Innovating Solar Technology: Natural Dye-Sensitized Cells for Sustainable Energy Solutions

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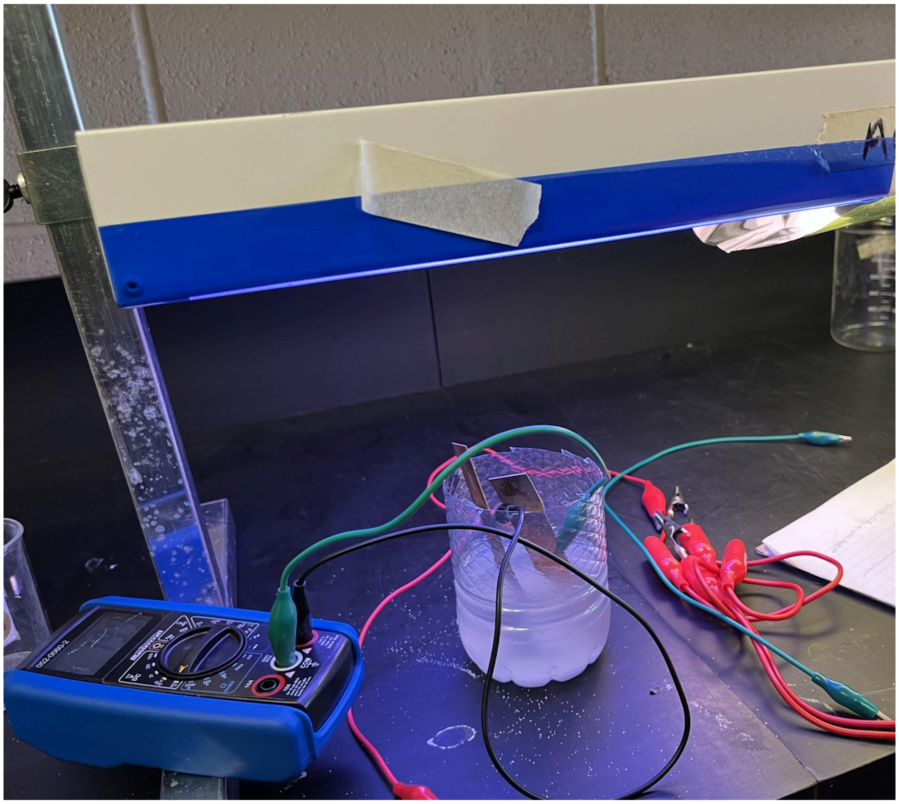
March 21, 2025

Introduction & Background

With the growing demand for renewable energy, dye-sensitized solar cells (DSSCs) have emerged as a promising alternative to conventional silicon-based solar panels. Unlike other photovoltaic cells, DSSCs incorporate a dye molecule to absorb light, thus generating electricity through the process of photoinduced electron transfer (Nature, 2017). This makes DSSCs flexible and semi-transparent, making them ideal for applications in building-integrated photovoltaics and portable electronic devices (ScienceDirect, 2022). DSSCs offer advantages such as lower production costs, flexible designs, and the ability to function in low-light conditions, making them an attractive option for sustainable energy solutions (IntechOpen, 2021). However, optimizing their efficiency remains a key challenge. One of the most critical factors in DSSC performance is the choice of dye, which plays a crucial role in light absorption and electron transfer.

Last year, we conducted an experiment investigating how different colors of light influence energy collection in solar cells, testing how photon energy, as determined by Planck's Law, correlates with voltage output. We found that shorter wavelengths, such as blue light, resulted in higher voltage outputs compared to longer wavelengths like red, aligning with the principle that higher-energy photons generate more electron excitations in the solar cell material. Building on this foundational understanding, we now aim to explore how different dye pigments can enhance solar energy conversion through DSSCs. By testing a variety of natural dyes, we hope to determine the most effective pigments for improving DSSC efficiency and assess their potential for real-world energy applications.

Figure 1: The experimental set-up from last year's BASEF project where voltage output was measured while the solar cell was exposed to different wavelengths of light.



A dye-sensitized solar cell (DSSC) consists of four main components: a photoanode, a sensitizing dye, an electrolyte, and a counter electrode. The photoanode is typically made of a mesoporous titanium dioxide (TiO_2) layer, which has a high surface area to absorb dye molecules. When light strikes the cell, the dye molecules absorb energy, exciting electrons from the valence band to the conduction band before injecting them into the TiO_2 layer (YouTube, 2023). These electrons then travel through the semiconductor material to a transparent conductive oxide (TCO) electrode, generating an electrical current.

