SASTA OLIPHANT SCIENCE AWARDS

SOUTH AUSTRALIAN SCIENCE TEACHERS ASSOCIATION

Prize Winner

Scientific Inquiry

Year 5-6

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Government of South Australia
Department for Education

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Dye-Sensitized Solar Cell

DSSC

"How can affect Dye-Sensitized Solar Cells?"

"What is the best colour of the Rainbow DSSC?"

- Types of Solar Cells and Comparison.
- What is a DSSC?
- How to create a simple DSSC sample?
- How Does the DSSC work?
- What factors can affect its operation?
- Can the DSSC non-toxic and organic?
- What can we use as the dyes?
- Advantages and disadvantages of the DSSC.
- How it can improve our life today?

Source: https://www.sciencemag.org/news/2018/04/solar-cells-work-low-light-could-charge-devices-indoors

JULY 2020

Abstract

The purpose of this study is to understand the impacts of various materials and factors on the power generation of dye-sensitized solar cells (DSSC) based on titanium dioxide electrode layer, so as to improve the photovoltaic conversion efficiency and promote the dye to absorb light energy more effectively and convert it into electric energy. The research can be extended to simple DSSC model creation using materials easily obtained in daily life, such as toothpaste, medical iodine solution, correction fluid etc., and how to use these technologies to improve our lives.

Research Motivation

Solar energy is the cleanest, most economical, and most accessible energy at present. The amount of energy that sunlight hits the ground is about 3×10^{24} Joules per year, which is equivalent to 10,000 times of the energy consumed by human beings every year. In other words, if 0.1% of all the solar energy on the earth can be converted into chemical energy or electric energy by using solar cells with 10% conversion efficiency, it will be enough to provide the required energy. With the awakening of environmental protection consciousness, the research and development of solar energy are becoming more and more popular. The use of solar cells can often be found in the surrounding of our lives, such as solar watches, foldable solar mobile power banks, solar courtyard lights and buildings powered by solar panels, etc.

Solar Watches

https://www.pinterest.com.au/pin/291045194670720760/

Foldable Solar Mobile Power Banks

http://gadgetsin.com/uploads/2019/10/tranmix_portable_waterproof_solar_charger_with_25000mah_power_bank_2.jpg

This Photo by Unknown Author is licensed under CC BY-SA-NC

https://technofaq.org/wp-content/uploads/2019/02/Solar-Street-Light-Poles-620x350.jpg

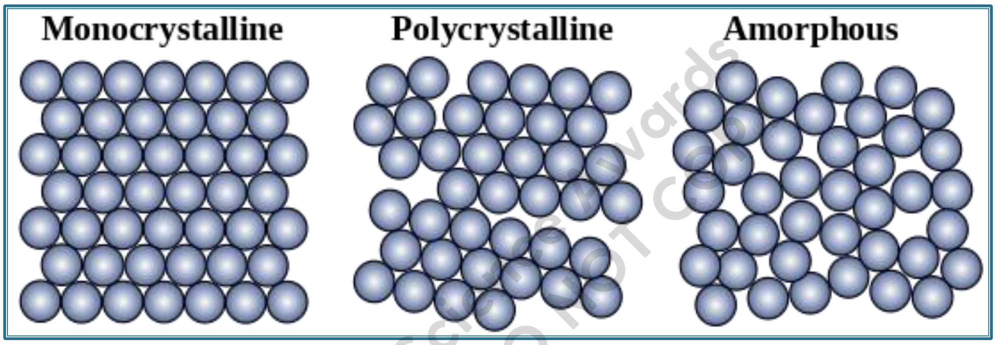
Solar cell is a kind of energy conversion component by using "*photovoltaic effect*", which is different from the "*photoelectric effect*" we usually observe in metal materials, solar cell is also called photovoltaic cell (PV cell). "Photo" refers to the meaning of light, while the voltaic refers to the voltages generated by light energy conversion, that is, electricity. Solar cells are green and environmentally friendly power generation, which will not produce greenhouse gases, and the power generation process will not cause pollution to the environment.

Introduction

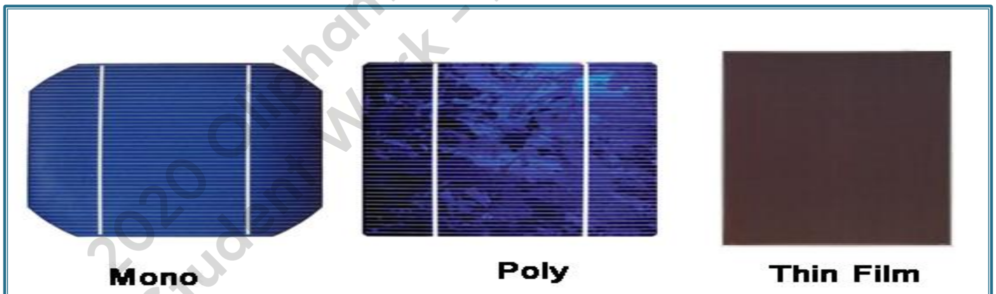
Different types of Solar Cells:

1. Silicon Solar Cells

The most common solar cells with higher power conversion rate we use today are mainly monocrystalline silicon, polycrystalline silicon, and amorphous silicon solar cells. All photovoltaic (PV) cells consist of two or more thin layers of semi-conducting material, most commonly silicon. When the semiconductor is exposed to light, electrical charges are generated, and this can be conducted away by metal contacts as direct current (DC). The electrical output from a single cell is small, so multiple cells are connected together to form a “string”, which produces a larger direct current. These solar cells belong to the first-generation solar cells. Although the technology is relatively mature, their manufacturing process is expensive and energy consumption is high. The monocrystalline has the highest efficiency, but it need higher crystallization technology, so the manufacturing cost is also the highest.



https://upload.wikimedia.org/wikipedia/commons/thumb/e/eb/Schematic_of_allotropic_forms_of_silcon_horizontal_plain.svg/550px-Schematic_of_allotropic_forms_of_silcon_horizontal_plain.svg.png



http://i.stack.imgur.com/OQPuA.jpg

2. Thin-Film Solar Cells

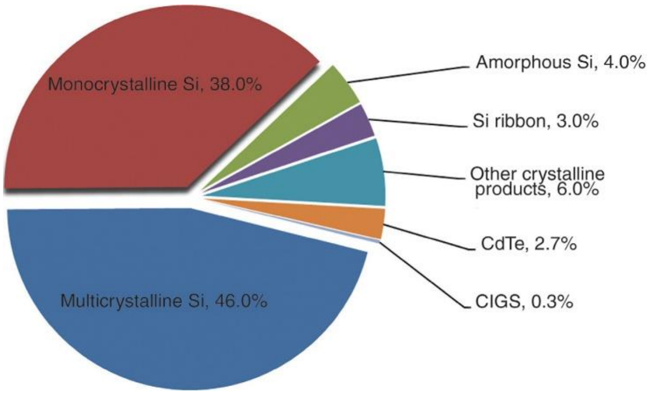
The Second-generation thin film solar cells are mad of compound semiconductors, such as binary compounds (Cadmium Telluride, CdTe; Gallium Arsenide, GaAs), ternary compounds (Copper Indium Selenide; CIS), and quaternary compounds (Copper Indium Gallium Selenide, CIGS). The advantages of this solar cells are its bendable flexibility and low cost, but its lower conversion efficiency and the disadvantages of light induced degradation. In addition, some of the materials might also cause environmental pollutions.

https://en.wikipedia.org/wiki/Thin-film_solar_cell#/media/File:Thin_Film_Flexible_Solar_PV_Installation_2.JPG

https://en.wikipedia.org/wiki/Thin-film_solar_cell#/media/File:Cigsep.jpg

https://en.wikipedia.org/wiki/Thin-film_solar_cell#/media/File:Thin_Film_Flexible_Solar_PV_Ken_Fields_1.JPG

Fig. 1. Market share of solar cell types sold during 2006.



SOURCE: https://www.sciencedirect.com/science/article/pii/S1369702107702754#fig1

- Monocrystalline Silicon PV panel: converts around 25.0% of the Sun's energy into electricity.
- Polycrystalline Silicon PV panel: average efficiency of around 20.4%.
- Amorphous Silicon PV panel: efficiency of 10.1%.

- Cadmium Telluride, CdTe: Around 8-9% of efficiency.
- Copper Indium Diselenide, CIS: Around 10-13% of efficiency.
- Gallium Arsenide, GaAs: Due to its toxicity and potential carcinogenic properties, there are only in rare application such as satellite or demonstration solar power.

3. Organic Solar Cells

The biggest different between the third-generation cell and the other two types is to add "organic matter" and nanotechnology in the process, such as dye-sensitized solar cells, nanocrystalline solar cells, polymer solar cells, to provide better energy generation with the lowest cost. My research topic, dye-sensitized solar cells (DSSC), belong to the organic solar cell group. It has the advantages of low manufacturing cost, less impact by sunlight angle and high temperature, and the cell has the characteristics of perspectivity and flexibility, which can be widely used in indoor light source power generation products.

What is a Dye-Sensitized Solar Cell?

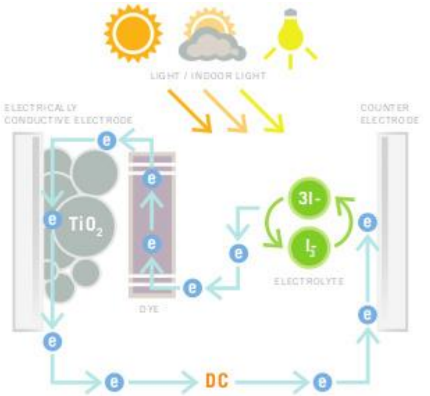
The Dye-Sensitized Solar Cell is composed of porous layer of titanium dioxide nanoparticles, covered with a molecular dye that absorbs sunlight, like the chlorophyll in green leaves. DSSC absorbs solar energy through plant dyes, and then excites the electrons, and uses nanoparticle TiO_2 to capture electrons and transfer them to ITO glass for power generation. After flowing through the external circuit, they are re-introduced into the cell on a metal electrode on the back, flowing into the electrolyte, then transports the electrons back to the dye molecules. This kind of cell uses nano-TiO_2 and organic dye polymer as materials and is developed by the bionic technology of photosynthesis with high compatibility with environment. This technology was first published by Grätzel in 1991, also known as "Grätzel cell", electric energy can be used directly or stored by a storage device. It has different colours due to different dyes, so it is also called a "Rainbow Photovoltaic (PV) Cell".

"How can we create the environmentally friendly

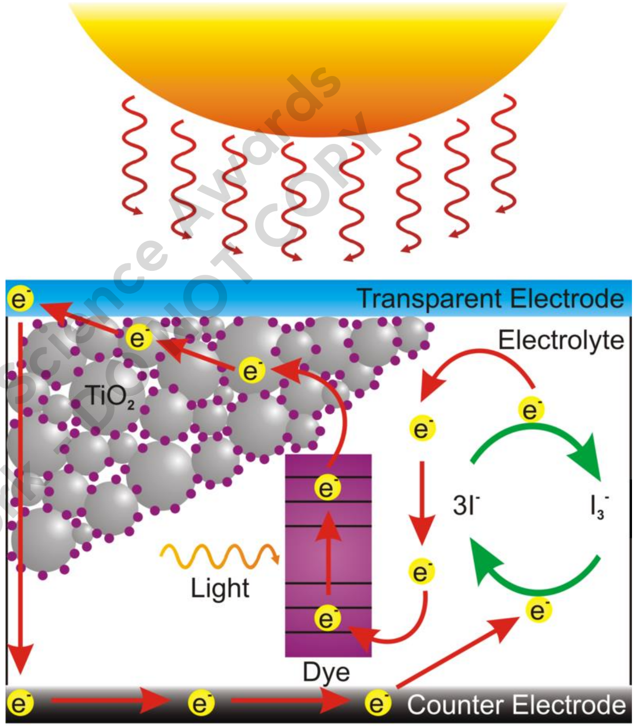
Dye-Sensitized Solar Cells (DSSC)?

What is the best colour of the Rainbow PV Cells?"

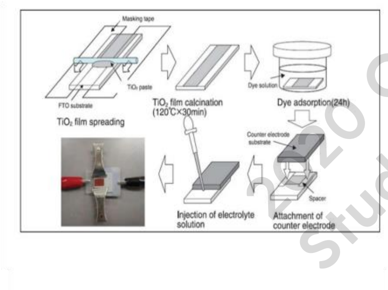
The absorption capacity of dark matter is better than light matter, a simple example of this phenomenon is wearing black clothes often heat up more than wearing bright and white clothes. If I use the idea of using "*colours*" to measure the voltages generated by my DSSCs, the dark blue violet anthocyanins have strong ability to absorb ultraviolet rays, can absorb and exaggerate the absorption range of the DSSCs. The dye with anthocyanins should be able to help to release more electrons in the process of absorbing light and generate higher voltages compared to other organic molecular dyes, for example, chlorophyll, and carotene, because of the difference of titanium dioxide adsorption capacity and spectral range. What is the best colour for rainbow dye-sensitized solar cells? My hypothesis is that the fruits or vegetables with darker colours and more anthocyanins will generate higher voltages and better choice for dyes. To start with this topic, I need to create my own DSSC sample, explain how it works and design several experiments to support my argument.



https://gcell.com/wp-content/uploads/DSSC_cycle.jpg



https://en.wikipedia.org/wiki/Dye-sensitized_solar_cell#/media/File:Dye_Sensitized_Solar_Cell_Scheme.png

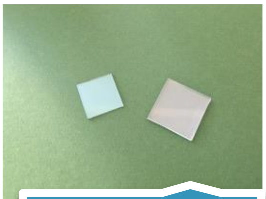


Mechanism of DSSCs

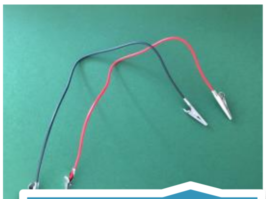
1. $S + \text{light} \longrightarrow S^*$
2. $S^* \xrightarrow{TiO_2} S^+ + e^-$
3. $S^+ + e^- \longrightarrow S$
4. $I_3 + 2e^- \longrightarrow 3I^-$

1. **Dye becomes Excited from the ground state (S) to the excited state (S*) by sunlight or indoor light.**
2. **Dye injects an electron rapidly to the TiO_2* (the conduction band), dye is oxidized in this process.**
3. **Electrons are transported through the semiconducting TiO_2, move through the load, and eventually reach the counter electrode.**
4. **The oxidized redox mediator, I_3, diffuses toward the counter electrode and then it is reduced to I^- ions.**

Materials & Equipment

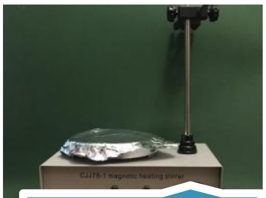

ITO Glass

Multimeter


Aligater Clips


Bottles & Petri dishes

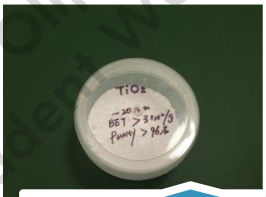

Beakers & Pipettes


Heating Plate


Binder Clips


Electrolyte (KI_3)

100% Ethanol (C_2H_5OH)



TiO2 Nanopartical

Acethic Acid (CH_3COOH)


Triton X-100 (or Dish Washing Liquid)


Candles

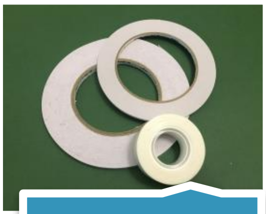

Electronic Scale

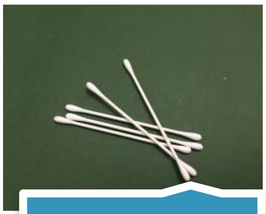
Disposble Glovers


Tweezer

Materials & Equipment


2B Pencil


Tapes

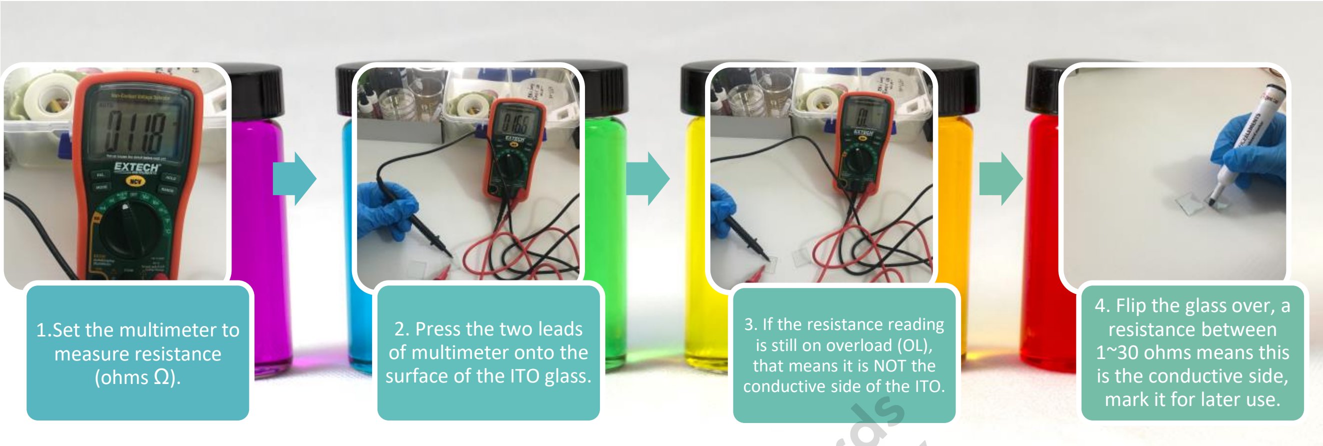

Cotton Swabs


Electronic Products

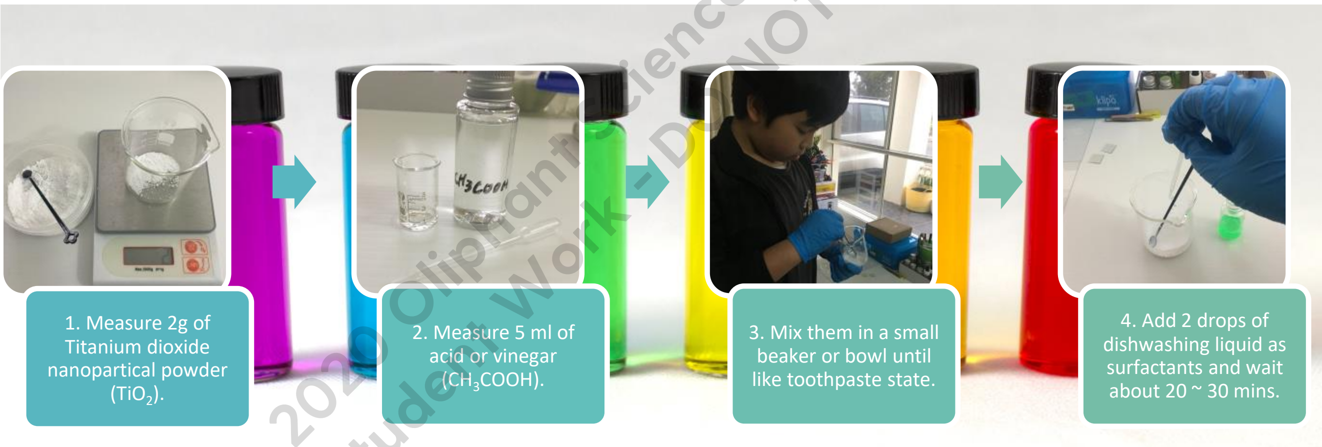
Equipment	Chemicals Used	Biologicals / Food
1 × Electronic Scale	1 × 500mL of 100% ethanol (C_2H_5OH)	Blueberries
1 × Heating Plate or Oven	1 × 50g of TiO_2 Nanoparticle Powder (Titanium Dioxide)	Blackberries
1 × Hot Glue Gun	1 × 5mL Acetic Acid (CH_3COOH)	Strawberries
1 × Safety Goggles	1 × 5mL of Triton X-100 surfactant (or Dish Washing Liquid)	Oranges
1 × Measuring Cylinder 100mL	1 × 10mL of Electrolytes – Potassium Triiodide (KI_3)	Carrots
3 × Tweezers	100 × ITO Glass (Indium Tin Oxide Coated Glass)	Spinach
1 × Long Stick, Ruler or Glass slide		
8 × Filter bags		
1 × Candle		
10 × Plastic Petri Dishes		
1 × Lighter		
10 × pair of Disposable Gloves		
30 × Binder Clips		
30 × Cotton Swabs		
6 × Alligator Clips		
10 × Plastic Pipettes		
2 × 100mL Beakers		
6 × 10 mL Plastic Bottles		
8 × Small Zip Bags		
1 × Box of Tissues		

