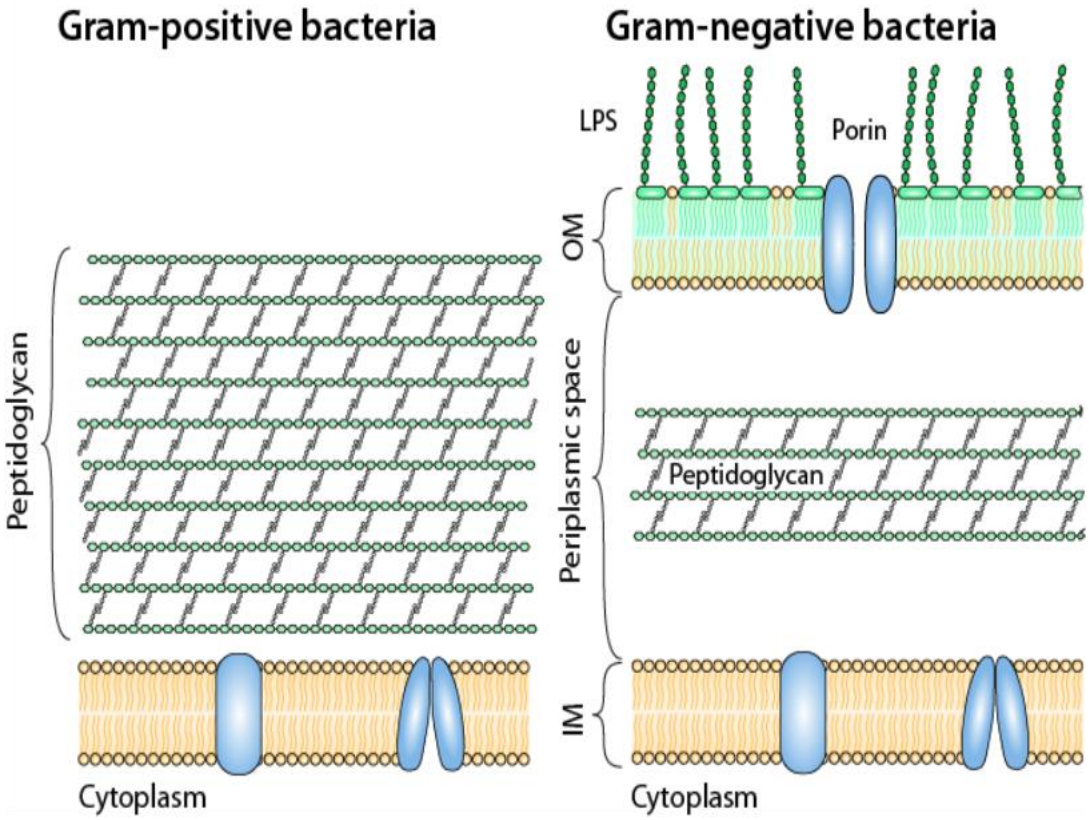


Figure 3.1.1.4: Periplasmic space between gram-negative and gram-positive bacteria (Image credit: Microbe Online) [23]

4. Outer membrane (in Gram-negative bacteria)

Resources I cited in these days:

[16] Toxopeus, J. (2024, April 10). *5.1 Membrane components and structure*. Online Textbook for Biol 395. Retrieved November 29, 2025, from https://pressbooks.atlanticoer-relatlantique.ca/advcellbiol/chapter/5-1-membrane-components-and structure/#:~:text=The%20lipid%20bilayer%20is%20in,therefore%20they%20increase%20membrane%20fluidity.

[17] Rye, C., Wise, R., Jurukovski, V., DeSaix, J., Choi, J., & Avissar, Y. (2016, October 21). *3.3 Lipids - Biology | OpenStax*. Retrieved November 29, 2025, from https://openstax.org/books/biology/pages/3-3-lipids

[18] *Khan Academy*. (n.d.). Retrieved November 29, 2025, from https://www.khanacademy.org/science/biology/structure-of-a-cell/prokaryotic-and-eukaryotic-cells/a/plasma-membrane-and-cytoplasm

[19] Bennett, John E, et al. *Mandell, Douglas, and Bennett's Principles and Practice of Infectious Diseases*. 8th ed., Philadelphia, Elsevier / Saunders, 2015.

[20] Salton, M. R., & Kim, K. (1996). *Structure*. Medical Microbiology - NCBI Bookshelf. Retrieved November 30, 2025, from https://www.ncbi.nlm.nih.gov/books/NBK8477/

[21] Tankeshwar, Acharya. "Differences between Gram Positive and Gram Negative Bacteria - Microbeonline." *Microbeonline*, 28 Dec. 2018, microbeonline.com/general-and-differential-characteristics-of-gram-positive-and-gram-negative-bacteria/. Accessed 30 Nov. 2025.