The electrolyte, usually composed of an iodide/triiodide (I^-/I_3^-) redox couple, replenishes the electrons lost by the dye, ensuring continuous operation of the cell (Springer, 2018). The counter electrode plays a crucial role in catalyzing the reduction of I_3^- back to I^-, completing the circuit. While platinum is commonly used due to its high conductivity and catalytic properties, we used graphite as a more accessible and cost-effective alternative. Graphite consists of sp^2-hybridized carbon atoms, where each carbon atom forms three covalent bonds in a hexagonal lattice, leaving one electron per atom delocalized (Byju's, n.d.). This delocalization enables high electrical conductivity and enhances its catalytic ability. Graphite acts as a catalyst by providing active sites for the redox reaction, facilitating the transfer of electrons to reduce triiodide (I_3^-) efficiently (ScienceDirect, 2018). Though not as effective as platinum, its layered structure and electron mobility allow it to accelerate the reaction, maintaining electron flow in the DSSC.

The photovoltaic process in DSSC is based on the semiconductor material and dye bandgap. The bandgap dictates the energy required for an electron to travel from the valence band to the conduction band. In DSSCs, photons with energy equal to or greater than the bandgap of the dye are absorbed by the dye, promoting electrons to a higher energy level. These electrons are then injected into the TiO_2 conduction band, which is approximately 3.2 eV in bandgap (Nature, 2017). The efficiency of the process depends on the energy level alignment of the dye and the TiO_2 conduction band.

Specific synthetic dyes, like N-719, have strong absorption characteristics in the visible range with a peak at 500 and 600 nm, resulting in an efficiency of approximately 5.3% (ScienceDirect, 2021). Various other natural dyes such as anthocyanins and betalains have varying bandgaps and thus absorb in different ranges of wavelengths. Anthocyanins, for instance, have strong absorption at 510 nm owing to the electron injection into TiO_2 by their hydroxyl and carbonyl functional groups (Nature, 2017). The process of dye-TiO_2 interaction also leads to an energy level shift called the HOMO-LUMO shift, which affects the efficiency of electron transfer (Tandfonline, 2022).

The performance of a dye-sensitized solar cell (DSSC) is greatly reliant on the specific dye utilized for sensitization since various dyes absorb at distinct wavelengths, hence influencing the solar cell's voltage and current generation (ScienceDirect, 2021). Synthetic dyes, such as N-719, have exhibited high efficiency of 5.3% attributed to their high absorption property in the visible range of 500–600 nm (ScienceDirect, 2021). Natural dyes from fruits and plants, including anthocyanins and betalains, are gaining popularity because they are environmentally friendly and inexpensive (PMC, 2023). Research has established that blueberry- and mulberry-derived dyes can achieve high power outputs, with mulberry-based dye-sensitized solar cells (DSSCs) performing better than blueberry-based DSSCs because mulberries contain more anthocyanins than blueberries (PMC, 2023).

Different dyes of different colors absorb light of different wavelengths, influencing DSSC efficiency. Red dyes, for instance, absorb highly in the visible range and therefore are more effective for DSSCs (ScienceDirect, 2021). Co-sensitization, or the use of a combination of a number of dyes, has been explored as a strategy to enhance light absorption and efficiency. A combination of anthocyanin and betalain, for instance, has been found to facilitate electron injection and increase light absorption, leading to efficiency enhancement (ResearchGate, 2016).

