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Harnessing Solar Energy Using Photosynthetic and Organic Pigments

A THESIS

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Harnessing Solar Energy Using Photosynthetic and Organic Pigments

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DEDICATION

This work is dedicated to my friends and family whom over the years never doubted that I would finish (though I am sure that they did at times!). Above all, I wish to thank my wife, Mandy, who has been my strongest writing partner.

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ABSTRACT OF THESIS

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ABSTRACT:

Fossil fuels are a finite energy resource that must be supplemented or replaced by more stable forms of electrical energy. Solar technology research strives to supplement and provide eventual replacement for fossil fuel technology. This experiment focused on the use of natural pigments as photo-sensitizers in the current generation of solar cells called dye sensitized solar cells (DSSCs). Pigments from purified chlorophyll *a,* chlorophyll *b*, chlorophyll *a/b*, crude spinach (*Spinacia oleracea)* extract, phycocyanin, and chlorophyllin were used to construct DSSCs and evaluated, along with a control containing no pigment, for solar energy conversion. The anode of the solar cells consisted of titanium dioxide (TiO_2) plates soaked in pigment solutions for twenty-four hours. The plates were assembled, along with an electrolyte sandwiched between cells, and a platinum-coated counter plate that functioned as the cathode. A gasket seal was placed between the plates and held together with rubber bands. The DSSCs were each tested for a maximum power (P_{max}) point and a resistor was selected that corresponded to the resistance at that point. The cells were randomly placed into a power block assembly located in an environmental chamber with lighting that provided an average of 27,590 lumens at the surface of DSSCs. With appropriate resistors in place, the cells were subjected to twelve-hour days and twelve-hour nights for ten days, and measurements were recorded every ten minutes. Data were collected to obtain values for voltage in millivolts (mV), current in microamps (μA), and power in microwatts (μW), as well as beginning and ending efficiencies in converting light to usable energy. Voltages were substantially higher during the day than at night for all pigments, except for the control, indicating that the pigments functioned as DSSCs. Hence, only daytime values were used for data analysis. Voltage during the ten-day experiment ranged from 3.99 to 274 mV; current ranged from 0.0180 to 41.9 μA, and power ranged from 0.00 to 11.3 μW. Chlorophyllin had the highest peak and least voltage (274 and 161 mV), highest peak and least current (41.9 and 21.8 μA), and highest peak and least power (11.3 and 4.84 μW). The ranking of the pigments for peak voltage was: Chlorophyllin = Crude Extract ≥ Chlorophyll *a* = Chlorophyll *a/b* ≥ Phycocyanin = Chlorophyll *b* > Control. The ranking for least voltage was: Chlorophyllin > Phycocyanin ≥ Chlorophyll *a/b* ≥ Crude Extract ≥ Chlorophyll *b* ≥ Chlorophyll *a* ≥ Control. Ranking for peak and least values were similar for current and power. Solar energy conversion (efficiency in converting light energy to usable energy in watts per square meter) for all treatments ranged from 0.000595 to 0.0217% at the beginning of the experiment, and was highest in cells constructed with chlorophyllin. Based on rankings from peak and ending voltage values, as well as other measurements, it was concluded that DSSCs constructed with chlorophyllin performed the best and lasted the longest as photo-sensitizers, compared to other pigments used in this investigation. The DSSCs constructed with crude extract performed almost as well as those constructed with chlorophyllin at the beginning of the experiment, but degradation of this naturally-made pigment may have prevented these cells from sustaining solar energy conversion for more than a few days. Other pigments demonstrated conversion values higher than those of control DSSCs which contained no pigments. The results from this project provide evidence that DSSCs can produce useable energy. More research is needed to enhance and prolong the efficiency of DSSCs in solar energy conversion.

INTRODUCTION

Current population increases, coupled with demands for higher standards of living, have resulted in a pressing need for more energy. The United States' energy production as of 2006 was 2.476 quadrillion British thermal units (Btu), whereas, the total energy consumption was 2.796 quadrillion Btu (United States Energy Information Agency of Independent Statistics and Analysis 2006). This energy shortfall has to be met with new and improved methodologies to both produce energy as well as make efficient use of currently available energy.

Existing technologies provide energies from oil, natural gas, coal, wind, solar, hydroelectric, geothermal, nuclear, and other sources. Of those choices, one of the easiest to consistently maintain is solar energy. It is estimated that 640 watts per square meter (W/m^2) are emitted upon Earth's surface daily. Middle latitudes receive more solar radiation, due to less seasonal change, and warm deserts receive more radiation due to lack of cloud cover and their (typical) middle-latitude locations. Even harnessing small percentages of the total amounts of these solar energies could help secure the energy needs for the United States for many years.

Solar Technology History

Solar technology has gone through three generations. The oldest silicon-based wafer technology was first developed at the Bell Laboratories (Chapin et al. 1954). These early cells demonstrated 10% conversion efficiency and were used primarily for space exploration (Goetzberger et al. 2003). These cells were composed of ribbon wafers, which are sheets of extremely thin silicon overlain with conducting metal sheets. The ribbon wafers achieved efficiencies of more than 15% in the conversion of solar energy into usable electrical energy. Other technologies quickly emerged to capitalize on the growing desire for efficiency and smaller size. Amorphous silicon wafers shrunk in thicknesses to micrometers, but maintained efficiencies of 8%. Various metals were used in the light conducting band of the solar cell. Metals introduced into the light conducting band, such as cadmium and copper, improved the efficiency of these solar cells to 16% and 18% respectively (Goetzberger et al. 2003).

The aforementioned technologies utilized either silicon or overlapping layers of different conducting strength metals, embedded within silicon to trap light energy. Trapping the solar energies also had the compounding effect of increasing the temperature of the devices. As temperatures of the silicon solar cells increase, the efficiency of the cell decreases (Goetzberger et al. 2003). This buildup of heat limits the temperature range that these solar cells are effective. To compensate, thinner but less efficient silicon cells were constructed to allow for better heat dispersion. These cells, typical of the second generation of solar technology, are the solar cells most ubiquitous in common applications (Goetzberger et al. 2003).

Researchers began to reexamine the basic principles of light to chemical energy conversion utilized by plants. A new version of the second generation solar cell was introduced when O'Reagan and Grätzel published an article in the journal *Nature* that demonstrated light to electricity conversion efficiencies of 7.1 to 7.9%, using what is known as thin film solar cells (1991). These solar cells used TiO_2 impregnated with dyes and/or pigments to function as receptors for electron excitement. Unique to this process of thin film solar cells is that the materials used are not pure and hence more cost effective than the more expensive silicon.