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Dec 1-7, 2025

In these days I began researching a little about the experimental procedure. Despite many attempts, I did not find anything helpful. I began coming up with an extremely rough procedure. I did this so I could better direct my research to be more linked with the project. So far here's the idea: Make LB agar plates with graphite incorporated into the matrix. There will be a patterned stencil that will be placed on the agar and will be removed once the LB agar is cooled. Then I will

add safe E. coli strains such as K12 in the stenciled channels. Electrodes will be added to measure conductivity using an electrical sensor and an Arduino module. This is the only possible method that I have found feasible enough to perform. Today I ordered a 0.1-2.5 µL micropipette along with pipette tips. I ordered two different groups: one that would fit on the 0.1-2.5 µL micropipette and the other that would fit on a 10-100 µL micropipette that I had from before. I also purchased an INA219 sensor that would measure the current in an electrical system. That's all I did this week.

Dec 8-13, 2025

In these days the parts I ordered arrived. I received the sensor, the micropipette, and its accessories. I submitted my project for review through the CYSF portal. The committee will ensure that my project is safe and allowed for the fair. Here's what I submitted:

Purpose of experiment or research
To investigate the possibility of growing living electronic circuits using bacteria strains embedded in a hydrogel complex.

Description of experiment or research study
My project explores the possibility of growing biodegradable, living electronic circuits using bacterial strains such as Escherichia coli K12. Instead of making circuits with mined materials such as copper and other rare earth metals, I plan to use bacterial growth along patterned hydrogel biofilm to produce conductive pathways. This project investigates two separate pathways: 1. Conductive protein pathway: Some bacteria can naturally produce nanowires or conductive proteins such as pillin fibers. By growing such bacteria along patterned hydrogels, I hope to guide them into forming a biofilm capable of conducting electricity. 2. Metal reduction pathway: Certain bacteria can reduce metal ions, such as ferric citrate, or incorporate conductive particles, such as graphite, into their biofilm. This would allow for the formation of a conductive mixture along the growth channels. All chemicals/bacteria required:
Lb agar
Agarose
Graphite
Ferric Chloride
E. coli K12 (nonpathogenic)
All reagents and bacteria will be used/tested in a safe environment with supervision. Safety equipment will be utilized at all times to ensure the safety of everyone.

Where will experiments take place?*
At my home

What is the animal species?
Escherichia coli dh5a (non-pathogenic strain)

Risk level
Low Risk

I also completed research for my document. I decided to complete a lot these days due to less time available in the future. Here is what I completed:

Outer membrane (in Gram-negative bacteria)
A second lipid bilayer is located on the outside of the peptidoglycan layer; however, this layer is asymmetrical; it is not composed of phospholipids on both sides. The inner section of the membrane is composed of phospholipids, while the outer segment primarily contains **lipopolysaccharides,** lipoproteins, and outer-membrane proteins [22].
Lipopolysaccharides (LPS), also known as endotoxins, play a crucial role in constructing outer membranes for gram-negative bacteria. They contain a lipid anchor, a core oligosaccharide, and an O antigen polysaccharide [24], [27].
The outer membrane plays an important role by serving as a permeability barrier that restricts the flow of large hydrophobic molecules, toxins, detergents, etc. It also aids by stabilizing the inner membrane.

3.2 Surface Structures and Extracellular Matrix Components

Bacterial surface structures and extracellular substances are an essential part of how microbes adhere, organize, and mechanically construct communities such as biofilms, which directly impact the formation of physical properties of living conductors in this project. Pili/pilus and fimbriae are thin, hair-like protein tubes that extend outwards from the cytoplasmic membrane of prokaryotes such as bacteria [28]. They are composed of repeating pilin subunits that extend from the cell's surface. These structures commence the initial adhesion phase to the surfaces and other cells. They are crucial to early biofilm formation; for example, type I pili in Escherichia coli significantly enhance the attachment to both biotic and abiotic surfaces [29]. Curli fimbriae are a special class of amyloid protein fibers found in enteric bacteria and serve as structural adhesions and control both cell-cell and cell-surface contacts in developed biofilms [30]. Flagella, composed of flagellin proteins, are long, whip-like filaments that primarily provide motility and also contribute to surface approach and stable contact prior to biofilm matrix deposition.

The extracellular polymeric substance (EPS) matrix is produced by successful biofilm communities and is a highly complex and hydrated network of organic polymers (polysaccharides, proteins, and DNA) created by microorganisms [32]. It is composed mainly of exopolysaccharides, which act as a 'molecular glue' joining cells to surfaces and each other, contributing to mechanical adhesion and resistance to chemical and physical stresses [33]. Extracellular DNA (eDNA) is released through active secretion and flows through the matrix and acts as a structural connector between the cells. Extracellular proteins join EPS components and reinforce the matrix structurally, while enzymes within the EPS enable modelling of the biofilm in response to environmental changes [34].