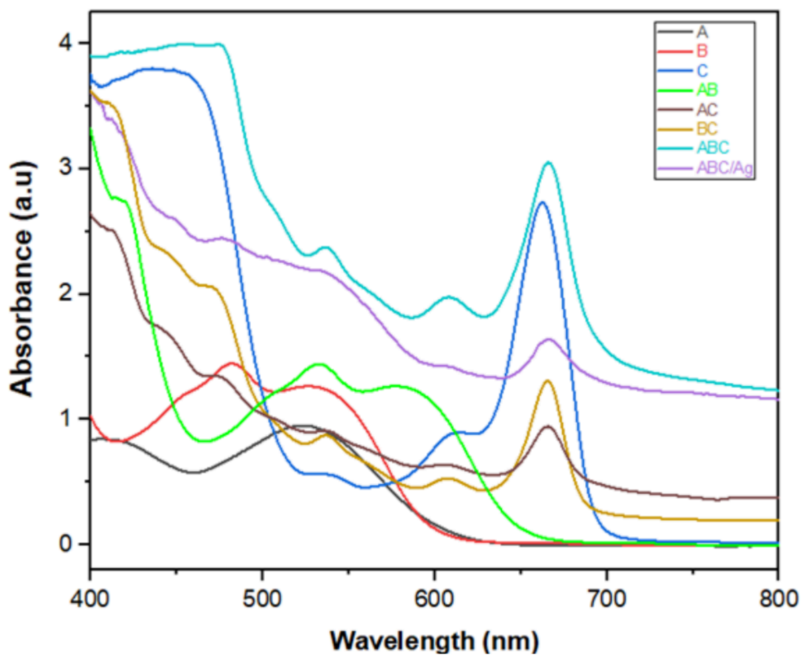
Similarly, the use of a combination of three dyes—anthocyanin, betalain, and chlorophyll—has been found to improve the absorption spectrum and increase the efficiency of DSSCs up to 0.602% (Tandfonline, 2022).

However, different studies have provided different conclusions about the effectiveness of various dyes. Research has shown that chlorophyll has the highest absorption intensity at its peak wavelengths, effectively absorbing light in the red, blue, and violet regions of the spectrum, with an absorption maximum around 670 nm (IntechOpen). In contrast, anthocyanins primarily absorb light in the green and red regions (510–580 nm) with a narrower spectral range, limiting their capacity to harness solar energy across multiple wavelengths (Nature, 2017). One study demonstrated that the combination of chlorophyll and anthocyanin in a 20:80 ratio greatly improved the efficiency of DSSCs, with a conversion efficiency of 0.847%, which was much higher compared to the use of chlorophyll (0.466%) or anthocyanin (0.531%) individually (IntechOpen, 2021).

Recent findings from Kyushu University (2024) further support the superior performance of chlorophyll. It is shown that chlorophyll exhibits a broad absorption spectrum, with intense peaks in the red (670 nm), blue, and violet regions of the visible spectrum (Kyushu University, 2024). Notably, chlorophyll's absorption intensity at these wavelengths surpasses not only anthocyanins but also combinations of anthocyanins and betalains (Kyushu University, 2024; Figure 2). This enhanced absorption capability allows chlorophyll to generate more electron excitations, leading to improved voltage output and overall efficiency in DSSCs. Conversely, another study demonstrated that betalain dyes exhibited the highest conversion efficiency

(0.47%), outperforming anthocyanin-based DSSCs (0.14%) and even their mixtures (0.20%) (ResearchGate, 2016).

Figure 2: The absorbance of wavelengths of light by various pigments in dyes individually as well as combinations of the dyes, where A represents anthocyanin, B is betalain, and C is chlorophyll (Kyushu University, 2024).



In spite of their merits, DSSCs are confronted with issues of low efficiency, stability, and scaling up (Springer, 2018). Natural dyes, although inexpensive and non-toxic, tend to be less stable and have a limited absorption spectrum compared to synthetic dyes (ScienceDirect, 2022). Scientists are trying different strategies, including the use of transition metal complexes, solid-state electrolytes, and tandem DSSC architectures, to enhance performance and stability

(ScienceDirect, 2022). Additionally, advancements in TiO_2 nanostructures and co-sensitization approaches continue to enhance the potential of DSSCs for real-world applications.

Purpose

The purpose of this study is to investigate how different dye pigments influence the voltage output of a dye-sensitized solar cell (DSSC) by testing a variety of natural dyes. Initially, we aimed to explore the effects of curcumin (from turmeric), betalain (from beets), chlorophyll (from spinach), and anthocyanin (from blueberries) on DSSC performance. These dyes were selected based on their distinct light absorption properties and potential for efficient electron transfer, as highlighted in prior research. However, due to resource constraints and the challenges of optimizing the DSSC assembly, we narrowed our focus to chlorophyll and anthocyanin, as these were the most well-documented and accessible dyes in our research.

By analyzing how pigment composition affects light absorption and electron transfer, we hope to gain insights into optimizing dye selection for improved DSSC performance. This study also lays the groundwork for future experiments involving a broader range of natural dyes, including curcumin and betalain, to further advance the efficiency and applicability of DSSCs in sustainable energy solutions.