The simplicity of thin film solar cells instituted a major turnaround from previously-used layering systems. Conductive glass coated with TiO_2, impregnated with dye, and placed in contact with a redox mediator (electron donor) facilitates an electron flow similar to photosynthesis (O'Regan and Grätzel 1991). These cells, called dye sensitized solar cells (DSSCs), mimic photosynthetic processes by enabling the conversion of light into useable energy. In these solar cells, TiO_2 acts as the electron acceptor and iodine replaces water as the redox mediator.

Melvin Calvin was one of the first to investigate chlorophyll analogs for their potential to transform light energy into chemical energy (Salisbury and Ross 1992). In the 1930s, Calvin manipulated the excited triplet states of chlorophyll intermediates involved in electron transfer. Initial results did show some electrical production from the intermediaries (Salisbury and Ross 1992). However, further research was not actively pursued at the time. This is possibly due to the efficiencies of solar cells that mimicked photosynthesis waned in comparison to the energy conversion efficiencies of silicon wafers. Recent research, however, on the development of wet solar cells (Lewis 1995), and photosynthetically active solar cells (Borisov and Sidordin 2003) has brought new interest in the potential use of artificial photosynthesis and electron flow to produce useable energy.

Dye versus Pigment

It is important to note the differences between pigments and dyes. A pigment, in the classical sense, is any colored agent that is maintained as an insoluble suspension within the vehicle that contains it. A dye can be thoroughly dissolved in a solvent. It is possible for a pigment to be reclassified as a dye if the pigment suspension is dissolved in a different medium (Zollinger 1987). There is no distinction between organic or inorganic colorants when using these broad definitions of dye and pigment.

In the biological sense, a pigment is a naturally-occurring colorant produced through biochemical processes (Kumar and Sinah 2004). Chlorophylls, carotenoids, and anthocyanins are classified as pigments due to the biological pathways that synthesize them, regardless of their ability to dissolve or not. Anything not derived from a biological organism can be classified as a dye, particularly if it is artificially produced and can be dissolved in an appropriate solvent. For the remainder of this thesis the term 'dye' will be associated as an artificial colorant, not produced by biological organisms. The term, ‘pigment,’ in this thesis, refers to any colorant produced via biological processes.

Photosynthetic Pigments

The light reactions of photosynthesis for higher order plants can be separated into two distinct parts identified as Photosystems I and II. Both complement each other in the shuttling of electrons towards usable chemical energy during a process called non-cyclic photophosphorylation. Reaction centers in Photosystems I and II use pigments embedded within membranes to capture photons streaming from a light source and shuttle electron excitation energy through a cascade of chemical reactions. The ultimate result is chemical energy available for growth, development, reproduction, repair, and other metabolic processes.

Eukaryotic photosynthesis requires the primary pigments, chlorophyll *a* and *b*, which make up the molecular constituent that is commonly called chlorophyll. Ordinarily, a photosynthetic eukaryote is green in color. The green color is the reflected light wavelengths that were not absorbed by photosynthetic pigments. The chlorophylls *a* and *b* are blue-green and yellow-green respectively (Taiz and Zeiger 2006). The colloquial term, ‘chlorophyll,’ refers to a large category of different molecules of similar structure that work together to harness solar energy.

In non-cyclic photophosphorylation, chlorophyll molecules, associated with enzymes, use photon energy to catalyze the splitting of water and release of electrons. These electrons are then shuttled through a cascade of events to ultimately reduce NADP to form NADPH. One of the electron transport systems in non-cyclic photophosphorylation also enables production of a proton gradient, which is used by a sophisticated enzyme complex to phosphorylate ADP and hence, form ATP (Bidlack and Jansky 2011).

Primary pigments can also be composed of a number of structurally-similar conformations which include the bacteriochlorophylls, pheophytins, bacteriopheophytins, and bilins. Chlorophyll takes alternate forms based upon minute differences in its chemical structure; the name chlorophyll does not change, but its designation changes, based upon the order that different chlorophyll variants were discovered. The different designates of chlorophyll span from *a* to *g*. The eukaryotic chlorophyll *a* is found in nearly all species of photosynthesizing organisms (Goodwin and Mercer 1983). Each chlorophyll variant is characteristic of an evolutionary pathway unique to the family of that species. For instance, chlorophyll *d*, which is found in cyanobacteria, is structurally similar to chlorophyll *a*, but chlorophyll *d* is not found in higher order plants. This similarity provides evolutionary evidence to substantiate a common ancestor, possessing a variant of chlorophyll from anoxygenic to oxygenic photosynthesis (Blankenship and Hartman 1998). Other photo-active pigments of pheophytins and bacteriopheophytins are also present in nearly all forms of photosynthetic organisms and are among the first degradation products produced during the light reaction (Markvart and Landsberg 2002).

The structure of chlorophyll includes a magnesium ion embedded within a tetrapyrole ring of porphyrins with a cyclopentatone ring. An indication of an evolutionary link to eukaryotic ancestors is that the structure of chlorophyll is similar in shape to hemoglobin molecules present in animals. The various differences between all the different chlorophylls stem from the substitution of an aldehyde group for a methyl group on the porphyrin ring, surrounding the magnesium ion (Hopkins and Hüner 2009). In prokaryotes, at the methyl group attachment, the cyclopentane group is saturated in comparison to the eukaryotic form of chlorophyll, which is unsaturated (Green 2001). The prokaryotic form of chlorophyll, bacteriochlorophyll, is found in nearly all prokaryotes other than the cyanobacteria.

The chlorophyll molecule harnesses this light energy at the optimal angle to focus the photons onto the porphyrin ring. Due to their arrangement within the thylakoid membrane, chlorophyll molecules are not free to move about; instead they are bound together to form a macromolecule made of multiple units surrounding a central core. The structure of this macromolecule is composed of 12 core subunits, 4 different light-harvesting scaffoldings arranged in a half moon shape on one side of the superstructure, 45 transmembrane helices, 167 chlorophylls, 3 Fe-S clusters, and 2 phylloquinones (Ben-Shem et al. 2003). The large size of the macromolecule can make the most effective use of photons that strike from shallower angles.

In addition to the primary pigments, other pigments assist in capturing a broader range of light energy, collectively termed antennae pigments. Carotenoids are some of the more readily known antenna pigments, and are generally grouped as either carotenes or xanthophylls. The structures of carotenoids include a branched chain of isoprene units that terminate with the compound phytoene (Blankenship 2002). These carotenoids are found embedded in the thylakoid membrane and are noncovalently attracted to the proteins present therein. In most plants and algae, beta-carotene and a xanthophyll lutein are the most abundant of all carotenoids found in the thylakoid membrane (Taiz and Zeiger 2006). These carotenoids are critical for absorbing some of the energy in the visible spectrum that would ordinarily be unavailable to the primary chlorophylls. These pigments capture this light energy and ultimately assist in the conversion of light energy into biochemical energy for the plant in a process called inductive resonance transfer (Taiz and Zeiger 2006).