3.3 Biofilm Lifecycle, Regulation, and Spatial Design

Biofilm transformation is a multi-step process in which planktonic bacteria transition from free-living cells to surface-attached embedded organisms. Initially, the individual cells loosely associate with a surface through reversible physical contact. But as they sense the surface, they switch physical characteristics, adhesions, and extracellular structures [35]. This initial phase is not stable and is accompanied by adhesions. After the bacteria have attached to the surface, they begin to reproduce and multiply rapidly. During this time, they also produce a slimy matrix that is composed of extracellular polymeric substances (EPS). These act as a barrier from the external environment, shielding the bacteria. As the culture matures, parts of the biofilm dry out and break free from the main biofilm. They land in new areas, and the bacteria begin to secrete nutrients, starting the life cycle of a new biofilm [34], [36], [37]. The diagram below illustrates the life cycle of a biofilm from formation to maturity.

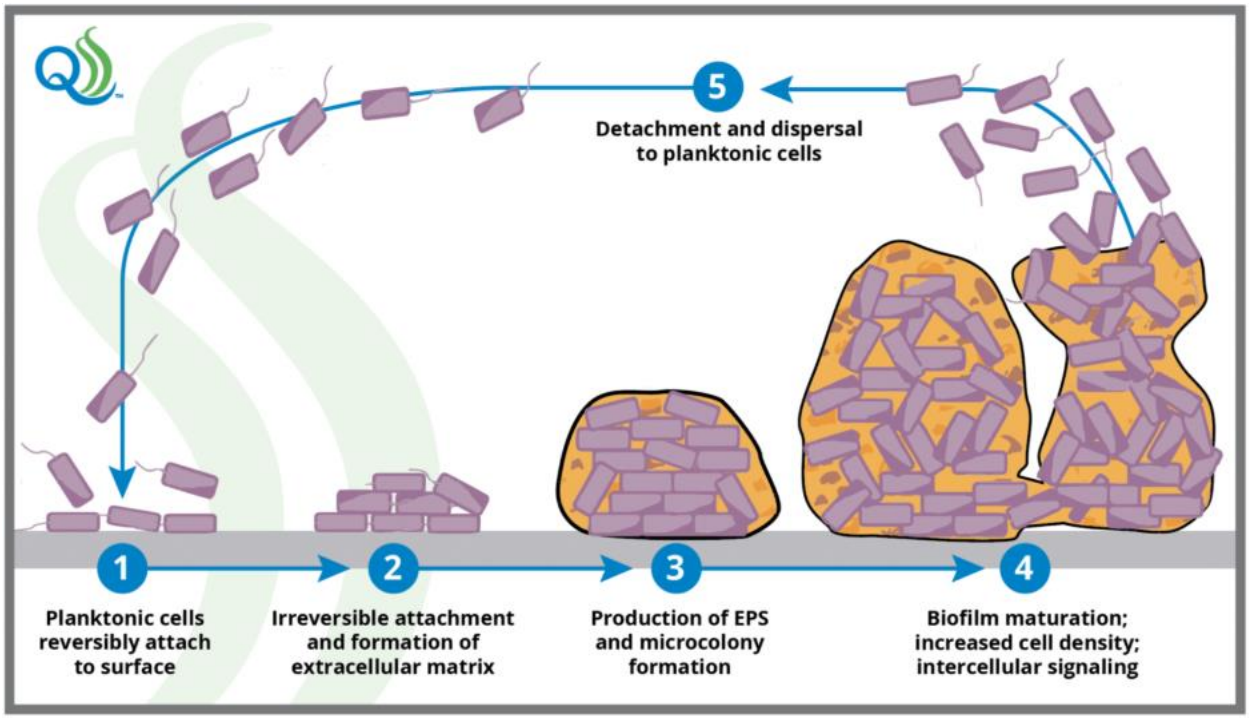

Figure 3.3.1: Life cycle of a biofilm (Image Credit: Qualitru) [35]

4. Curli System and Extracellular Amyloid Fibers

4.1 Curli Fibers Function and Importance

Curli fibers are a class of extracellular functional amyloid protein fibers primarily produced by Gram-negative enteric bacteria such as Escherichia coli and Salmonella spp., where they form a major structural component of the biofilm extracellular matrix (ECM) and regulate adhesion and environmental stresses. Structurally, curli are long fibrils with a cross-β sheet conformation assembled through biogenesis in which monomeric subunits are secreted and polymerized on the cell surface [30], [38]. Unlike pathological amyloids, which are associated with human neurodegenerative diseases such as Alzheimer's or Parkinson's, which are caused by misfolded proteins building up in tissues, curli represent functional amyloids, which serve physiological roles. They promote surface adhesion, cell-cell attachment, and biofilm structural support [30], [39]. The figure below depicts the formation of curli through CsgA subunits.