Hypothesis & Research Question

Our research question is: *"How do different dye pigments affect the voltage output of a dye-sensitized solar cell (DSSC)?"*

Chlorophyll-based dyes will significantly enhance the efficiency of dye-sensitized solar cells (DSSCs) compared to anthocyanin-based dyes. This hypothesis is based on chlorophyll’s broader absorption spectrum and stronger electron injection efficiency, both of which contribute to improved voltage output. Chlorophyll has intense absorption peaks in the red (670 nm), blue, and violet regions, allowing it to absorb a wider range of light and generate more photoexcited electrons (Kyushu University, 2024). These excited electrons are efficiently injected into the TiO_2 conduction band, leading to improved charge transfer and higher voltage output (IntechOpen, 2021).

In contrast, anthocyanins primarily absorb light in the green and red regions (510–580 nm) with a narrower spectral range, which limits their ability to capture solar energy across multiple wavelengths (Nature, 2017). Since their absorption is more restricted, fewer photons are available to excite electrons, reducing the number of charge carriers that contribute to electricity generation in DSSCs. Additionally, anthocyanins have been found to exhibit weaker electron injection properties than chlorophyll, which further decreases their efficiency (ResearchGate, 2016).

While betalains have been reported to achieve comparable efficiency to chlorophyll in some cases (ResearchGate, 2016), they were not tested in this experiment due to resource constraints.

However, based on chlorophyll's broader absorption range and stronger electron transfer capabilities, it is expected that DSSCs incorporating chlorophyll-based dyes will produce a higher voltage output than those using anthocyanin-based dyes.

Materials

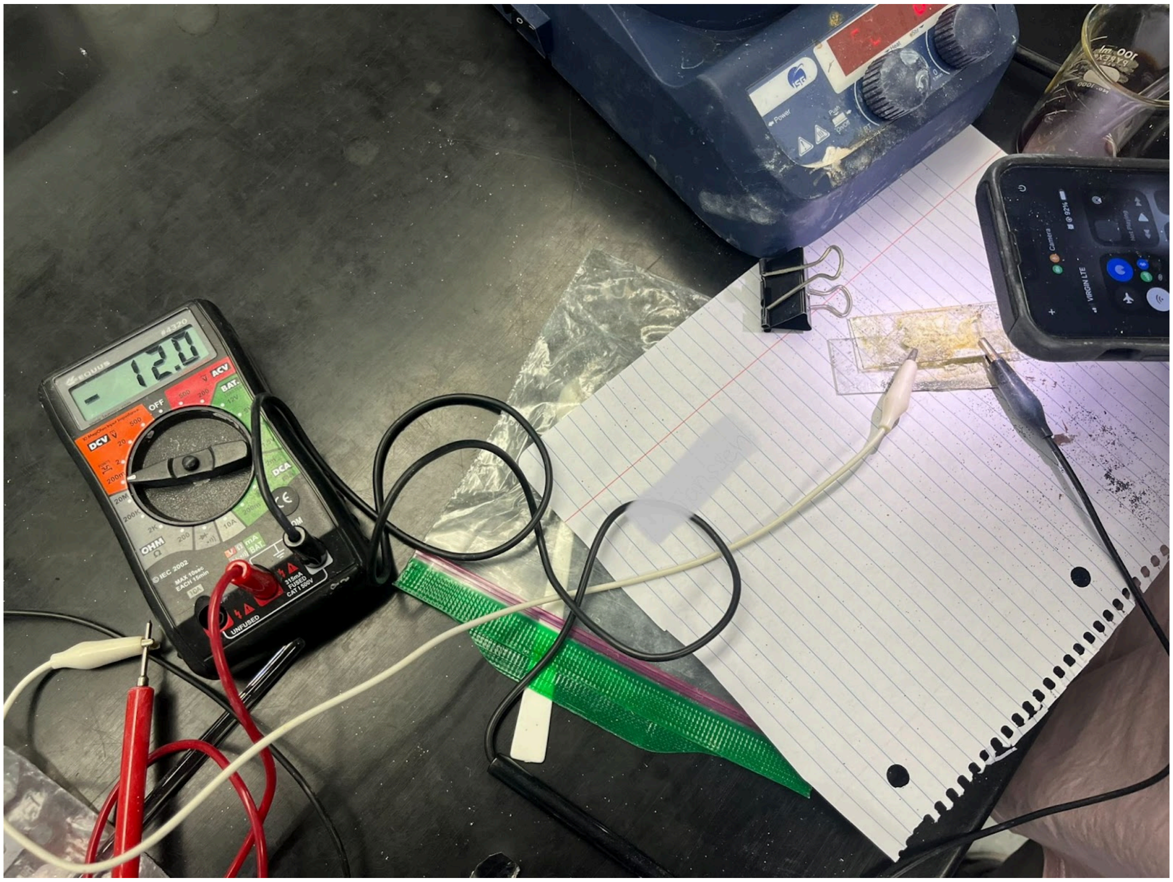
- ☐ Microscope slides
- ☐ Titanium dioxide (TiO_2) powder
- ☐ 10 grams of blueberries
- ☐ 10 grams of spinach
- ☐ 95% ethanol
- ☐ 5% acetic acid (vinegar)
- ☐ Iodine solution
- ☐ Graphite powder
- ☐ Binder clips
- ☐ Batteries
- ☐ Crocodile clips
- ☐ Tape
- ☐ Multimeter
- ☐ Hot plate
- ☐ Coffee filter