Other organisms such as red algae (Phylum Rhodophyta) utilize secondary pigments such as phycocyanins (French and Young 1951). These phycocyanins are water soluble pigments that exist outside the thylakoid membrane and aggregate into a structure called the phycobilisome, which shuttles energy into Photosystem II (Grossman et al. 1953). These pigments assist natural chlorophylls in harvesting light energies that dissipate in the water column. Only higher energy wavelengths of light exist in deeper columns of water.

Dye Sensitized Solar Cells

Multiple organic dyes have demonstrated their ability to act as photosensitizers for solar cells. Cyanine dyes (Ehret et al. 2001), porphyrin structured dyes (Kay et al. 1994: Cherian and Wamser 2000: Odobel et al. 2003: Amao and Komori 2004: Amao and Yamada 2005), coumarin dyes (Hara et al. 2003), as well as anthocyanins (Cherepy et al. 1997: Dai and Rabini 2002) and carotenoids (Amao et al. 2006) have been used to demonstrate the capabilities of different biological photosensitizers in converting light into electrical energy. Several factors are determinate for the success of a potential dye or pigment as an effective photosensitizer. These include a conjugated system of molecules, the energy levels of the molecule, excited state lifetimes of the molecule, and the anchoring groups of the dye to the nanocrystalline surface.

Conjugated system

A conjugated system is an organic molecule with atomic orbital and double bonds that form a generalized delocalization of the electron cloud of the molecule's individual atoms (Smith and March 2007). All electrons of the highest orbital are able to flow from one atom to another. The alignment of the outer orbital with a group of atoms within the molecule further increases its stability and lowers its overall energy. Ordinarily, the more conjugated bonds there are in a molecule, the more delocalization of the electron cloud exists within that molecule (Gorman and Marder 1993). This delocalization lowers the energy necessary for the electron to transition from the highest pi bonding orbital and the lowest energy pi anti-bonding orbital. The difference in the energy between these two orbitals can also be referred to as an energy gap or band gap. Thus, the movement of an electron from one point to another within the molecule takes less energy to transport in a delocalized system (Thekinneydath and Louis 2010).

Energy Levels

The molecular energy levels of the dye or pigments in DSSCs are determined, in part, by their ability to introduce an electron into the conduction band of TiO_2. This is found by comparing the energy differences between the conduction band of the TiO_2 and the oxidation potential of the excited dye or pigment attached to the TiO_2 (Sheng et al. 2008). Calculations of the potential energies of the electron in the highest orbital are generally set to zero, causing the bound electron shell to have negative values. To overcome these negative values, energy must be provided for the system which, in the case of DSSCs, is provided by light. An excited molecule with higher energies than the anchoring molecules will possess a thermodynamically favorable flow of energy from the excited molecule to the anchor molecule (Kuciauskas et al. 2001). For a successful dye to be an efficient energy carrier, it must have a high excited state energy positive value, and the conduction band needs to be a low negative number.

Excitation Lifetimes

A pigment or dye transfers the excited electron to its anchoring group at a particular speed, after which it is returned to a receptive state (Jingrui et al. 2008). When a wavelength of light strikes a dye or a pigment, the electrons of the dye or pigment become excited and jump to a higher energy level. This frees the electron to migrate towards lower energy states in adjoining atoms or molecules. For DSSCs, the higher energy electron passes to the anchoring TiO_2 and can be measured. An example is the recharging rate of an excited electron of a carotenoid that is struck with a photon. The carotenoid pigment enters into an excited state and the time to fall back again to its receptive state is about 366 femtoseconds (Niedzwiedzki et al. 2006). The faster the cycling of the dye from excited to receptive state, the more photons the dye can convert to electrical energy in a given unit of time.

Anchoring Groups

An anchoring group provides bonding between two different molecular groups, such as the TiO_2 substrate and pigment molecules (Taffa et al. 2009). If a strong anchor is not established between the dye/pigment and the substrate, electron flow is restricted. Currently, carboxyl bonds with secondary hydroxyl bonding tend to show the highest electron flow (Sepehrifard et al. 2008). Carboxyl groups are found in many synthetic dyes currently being used in DSSCs. Many pigments rely on carboxyl, hydroxyl and ether group attachments to their anchoring point to facilitate electron movement (Vokacova and Burda 2007).

Pigments and dyes that have bonds closer to their anchoring points may show increased efficiencies. This may be due to the smaller energy gap between the conjugated system and the anchoring group (Ernstorfer et al. 2006). Much like potential energy, an electron has to overcome a resistance barrier before it can be carried across to the conductive band of its anchoring molecule. A closer bonding will encourage secondary anchoring sites, such as carboxyl and hydroxyl groups. Close attachments assist in maintaining the higher excited molecular state over a shorter distance. This allows a stronger difference in the potential energies between the systems resulting in a more thermodynamically favorable flow of electrons from dye to substrate (Kathiravan and Renganathan 2009).

Dyes

Ultra-violet light proves to be a limiting factor in the longevity of many dyes. However properly filtered; these dyes can be very photostable (Tennakone et al. 1997). Other dyes, such as ruthenium-based dyes, are actively being investigated for their potential as broad light spectrum synthetics with an absorbance range from 300 to 740 nm. Ruthenium-based dyes possess a moderately strong potential energy of 0.455 volts, allowing them to overcome the relatively weak TiO_2 conducting band gap (Grätzel 2005). These dyes can currently achieve an 11% conversion efficiently of light into electrical energy. Depending upon the cost of dyes used in DSSCs and production costs, these types of solar energy devices may be good alternatives to the relatively expensive silicon wafers used in energy conversion.

The primary hurdles effecting ruthenium dyes include cost and synthesis. The dye, cis-bis (4, 4-dicarboxy-2, 2-bipyridine) dithiocyanato ruthenium (II), more commonly known as N3, currently holds the 11% overall efficiency value that is typically achieved with DSSCs (Grätzel 2005). However, with a price tag approaching $1,000 per gram, N3's cost discourages many scientists wanting to experiment with this novel dye complex. Roughly 12 tons of ruthenium are mined each year, with world reserves estimated to be 5,000 tons (Emsley 2003). The rarity of this metal will continue to push prices higher as more ruthenium is mined to accommodate growing demands. To offset the growing costs of ruthenium, natural pigments synthesized from plants are being investigated as a potential source of photosynthesizing elements for DSSCs.