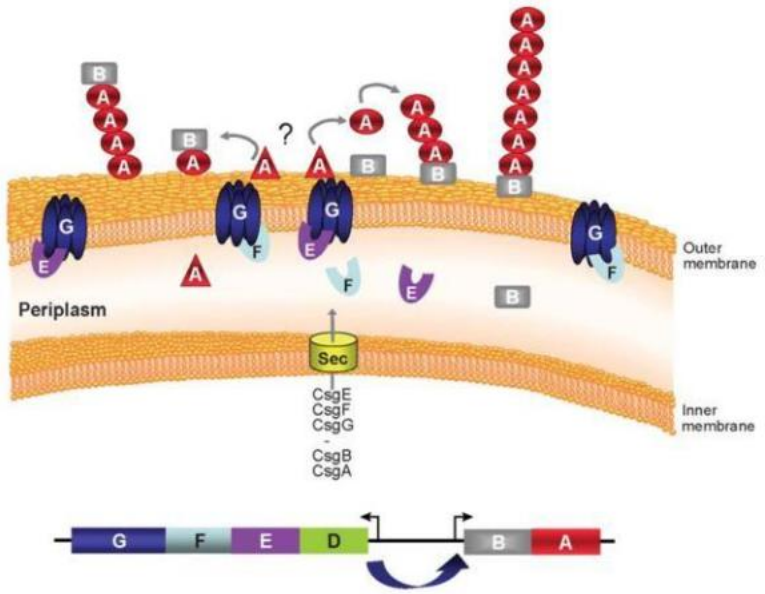

Figure 4.1.1: Formation of amyloid curli fibers within prokaryotic cells (Image Credit: National Library of Medicine) [30]

4.2 Electron Transport in Protein Fibers

Electron transport in biological materials can be explained utilizing three theoretical mechanisms: (i) thermally activated hopping or tunneling between localized redox-activated sites, (ii) through-bond conduction along partially conjugated pathways made by aromatic amino acids, and (iii) metal-controlled electron transfer when transition metals or cofactors (substances essential for enzyme activity) are directed towards protein scaffolds [40].

(i) In most traditional proteins electrons move by hopping or tunneling between cofactors or redox-active sites. The rates of electron transfer decrease exponentially as distance increases [41], [42]. A commonly used formula is the exponential distance dependence of the electron transfer rate: $k_{ET}=k_0 e^{-\beta R}$

1.

Where:

k_{ET}
is the rate constant for the electron transfer process

k_0
is the exponential factor

β
is the decay constant which shows how quickly the rate decreases as the distance increases

R
is the distance between the electron donor and acceptor.

[43], [44], [45]

(ii) In amyloid and fibrous proteins, additional methods of electron transfer arise. These include stacks of aromatic residues (e.g., phenylalanine, tyrosine, and tryptophan), which can allow partial through-bond or π-π assisted transport, producing conductivities higher than expected for simple polypeptides, a rare phenomenon seen in protein-electronics [46], [47].

(iii) If metal ions or clusters are controlled (for example, through histidine, cysteine, or acidic residues), electrons can also move through metal hopping or mixed protein-metal methods, eventually leading to biological electron transfer chains [46], [48].

5. Microbial Nanowires

5.1 Definition and Types of Microbial Nanowires

Microbes that participate in extracellular electron transfer (EET) have a diversity of extracellular conductive appendages, each structurally different from one another yet fully functional and aimed at transporting electrons from the cell to the external matrix [49]. One well-known example of this includes protein nanowires produced by Geobacter species; these are threadlike pili composed of pilA subunits that have been shown to be highly conductive and crucial for the reduction of insoluble Fe(III) oxides. They also play a crucial role in long-range electron transport in electroactive bacteria [51]. Conductivity in these nanowires is believed to arise from the dense packing of aromatic amino acids and specific cytochromes (a protein class containing iron molecules that catalyze redox reactions) that facilitate charge distribution over micrometer scales [52].

[50], [53]

6. Biomineralization, Microbial Metal Reduction, and Templating Chemistry

6.1 Fundamental Concepts in Biomineralization

Biomineralization refers to the natural process by which living organisms precipitate inorganic minerals from their environments, often because of biological activity that changes local chemical conditions or directs crystal formation. In microbial systems, researchers have discovered two main pathways: biologically induced mineralization (BIM) and biologically controlled mineralization (BCM) [55]. In BIM, the metabolic activities of microbes change the surrounding microenvironment in ways that lead to mineral precipitation without direct genetic control over the minerals' nucleation. For example, changes in local pH from microbial metabolism can produce carbonate or metal oxide precipitation on or near cell surfaces or within biofilms [54], [56]. In contrast, in BCM, organisms apply precise biological regulation over mineral formation, controlling where, when, and how minerals nucleate, grow, and assemble [58]. One classic example includes magnetosome formation in magnetotactic bacteria, where vessels inside cells guide iron uptake and magnetite crystal formation into similar chains with precise size and morphology [57].

Microorganisms are capable of producing different types of biominerals, including iron oxides and hydroxides, sulfides, carbonates, and metal nanoparticles (e.g., silver, gold) through these processes [59], [60]. In many microbial systems, the role of organic matrices, mainly extracellular polymeric substances composed of polysaccharides, proteins, nucleic acids, and lipids, is critical for nucleation and growth [61]. EPS provides functional groups such as carboxyl, phosphate, and sulfate, which bind to metal cations, concentrating ions locally, and lowering the energetic barrier for mineral nucleation [62].

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Dec 14, 2025

Today I got my project approved by the CYSF committee. This is a big green flag and I can start ordering the necessary materials and chemicals I need for this project.