Methodology

1. A paste was created by mixing graphite powder with water. One side of a microscope slide was coated with an even layer of graphite. A multimeter and battery were used to check the conductivity of the coated side, ensuring it had low resistance.
2. The slide was then taped to a table, with one border covered by 3 mm of tape and the other three borders covered by 1 mm of tape. This setup created a raised edge for the TiO_2 paste.
3. 1 g of TiO_2 powder was weighed and placed in a mortar. While grinding with a pestle, 2 mL of ethanol was slowly added until the mixture reached a watery sunscreen consistency.
4. Using a spatula, 3 drops of the TiO_2 paste were spread onto the conductive side of the slide. A glass stirring rod was then used to evenly distribute the paste, ensuring a thin, uniform layer.
5. The tape was removed, and the slide was heated over a hot plate to evaporate the solvent and bind the TiO_2 to the slide. The inner tip of the flame was carefully positioned to just touch the slide for even heating. The slide was then allowed to cool completely before proceeding.
6. To prepare the dye, 10 g of blueberries were crushed in a mortar. The crushed material was mixed with 12 mL of 95% ethanol and 36 mL of 5% vinegar.
7. The mixture was filtered using a coffee filter to obtain a clear dye solution.
8. The TiO_2-coated slide was submerged in the dye solution for 10 minutes to allow the dye molecules to absorb onto the TiO_2. After 10 minutes, the slide was gently rinsed with water once and ethanol twice to remove excess dye and impurities.

9. A new microscope slide was coated with a thin, even layer of graphite paste, ensuring the entire surface was covered.
10. Next, 2-3 drops of iodine solution were placed onto the graphite-coated slide. The dye-soaked TiO_2 slide was carefully placed on top of the graphite-coated slide, ensuring the edges overhung slightly for electrical connections.
11. The slides were then secured together using binder clips on the sides that aligned completely.
12. The overhanging edges of the assembled solar cell were connected to a multimeter using alligator clips to measure the voltage.
13. Steps 1 to 12 were then repeated using spinach as the dye source.

Figure 3: The experimental set-up for testing the voltage output from different coloured-dye sensitized solar cells.



Data & Results

Table 1: The experimental data of voltage output in mV from different coloured-dye sensitized solar cells.

Pigment from dye used in solar cell	**Voltage output (mV)**			
	Trial #1	Trial #2	Trial #3	Average
Chlorophyll	23.3	22.8	23.6	23.2
Anthocyanin	9.8	10.2	11.2	10.4

Analysis of Data

The results of our experiment demonstrate that chlorophyll-based dyes significantly outperform anthocyanin-based dyes in terms of voltage output. Chlorophyll-based DSSCs produced an average voltage of 23.2 mV, while anthocyanin-based DSSCs produced an average voltage of 10.4 mV. This aligns with previous research indicating that chlorophyll has strong absorption characteristics in the visible spectrum, particularly in the red and blue regions, which are critical for efficient light harvesting and electron transfer (IntechOpen, 2021).