Natural Pigments

Early in the development of DSSCs, Grätzel examined the potential of using chlorophyll and its derivatives for its energy conversion capabilities, and achieved 3.5% efficiency at the 670 nm wavelength (Kay and Grätzel 1993). Grätzel's natural pigment investigations continued with anthocyanins as a pigment source for the cell, but conversion efficiencies were only 0.56% (Cherepy et al. 1997). He quickly moved away from the concept of natural pigments as the photosensitizer for DSSCs, as these pigments only cover a limited wavelength range (Grätzel 2001). Grätzel's transition away from natural pigments could also be the result of his development of the N3 dye molecule which is considered the standard DSSC dye molecule (O'Regan and Grätzel 1991).

Despite the poor conversion efficiencies of natural pigments reported by O'Regan and Grätzel (1991), research has continued with natural pigments in other laboratories. In 1997, V.V.

Nikandrov and team worked on the porphyrin ring structures that are prevalent throughout nature. They investigated mammalian ferritin as a photocatalyst. Their work concluded that shape is very important for a dye or pigment to be considered as a photocatalyst candidate. Coumarin based dyes were examined in 2003 by Hara and coworkers. Nearly 6% conversion efficiencies were demonstrated due to the chemical binding of the carboxyl group in coumarins to TiO_2. In 2004, Yutaka Amao and Tasuku Komori examined the effects of chlorine-e6 derived from the chlorophyll of *Spirulina* as a photocatalyst. Results suggested that the conversion efficiency for chloroine-e6 efficiencies was about 7.40% at 400 nm. Later that year, Yutaka Amao and team reported a new efficiency of 11% at 400 nm from the same pigment.

The chlorophyll of *Spirulina* was later examined by Kathiravan and team in 2005 to observe the conversion of photons to current via the carboxyl attachment of the pigment to the TiO_2. Kathiravan et al. (2009) examined the phycobiliprotein of red algae, phycocanin, and suggested its possible use as a photocatalyst in DSSC's, but did not report voltage characteristics for phycocyanin. In 2009, Paola De Padova and team also examined relationships with chlorophylls *a* and *b*, carmic acid, beta carotenes, and crude extracts of the black mulberry, *Morus nigra*, as photosensitizing elements. The research concluded that a mixture of natural pigments produced better voltages and currents than the individual pigments.

Goals and Objectives:

Current research focuses on dyes and pigments with characteristics similar to chlorophyll (Ichimura et al. 1996, Hara et al. 2001). Previous investigations at the University of Central Oklahoma (UCO), for instance, have enabled construction of primitive photovoltaic cells with plant pigments that produce voltage of under 150 millivolts (Overall et al. 2004). Expansion and modifications of this research, through use of refined methodology and different photosynthetic pigments, have the potential to improve voltages produced and enhance conversion of solar energy into measurable electrical energy. Hence, research for this thesis is focused on two aspects:

1) To gather experimental experience on the preparation of the dye-sensitized, nanostructured solar cells.
2) To integrate organic components into solar cells to maximize solar conversion efficiencies.

The null hypotheses for this thesis were as follows:

1) Pigment types will not alter the voltage, current, or power values produced by photovoltaic cells.
2) Light will have no effect on the voltage, current, or power values produced by the photovoltaic cells.
3) Age of the photovoltaic cell and its components will have no effect upon the voltage, current, or power values.

The alternate hypotheses for this thesis were as follows:

1) Pigment types will result in photovoltaic cells that produce different voltage, current, and power values.
2) Light will stimulate production of voltage, current, and power and provide discernable differences in readings taken in the light and in the dark.
3) Age of the photovoltaic cell and its components will have significant effects upon the voltage, current, and power values.

MATERIALS AND METHODS

Materials Purchased

Isolates of chlorophyll *a* and *b* were purchased from Sigma Aldrich, St. Louis, MO. These isolates were made from the blue-green algae, *Spirulina*. Chlorophyllin and phycocyanin isolated from *Spirulina* were also purchased from Sigma Aldrich. Methanol and all other chemical reagents were also purchased from Sigma Aldrich.

Spinach (*Spinacia oleracea*) was purchased from a local supermarket, Homeland Stores. Titanium dioxide (TiO_2) anode plates, platinum-coated cathode plates, and thermoplastic gaskets (Suryln© 30) were purchased from Dyesol (Queanbeyan, Australia).

Treatments

Different treatments (chlorophyll *a*, chlorophyll *b*, chlorophyll *a/b*, crude extracts of spinach, phycocyanin, and chlorophyllin) were evaluated to determine the potential for using plant pigments as light-absorbing receptors for solar cells. Target concentrations of pigments were based upon the concentrations of chlorophyll *a* and *b* present in crude extracts, which served as a baseline for other treatments. Individual chlorophyll *a* and *b* concentrations, as well as the chlorophyll *a/b* ratio, were adjusted to equate these concentrations present in the crude extracts. Phycocyanin and chlorophyllin concentrations were adjusted to equate the concentration of chlorophyll *a* present in the crude extracts. A treatment of no pigment was used as the control.

Chlorophyll Isolation

The crude extract was partially purified similar to the procedure outlined by Iryama et al. (1977). Slight modifications were made for the use of methanol as the extraction solution. Spinach was kept in the refrigerator at 4 ^{o}C to keep cold. Exactly 10.0 g of spinach leaves were

