**Answer Key: Color Solar Power!**

**Pre-lab Questions**

1. How does the electronic structure of different materials affect their conductivity? What makes a material an insulator, conductor, or a semiconductor?

   In a conductor, electrons are loosely bound and can move freely through the material such as in the "sea of electrons" model for metals. Insulators like non-metals do not conduct electricity because the electrons are tightly-bound. The conductivity of semi conductors lie between conductors and insulators with atoms arranged in a lattice structure.

2. What is the photoelectric effect?

   Photoelectric effect is the ejection of electrons by certain metals when they absorb light with a frequency above a threshold frequency.

3. Define the following terms:
   
   a. Electrochemistry: conversion between chemical energy and electrical energy involving redox reactions.
   
   b. Cathode: the electrode where reduction (gain of electron/s) takes place
   
   c. Anode: the electrode where oxidation (loss of electron/s) takes place
   
   d. Electrolyte: a compound that conducts an electric current when it is in aqueous solution or in the molten state
   
   e. Voltage: a measure of the energy required to move a certain electric charge between the cathode and the anode.

4. The processes involved in dye-sensitized solar cells or DSCs are said to mimic the process of photosynthesis. Explain why this is so. How are the two processes similar? How are the two processes different?

   In photosynthesis, light energy from the sun is converted to chemical energy (food or glucose) in the plants. In dye-sensitized solar cells, light energy is converted to electrical energy. Both processes use plant pigments that absorbs light and produces electrons.

5. Explain the disadvantages of using silicon-based solar cells and organic photovoltaics. The disadvantages of using silicon-based solar cells and organic photovoltaics are the limited supply and high cost of the materials used in these types of solar cells.

6. What is the role of the natural pigments in dye-sensitized solar cells?

   The natural pigments or dyes serve as light-harvesting agents in the solar cell.
Data

Voltage Indoors for Control (no dye) *teacher may provide result | 0 volt

Data Table 1: Voltage (volts) Produced Using Different Types of Light Source

<table>
<thead>
<tr>
<th>Type of Light</th>
<th>Source of Dye</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Black berries</td>
</tr>
<tr>
<td>No light / dark</td>
<td>0.00</td>
</tr>
<tr>
<td>Indoors</td>
<td>0.34</td>
</tr>
<tr>
<td>Outdoors</td>
<td>0.42</td>
</tr>
<tr>
<td>Cellphone</td>
<td>0.35</td>
</tr>
<tr>
<td>UV light</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Current Indoors for Control (no dye) *teacher may provide result | 0 milliamps

Data Table 2: Current (in milliamps) Produced Using Different Types of Light Source

<table>
<thead>
<tr>
<th>Type of Light</th>
<th>Source of Dye</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Black berries</td>
</tr>
<tr>
<td>No light / dark</td>
<td>0.00</td>
</tr>
<tr>
<td>Indoors</td>
<td>0.41</td>
</tr>
<tr>
<td>Outdoors</td>
<td>0.69</td>
</tr>
<tr>
<td>Cellphone</td>
<td>0.57</td>
</tr>
<tr>
<td>UV light</td>
<td>0.62</td>
</tr>
</tbody>
</table>
Calculations
Using the results for voltage and current, calculate the power in watts for each dye-light source combination. The power is calculated by multiplying the voltage in volts by the current in amperes. Record your results in Table 3. The formula is

\[
\text{Power (in watts)} = \text{Voltage (in volts)} \times \text{Current (in amperes)}
\]

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<td>No light / dark</td>
<td>0.00</td>
</tr>
<tr>
<td>Indoors</td>
<td>0.14</td>
</tr>
<tr>
<td>Outdoors</td>
<td>0.29</td>
</tr>
<tr>
<td>Cellphone</td>
<td>0.20</td>
</tr>
<tr>
<td>UV light</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Electricity Generated by Natural Dyes using Different Light Source
Analysis

1. Answer the following questions regarding the power produced by the samples:

   a. Dye source with the highest power indoors: **Blackberry and the hibiscus produced**

   b. Dye source with the highest power outdoors: **Blackberry, hibiscus, red cabbage, and raspberry**

   c. Dye source with the highest power using cell phone as light source: **Blackberry**

   d. Dye source with the highest power using UV Light: **Spinach and the red cabbage**

   e. Dye source with the lowest power indoors: **Spinach**

   f. Dye source with the lowest power outdoors: **Beet Root**

   g. Dye source with the lowest power using cell phone as light source: **Beet Root**

   h. Dye source with the lowest power using UV Light: **Beet Root**

   i. Relate this observation to the color of the dye extracted from these fruits/vegetables. **The dark-colored, purple fruits like blackberry, hibiscus, and red cabbage generally produced high power using cell phone, indoor or outdoor sources of light. The spinach extract, although not purple but dark green, produced the highest power using UV light.**

2. Considering each dye, is there a general trend for the voltage and current in terms of the type of light source? **The power values for outdoors and UV are relatively high compared to indoor and cell phone type of light.**

3. How would you compare the voltage and current produced using indoor artificial light to using the light outdoors especially on a sunny day? **In all the fruits and vegetables tested, the voltage and the current values when using outdoor light source are higher than the values for indoor light source. The power values are also significantly higher for outdoors, in some cases even five to six times higher such as for red cabbage and raspberries.**

4. What is the effect on voltage when the solar cell is exposed to ultraviolet (UV) light? **Give a possible explanation for this result. The power values for all fruits and vegetables tested using UV light are higher compared to indoor values.**

   (Students may hypothesize that because UV light is known to have higher energy than white indoor light, it would follow that the power generated will be higher too. However, based on literature, the reason why power values are initially higher is because the energy is now high enough to cause the electrons in the
nanocrystalline TiO₂ to also be ejected in addition to the electrons coming from the "excited" state dye molecule. This is explained as the electrons being able to go the "conduction band" of titanium oxide. The effect of ultraviolet radiation is actually photodegradation of the natural dye and the iodine electrolyte too. A very practical application of this is the prohibition of using camera with flash in museums. Light, even UV-filtered, damages the natural dyes present in paintings and textiles. Thermal stability is another issue when using natural dyes. It may be worth mentioning that this is the reason why the effort to use natural dyes in baking and cooking has not been completely successful. Beetroot juice, for example, turns brown when heated.)

5. What difficulty did you encounter when extracting the dyes from the fruits and vegetables?
   The extract from blueberry did not appear to be blue in color. Instead it was cream/yellowish in color which is the characteristic color of the tissue inside the fruit. More fruit is probably needed to be able to obtain a darker blue extract.

Conclusion
Which dye-light source combination produced the greatest electrical power? And which combination produced the least electrical power?

The raspberries and blackberries with outdoor light source had the greatest power values whereas spinach with indoor light source had the lowest power value. Note that the coated plate with spinach had the lightest color after preparation indicating that there were not a lot of spinach dye molecules that adhered to the titanium oxide coating. This is caused by the lack of hydroxyl (-OH) groups in chlorophyll pigment which is the major dye in spinach. The hydroxyl group in the dye molecule facilitates the adsorption of the dye to the surface of the nanocrystalline TiO₂.