To assess the effectiveness of each dye, we estimated the power conversion efficiency (η) by considering the input power from classroom lighting, which we approximate at 7 mW/cm^2 for fluorescent lights. The current for both cells in the experiment was measured to be 0.1 mA:

$$power\ efficiency\ (\eta)\ \% = \frac{Voltage\ input \times Current}{Power\ input} \times 100\%$$

$$\eta_{chlorophyll}\ \% = \frac{(23.2\ mV) \times (0.1\ mA)}{7\ mW} \times 100\% = \frac{(0.0232\ V) \times (0.0001\ A)}{0.007\ W} \times 100\%$$

$$\eta_{chlorophyll}\ \% = 0.000331 \times 100\% = 0.0331\%$$

$$\eta_{chlorophyll}\ \% = \frac{(10.4\ mV) \times (0.1\ mA)}{7\ mW} \times 100\% = \frac{(0.0104\ V) \times (0.0001\ A)}{0.007\ W} \times 100\%$$

$$\eta_{chlorophyll}\ \% = 0.000149 \times 100\% = 0.0149\%$$

These calculations indicate that chlorophyll DSSCs were approximately 2.2 times more efficient than anthocyanin DSSCs under identical lighting conditions. This efficiency difference can be attributed to chlorophyll's broader absorption spectrum, which allows it to capture a wider range of visible light wavelengths and inject electrons more effectively into the TiO_2 conduction band. In contrast, anthocyanins primarily absorb in the green-red region (510–580 nm), which limits the number of photons available for energy conversion (Nature, 2017).

The superior performance of chlorophyll can be attributed to its broad absorption spectrum and its ability to inject electrons into the TiO_2 conduction band effectively. Anthocyanins, while effective in absorbing light in the green and red regions, have a narrower absorption range and may not generate as many electron excitations as chlorophyll (Nature, 2017). This difference in light absorption and electron transfer efficiency likely explains the higher voltage output observed in chlorophyll-based DSSCs.

Our findings are consistent with studies that highlight the importance of dye selection in DSSC performance. For example, one study demonstrated that the combination of chlorophyll and anthocyanin in a 20:80 ratio greatly improved the efficiency of DSSCs, achieving a conversion efficiency of 0.847%, which was significantly higher compared to the use of chlorophyll (0.466%) or anthocyanin (0.531%) individually (IntechOpen, 2021). This suggests that chlorophyll's electron injection properties are highly effective, especially when combined with other dyes to broaden the absorption spectrum.

However, the efficiencies observed in our experiment (0.0331% for chlorophyll and 0.0149% for anthocyanin) are lower than those reported in other studies. This discrepancy can be attributed to several factors:

- Lighting Conditions: Our experiment was conducted under classroom fluorescent lighting, which has a lower intensity of approximately 7 mW/cm^2 compared to light sources used in other experiments. This significantly reduces the number of photons available for absorption, leading to lower voltage outputs and efficiencies.
- Dye Concentration and Adsorption: The concentration of the dye solution and the adsorption time on the TiO_2 layer can greatly influence DSSC performance. In our experiment, the dye adsorption process may not have been optimized, resulting in fewer dye molecules being attached to the TiO_2 surface and, consequently, lower light absorption and electron injection.
- Counter Electrode Material: While graphite is a cost-effective alternative to platinum, it is less efficient as a catalyst for the redox reaction. The lower catalytic activity of the graphite power may have reduced the rate of electron transfer at the counter electrode, contributing to lower efficiencies (ScienceDirect, 2018).
- Experimental Setup: Variations in the thickness of the TiO_2 layer, the uniformity of dye adsorption, and the alignment of the cell components can also impact efficiency. Small inconsistencies in these factors during the assembly process may have contributed to the lower performance observed in our experiment.

While our results demonstrate that chlorophyll-based dyes outperform anthocyanin-based dyes, it is important to note that our experiment was limited to two dyes due to resource constraints. Future studies should explore a wider range of dyes, including betalains and curcumin, to provide a more comprehensive comparison. Additionally, while our experiment did not test co-sensitization, the strong performance of chlorophyll alone suggests it could be a key component in future DSSC designs.

For instance, research has shown that combining chlorophyll with anthocyanins in a 20:80 ratio can achieve a conversion efficiency of 0.847%, significantly higher than using either dye individually (IntechOpen, 2021). Similarly, co-sensitization with betalains has been shown to enhance light absorption and electron injection, further improving DSSC performance (ResearchGate, 2016). These findings underscore the potential of chlorophyll as a primary sensitizer in DSSCs, either alone or in combination with other dyes.