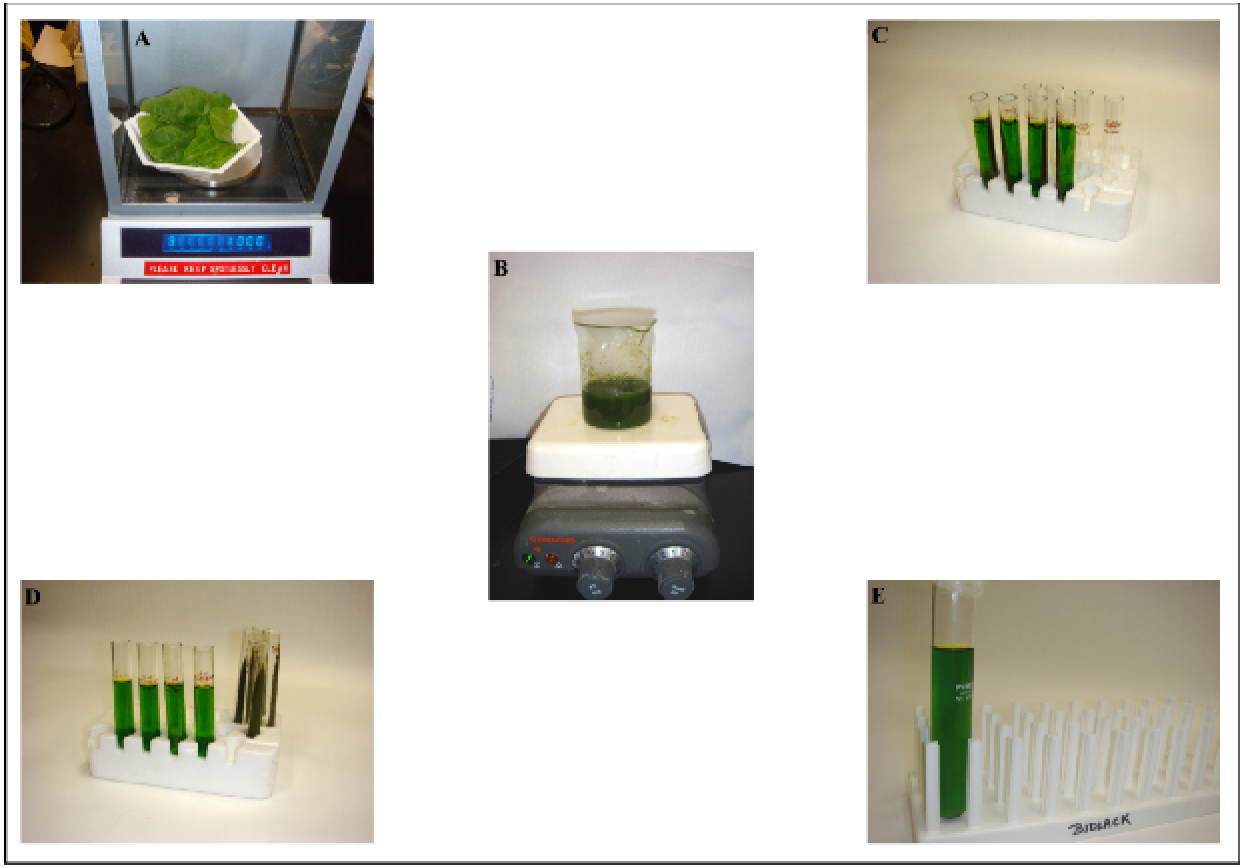

Figure 1: Processing steps of crude extract. Spinach stems were removed and the leaves were weighed to 10.0 g (A). The leaves were then ground with a homogenizer with 50 mL of methanol until thoroughly blended and stirred (B) for one hour to extract as much as the pigment as possible. Centrifuge tubes (C) were filled with crude extract sample after passing through four layers of cheese cloth to remove rough impurities. The crude extract was then centrifuged twice (D) to further clarify the sample. The final centrifugation produced crude extract samples that were used for preparation of photovoltaic cells.

weighed and torn into small pieces and placed in a 100 mL beaker (Figure 1A). Then, 50 mL of methanol at 4 ^{o}C were added to the beaker with the spinach leaves. A tissue homogenizer (IKA-Labortechnik Ultra-Turrax T25, Staufen, Germany) was used at medium speed (13,500 rpm) and the leaves and methanol were homogenized blended for three minutes.

The slurry was stirred rigorously at room temperature for one hour to extract the chlorophyll with methanol (Figure 1B). The slurry solution was poured through four layers of cheesecloth into a cold, 4 ^{o}C, beaker. The solution was then transferred to four cold, 4 ^{o}C, 15 mL centrifuge tubes (Figure 1C). Centrifugation occurred in a Beckman J2-21 centrifuge (Beckman Instruments, Palo Alto, CA) with a JA-17 cm circumference rotor and maintained at 4 ºC. The slurry was first centrifuged at 5,000 rpm (3,440 *g*) for ten minutes. The resulting supernatant was then transferred to another clean, cold, 4 ^{o}C, 15 mL centrifuge tube and the pellet was discarded (Figure 1D). The supernatant, containing chlorophyll in methanol, was centrifuged again at 8,500 rpm (9,950 *g*) to pellet remaining chloroplasts and other debris. The final supernatant from the four centrifuge tubes was then combined into a clean, cold 100 mL test tube, covered, and stored at -20^{o}C for no longer than 12 hours (Figure 1E).

Absorbance

Chlorophyll concentrations were analyzed using a Varian Cary 50 UV-Vis spectrophotometer (Varian Inc., Palo Alto, California). The cold crude extract was shaken gently to ensure uniformity of the chlorophyll suspension prior to analysis. The spectrophotometer was standardized using cold, 4 ^{o}C methanol. A 3.0 mL sample of the chlorophyll suspension was placed into a cuvette and its absorbance was measured. The crude extract's absorbance was measured five times at 647 nm and the average reading was recorded and repeated at the 664 nm wavelength. An example of the data obtained for one chlorophyll suspension is provided in Table 1.

Table 1: The simple reads report from the Cary 50 UV-Vis spectrophotometer. The report indicates the absorption levels of the sample crude extract. Numbers in parentheses are negative.

Read	Absorption	nm
Zero	(0.1180)	647
1	1.3451	647
2	1.3455	647
3	1.3465	647
4	1.3479	647
5	1.3462	647
6	1.9700	664
7	1.9644	664
8	1.9713	664
9	1.9738	664
10	1.9716	664

The absorbencies were used to calculate concentrations of chlorophyll a and b in the methanol solution. Equations, as modified by Ritchie (2006 and 2008), allowed for analyses of chlorophyll concentrations in methanol. The equations provided for chlorophyll concentrations in micrograms per liter. The equations were as follows:

Chlorophyll *a*:

$$-8.0962 \text{ (Abs 647)} + 16.5169 \text{ (Abs 664)}$$

Chlorophyll *b*:

$$27.445 \text{ (Abs 647)} - 12.1688 \text{ (Abs 664)}$$

Concentration

The concentrations of chlorophyll *a* and chlorophyll *b* in crude extracts were used as the basis to determine concentrations of chlorophyll *a*, chlorophyll *b*, the ratio of chlorophyll *a/b*, and concentrations of samples for other pigments. The concentrations necessary for the remaining samples were determined using the following dilution equation:

$$C_1V_1=C_2V_2$$

C_1 is the concentration of the solution to be diluted, V_1 is the volume of the solution to be diluted, C_2 is the final concentration of the solution, and V_2 is the final volume after dilution.