Create a DSSC Sample

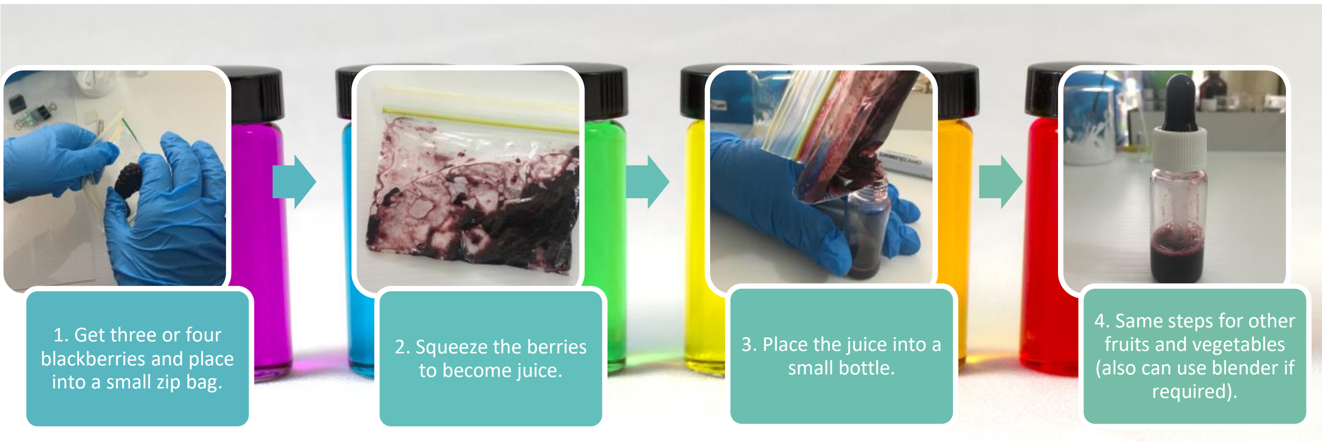
Step1: Determine the conductive side of ITO glass slides.



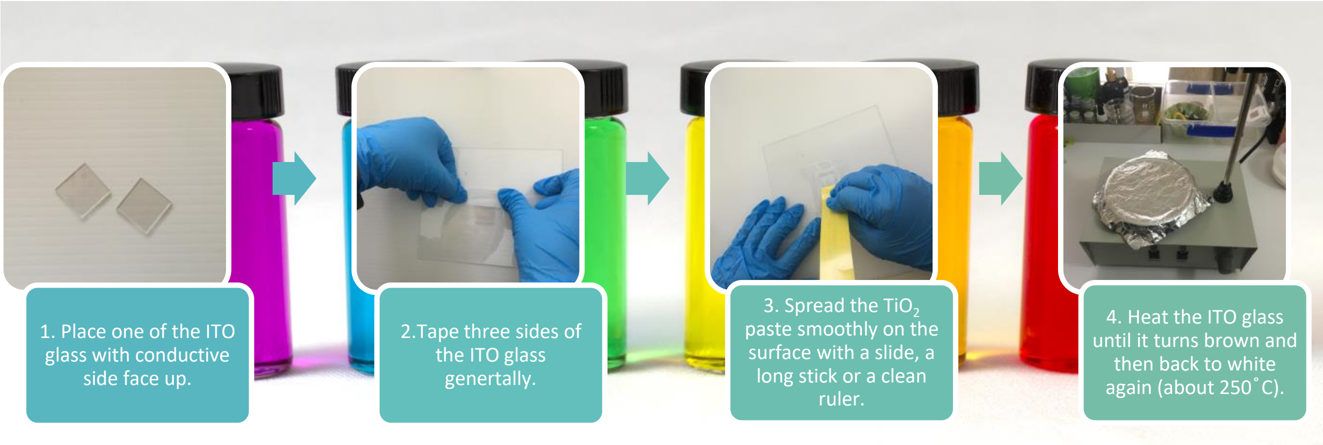
Step 2: Preparing the TiO_2 paste.



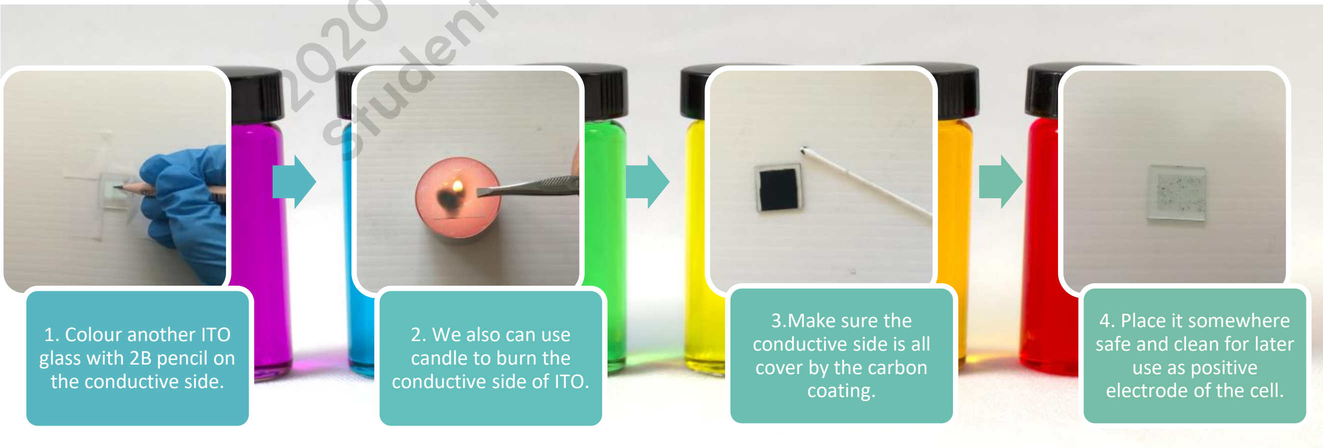
Step 3: Preparing the dyes.

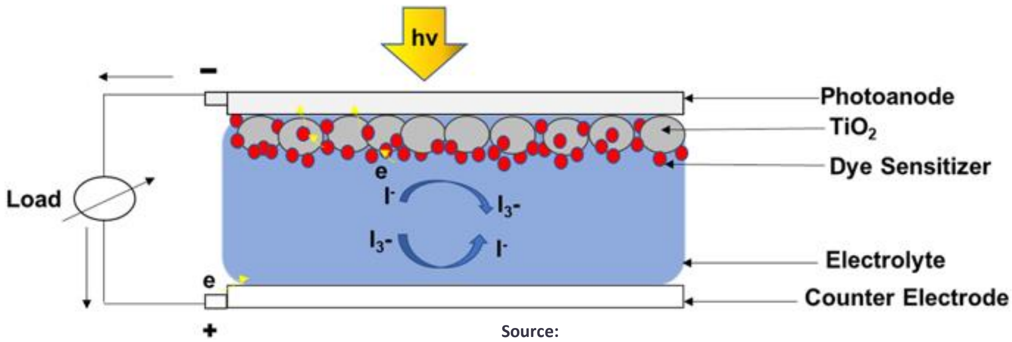


Step 4: Coating the ITO as the photoelectrode (Negative Electrode) of DSSC.



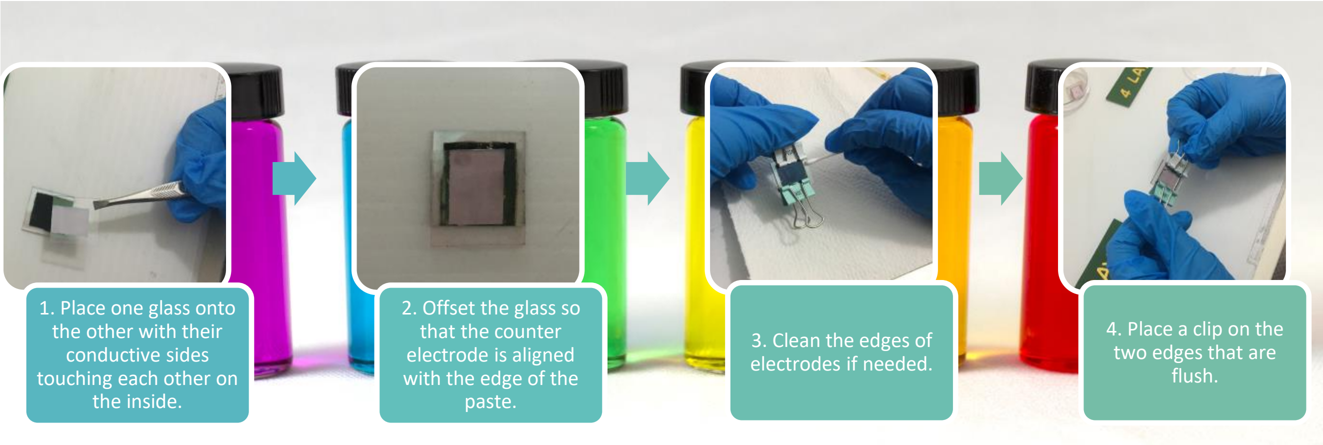
Step 5: Creating the counter electrode (Positive Electrode) of DSSC with carbon coating.



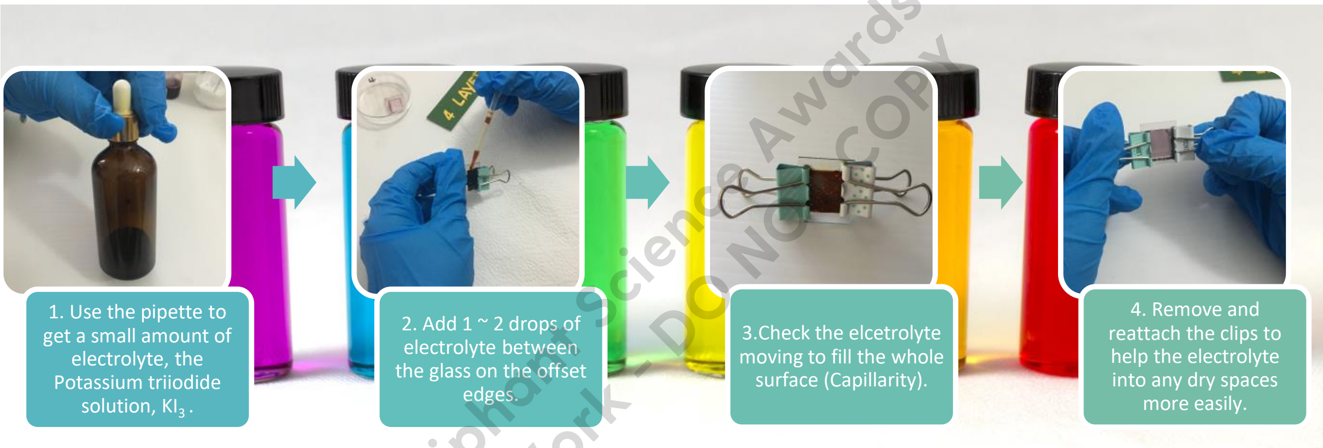


Source:
https://media.springernature.com/m685/springer-static/image/art%3A10.1038%2Fs41598-018-35388-2/MediaObjects/41598_2018_35388_Fig1_HTML.png

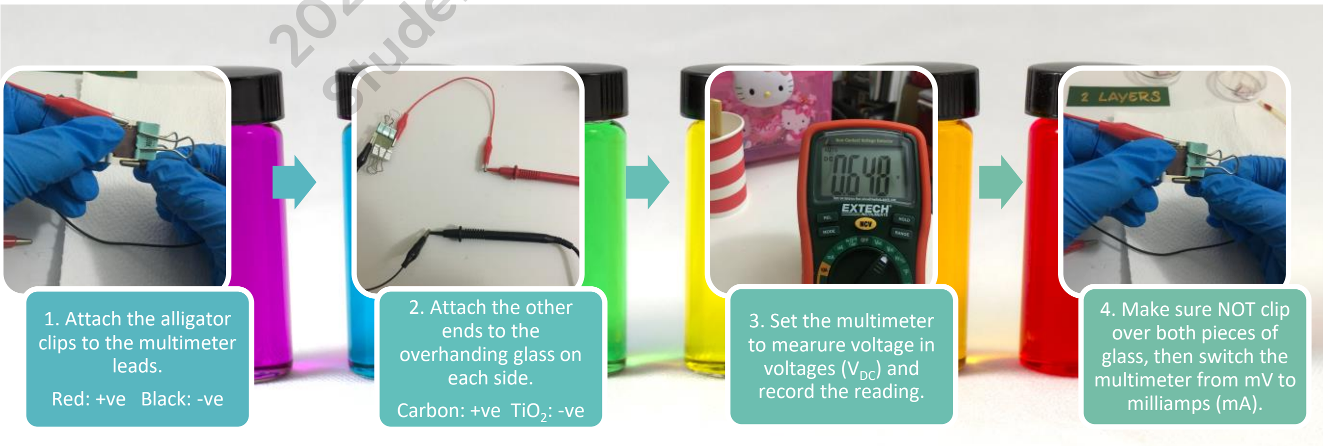
Step 6: Combining the parts of DSSC.



Step 7: Adding the electrolyte into the DSSC.



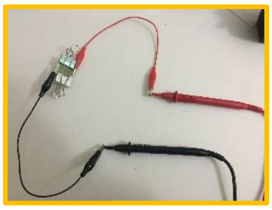
Step 8: Testing the DSSC and measure the voltages and microamps.

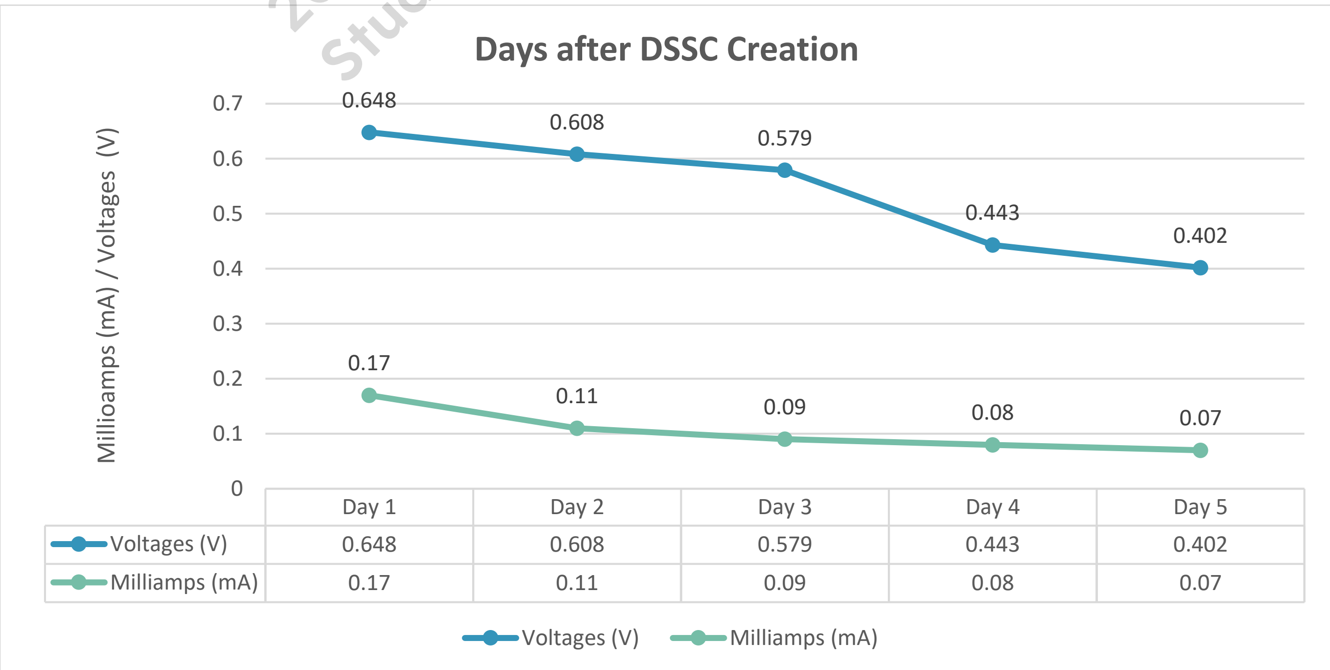


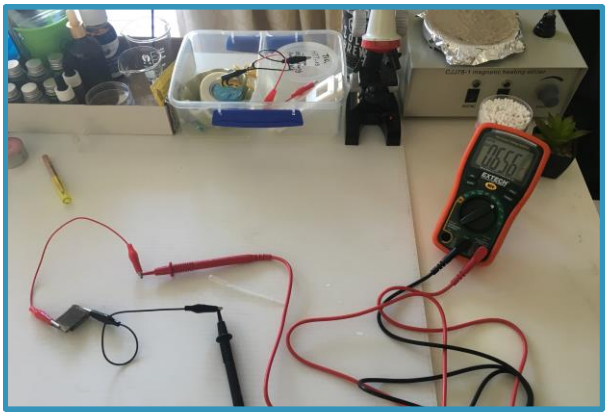
Results:

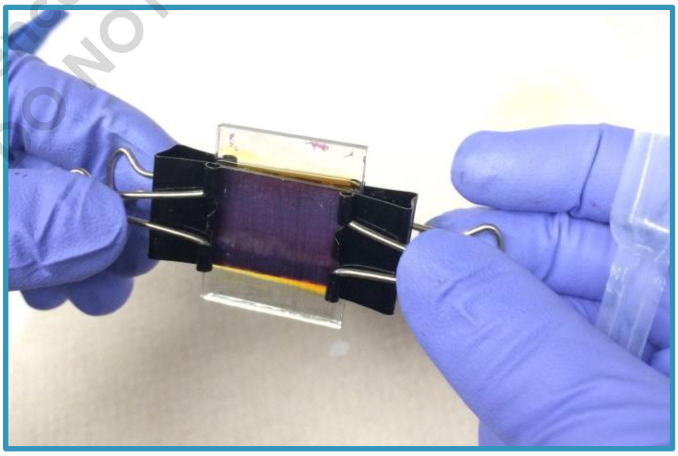
The DSSC I created can generate 0.65V and 0.17mA. After recording and comparing the voltages and microamps generated by the DSSC every day with similar sunlight environment, I found that the voltages and current are gradually declined. The main reason may be the loss of electrolyte. Therefore, the sell packaging technology is a problem the at needs to be solved in my experiment. In the later experiment, I will try different ways to package the DSSC, hoping to solve the problem of electrolyte loss.