Safety Committee Dec. 14, 2025, 10:43 a.m.	Ethics And Due Care Form 2A for project 'Programmable Living Bacterial Circuits.: Puneet Dhillon' is approved.

Dec 15-20, 2025:

In this week I ordered iron chloride ($FeCl_3$) along with glass storage bottles in which I will heat my media. I ordered these from Amazon. I also completed my entire research for this project. If I

have time in the future, I will add on to my research to add more info and depth to this project. For now, here's the rest of the research:

6.2 Chemical and Thermodynamic Factors of Microbial Metal Reduction

In microbial systems, metal ion reduction is controlled by redox (reduction oxidation) chemistry and thermodynamic principles. Electrons must flow from a donor with a more negative potential to an acceptor with a more positive reduction potential to create a spontaneous (thermodynamically favorable) reaction [63]. Microorganisms generate electrons through metabolism into electron transport proteins and redox-active enzymes. It reduces a suitable acceptor such as a metal ion, e.g., $Fe^{3+} \rightarrow Fe^{2+}$ [64]

Standard reduction potentials (E^0) provide a qualitative measure of the tendency of an ion or substance to gain electrons (be reduced) or lose electrons (be oxidized). A higher positive E^0 indicates a stronger tendency to gain electrons. For example, silver ions ($Ag^+ + e^- \rightarrow Ag^0$) have a relatively high standard reduction potential of ≈ +0.80 V, which demonstrates strong oxidizing power, making them largely reducible by microbial electron donors with a lower potential [65]. In contrast, other metal ions such as Fe^{3+}/ Fe^{2+} (≈ +0.77 V) or MnO_2/Mn^{2+} (≈ +0.38 V) are also biologically reducible but depend on local conditions such as pH and temperature [66].

Table of common metal redox values and reduction potential (standard conditions, 25°C and pH 7)

Metal Redox Couples	Approx. E^0 (V)	Reduction tendency
$Ag^+ + e^- \rightarrow Ag^0$	+ 0.80	Highly favorable → Readily reduced
$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.77	Favorable → Common microbial acceptor
$Na^+(aq) + e^- \rightarrow Na(s)$	-2.71	Favorable → Common oxidizer
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	+0.34	Less favorable → Reducer
$AgCl(s) + e^- \rightarrow Ag(s) + Cl^-(aq)$	+0.22	Less favorable → Reducer

*Note: Exact E^0 values may vary with pH and other conditions. [67]

6.3 Carbon-based Templating: Graphite/Graphene Integration with Biofilms

In carbon-based substances, electrically conductive carbon allotropes such as graphite nanoplatelets (xGnP), graphene oxide (GO), and carbon nanotubes (CNTs) serve as effective conductive fillers because of their inherent sp^2 carbon bonding and high aspect ratios [69]. These enable the formation of interconnected electron pathways at low concentrations. Graphite and graphene consist of covalently bonded carbon atoms in planar hexagonal lattices with delocalized π-electron systems that encourage electrical conduction along the sheet plane. CNTs

are cylindrical tubes of sp^2 carbon that have an extremely high aspect ratio that assists with network formation [68]. Graphene and GO also introduce oxygen-containing functional groups such as hydroxyl and carboxyl, which allow for more organic chemical interactions such as hydrogen bonding, π-π stacking, and covalent linkage with organic polymers [70]. Graphene is one of the strongest materials due to its single layer of carbon atoms bonded together in a 2-dimensional honeycomb lattice. It forms strong sigma (σ) bonds along with delocalized pi (π) bonds. Graphene's structure is depicted in figure 6.3.1.

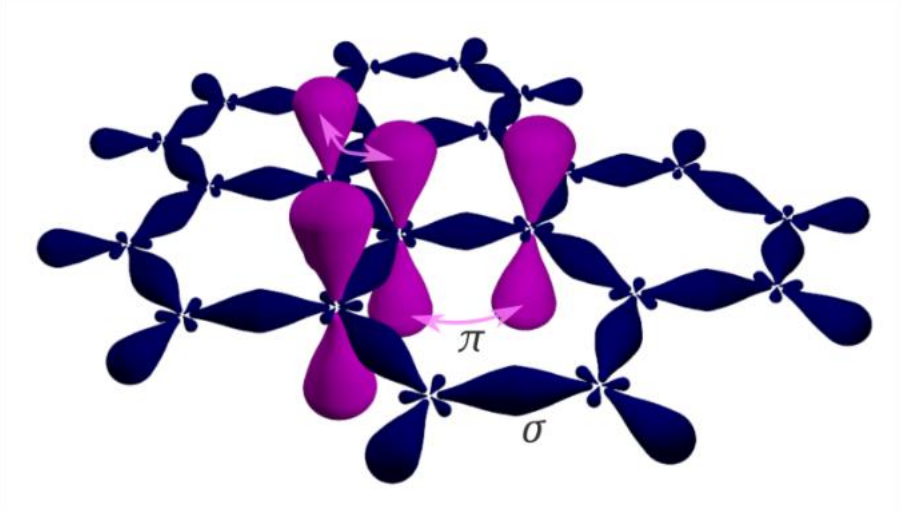

Figure 6.3.1: The structure of graphene (Image Credit: Wikipedia) [71]

Within a biofilm matrix, extracellular polymeric substances can inactivate graphite or graphene through hydrophobic interactions and π-π stacking between aromatic substances and sp^2 carbon surfaces, allowing for even dispersion.