Concentrations of stock solutions were as follows: Chlorophyllin = 100 mg/L; Chlorophylls *a* and *b* = 0.025 mg/L; Phycocyanin = 5.0 mg/L. All stock solutions were kept at -20 ^{o}C with the flasks shrouded in foil to minimize any light interaction with the pigments. The refined pigments were diluted with pure methanol to 50.0 mL in separate flasks to the appropriate concentration of pigments found in crude extracts (Figure 2). Refined chlorophyll *a* and chlorophyll *b* were diluted to the concentrations of the naturally-occurring pigment present in the crude extract which ranged from 21.7 to 32.6 μg/L for chlorophyll *a* and 12.8 to 15.6 μg/L for

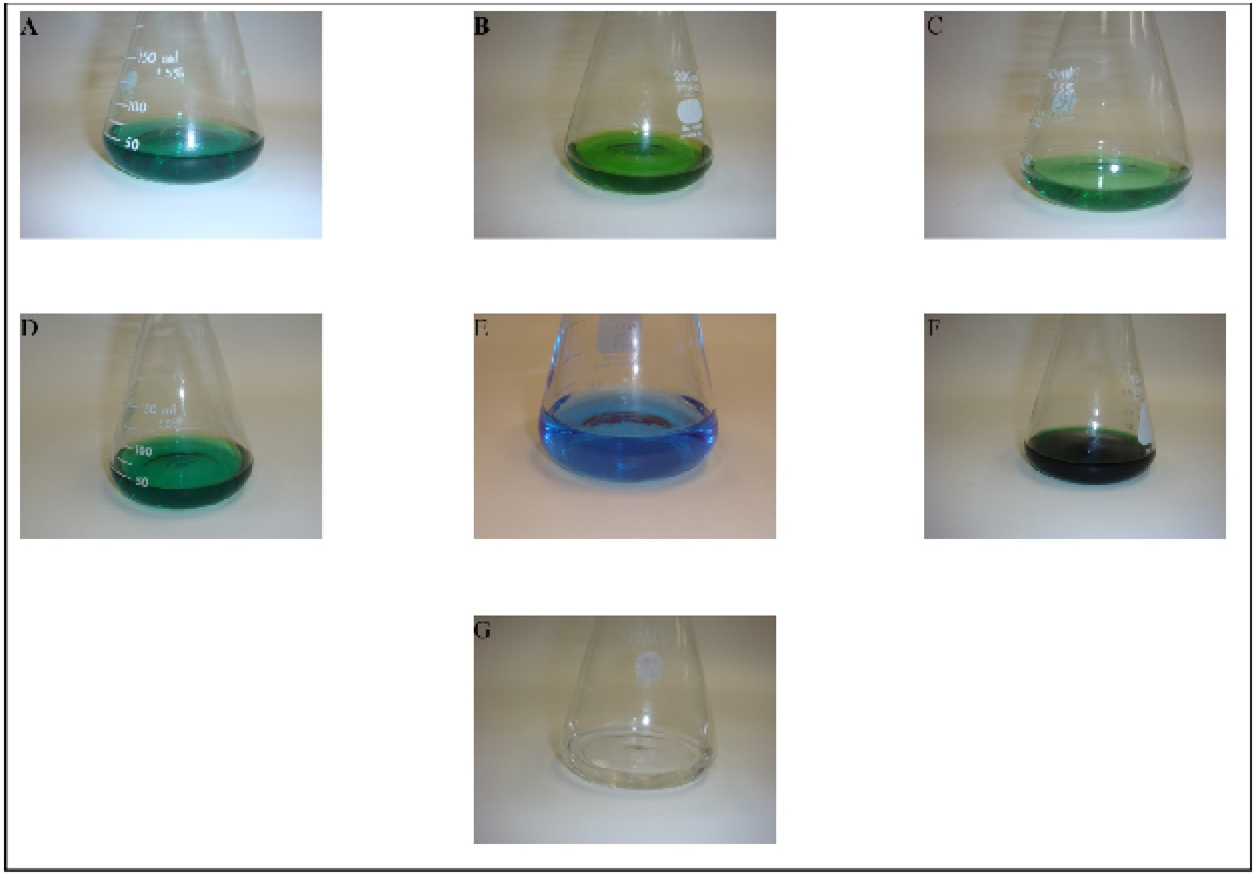

Figure 2: Pigments and their colors used to stain the TiO_2 plates. Refined chlorophyll *a* (A) was adjusted to the concentration of chlorophyll *a* from crude extract (D). Refined chlorophyll *b* (B) was adjusted according to the concentrations of chlorophyll *b* found in the crude extract. Refined chlorophyll *a*/*b* ratio (C) was adjusted to the ratio of chlorophyll *a*/*b* found in the crude extract. Phycocyanin (E) was adjusted to the concentration of chlorophyll *a* found from crude extract. Chlorophyllin (F) was adjusted to the concentration of chlorophyll *a* found in the crude extract. The control (G), methanol, contained no pigments.

chlorophyll *b*. The chlorophyll *a/b* concentration was adjusted to equate the ratio of chlorophyll *a/b* in the crude extract. The concentrations of chlorophyllin and phycocyanin were based upon the concentrations of chlorophyll *a* from the crude extract. The control consisted of pure methanol and no pigment. The 50.0 mL pigment samples were each poured into a respectively labeled Petri dish. Four TiO_2 plates from Dyesol were lowered into the pigment solution with the TiO_2 side up. All solutions were sealed with masking tape and placed into the refrigerator at 4 ^oC for 48 hours to allow full pigment impregnation into the active TiO_2 surface.

Cell Construction

The plates were then removed from the flask and 5.0 mL of methanol was sprayed onto the plates to gently to remove any non-bonded pigments from the surface. The plates were then allowed to air dry at room temperature (Figure 3).

A thermoplastic gasket was laid around the active area of the TiO_2 plate (with pigment) and functioned as the anode. Two microliters of solution containing 0.50 M potassium iodide and 0.05 M iodine, dissolved in ethylene glycol, were applied to the stained TiO_2 plate as the electrolyte. The platinum-coated plate, that functioned as the cathode, was placed on top of the TiO_2 active surface, and squeezed gently together with the anode plate (TiO_2 impregnated with pigment) to remove air bubbles. The plates were then held together with small rubber bands, being careful to not cover any area of the glass that contained pigment.