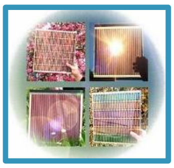
In addition, the generated voltage and current are too weak to drive small electrical appliances, such as small alarm buzzer, calculator, or digital thermometer. In one of the later experiments, I will connect several DSSC in series to try to drive these small electrical appliances.

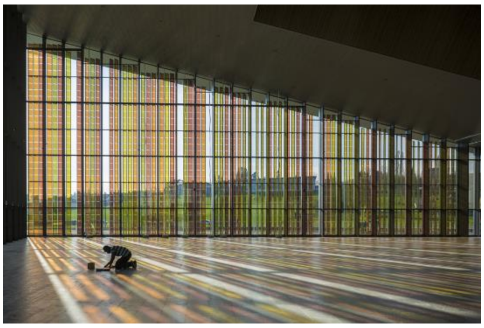
Fixed Variable DSSC	**Independent Variables (Days after DSSC Creation)**				
	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**
					
Dependent Variables	**V**	**V**	**V**	**V**	**V**
Voltages (V)	**0.648**	**0.608**	**0.579**	**0.443**	**0.402**
	mA	**mA**	**mA**	**mA**	**mA**
Milliamps (mA)	**0.17**	**0.11**	**0.09**	**0.08**	**0.07**









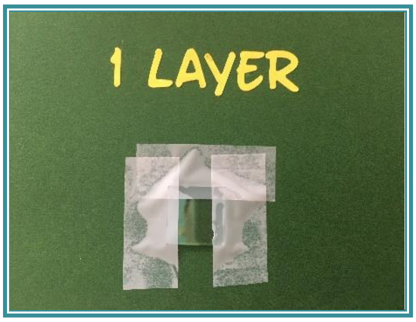


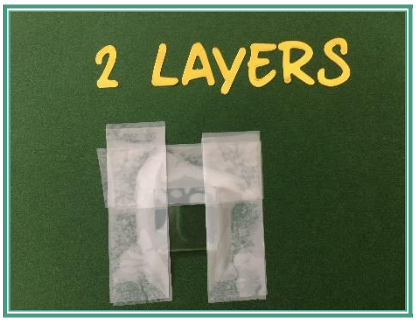
Source: https://energycue.it/wp-content/uploads/2016/12/swisscentClose-up-Engineering.jpg

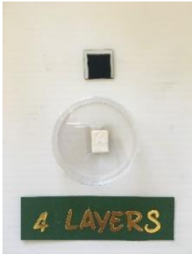
https://kknews.cc/news/5avzqvk.html

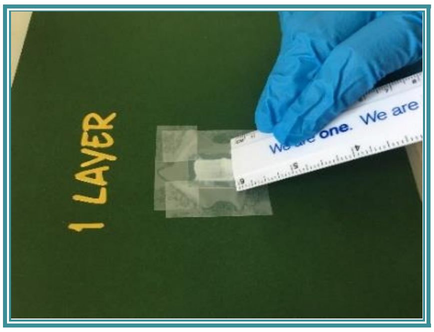
Experiment 1. Will the thickness of TiO_2 paste influence the voltages converted by DSSC?

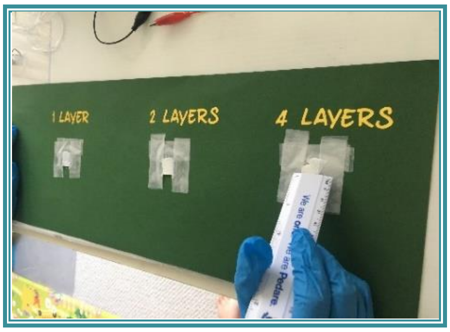
Different thickness of TiO_2: (1) 1 layer of tape thickness (2) 2 layers of tapes thickness, and (3) 4 layers of tape thickness have been used separately.

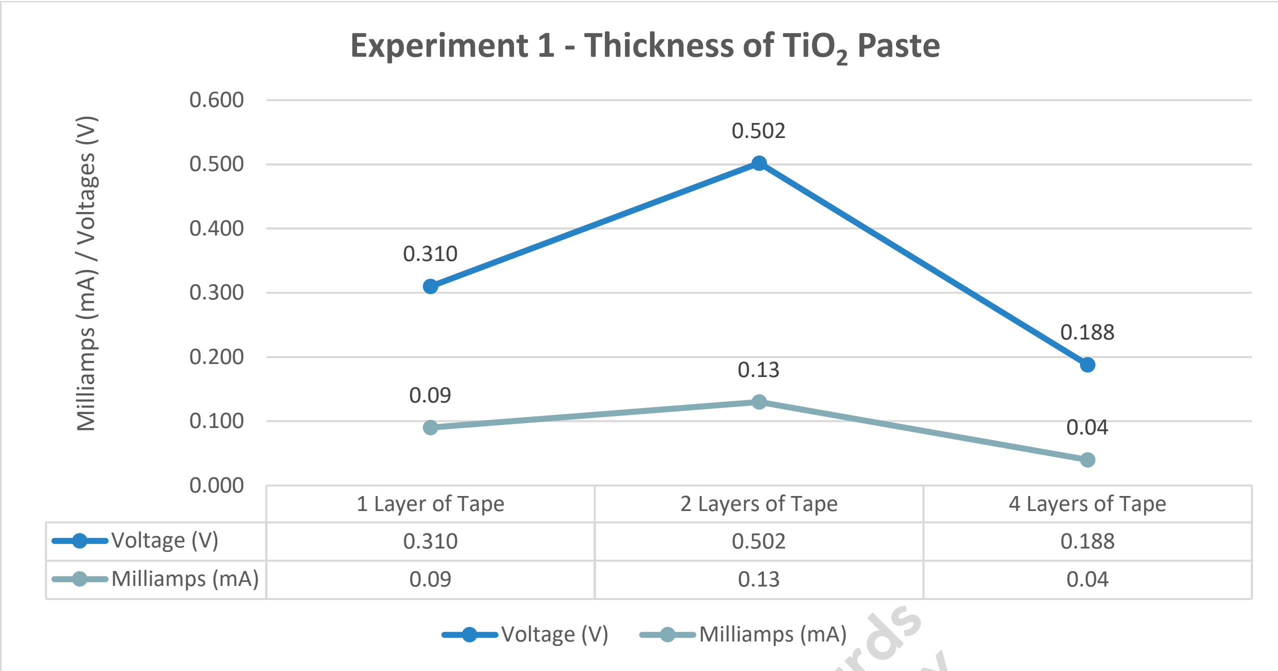




Fixed Factors	Independent Variable – Thickness of TiO_2 (Photoelectrode, Negative Electrode)		
	1 Layer of Tape Thickness	2 Layers of Tape Thickness	4 Layers of Tape Thickness
DSSC with fixed: Carbon coating (Candle coating); TiO_2 Paste; Electrolyte (KI_3); Dye (Blackberry); Sunlight Environment (Indoor light); Testing the cell 10 mins after the creation.	 	 	 
Dependent Variables	**V**	**V**	**V**
Voltages (V)	**0.310**	**0.502**	**0.106**
	mA	**mA**	**mA**
Milliamps (mA)	**0.09**	**0.13**	**0.04**

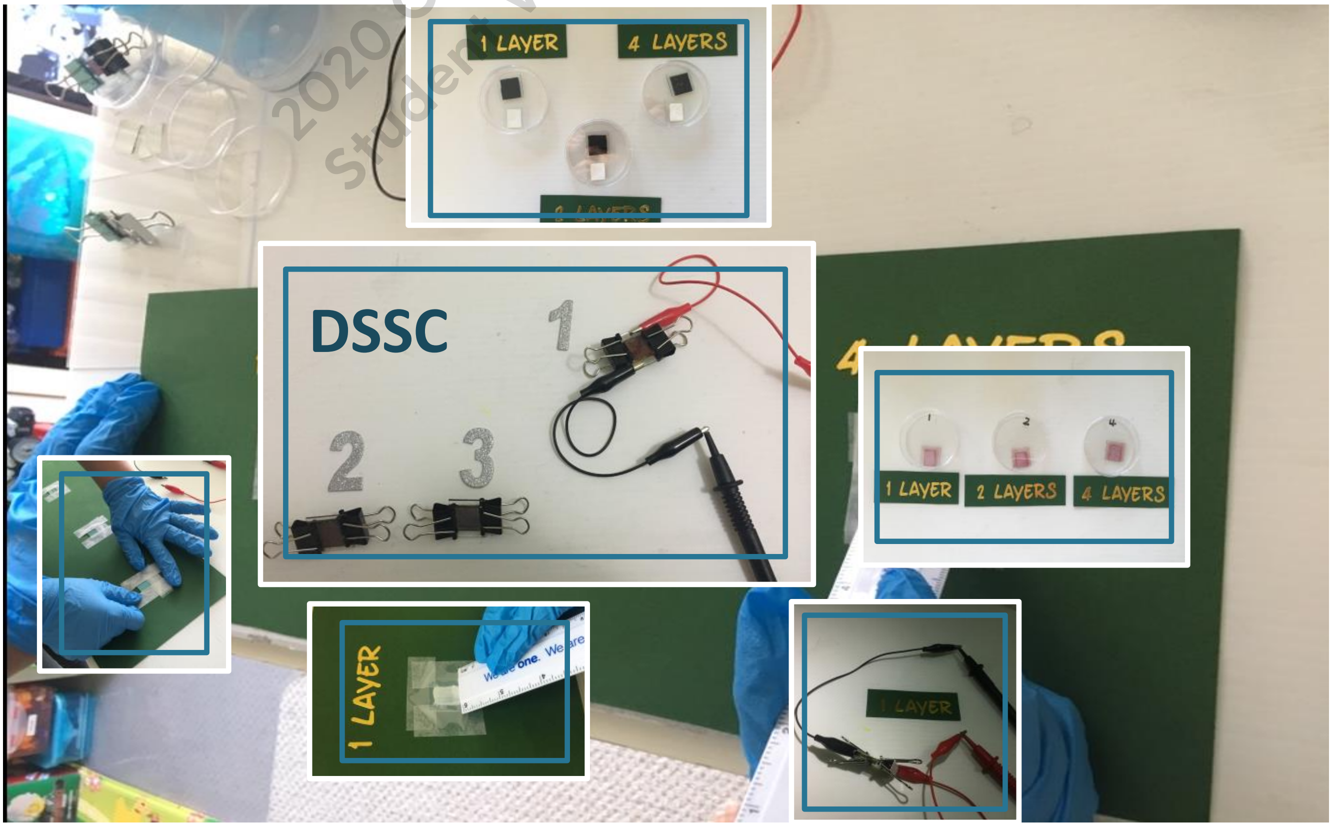






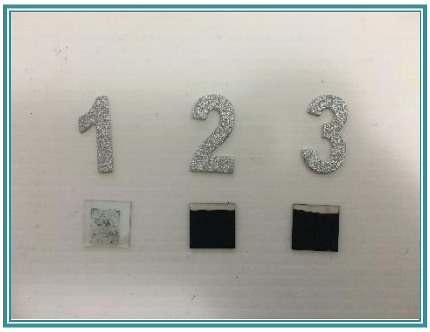
<u>Results of Exp. 1</u>:

From the this experiment, we can find out that the voltage generated by the DSSC will increase with the number of layers of tape (voltage increased from I layer to 2 layers), but the voltage of 4 layers of tape is lower than that of one and two layers of titanium dioxide film. Too thick titanium dioxide film is easy to break after heating, which leads to the dye cannot be adhered, and the voltage will be reduced. In addition, thicker titanium dioxide film will block the light source and affect the light transmittance, which may also affect the output voltage. Therefore, we are not coating the thicker the better, the suitable thickness of titanium dioxide film helps to achieve better results.

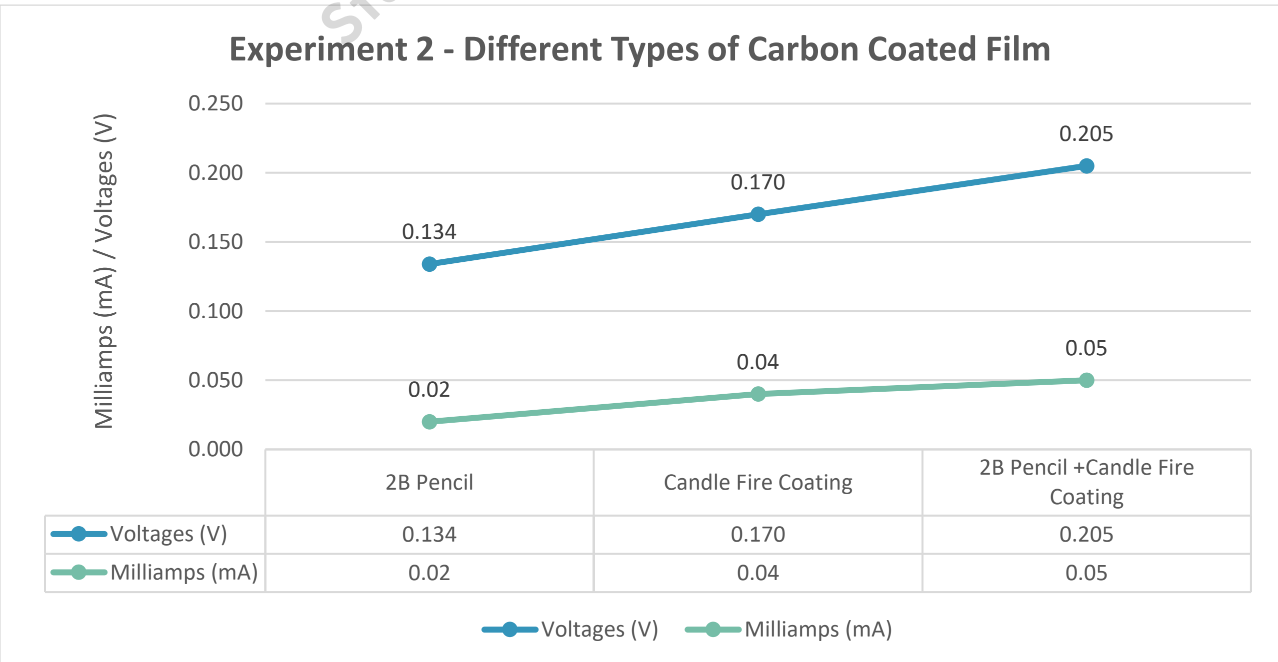


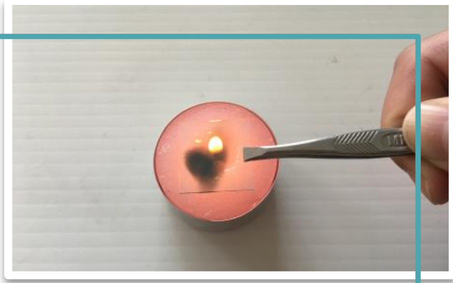
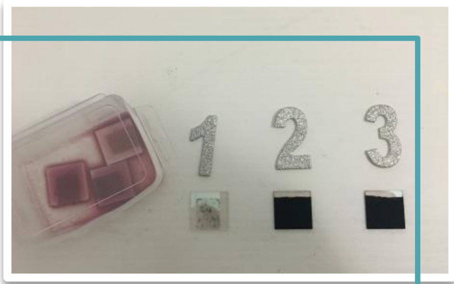
Experiment 2. Will the different types of carbon film influence the voltages converted by DSSC?

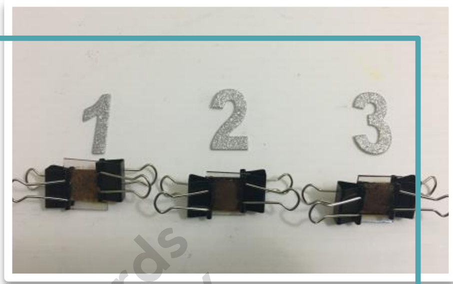
Different carbon films of anode: (1) 2B pencil (2) candle fire and (3) 2B pencil + candle fire.