7. Materials Science and Design for Living Conductors

7.1 Hydrogel Principles

Hydrogel scaffolds are three-dimensional, hydrophilic polymer networks that hold large amounts of water and provide a soft, hydrated environment through which nutrients and cells interact with one another [73]. The physical properties, pore size, stiffness, diffusivity, and surface chemistry all determine how cells stick to move within, etc. And therefore, determine shape patterns of biofilm formation and growth guidance for living conductors [74].

Hydrogels differ vastly based on what they are composed of. Natural hydrogels derived from polysaccharides (e.g., alginate, agarose) or proteins (e.g., collagen, gelatin) demonstrate higher biocompatibility and inherent bioactivity that encourage cell adhesion and biofilm formation due to their high resemblance to extracellular matrices. They, however, have lower mechanical strength and higher degradability, which reduce pattern stability in the long run [75]. Synthetic

hydrogels, constructed from materials such as poly(ethylene glycol) or polyacrylamide, provide precise control over pore size and mechanical stiffness with excellent consistency [76].

7.2 Adhesion, Mechanical Integrity, and Durability

Adhesion and mechanical integrity are extremely important for ensuring that biologically derived conductors such as protein fibers or mineralized networks remain stable and functional under real-world stresses such as bending, swelling, drying, and deformation [77]. In hydrogel systems, strong adhesion between different phases and the surrounding polymer network prevents cracking by allowing for stress transfer across the gel [78]. Studies show that chemically enhanced hydrogels significantly increase interfacial shear strength compared to unmodified systems, illustrating how molecular-scale bonding influences mechanical performance [79].

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Dec 21-25, 2025:

Here is the work I completed in these days:

8. Electrical Theories Relevant to Biological and Combined Systems

8.1 Key Electrical Parameters and Definitions

Conductivity and resistance are crucial physical properties that describe a material's inherent ability to conduct or oppose the flow of electric current. Electrical resistivity (symbol ρ, units Ω·m) demonstrates how strongly a material resists current. A high resistivity means the material opposes current (as in insulators), while a low resistivity means it allows current to pass through easily (as in conductors). Electrical conductivity (symbol σ, units Siemens per meter, S/m) is defined as the inverse of resistivity, $\sigma = 1/\rho$, and represents how willingly a material permits the flow of a charge under an applied electric field, regardless of its geometric shape or size.

[80]

In contrast to these material-level properties, electrical resistance (symbol R, units Ω) and conductance (symbol G, units S) describe the behavior of a specific object or component [81].

Resistance measures the opposition to current in a particular conductor and depends not only on the material's resistivity but also on the conductor's geometry. For a uniform conductor of constant cross-sectional area A and length L, resistance is directly proportional to length and inversely proportional to cross-sectional area according to the formula below:

$R=\rho LAR=\rho LA$

This explains why thinner wires resist more than short, thick wires [82]. Figure 8.1.1 illustrates this formula.

Figure 8.1.1: The relationships between the area and length of a pipe affecting resistance (Image Credit: lumenlearning.com) [83]

8.2 Microscopic Conduction Methods in Biological Materials

In biological and biohybrid systems, electron transport occurs through different microscopic mechanisms depending on distance and molecular structure. Quantum tunneling is more effective over very short distances (a few nanometers) where electrons cross barriers, and the probability of quantum tunneling decreases exponentially as distance increases [84]. For longer paths, hopping proves to be more efficient as electrons jump between localized states, showing stronger temperature dependence and weaker distance dependence than tunneling [85].

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Dec 26-Jan 10

I have realized that there is a huge time crunch. I still have to order and start my experiment, and I am greatly off the hoped-for schedule. Due to this time crunch I will have to make my logbook entries less detailed. This is unfavorable, but I have no choice. To combat this, I will make a more detailed logbook once the time crunch passes. Once the schoolwide science fair is over, I will add more detail to each entry to help support the process. Anyways, these days I have ordered and gathered all my required materials. These include special orders and all other equipment needed.

Dec 12-Jan 19

In these days I have finished formulating an experimental outline of the project. To see that, please visit the document that contains the formal report for this project. I have tested a few dishes and recorded possible errors and solutions. In these days I have also designed and printed the patterning tools required for my project. I 3D printed these.

Dec 21-Jan 24

In these days I have identified errors in past trials and came up with feasible solutions. These errors could significantly alter the results of my experiment. These are all documented in the official report.