Solar Cell Assembly

A resistor from Radio Shack (Ft. Worth, TX) was selected at ± 20% of the maximum power point of each specific solar cell. A power block was constructed to provide multiple voltage measurements over the course of the experiment (Figure 4). The power block's construction allowed for anchoring of the solar cell with the appropriate resistor in series with the circuit. Voltages were measured using a PICO (Cambridgeshire, United Kingdom) ADC-16 High

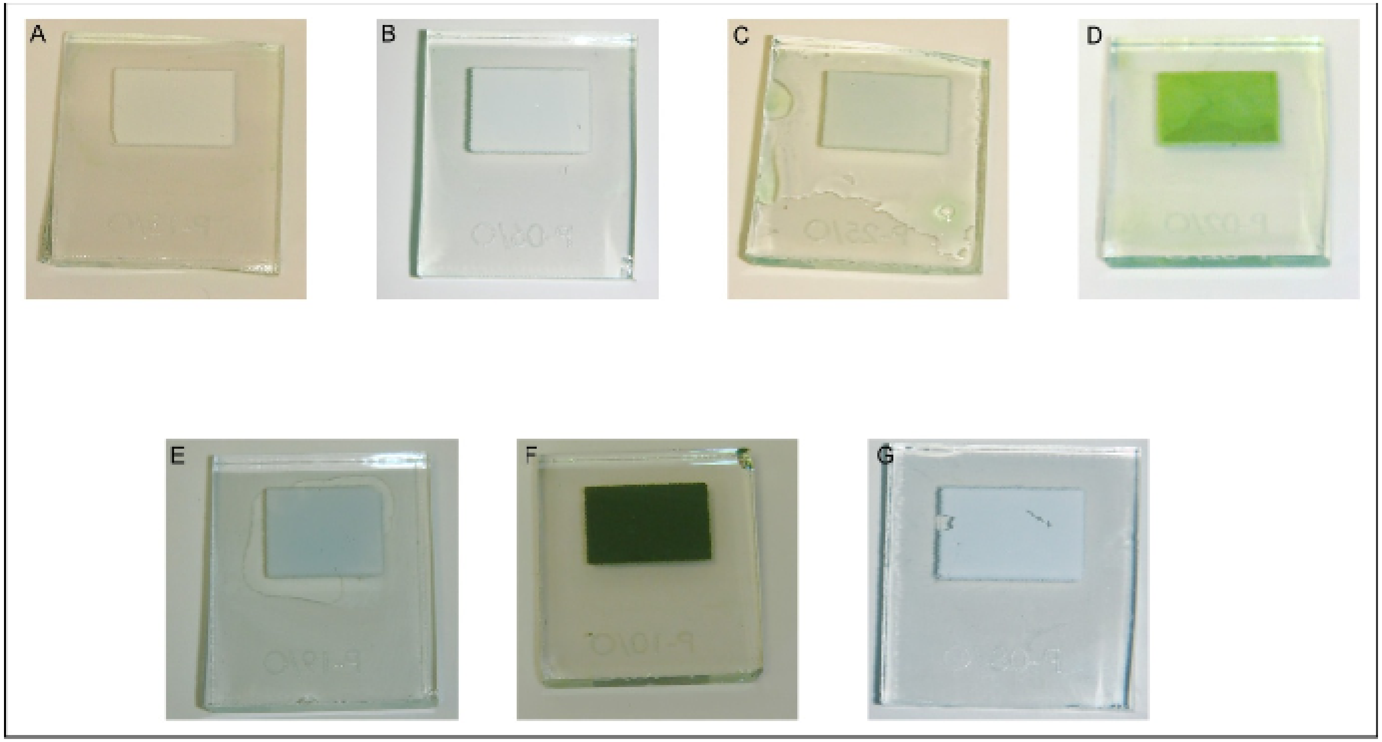

Figure 3: TiO_2 plates following the pigment staining. Chlorophyll *a* (A), chlorophyll *b* (B), chlorophyll *a/b* (C), crude extract (D), phycocyanin (E), chlorophyllin (F), and the control (G) were stained for the same length of time in their respective pigments.

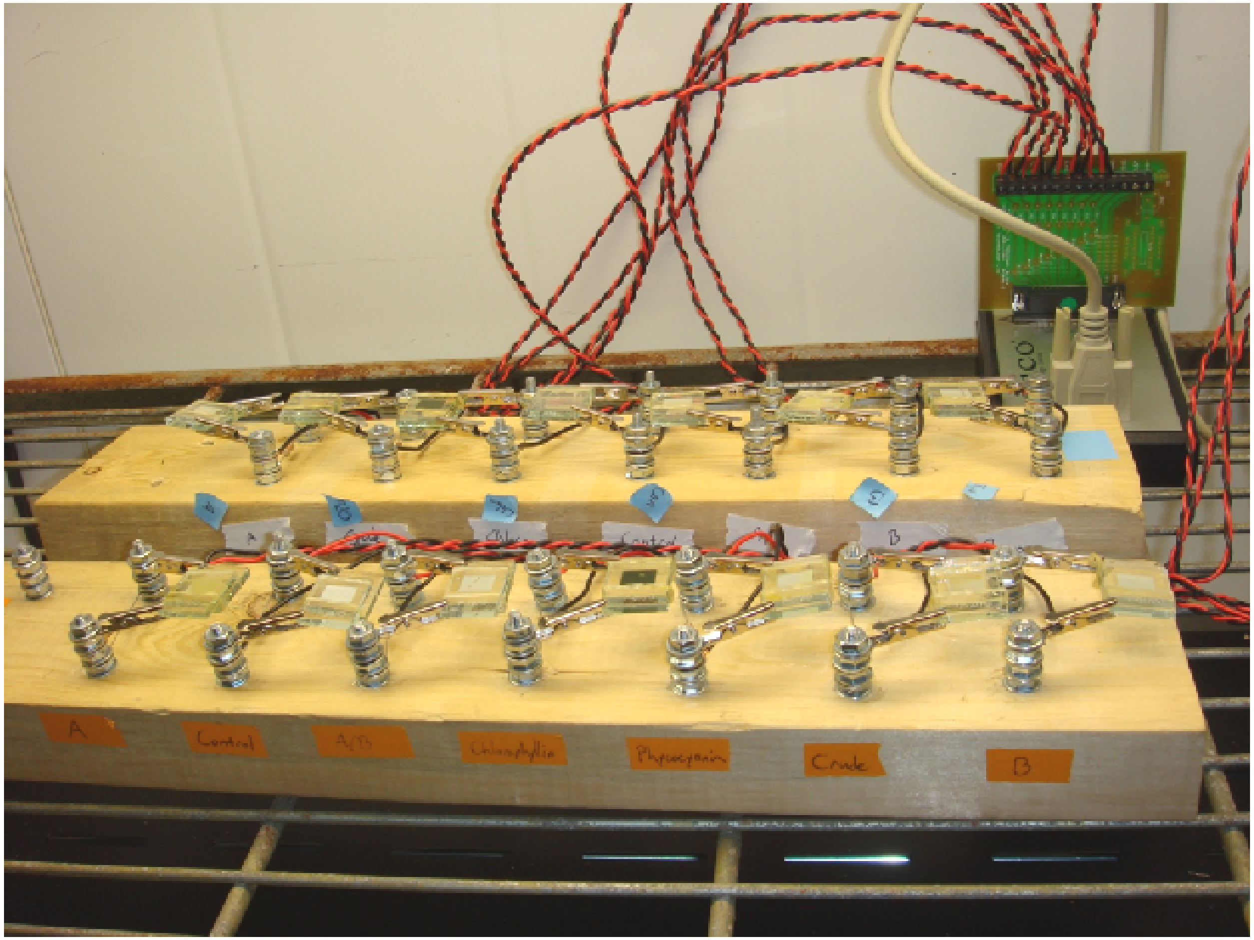

Figure 4: Power blocks arranged under the lights of the environmental chamber. A PICO logger can be seen in the background that was used to measure voltages every ten minutes for ten days.

resolution data logger with the electrical leads connected to the logger, placed in parallel to the circuit.