Fixed Factors DSSC	**Independent Variable – Carbon Film of Counter Electrode (Positive Electrode)**		
	(1) 2B Pencil	(2) Candle Fire	(3) 2B Pencil + Candle Fire
DSSC with fixed: TiO_2 Paste (1-layer thickness) Electrolyte (KI_3) Dye (Blackberry) Indoor light Environment Testing the cell 10 mins after the creation.			
Dependent Variables	**V**	**V**	**V**
Voltages (V)	**0.134**	**0.170**	**0.205**
	mA	**mA**	**mA**
Milliamps (mA)	**0.02**	**0.04**	**0.05**

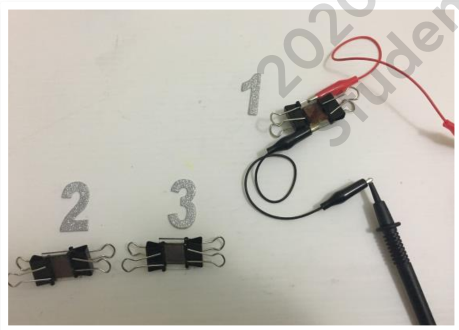


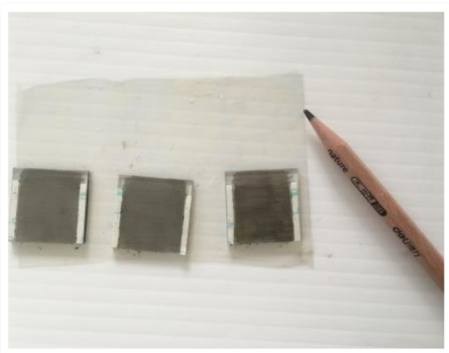





<u>Results of Exp. 2:</u>

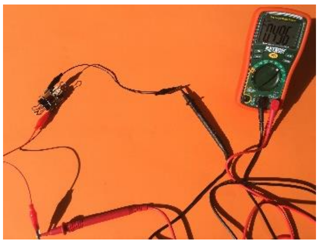
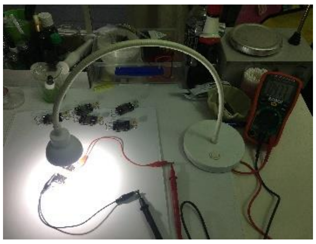
I can see from this experiment that the amount of carbon coating of anode will also affect the output of voltage. The third group of samples can get the highest voltage, but I can see the output voltages and currents are much lower compared to the Experiment 1 mentioned previously. The main reason may be that the titanium dioxide paste used to create the samples was as same as the first experiment a few days ago, the new paste has not been redeployed, leading to the output voltage figures are not ideal. Therefore, I suggest that new titanium dioxide paste should be re-mix every time in order to reduce the possible errors in the experiments.



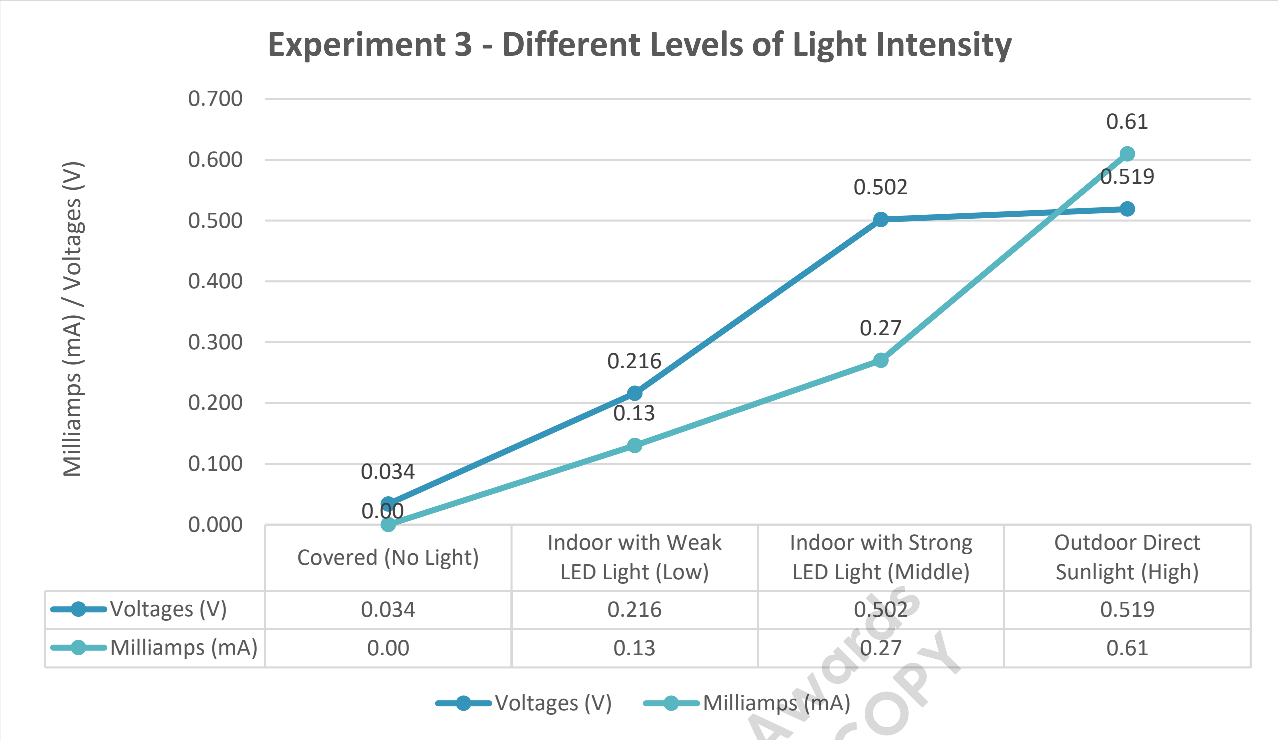



Experiment 3. Does the intensity of light influence the voltages generated by the DSSC?

I place the DSSC under different intensity of light environment to see how the light intensity influences the voltage and current generated by the cell.

Outdoor with Direct Sunlight (High Intensity)	Indoor with Strong LED light (Middle Intensity)	Indoor with Weak LED Light (Weak Intensity)	Indoor covered without Light (No Light)
			

Fixed Factors DSSC	Independent Variable – Intensity of Light			
	Outdoor (High) with direct sunlight	Indoor (Middle) with Strong LED light	Indoor (Weak) with Weak LED light	Indoor (No Light) covered / No Light
DSSC with fixed: TiO_2 Paste (1-layer thickness) Carbon Coating Electrolyte (KI_3) Dye (Blackberry) Testing the cell 10 mins after the creation.	 	 	 	 
Dependent Variables	**V**	**V**	**V**	**V**
Voltages (V)	**0.519**	**0.502**	**0.216**	**0.034**
	mA	**mA**	**mA**	**mA**
Milliamps (mA)	**0.61**	**0.27**	**0.13**	**0.00**



	Covered (No Light)	Indoor with Weak LED Light (Low)	Indoor with Strong LED Light (Middle)	Outdoor Direct Sunlight (High)
Voltages (V)	0.034	0.216	0.502	0.519
Milliamps (mA)	0.00	0.13	0.27	0.61

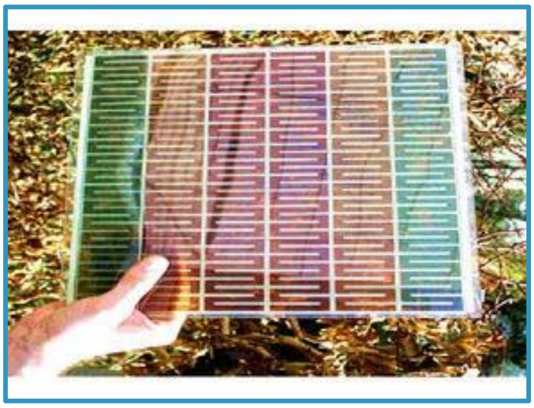
https://gadgetynews.com/wp-content/uploads/2009/07/DSSC.JPG

http://edelweisspublications.com/edelweiss/figures/joh-18-104_figure_4.png

Results of Exp. 3:

It can be seen from the experimental data that the voltages generated by the DSSC is related to the light intensity. When the light intensity is higher, the voltage generated will be higher, because of the principle of DSSC, the organic pigment in the cell needs to be irradiated by light to release electrons. Therefore, the stronger the light intensity is, the more easily the electrons in the pigment molecules jump to the excited state, and the voltage generated is also higher.

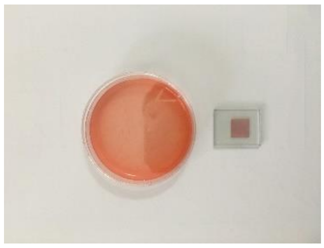
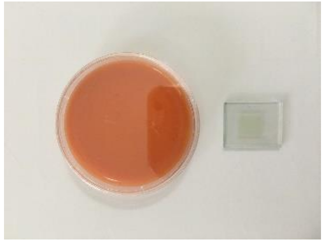
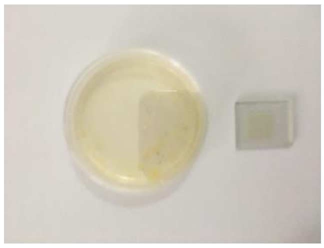
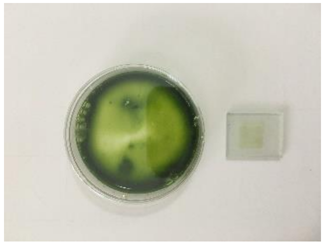
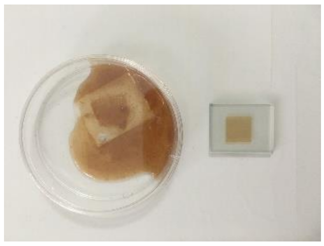
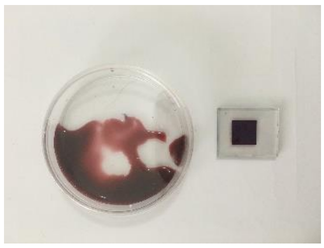
https://www.pinterest.com.au/pin/69031806761907247/



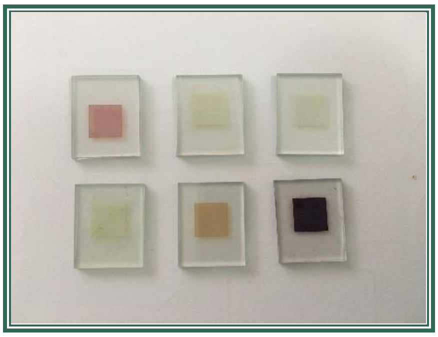
http://www.blogcdn.com/www.engadget.com/media/2007/04/solar-panel-new-zealand.jpg

Experiment 4. How does different colour of pigments affect the voltages generated by the DSSC?

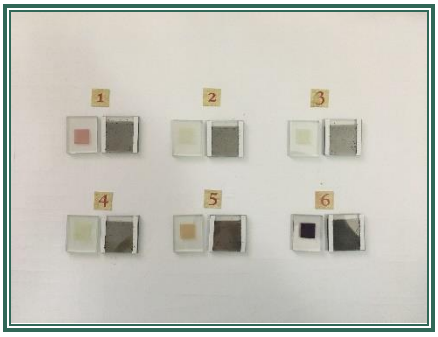
Use different kinds of fruit/vegetable juices as the dye of DSSC, observe the voltage changes.

Organic Dyes from Fruits/Vegetables			
Dyes	**Colours**	**Contents/Features**	**Colours of Dyes**
Strawberry		**Anthocyanins** • Less stable. • Soluble in water. • Absorb ultraviolet rays. • Natural antioxidants.	
Carrot		**Carotene** • More stable. • Insoluble in water. • Light absorption. • Photosynthesis.	
Orange		**Carotene** • More stable. • Insoluble in water. • Light absorption. • Photosynthesis.	
Spinach		**Chlorophyll** • More stable. • Insoluble in water. • Light absorption. • Photosynthesis.	
Blueberry		**Anthocyanins** • Less stable. • Soluble in water. • Absorb ultraviolet rays. • Natural antioxidants.	
Blackberry		**Anthocyanins** • Less stable. • Soluble in water. • Absorb ultraviolet rays. • Natural antioxidants.	

Method Steps:

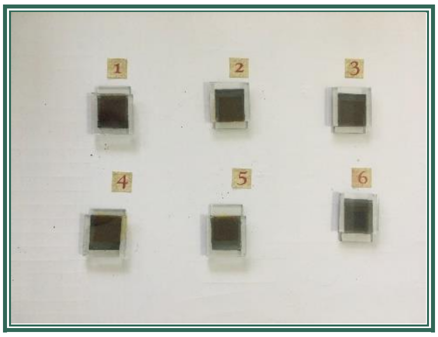


1. **Preparing the anode.**

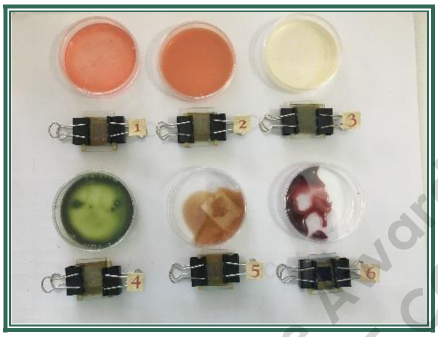


2. Preparing the cathode.

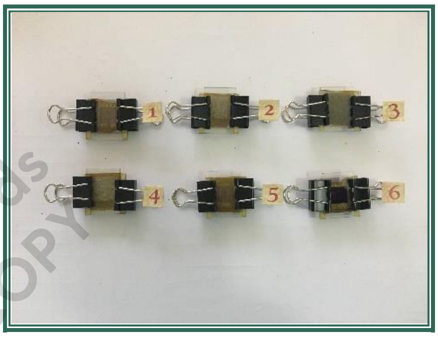
3. Adding the electrolyte.



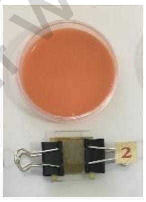
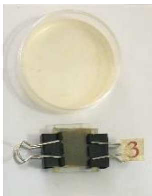
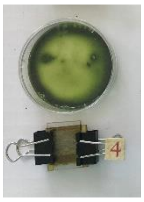
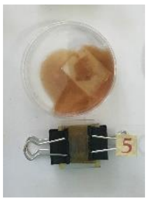
4. Combining the parts.



5. Putting the clips.



6. Ready for testing.

Fixed Factors DSSC	**Independent Variable - Different Kinds of Dyes**					
	Strawberry	Carrot	Orange	Spinach	Blueberry	Blackberry
DSSC with fixed: TiO_2 Paste (1-layer thickness) Electrolyte (KI_3) Carbon (2B Pencil) Under LED solar simulator Testing the cell 20 mins after the creation.						

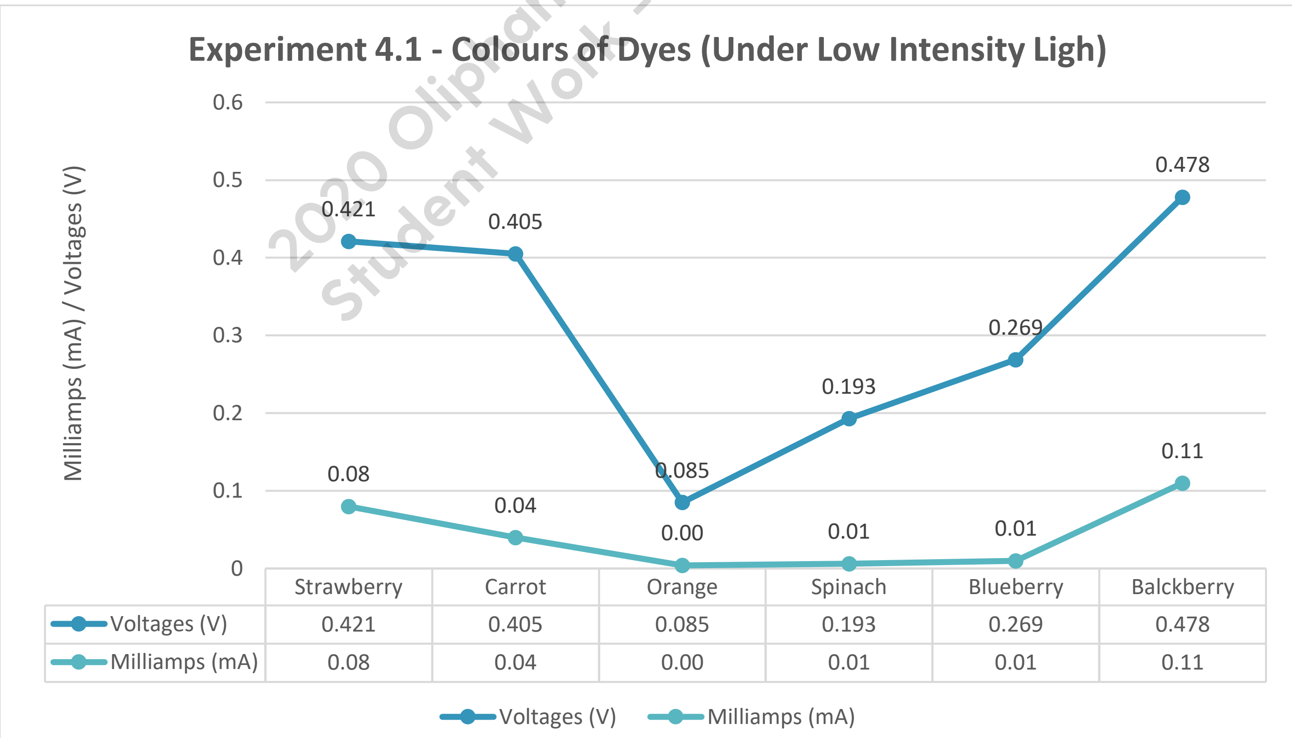
Hypothesis:

The absorption capacity of dark matter is better than the light matter, a simple example of this phenomenon is wearing black clothes often heat up more than wearing bright and white clothes. If I use the idea of using "*colours*" to measure the electricity generated by my DSSCs, the dark blue violet anthocyanins have strong ability to absorb ultraviolet rays, can absorb and exaggerate the absorption range of the DSSCs. It should be able to help to release more electrons in the process of absorbing light and generate high voltages compared to other organic molecular dyes, for example, chlorophyll and carotene.

"What is the best colour for rainbow PV cells?" **My hypothesis is that organic pigments from fruits or vegetables with darker colour and more anthocyanins will be the better choice to create the DSSC.** I've designed several experiments to support my argument.

Experiment 4.1: Under LED Solar Simulator – Low Intensity.