Jan 25-28

In this time period I tested out my circuit using the methods described in Phase 4. Here is all the raw data collected over these days:

Original data collected:

12 Hours:

Agar+bacteria										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.5	2	3.27	-0.4	2	3.27	-0.4	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.5	2	3.27	-0.4	2	3.27	-0.4	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.5	2	3.27	-0.5	2	3.27	-0.4	2
Bacteria+Agar+Graphite										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power

		3.26	-0.4	2	3.27	-0.4	2	3.27	-0.5	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.6	2	3.27	-0.6	2	3.27	-0.5	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.8	2	3.26	-1.2	3	3.26	-0.6	2
Bacteria+ Agar+ FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.3	3	3.26	-1	3	3.26	-1.1	1
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.4	5	3.26	-1	3	3.26	-1.2	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.5	3	3.26	-1.4	5	3.26	-1.2	3

Bacteria+Agar+Graphite+FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.6	5	3.26	-1.2	3	3.26	-1	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.3	3	3.27	-1.1	3	3.26	-1.3	5
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	3	3.26	-0.9	3	3.26	-0.8	2
Plain Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power

		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.1	2	3.26	-0.1	2	3.27	-0.2	2
Graphite+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.3	2	3.26	-0.4	2	3.27	-0.3	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.4	2	3.27	-0.4	2	3.27	-0.5	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.4	2	3.27	-0.3	2	3.26	-0.4	2
FeCl3+Agar										
	Triangle									
		Site 1			Site 2			Site 3		

		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.6	2	3.27	-0.6	2	3.26	-0.6	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.26	-0.7	2	3.26	-0.8	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.9	3	3.26	-0.9	3	3.26	-0.8	3

24 Hours:

Agar+bacteria										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.5	2	3.26	-0.6	2	3.26	-0.6	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.4	2	3.27	-0.4	2	3.27	-0.4	2

	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.3	2	3.27	-0.3	2	3.27	-0.4	2
Bacteria+Agar+Graphite										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.4	2	3.26	-0.8	3	3.27	-0.7	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.8	3	3.26	-0.7	2	3.27	-0.5	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-0.5	2	3.27	-0.5	2
Bacteria+ Agar+ FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.2	3	3.26	-1.2	5	3.26	-1.4	5

	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2	7	3.26	-1.7	5	3.26	-1.6	5
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.6	5	3.26	-1.7	5	3.26	-1.6	5
Bacteria+Agar+Graphite+FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.3	7	3.26	-1.7	5	3.26	-2.2	7
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.3	8	3.26	-1.7	5	3.26	-1.5	5
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-1.4	5	3.26	-1.2	3	3.26	-1.3	5

Plain Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.2	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.2	2	3.26	-0.1	2	3.26	-0.1	2
Graphite+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.6	2	3.26	-0.4	2	3.26	-0.4	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power

		3.26	-0.4	2	3.26	-0.4	2	3.26	-0.4	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.5	2	3.26	-0.6	2	3.26	-0.5	2
FeCl3+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.9	3	3.26	-0.7	3	3.26	-0.8	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-0.9	3	3.26	-0.8	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.9	3	3.26	-1	3	3.26	-0.9	3

48 Hours:

Agar+bacteria										

	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	3	3.26	-0.9	3	3.26	-0.8	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.1	3	3.26	-0.8	3	3.26	-1	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-8	3	3.27	-0.8	3	3.26	-1	3
Bacteria+Agar+Graphite										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-0.8	3	3.26	-0.8	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-0.8	3	3.26	-0.9	3

	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.27	-0.7	2	3.26	-0.8	3
Bacteria+ Agar+ FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.3	5	3.26	-1.5	5	3.26	-1.9	7
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.3	8	3.26	-2	7	3.26	-1.6	5
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.1	7	3.26	-1.9	7	3.27	-1.9	7
Bacteria+Agar+Graphite+FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.4	8	3.26	-2	7	3.26	-2	7

	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.2	7	3.26	-1.8	7	3.26	-2.1	7
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2.2	7	3.26	-1.4	5	3.26	-1.7	5
Plain Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.2	2	3.26	-0.1	2

Graphite+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-1	3	3.26	-0.8	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.8	3	3.26	-0.9	3	3.26	-0.8	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	3	3.26	-0.8	2	3.26	-1	3
FeCl3+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.27	-0.9	3	3.26	-1	3	3.27	-0.9	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	3	3.26	-1	3	3.26	-1.4	5

	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.4	5	3.26	-2	6	3.26	-1.8	5

72 Hours:

Agar+bacteria										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.26	-0.7	2	3.26	-0.8	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.1	3	3.26	-0.6	2	3.26	-0.6	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.26	-0.6	3	3.26	-1	3
Bacteria+Agar+Graphite										

	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.26	-0.6	2	3.26	-0.5	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.5	2	3.26	-0.4	2	3.26	-0.4	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.3	2	3.26	-0.4	2	3.26	-0.4	2
Bacteria+ Agar+ FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.2	5	3.26	-1.3	5	3.26	-1.3	5
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.1	3	3.26	-1.2	3	3.26	-1.2	3