Conclusion

Our experiment demonstrates that chlorophyll-based dyes significantly enhance the voltage output of dye-sensitized solar cells (DSSCs) compared to anthocyanin-based dyes. Chlorophyll-based DSSCs achieved an average voltage output of 23.2 mV, corresponding to a power conversion efficiency of 0.0331%, while anthocyanin-based DSSCs produced an average voltage of 10.4 mV, with an efficiency of 0.0149%. These results highlight chlorophyll’s superior ability to absorb a broader range of visible light wavelengths, particularly in the red, blue, and violet regions, and its efficient electron injection properties, which are critical for generating higher voltage outputs (Kyushu University, 2024; IntechOpen, 2021).

While the efficiencies achieved in our experiment are lower than those reported for synthetic dyes like N-719 with an efficiency of 5.3% (ScienceDirect, 2021), they underscore the potential of natural dyes as a sustainable and cost-effective alternative. Chlorophyll, extracted from readily available sources such as spinach, offers an environmentally friendly and biodegradable option for DSSCs, making it particularly appealing for applications in resource-limited settings.

Furthermore, the relatively low efficiencies observed in our experiment can be attributed to factors such as suboptimal lighting conditions, dye adsorption processes, and the use of a graphite counter electrode instead of platinum. However, these results provide a strong foundation for future improvements. For instance, even small increases in efficiency—achievable through optimized dye concentrations, better electrolyte formulations, or improved cell assembly—could make natural dye-based DSSCs a viable option for practical applications.

In summary, our findings highlight the promise of chlorophyll-based dyes for DSSCs, offering a balance between performance, cost, and environmental sustainability. While further optimization is needed to bridge the gap between natural and synthetic dyes, the accessibility and eco-friendliness of natural dyes make them a compelling choice for advancing renewable energy technologies.

Next Steps

1. Co-Sensitization: Future experiments should explore co-sensitization strategies, combining chlorophyll with other dyes (e.g. anthocyanins or betalains) to enhance light absorption and efficiency. Research has shown that dye mixtures can improve DSSC performance by broadening the absorption spectrum and optimizing electron transfer.

2. Testing Additional Dyes: Expanding the study to include other natural dyes, such as betalains (from beets) and curcumin (from turmeric) which we were unable to perform in this experiment, would provide a more comprehensive understanding of how different pigments affect DSSC performance.

3. Using Platinum as the Counter Electrode: Replacing graphite with platinum as the counter electrode material could significantly improve DSSC efficiency. Platinum is widely recognized for its superior catalytic properties and high conductivity, which enhance the reduction of the electrolyte (iodide/triiodide) and improve electron transfer rates (ScienceDirect, 2018).

Real-Life Applications

DSSCs can be integrated into windows and facades of buildings, providing a semi-transparent and aesthetically pleasing source of renewable energy. The availability of lightweight, flexible dye-sensitized cells or modules makes them attractive for such applications (ResearchGate, 2016; Saifullah, Gwak, & Yun, 2016).

The flexibility and low-light performance of DSSCs also make them ideal for powering portable devices, such as smartphones and wearable technology. DSSCs can produce electricity under low-light conditions, including indoor lighting, making them suitable for indoor applications (Tao et al., 2019).

Furthermore, DSSCs can harvest energy from indoor lighting, making them suitable for powering sensors and low-power devices in smart homes and offices. Their ability to operate efficiently under indoor lighting conditions highlights their potential for indoor applications (Freitag et al., 2017)

In addition to their practical applications, DSSCs using natural dyes offer environmental benefits, as they are biodegradable and non-toxic, making them a more sustainable option compared to synthetic dyes. In summary, our findings suggest that chlorophyll-based dyes hold significant promise for enhancing DSSC performance. By exploring co-sensitization strategies, testing additional natural dyes, and optimizing cell components, we can further advance the efficiency and applicability of DSSCs in various real-life scenarios.

Acknowledgements

We would like to express our sincere gratitude to Ms. Janssen, Ms. Chan and Ms. Kim for their invaluable guidance and supervision throughout this project. Their support and mentorship were instrumental in refining our approach and ensuring the project's success. We also extend our appreciation to Dr. Satyendra Narayan from Sheridan College for his insightful guidance and expertise, which greatly contributed to our understanding and development of the project. Their encouragement and contributions were essential in helping us navigate challenges and achieve our goals.

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