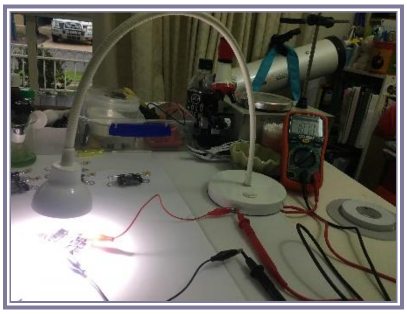
Dependent Variables	Strawberry	Carrot	Orange	Spinach	Blueberry	Blackberry
						
Voltages (V)	mV	mV	mV	mV	mV	mV
	0.421	0.405	0.085	0.193	0.269	0.478
Milliamps (mA)	mA	mA	mA	mA	mA	mA
	0.08	0.04	0.00	0.01	0.01	0.11



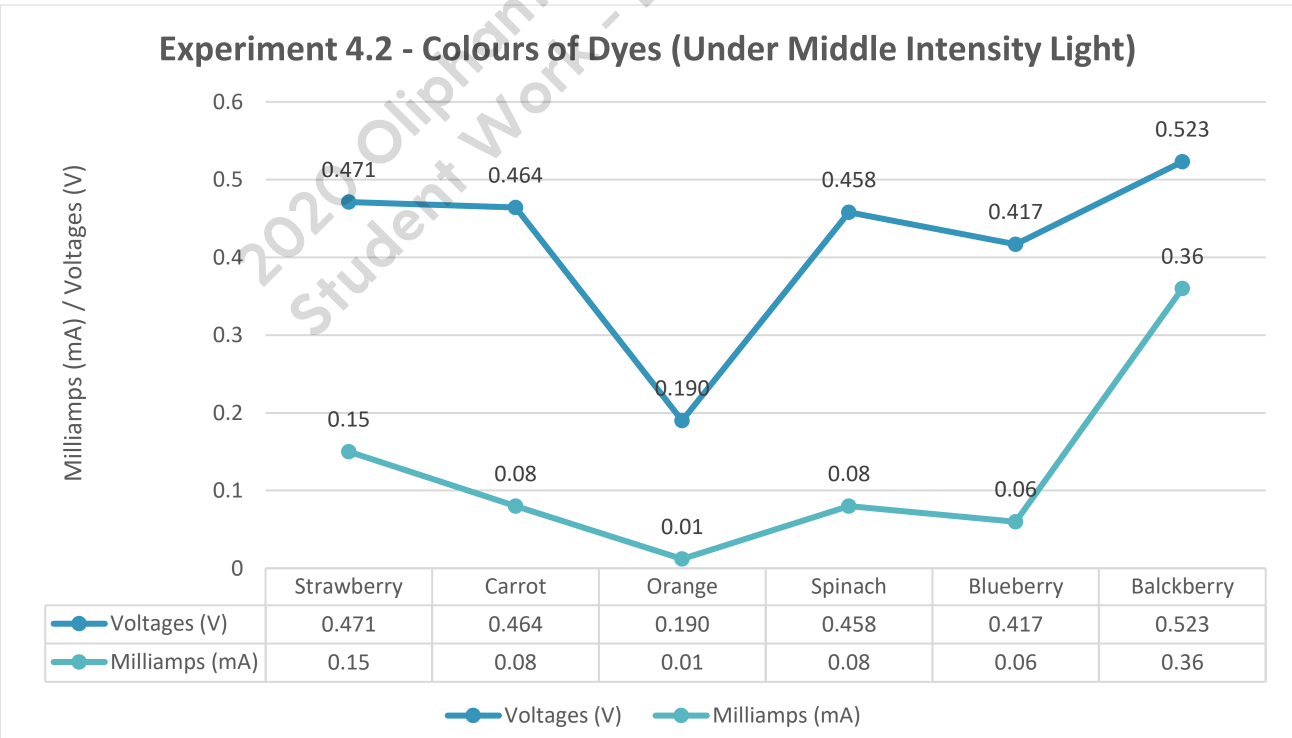
Results of Exp. 4.1:

The cell that uses blackberry juice as a dye can generate the highest electricity, and the one uses orange juice as a dye generates the lowest voltage when we shine a small LED torch on the cells we created using different juices as dyes.

Experiment 4.2: Under Strong LED Light – Middle Intensity.



Dependent Variables	Strawberry	Carrot	Orange	Spinach	Blueberry	Blackberry
						
Voltages (V)	**mV**	**mV**	**mV**	**mV**	**mV**	**mV**
	0.471	**0.464**	**0.190**	**0.458**	**0.417**	**0.523**
Milliamps (mA)	**mA**	**mA**	**mA**	**mA**	**mA**	**mA**
	0.15	**0.08**	**0.01**	**0.08**	**0.06**	**0.36**

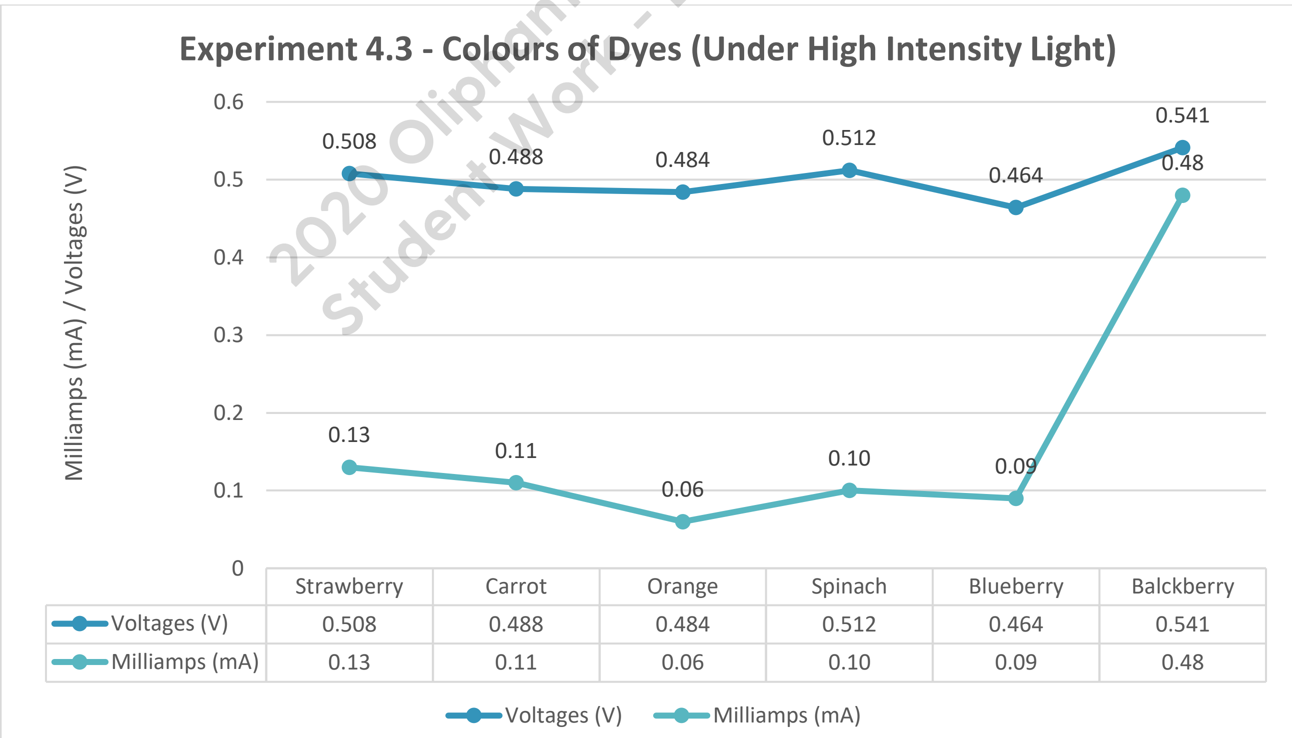


Result of Exp. 4.2:

We can see that the cell uses blackberry juice as a dye also generate the highest electricity when we shine a LED table lamp on the cells. It is worth noting that green spinach with chlorophyll produces more increases in electricity than other organic pigments under strong light compared to low light intensity.

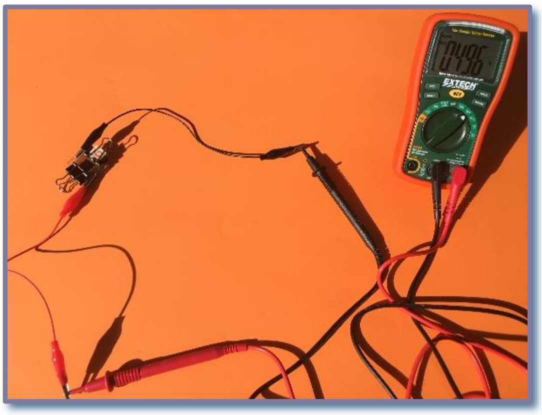
Experiment 4.3: Under Direct Sunlight – High Intensity.

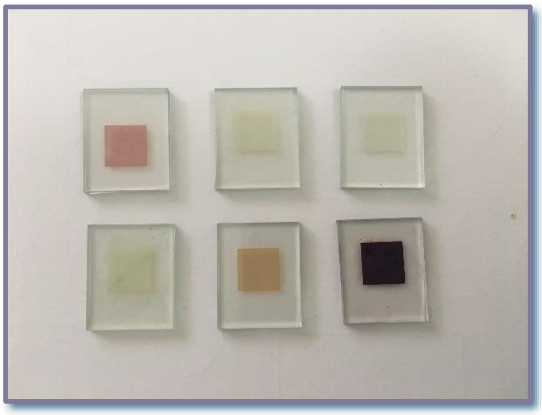
Dependent Variables	Strawberry	Carrot	Orange	Spinach	Blueberry	Blackberry
						
Voltages (V)	mV	mV	mV	mV	mV	mV
	0.508	0.488	0.484	0.512	0.464	0.541
Milliamps (mA)	mA	mA	mA	mA	mA	mA
	0.13	0.11	0.06	0.10	0.09	0.48

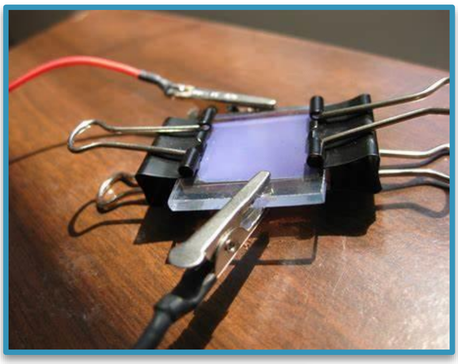


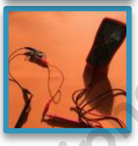
Results of Exp. 4.3:

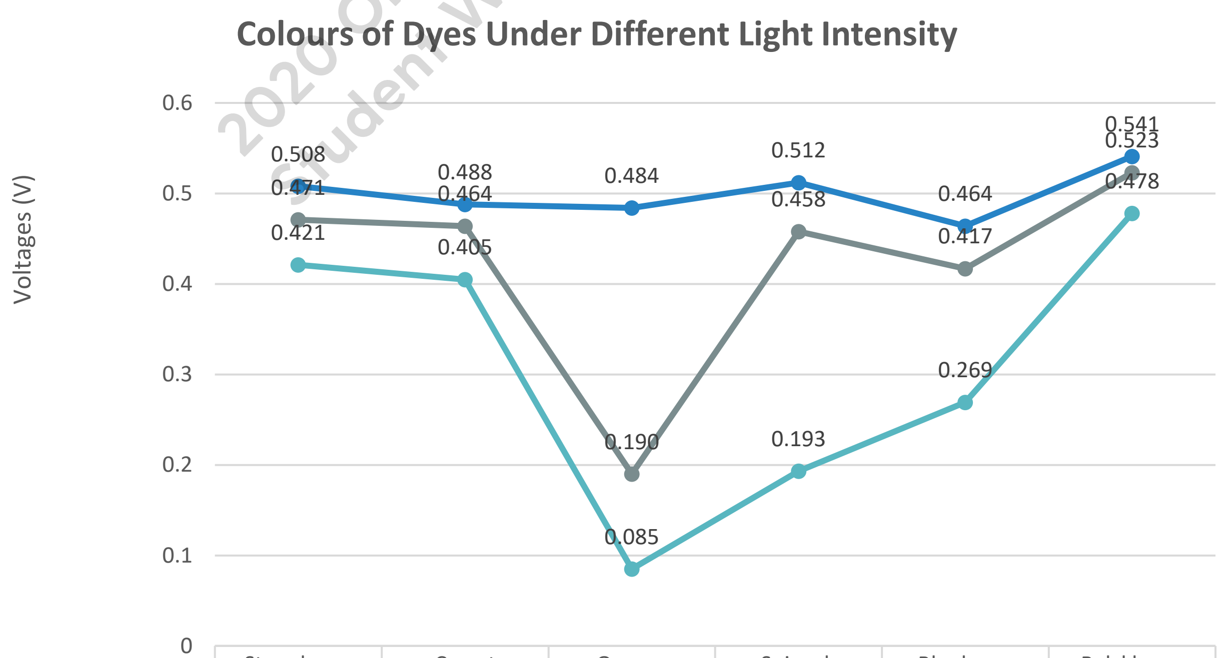
Under the direct sunlight, most cells generate similar electricity. The cell sample made of blackberry juice still produces the highest voltage, even the one made of orange juice can generate similar voltage as the cell made of blackberry or strawberry juice.











	Strawberry	Carrot	Orange	Spinach	Blueberry	Balckberry
Weak Intensity	0.421	0.405	0.085	0.193	0.269	0.478
Middle Intensity	0.471	0.464	0.190	0.458	0.417	0.523
High Intensity	0.508	0.488	0.484	0.512	0.464	0.541

Weak Intensity   Middle Intensity   High Intensity

Results of Exp. 4:

It can be observed from the above experiments that when strawberry, blackberry, and other berry fruits rich in anthocyanins are used as dyes, they can generate higher voltage and electricity than other fruits or vegetables rich in carotene and chlorophyll. The main reason is that anthocyanins can absorb more ultraviolet rays and have high antioxidant properties. It can effectively reduce the damage of organic pigment caused by contact with the environment and avoid the decreasing of photovoltaic conversion rate caused by oxidation.

However, one of my experiment samples uses blueberry as a dye, which is also high in anthocyanin and should generate high voltage, but the experimental data is not ideal and not support my argument, even far lower than other carotenes orange fruits and green chlorophyll vegetables. My observation may be due to the fact that the blueberry pulp wasn't filtered, and only small number of blueberries been used when extracting pigment. The titanium dioxide film is not easy to colour, so it is unable to play the good function of the pigment. Therefore, I am especially doing the second group of blueberry sample to compare with the first one, extracting better blueberry pigment as the dye, to see if it can support my hypothesis.

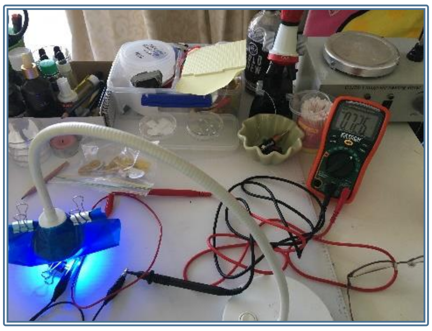
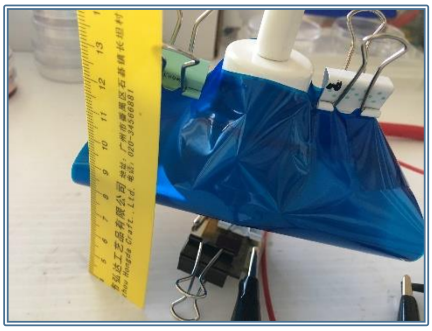
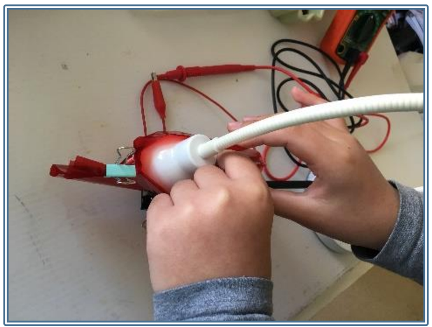
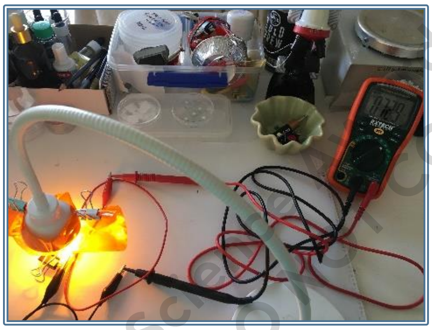
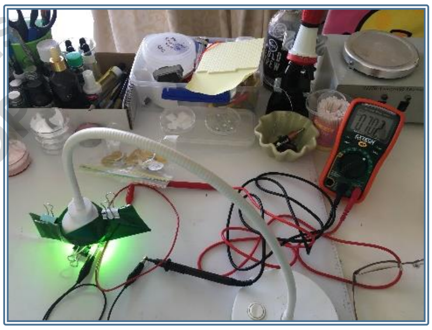
Fixed Factors DSSC	Independent Variable – Different Blueberry Juices			
	First sample (No Filtered)		Second Sample (Filtered)	
DSSC with fixed:	Indoor Light	Direct Sunlight	Indoor Light	Direct Sunlight
TiO_2 Paste (1-layer thickness) Electrolyte (KI_3) Testing the cell 10 mins after the creation.				
Dependent Variables	V	V	V	V
Voltages (V)	0.417	0.464	0.494	0.531
Milliamps (mA)	mA	mA	mA	mA
	0.06	0.09	0.12	0.18

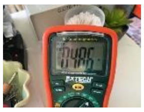
From the data above we can see, when we use the re-extract and filtered blueberry juice as a dye to create a DSSC, the voltage generated by it will be greatly increased (from 0.417 V to 0.494V indoor and 0.464V to 0.531V outdoor).

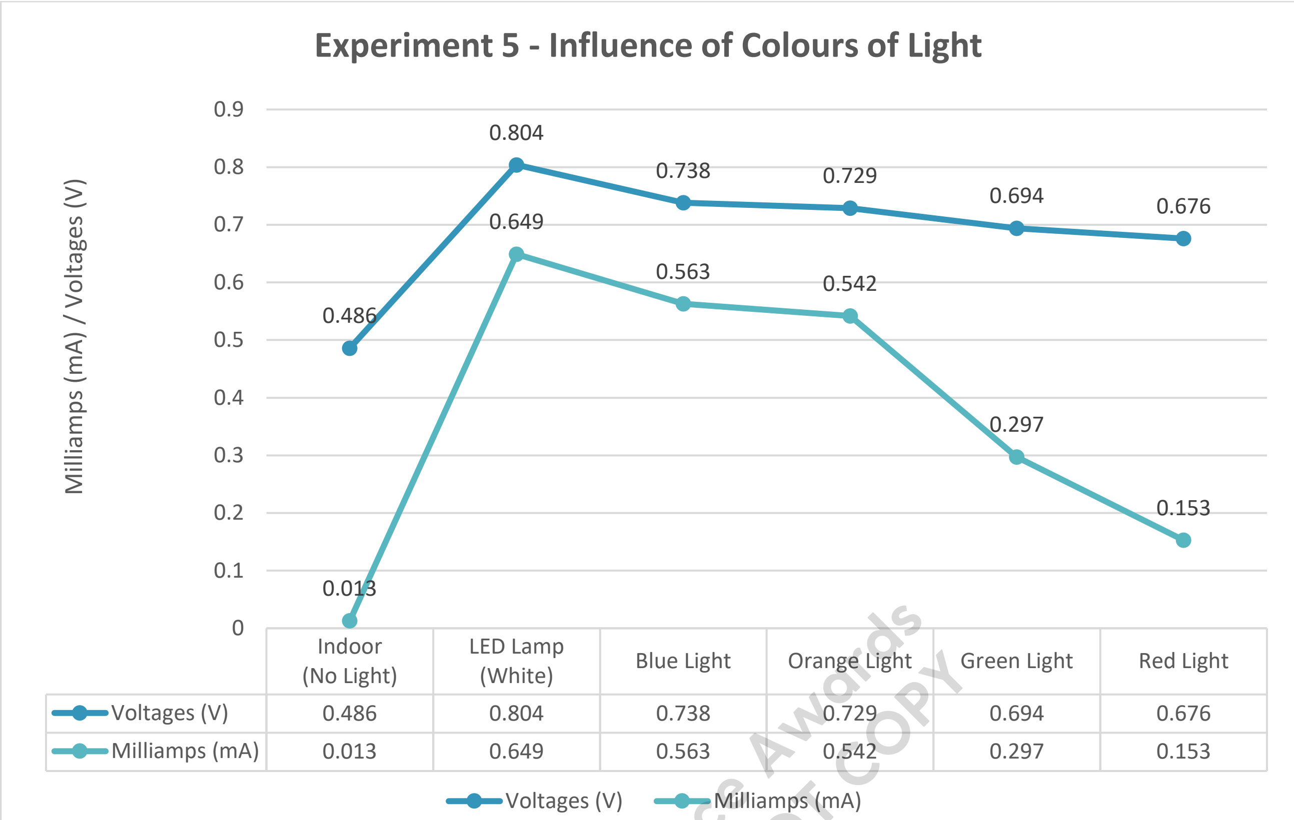
Therefore, the sample quality of pigments will also affect the cell quality we created. It supports my hypothesis that fruits and vegetable with higher anthocyanidins can generate higher electricity because they can absorb more ultraviolet rays.