	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.2	3	3.26	-1	3	3.26	-1	3
Bacteria+Agar+Graphite+FeCl3										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.5	5	3.26	-1.3	5	3.26	-1.5	5
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	3	3.26	-1.5	7	3.26	-1	3
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-2	8	3.26	-1.9	7	3.26	-2	8
Plain Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-1	2	3.26	-0.1	2

	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.2	2	3.26	-0.1	2	3.26	-0.1	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.1	2	3.26	-0.1	2	3.26	-0.1	2
Graphite+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.9	3	3.26	-0.6	2	3.26	-0.5	2
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.7	2	3.26	-0.6	2	3.26	-0.5	2
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-0.6	2	3.26	-0.4	2	3.26	-0.9	3

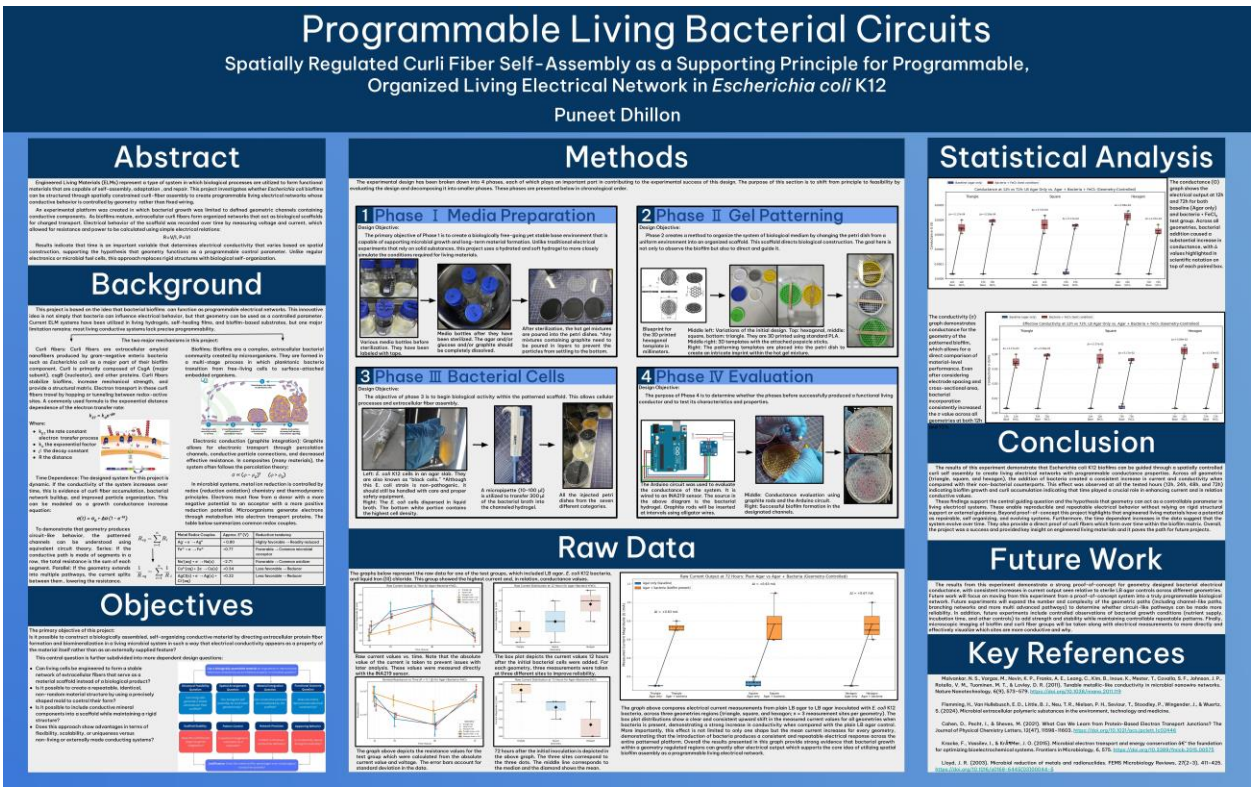
FeCl3+Agar										
	Triangle									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1	5	3.26	-0.9	3	3.26	-1	3
	Square									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.1	3	3.26	-0.9	3	3.26	-1.2	5
	Hexagon									
		Site 1			Site 2			Site 3		
		Load voltage	Current	Power	Load voltage	Current	Power	Load voltage	Current	Power
		3.26	-1.2	3	3.26	-0.7	2	3.26	-0.8	3

Jan 30 – Feb 9

In these days I took all of my raw data, and I made graphs and properly analyzed all my data. All graphs presented were made in google colab and all ANOVAs were conducted in Excel.

Feb 10 – 16

In these days I made my poster for the school wide science fair which will occur on Feb 20. I printed the poster on A4 sheets of paper and printed them out and glued them onto my trifold. The design of this original poster is the following:



Feb 17 – 19

In these days I worked on my presentation for the school-wide science fair. I practiced infront of friends and did mock judge Q&A. I worked on my presentating skills and ensured my presentation was clear and concise.

Feb 20

Today was the school-wide science fair. I presented my project to 7 different judges.