Experiment 5. Does the colour of light influence the voltages generated by the DSSC?

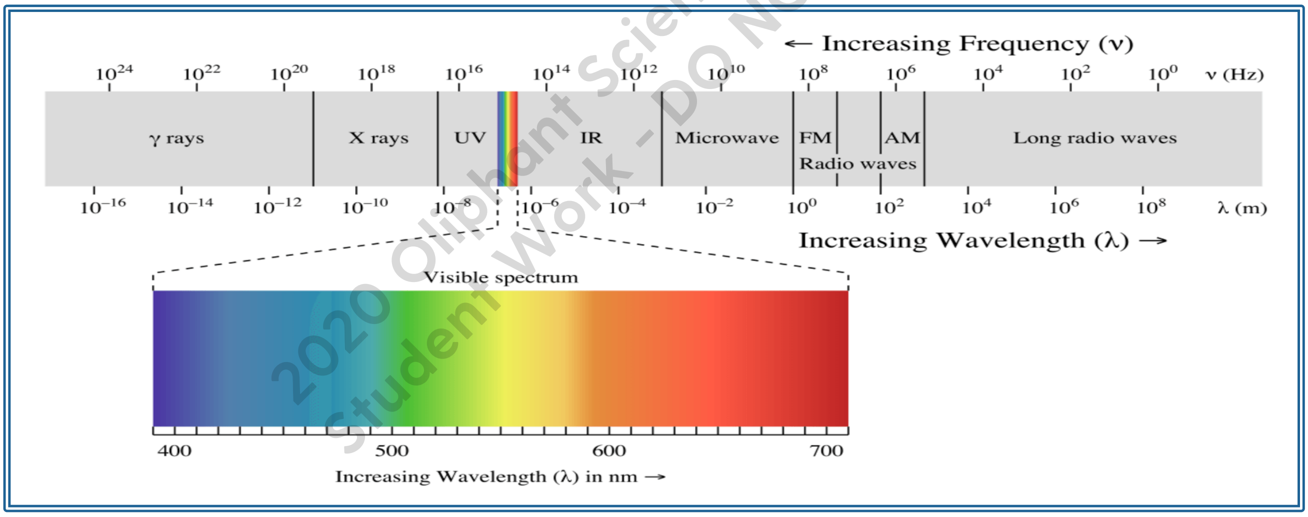
Using four different transparent cellophanes cover the LED table lamp and observe to see if different colours of light will affect the voltage generated by DSSCs? Make sure the distance between the DSSC and table lamp is fixed.

Fixed Factors DSSC	Independent Variable – Different Colours of Light (Cellophanes)					
	Indoor No Light	LED Table Lamp	Blue Cellophane	Orange Cellophane	Green Cellophane	Red Cellophane
DSSC with fixed: TiO$_2$ Paste (1-layer thickness) Electrolyte (KI$_3$) Dye (Blackberry) Testing the cell 10 mins after the creation. Distance from LED lamp to the cell (4Cm) Layers of cellophane (3 layers)	  	  	  	  	  	  
Dependent Variables	**V**	**V**	**V**	**V**	**V**	**V**
Voltages (V)	**0.486**	**0.802**	**0.738**	**0.729**	**0.694**	**0.676**
	mA	**mA**	**mA**	**mA**	**mA**	**mA**
Milliamps (mA)	**0.013**	**0.649**	**0.563**	**0.542**	**0.297**	**0.153**



	Indoor (No Light)	LED Lamp (White)	Blue Light	Orange Light	Green Light	Red Light
Voltages (V)	0.486	0.804	0.738	0.729	0.694	0.676
Milliamps (mA)	0.013	0.649	0.563	0.542	0.297	0.153



https://opentextbc.ca/introductiontopsychology/wp-content/uploads/sites/9/2013/11/b4eaddac5823123ca0aa5e6abe24da3d.jpg

Results of Exp. 5:

From the data above, I can see there is no significant difference between different colours of light, except the red colour (wavelength closes to infrared region, IR). When the wavelength is over 600~700nm, the voltage generated by the DSSC drops when we use red cellophane to cover the table lamp.

The wavelength range of sunlight is 280~3600nm, which usually distinguishes ultraviolet, visible, and infrared regions. The wavelength range of the human eye can detect is 380~760nm, which can distinguish various colours. Titanium dioxide film can only absorb sunlight in the ultraviolet region (10~400nm), which limits the photoelectric conversion effect. Therefore, the absorption range of the DSSC can be expanded by dyes, the dye containing anthocyanins in the blue colour mainly absorb the visible light from the infrared light to the red light in the solar spectrum.

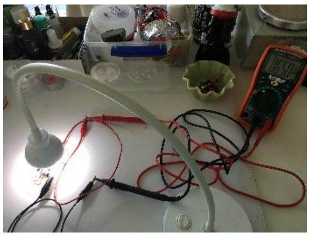
Experiment 6. Substitutions of materials of DSSCs.

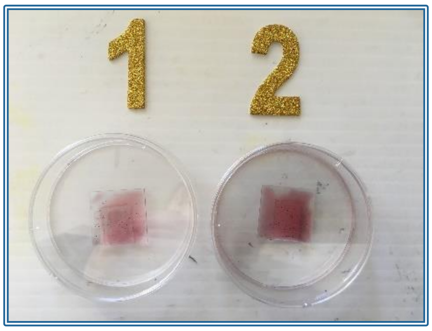
1a. Replacement of titanium dioxide – 5 mins after creation (only for toothpaste and correction fluid film DSSCs compared with my best DSSC model).

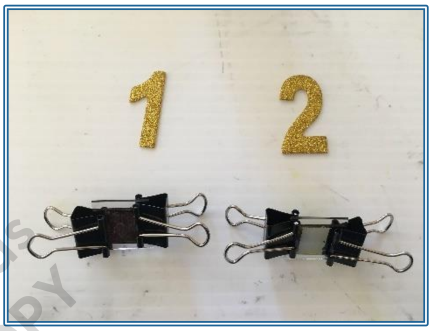
When I started to do this project, I found that this is a very interesting and experimental research. We can find some substitutes for experimental materials in our daily life, such as toothpaste containing titanium dioxide, correction fluid or correction tape to replace titanium dioxide paste made in the laboratory, although the concentration and purity of titanium dioxide is not as high as that of nanoparticular titanium oxide powder in the laboratory, but still can generate a small amount of voltage. The use of alternative materials that are easy to find in life can reduce the cost of experiments and the difficulty of finding special materials, which is safer and suitable for students.

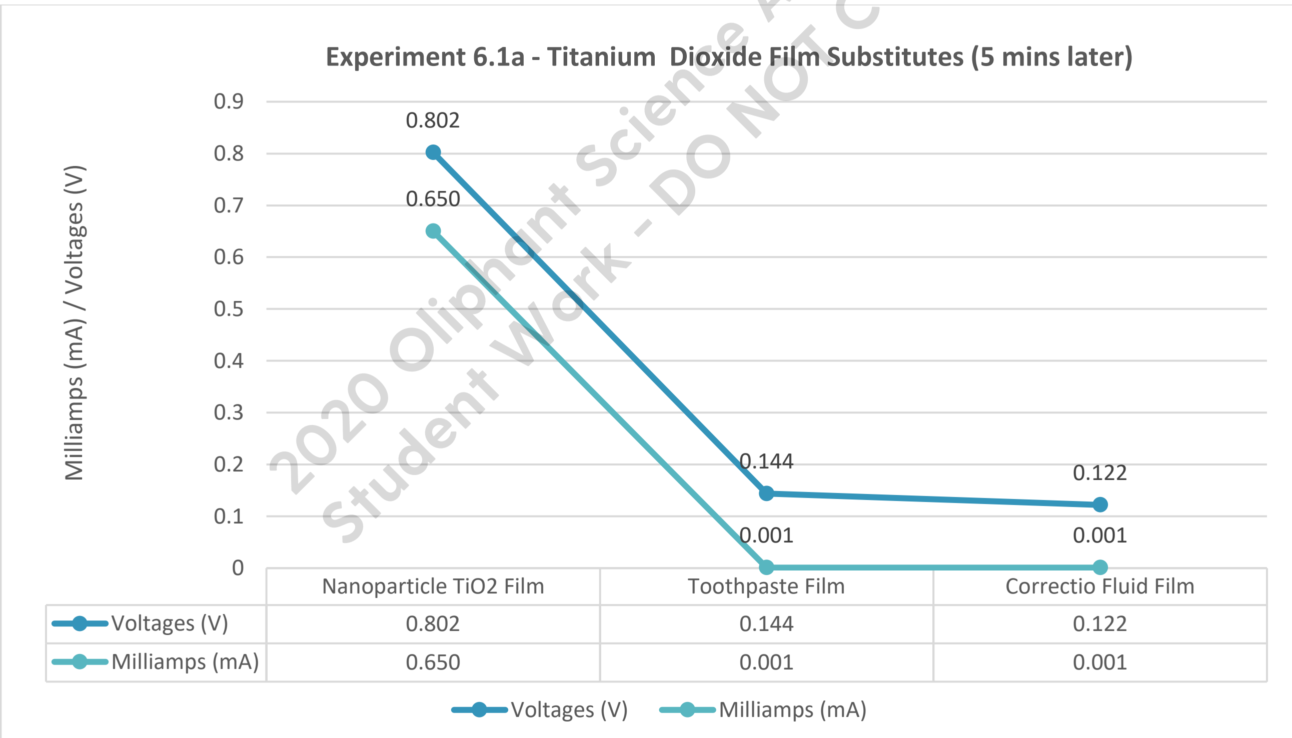
Toothpaste containing titanium dioxide

Correction Fluid

Fixed Factors DSSC	Independent Variable – Different TiO_2 Films		
	Nanoparticle TiO_2 Powder	(1) Toothpaste Film	(2) Correction Fluid Film
DSSC with fixed: Electrolyte (KI_3) Dye (Blackberry) Carbon Film (candle Fire) **Testing the cell 5 mins after the creation.** Distance from LED lamp to the cell (4Cm)	 	 	 
Dependent Variables	**V**	**V**	**V**
Voltages (V)	**0.802**	**0.144**	**0.122**
	mA	**mA**	**mA**
Milliamps (mA)	**0.650**	**0.001**	**0.001**





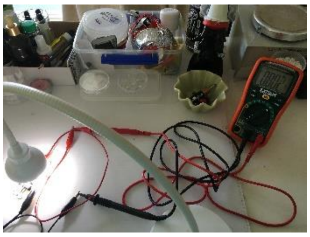
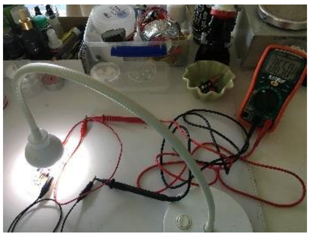


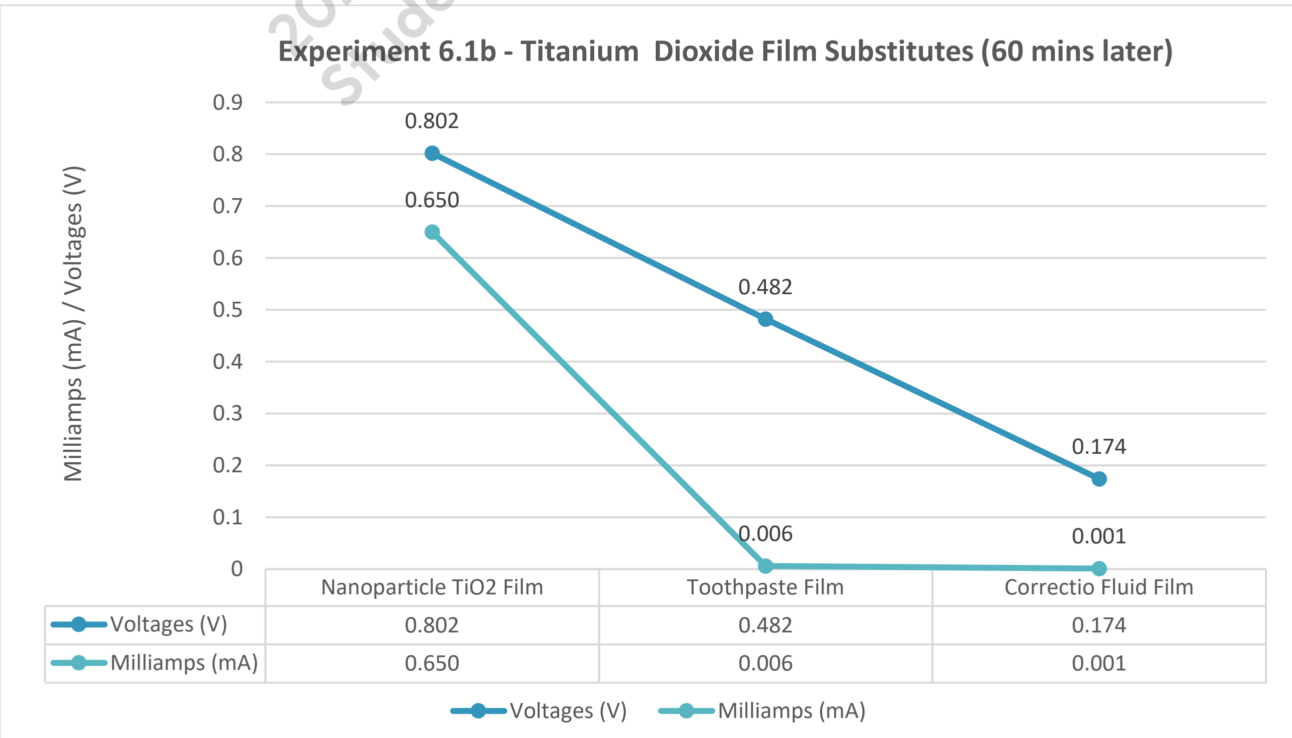
	Nanoparticle TiO2 Film	Toothpaste Film	Correctio Fluid Film
Voltages (V)	0.802	0.144	0.122
Milliamps (mA)	0.650	0.001	0.001

Results of Exp. 6.1a:

From the experimental data above, what surprised me was that the toothpaste containing titanium dioxide generated a higher voltage than I thought, and the cell made of correction fluid could also generate a small amount of voltage 5 minutes after the creation. The DSSC made of toothpaste generated higher voltage than the one made of correction fluid; the main reason should be the different of light transmission. The correction fluid is not transparent, dyes are not easy to colour and light is not easy to enter to excite the dye, so the voltage generated is relatively lower. Next part of experiment 6.1, I will test the voltages generated by DSSCs 60 minutes after the creation and compare the differences between different light intensity.

1b. Replacement of titanium dioxide – 60 mins after creation (only for toothpaste and correction fluid film DSSCs compared with my best DSSC sample).

Fixed Factors DSSC	Independent Variable – Different TiO_2 Films		
	Nanoparticle TiO_2 Powder	(1) Toothpaste Film	(2) Correction Fluid Film
DSSC with fixed: Electrolyte (KI_3) Dye (Blackberry) Carbon film (candle fire) **Testing the cell 60 mins after the creation.** Distance from LED lamp to the cell (4Cm)	 	 	 
Dependent Variables	**V**	**V**	**V**
Voltages (V)	**0.802**	**0.482**	**0.174**
Milliamps (mA)	**mA**	**mA**	**mA**
	0.650	**0.006**	**0.001**



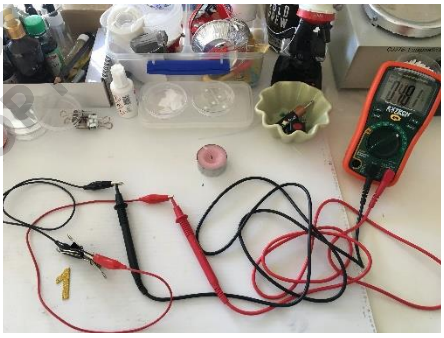
Results of Exp. 6.1b:

With the time increase of DSSCs completion time, the cell will produce higher voltage after absorbing enough light source. The voltages and currents generated by the DSSC at 60 minutes after the cells are created are significantly increased compared with that when the DSSC is just created, including both the cells made of toothpaste and correction fluid.

However, if the light source is absorbed up to a certain level, the illumination may not be positively proportional to the voltage generated by the DSSC and may even decline.

<table>
<tr><td rowspan="6">DSSC with fixed:

Dye (Blackberry)
Electrolyte (KI_3)
Carbon film (candle fire)
Testing the cell 60 mins after the creation.
Distance from LED lamp to the cell


</td><td colspan="2">(1) Toothpaste Film</td></tr>
<tr><td>Strong Light Intensity
0.482V</td><td>Weak Light Intensity
0.481V</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">(2) Correction Fluid Film</td></tr>
<tr><td>Strong Light Intensity
0.174V</td><td>Weak Light Intensity
0.080V</td></tr>
<tr><td></td><td></td></tr>
</table>

From the experiment above, I can find out that after the DSSC made of toothpaste absorbed enough light source, the light intensity did not significantly change the voltage generated. However, even after a long period of illumination, the light intensity still significantly affected the voltage generated by the DSSC made of correction fluid. The main reason should be the opacity of correction fluid, so it needs stronger light exposure to generate voltage. In addition to the experiment of dye colours affecting the voltages generated by the DSSCs (Experiment 4), this experiment is my favorite one, because of this experiment I began to care about the composition of materials, medicines, and foods around me; what kind of materials can be used for experiments, and what can be used as substitutes. This experiment will be of great help and inspiration for my scientific research in the future.

2. *Replacement of electrolyte –Potassium Triiodide Solution (KI_3)*

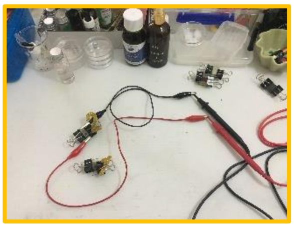
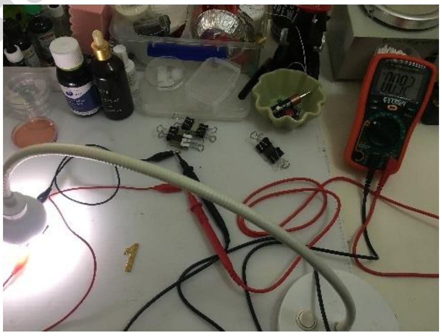
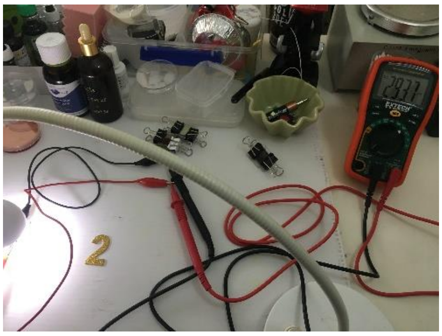
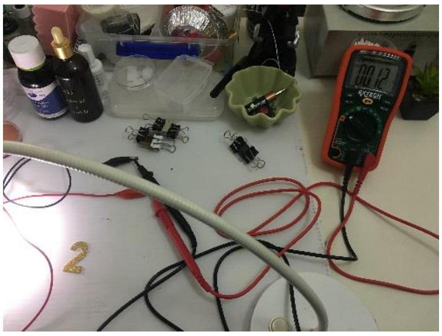
Except in the school laboratory or other research units, students are not easily access to some inflammable or higher risk materials, especially the younger children, Therefore, it is a convenient method to use the materials that are easy to obtain at home, and also can educate children about the composition of medications or articles. I use the Aqueous Iodine Solution as the substitute of electrolyte I created. Both of them contain Potassium Iodide and Iodine but in different Molar concentrations. Although the crystal of iodine is purple black, it turns yellow brown when dissolved in water.

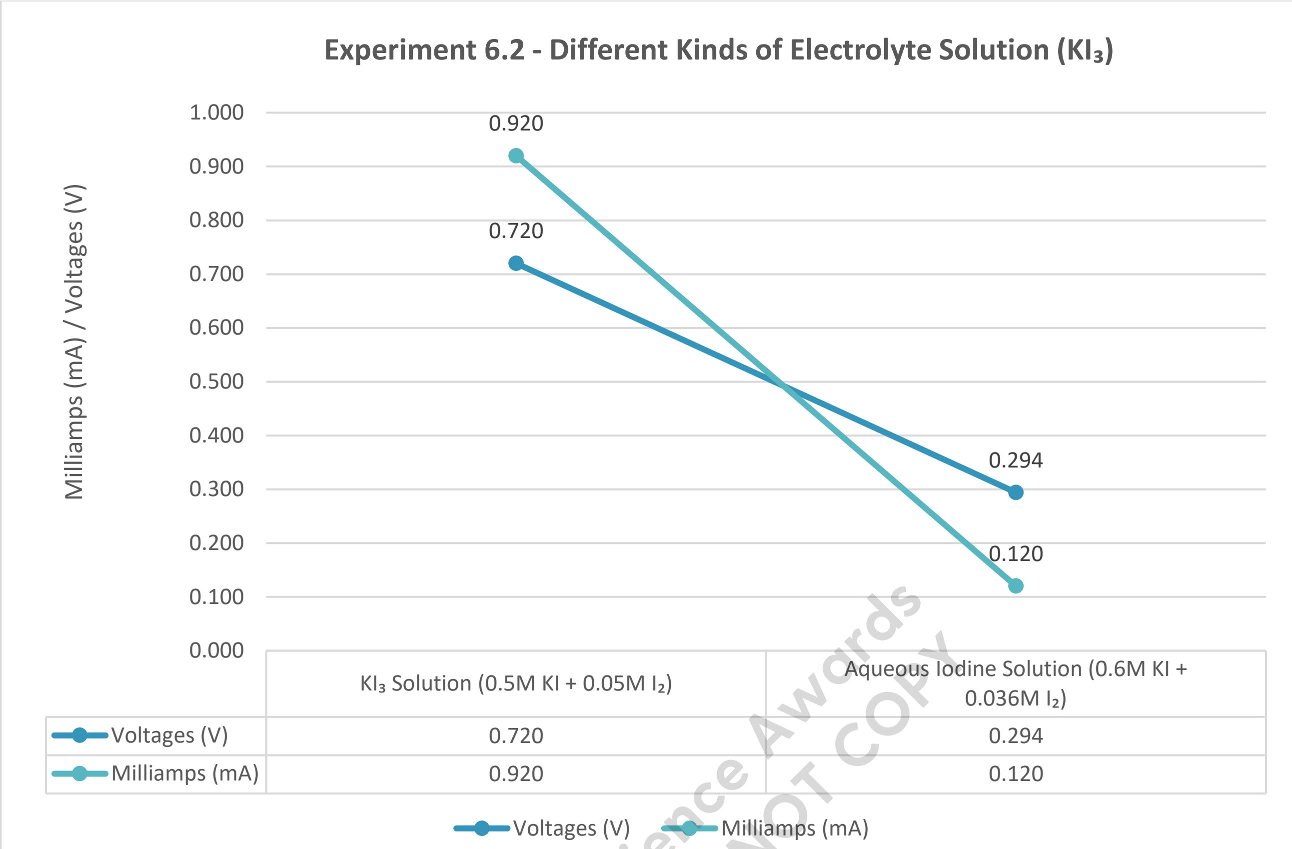
David Craig Aqueous Iodine Solution - I_2 5% w/v, KI 10% w/v

Lugol's Iodine

Miss Lizzy Iodine

Dark brown solution

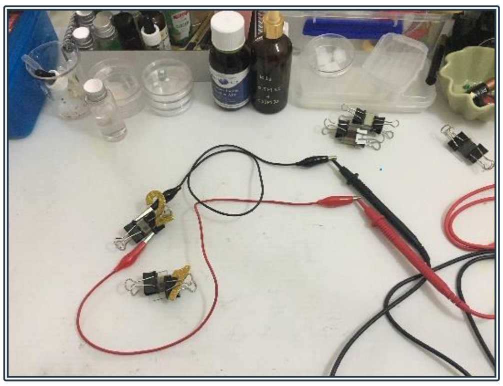
Fixed Factors DSSC	Dependent Variable – Different Electrolyte Solution	
	KI_3 (0.5M KI + 0.05M I_2)	David Craig Aqueous Iodine Solution (0.6M KI + 0.036M I_2)
DSSC with fixed: TiO_2 Paste (1-layer thickness) Dye (Blackberry) Carbon film (candle fire) Testing the cell 10 mins after the creation.  	 	 
Dependent Variables	V	V
Voltages (V)	0.720	0.294
	mA	mA
Milliamps (mA)	0.92	0.12

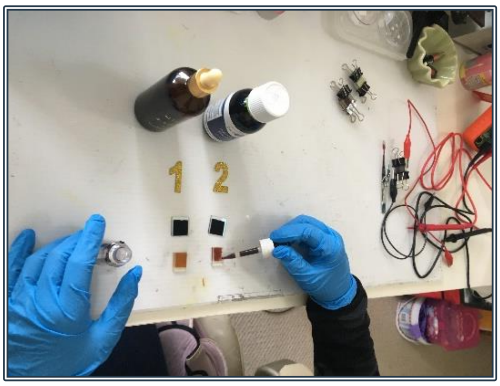


Results of Exp. 6.2:

The above experimental results show that Potassium Triiodide Solution with different concentrations of KI and I_2 can be used in DSSC as electrolyte, but the voltage and current generated will be different. The voltage generated by the cell using the medical iodine solution is relatively weaker compared to the KI_3 produced in laboratory, but it is relatively easier to obtain. It is more convenient and safer for younger students to do the experiment.

The function of electrolyte is to transfer electrons from the counter electrode to the photoelectrode to reduce the oxidized dye molecules on the photoelectrode. Generally, I_3^- / I^- are the most common redox pair ions in the electrolyte of DSSCs, because I_3^- and I^- have good reversibility and high diffusion, the redox energy level also has a good match that of dye. That is the main reason why I chose KI_3 solution as electrolyte. However, the disadvantage of iodine system is its high light absorption, it will compete with dyes to absorb radiation, but the advantages is that the material is relatively easier to obtain.

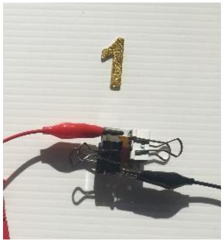
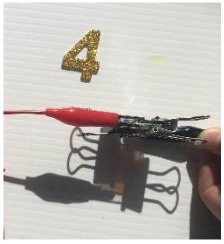
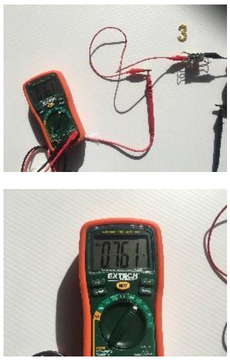
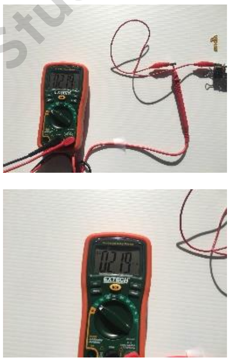
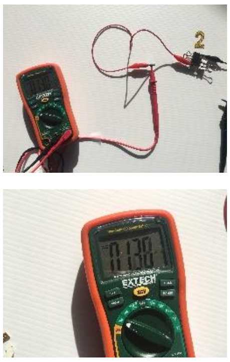
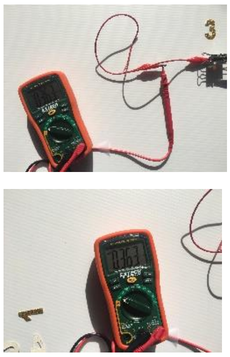
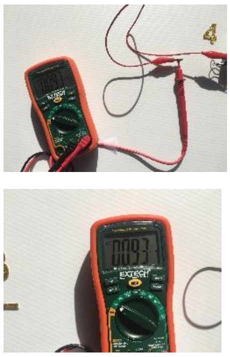


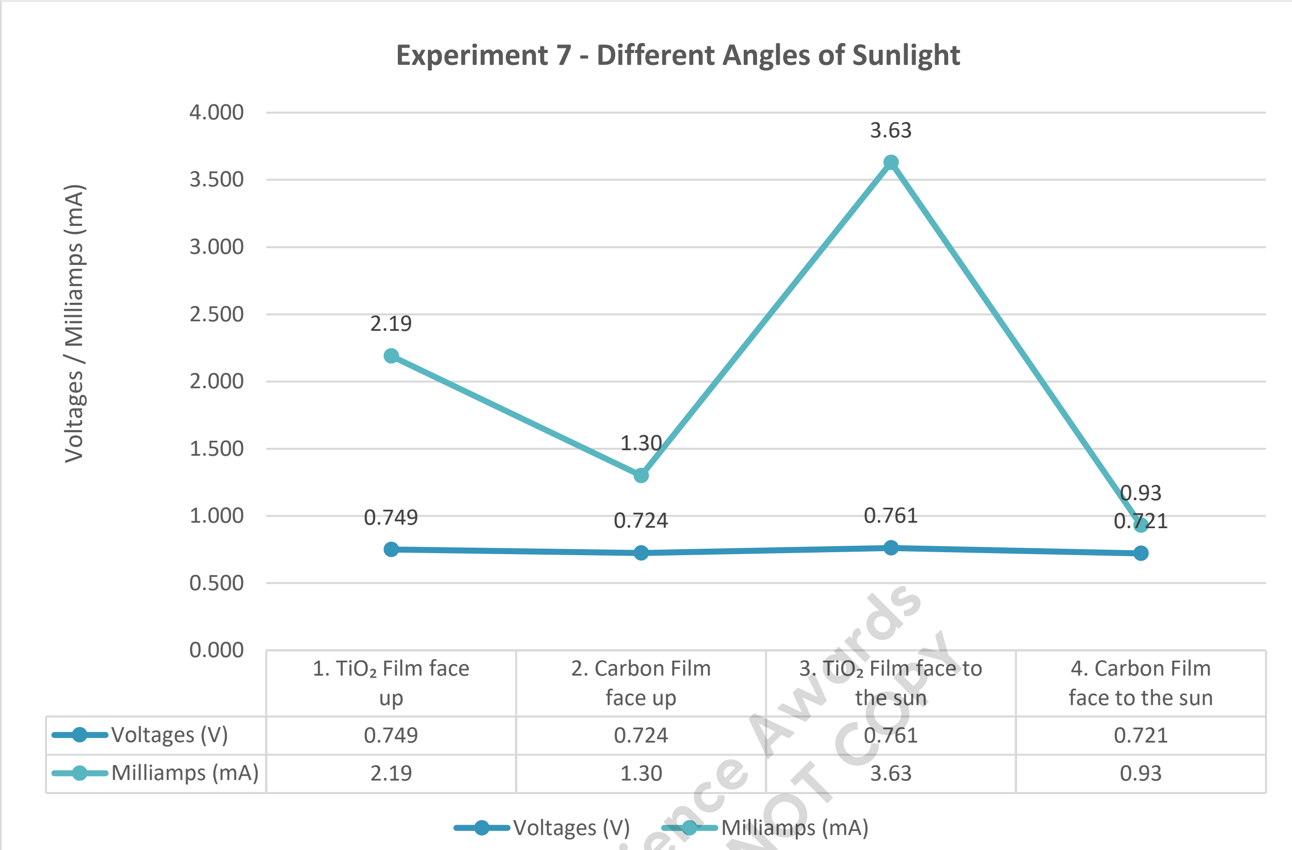


Experiment 7. Will the angles of light influence the voltages generated by the DSSC?

Move the self-made DSSC and multimeter to outdoor where the sun can shine, and then measure the changes of the output voltage and current of the DSSC under different sunlight angles. Choose a sunny noon and place the DSSC model under the sunlight, turning the cell at different angles to see the influence of the light angle on the power generation.

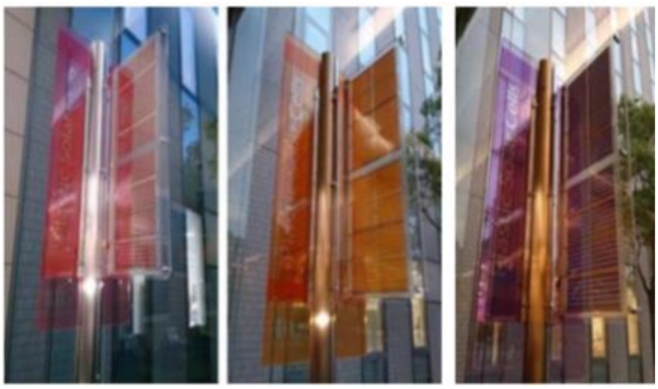
1. **Let the photoelectrode TiO_2 Film face up.**
2. **Let the counter electrode Carbon Film face up.**
3. **Let the photoelectrode TiO_2 Film face to the sun.**
4. **Let the photoelectrode TiO_2 Film face to the sun.**

Fixed Factors **DSSC**	**Independent Variable – Different Angles of Sunlight**			
	(1) TiO_2 Film face up.	(2) Carbon Film face up.	(3) TiO_2 Film face to sun.	(4) Carbon Film face to sun.
				
DSSC with fixed: TiO_2 Paste (1-layer thickness) Dye (Blackberry) Carbon film (candle Fire) Electrolyte (KI_3) Testing the cell 10 mins after the creation.				
				
Dependent Variables	**V**	**V**	**V**	**V**
Voltages (V)	**0.749**	**0.724**	**0.761**	**0.721**
Milliamps (mA)	**mA**	**mA**	**mA**	**mA**
	2.19	**1.30**	**3.63**	**0.93**



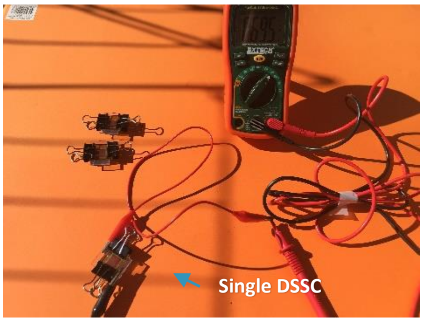
Results of Exp. 7:

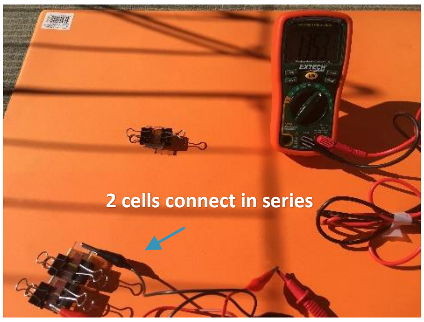
The output voltage and current value of the DSSC are small when the cell is not moved to the outdoor and exposed to sunlight or strong light. A well-made cell can reach a voltage of 05~0.6V under the illumination of effective light source, and even a higher voltage can be generated if the sunlight is sufficient. From the experimental data above, I can see both sides of a well-made DSSC can generate electricity by absorbing the light source. Due to high light transmittance of DSSC, the light source can easily penetrate the dye to generate voltage and current. Therefore, compared with the traditional silicon crystal solar cells, DSSC has lower requirements on light angels and intensity, and does not need a direct light source. The time limitation for generating electricity is relatively smaller, and it can generate power and charge anytime and anywhere without sufficient sunshine at noon. However, if the light is more direct to the TiO_2 film of the photoelectrode, higher voltage and current can be generated (for example, Group 3 data in this experiment).

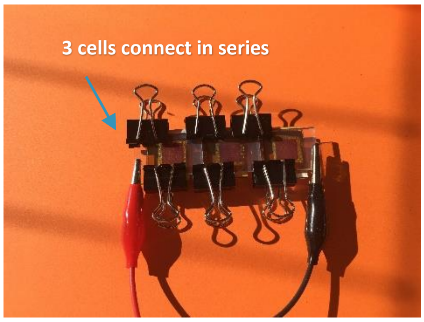


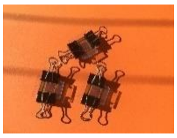
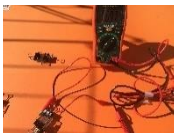
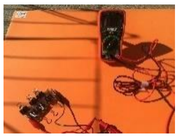
Experiment 8. Comparison of single DSSC and multiple cells in series.

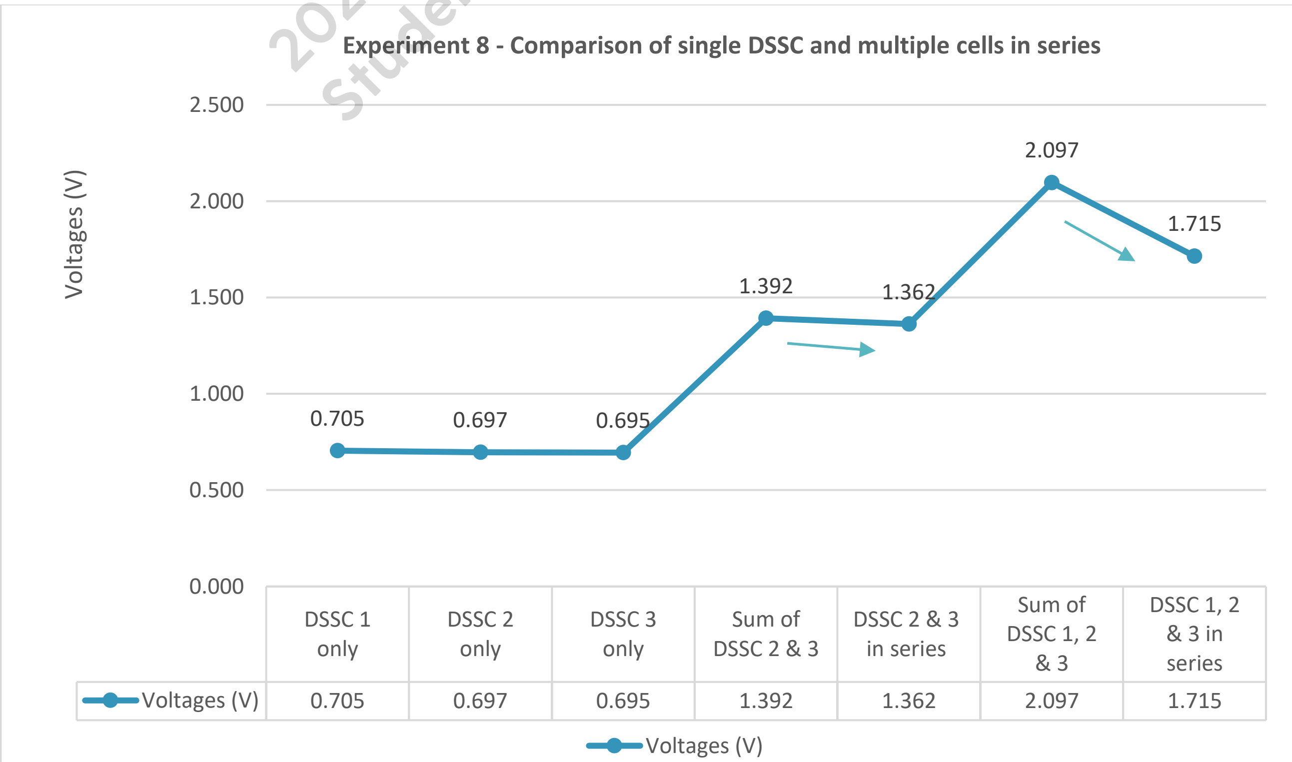
Connecting 2 or 3 DSSCs in series by using binder clips and comparing the voltages with single DSSC.







Fixed Factors	Variables – Numbers of DSSC connecting in series				
	DSSC ① only	DSSC ② only	DSSC ③ only	2 DSSCs in series ②+③	3 DSSCs in series ①+②+③
DSSC with fixed: TiO_2 Paste (1-layer thickness) Dye (Blackberry) Carbon film (2B pencil) Electrolyte (KI_3) Testing the cell 10 mins after the creation.	 	 	 	 	 
Results	V	V	V	V	V
Voltages (V)	0.705	0.697	0.695	1.362	1.715

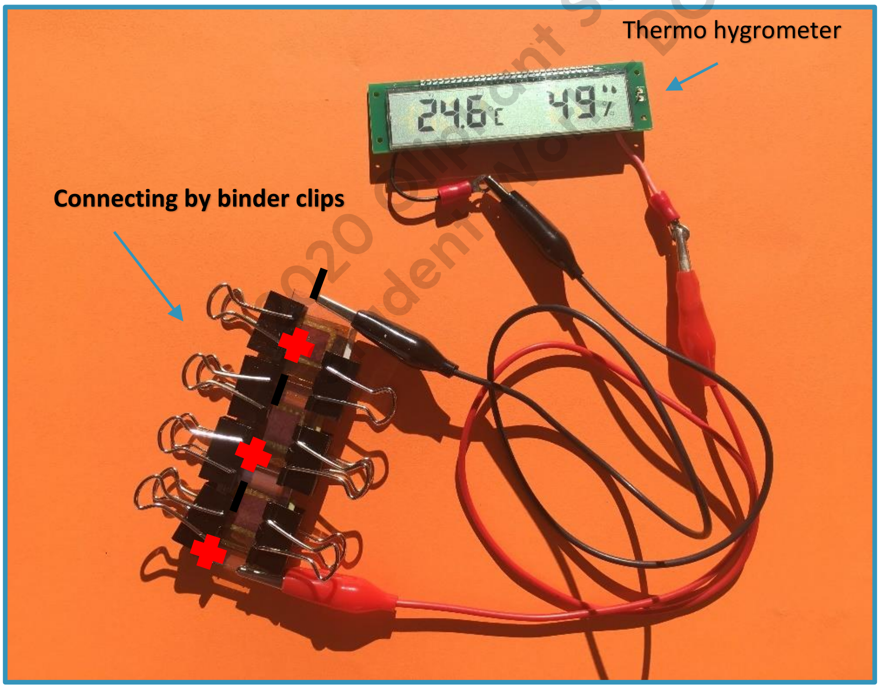


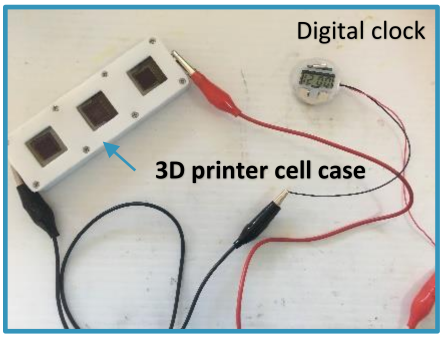
Results of Exp. 8:

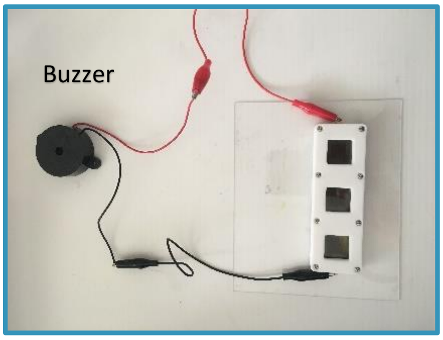
A single DSSC can generate around 0.7 voltage, but the voltage generated by two cells in series is less than the sum of the voltages generated by two separate DSSC models. When I connected three cells in series, the voltages generated is less than the sum of three cells. The voltages reduced from three in series are more than the voltages reduced from two cells in series. When the cells are connected in series, the voltage and current are unstable due to the internal resistance, so the generated voltage will be reduced. The poor contact during series connection will also affect the transmission of electrons.

When I measured the voltages indoor, one DSSC can generate 0.549V, but three cells in series only can generate 1.251V which is lower than the total voltage generated by three individual DSSC models.

One single DSSC model is not powerful enough to drive small appliances, but when I connected three cells in series by clips or place them into my 3D printed cell case, it can start a small electronic clock, or a small buzzer, although a small amount of electricity is reduced.







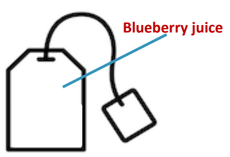
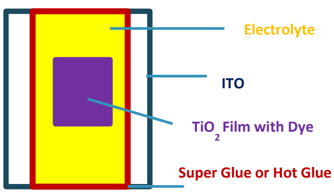
Conclusion

1. The suitable thickness of titanium dioxide film helps to achieve better results.
2. Different arrangement structure of anode carbon film can impact the conductivity of DSSC, compared with the loose stacking of graphite pencil, the reticular arrangement structure of Carbon black is much denser, so the conductivity is better.

3. The stronger the light intensity is, the more easily the electrons in the pigment molecules jump to the excited state, and the voltage generated is also higher.
4. The colours and types of dyes will affect the electricity generated by the DSSCs. Organic dyes made from fruits with high anthocyanins will be the suitable materials for DSSC production, hence dark purple fruits and vegetables will be the good choice, e.g. blackberries, black grapes, or eggplants.
5. The absorption range of the DSSC can be expanded by dyes, the dye containing anthocyanins in the dark blue colour mainly absorb the visible light from the infrared light to the red light in the solar spectrum.
6. The use of alternative materials that are easy to find around us can reduce the cost of experiments and the difficulty of finding special materials, which is suitable and helpful for students.
7. DSSC has lower requirements on light angles and intensity and does not need a direct light source.
8. When the cells are connected in series, the voltage and current are unstable due to the internal resistance, so the generated voltage will be reduced. The poor contact during series connection will also affect the transmission of electrons.

Problem Solving

I met different problems in doing the various experiments mentioned before, also try different ways to find answers and better solution, from which we also find substitutes for materials, for example, I used correction fluid and toothpaste instead of titanium dioxide film, medical iodine solution as electrolyte, whiteboard pens instead of dyes and so on. With the increase of the number of experiments, the DSSCs created by me can produce higher voltage, which means that my production technology is becoming more and more sophisticated. This can be said as my biggest harvest of this research.

Problems	**Failure of Extracting Blueberry Juice**	**Electrolyte Loss**	**Heating Problem**
	Mixing too much pulp into juice.	The cell is not under the completely encapsulation state.	The maximum temperature is not high enough.
Impacts	1. TiO_2 film couldn't colour completely. 2. Result doesn't match my prediction.	1. Only use clips combine the parts. 2. Electrolyte evaporated and loss.	1. Only 100~200°C, cannot dry the TiO_2 film completely. 2. It breaks easily when dyeing.
How to improve?	Re-extract and filtered the blueberry juice carefully.	Use glue or hot glue to package the cells or place a thin paper between the ITO to lock the electrolyte.	Use hair dryer to blow the TiO_2 film continuously.
Methods			

Future prospects and life related applications

1. Used as window glass.

The semi-transparent property of DSSC is very suitable for window materials in office buildings or domestic houses. When the sun shines on dye-sensitized glass building materials, various dyes can be selectively used to convert the indoor heating infrared and harmful ultraviolet absorption into usable electric energy. The energy also can be used in electric curtains and solar greenhouse, the electricity generated can be used for switch control, temperature and humidity adjustment and poser supply.


https://gadgetynews.com/wp-content/uploads/2009/07/Hana-Akari.JPG


https://kknews.cc/news/5avzqvk.html

2. Vehicle sunroof can genreate electricity.

Silicon solar cells have been applied to the skylight of vehicles, however, fue to the opacity and high cost of silicon solar cells, the use of automobile sunroofs is limited. Some vehicles manufacturers have applied for relevant patents and it is believed that it will be used in its automobile products in the near future. Cars can be recharged at any time, even under an indoor parking circumstance without direct sunlight.

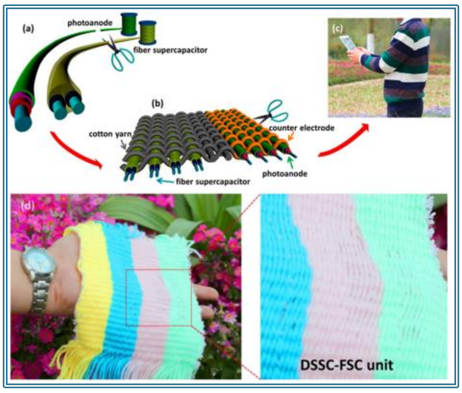

https://kknews.cc/news/5avzqvk.html


https://en.wikipedia.org/wiki/Photovoltaics#/media/File:Ombri%C3%A8re_SUDI_-_Sustainable_Urban_Design_&_Innovation.jpg

3. Linear Dye-Sensitized Solar Cell

The linear DSSC uses carbon nanotube fiber instead of rigid precious metal wire as counter electrode, which is simple to prepare, low cost, high strength, and good flexibility. Through traditional weaving technology, the linear solar cells can be woven into fabrics or integrated into clothes, pants, and other textiles like ordinary chemical fibers, making clothes like a large solar cell to realize their won power generation. This new type of solar fiber cell can convert the sunlight into electric energy and store the energy without connecting other batteries or storage devices, even at night when there is no direct sunlight. People can use DSSCs at will when there is a greater demand for electricity.

https://www.solarfabric.com/wp-content/uploads/2018/11/solar-cell-fabric-2.jpg



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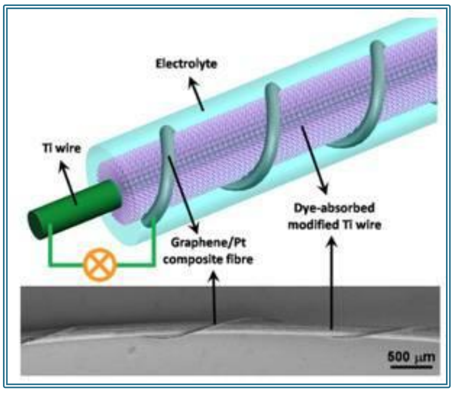

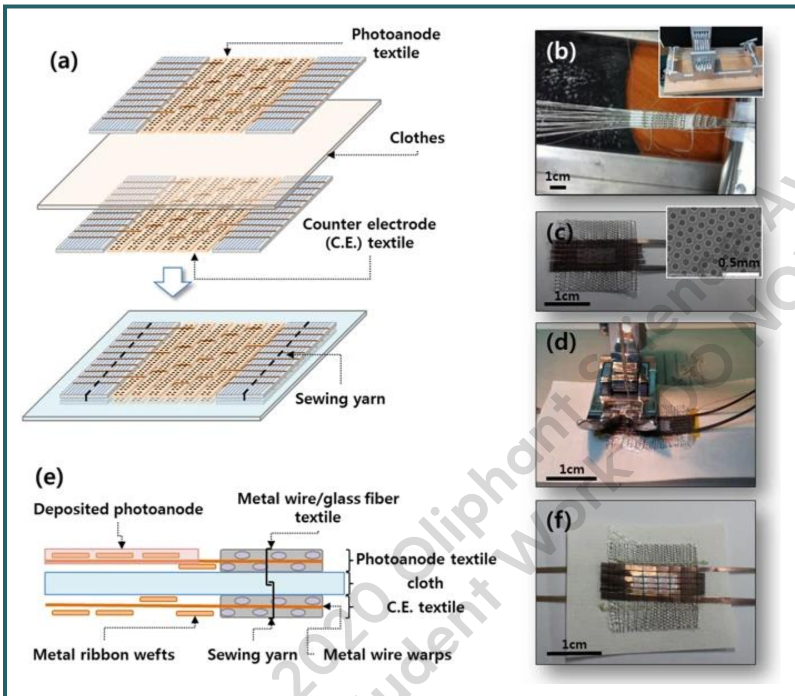

From: **Highly Flexible Dye-sensitized Solar Cells Produced by Sewing Textile Electrodes on Cloth**
Source:
https://www.nature.com/articles/srep05322
Min Ju Yun, Seung I. Cha, Seon Hee Seo & Dong Y. Lee (2015)

(a) Schematic illustration of the fabrication concept for textile-based dye-sensitized solar cells (DSSCs) made by sewing textile electrodes onto cloth or paper.
(b) Photograph of the loom (inset) used to weave the textile electrodes and
(c) a woven electrode. The inset shows an image of the stainless-steel ribbon with periodic holes.
(d) Photograph of the sewing process to attach the woven electrodes to Hanji, a Korean traditional paper.
(e) Schematic illustration showing the cross-sectional structure of the textile based DSSC prepared by sewing and
(f) photograph of a core-integrated textile-based DSSC fabricated by sewing textile electrodes onto Hanji. [8]

4. Used in everyday electronic products.

DSSC can generate electricity through ordinary indoor light, which is another choice of auxiliary power supply for electronic products we use everyday, for example, it can be directly built-in to products with low power consumption such as mobile watches, external foldable power banks, digital clocks, digital calculators and so on because of the flexible, lightweight and transparent features.

In addition to the transparent and flexible features mentioned above, its raw materials are rich, the cost in low, the process is simple, it has the advantage of large-scale production and some raw materials can be fully reused, which is of great sifnificance to the protection of environment. I believe that in the near future, there will be more related products and more diversified functions.

Advantages and Disadvantages of DSSCs

DSSC	Advantages	Disadvantages
	1. Easy process and low costs without semiconductor process. 2. The output power is high when the temperature is over 30°C and conversion efficiency is still high under low light intensity. 3. The range of absorption sunlight spectrum is larger, and both sides of the cell can absorb light, which is favorable for absorbing scattered light. 4. It has transparency and can be directly used in windows. 5. The colour of cell varies with the colour of dye used. 6. Compared with other materials or silicon crystal solar cells, TiO_2 has stable physical and chemical properties, and has no toxicity and environmental pollution compared with other materials or silicon-based solar cells. 7. The energy recovery period is shorter than the of silicon solar cells. 8. It can be made into highly flexible cell module. 9. Large size, mass production process potential.	1. The photoelectric conversion efficiency is lower than that of silicon-based solar cells. 2. The lifetime of the excited state of the dye is not long enough. 3. Electrolyte loss problem still need to be solved. 4. The photoelectric properties of organic material are poor, and the structure will be damaged by ultraviolet rays.  **Source:** https://assets.newatlas.com/dims4/default/5053bfe/2147483647/strip/true/crop/1024x683+0+43/resize/1200x800!/format/webp/quality/90/?url=http%3A%2F%2Fnewatlas-brightspot.s3.amazonaws.com%2Farchive%2Fsony-hana-mado-2.jpg

Summary

It is the dream of scientists to realize wearable solar clothes and 3C devices, DSSC are considered to be the most potential products. Scientist pointed out that although DSSC has gradually moved towards commercialization and mass production, there are still many challenges such as durability, product applicability and battery packaging. Different from the common and mass-produced silicon crystal solar cell, DSSC is easier to manufacture and low cost without semiconductor process and clean room equipment. It can absorb sunlight and transfer electrons through organic dyes without producing any pollution by just simple coating.

In the last two decades, dye-sensitized solar cells (DSSCs) have attracted more attention as an efficient alternative to economical photovoltaic devices, and the highest efficiency record has increased from 7% to 14%. How to effectively increase the photovoltaic conversion rate and the application of other related products will be the main topic of this decade, highly flexible wearable DSSCs is the most important subject among them.

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