Each power block consisted of one replication of the treatments that were tested. Each power block was numbered one through four. The treatments in each block were assigned a name that corresponded to its replication number (e.g. Chlorophyll *a*-1 was the chlorophyll *a* treatment in power block replication one) (Table 2). Each cell was secured into one of the power block's seven positions. The solar cell was clamped in place with the platinum cathode plate pointed away from the light. The resistor for each treatment was installed and the leads to the voltmeter were securely anchored to the power block.

Measurements

Beginning Power Curves

All solar cells were measured with a voltmeter in the environmental chamber to determine their voltage production as resistance was increased according to Ohm's law. The solar cells were connected in series to a variable resistor (Model RS-500, Elenco Electronics, Wheeling, IL) using banana clips attached to the tin-coated glass plate. A voltmeter was connected, in parallel, between the resistor and the solar cell. Light emitted upon solar cells was supplied by Tek Light systems fixtures (Sunlight Supply, Inc., Vancouver, WA) with four 39 Watt Philips (Amsterdam, The Netherlands) F39T5/841 high output bulbs. The intensity of light emitted upon solar cells averaged 27,590 lumens.

Ohms' law states that the current flowing between two points is directly proportional to the potential voltage across the two points, and inversely proportional to the resistance between them. The formula for this equation is written as:

$$I = V/R$$

Table 2: The position of each treatment assembled in the power block.

REPLICATION #1 First set of Cells	REPLICATION #2 Second set of Cells	REPLICATION #3 Third set of Cells	REPLICATION #4 Fourth set of Cells
Chlorophyll *a*-1	Chlorophyllin-2	Chlorophyll *a*-3	Chlorophyll *b*-4
Control-1	Chlorophyll *a/b*-2	Crude Extract-3	Chlorophyllin-4
Chlorophyll *a/b*-1	Phycocyanin-2	Chlorophyllin-3	Control-4
Chlorophyllin-1	Chlorophyll *a*-2	Control-3	Phycocyanin-4
Phycocyanin-1	Control-2	Chlorophyll *a/b*-3	Crude Extract-4
Crude Extract-1	Chlorophyll *a/b*-2	Chlorophyll *b*-3	Chlorophyll *a*-4
Chlorophyll *b*-1	Crude Extract-2	Phycocyanin-3	Chlorophyll *a/b*-4

An open circuit is indicated when resistance (R) is at the maximum point where maximum voltage (V) can pass across two points of a circuit, but no current (I). A closed circuit is measured when the resistance is set low enough so that no voltage crosses between two points, but the current is at the maximum.

In the environmental chamber, the variable resistor was steadily increased through fifty established resistances from 0.0 to 10,000,000 ohms (Ω). The voltages and resistances were recorded into Microsoft Excel® (Redmond, WA).

Using Microsoft Excel®, the power (watts) of each solar cell was calculated by multiplying the voltage by the current. Using these calculations, a maximum power point (P_{max}) was determined for each solar cell. For each solar cell, the resistance determined from the maximum power point was used for the subsequent longevity experiments

Ending Power Curves

After the completion of the 10 day/night cycles, the cells were removed and stored at 4 ^{o}C overnight. Power curves for the solar cells were obtained once again, using the same procedure outlined in the beginning power curve section.

Experimental Time Study

To record the changes that occurred with the solar cells the environmental chamber was programmed for 12 hours of light (day) followed by 12 hours of no light (night). The PICO data logger was programmed to record voltage measurements every ten minutes for ten days. The environmental chamber was locked and the window was sealed to prevent stray light from entering the chamber. Following the ten day experiment, the PICO data results were downloaded and analyzed using Microsoft Excel® and SAS.

Post-Experimental Calculations

Calculations were performed using the voltages collected from the PICO logger. Current and the power productions of the cells were calculated from the resistances and the voltages produced from each DSSC. The calculations for the voltage included the total average accumulated voltage, average daily voltage, median daily voltage, peak voltage, least daily voltage, beginning voltage, ending voltage , and total voltage change (Table 3). The calculations for the current included the total average accumulated current, average daily current, median daily current, peak current, least daily current, beginning current, ending current , and total current change (Table 4). The power calculations included the total average power, average daily power, median daily power, peak power, least daily power, beginning power, ending power, and total power change (Table 5). The results were analyzed using the SAS statistical software analysis of variance test (ANOVA) ($p < 0.05$).

Table 3: The calculations performed upon the voltage data collected from the solar cells.

Measurement	Acronym	How Measurement is Calculated
Total Accumulated Average Voltage	TAV	The sum of the positive voltages of the Average Daily Voltage
Average Daily Voltage	ADV	Total of positive voltages produced during each daylight cycle divided by the number of daylight measurements for that day
Median Daily Voltage	MDV	Median voltage of the Average Daily Voltage
Peak Voltage	PV	Peak voltage of the Average Daily Voltage
Least Voltage	LV	Lowest voltage of the Average Daily Voltage
Beginning Voltage	BV	Average voltage produced in the first daylight cycle
Ending Voltage	EV	Average voltage produced in the last daylight cycle
Total Voltage Change	TVC	Difference between Beginning Voltage and the Ending Voltage

Table 4: The calculations performed upon the current data derived from the solar cells.

Measurement	Acronym	How Measurement is Calculated
Total Accumulated Average Current	TAC	The sum of the positive currents of the Average Daily Current
Average Daily Current	ADC	Total of positive currents produced during each daylight cycle divided by the number of daylight measurements for that day
Median Daily Current	MDC	Median Current of the Average Daily Current
Peak Current	PC	Peak Current of the Average Daily Current
Least Current	LC	Lowest Current of the Average Daily Current
Beginning Current	BC	Average Current produced in the first daylight cycle
Ending Current	EC	Average Current produced in the last daylight cycle
Total Current Change	TCC	Difference between Beginning Current and the Ending Current

Table 5: The calculations performed upon the power data derived from the solar cells.

Measurement	Acronym	How Measurement is Calculated
Total Accumulated Average Power	TAP	The sum of the positive power productions of the Average Daily Power
Average Daily Power	ADP	Total of positive power produced during each daylight cycle divided by the number of daylight measurements for that day
Median Daily Power	MDP	Median Power of the Average Daily Power
Peak Power	PP	Peak Power of the Average Daily Power
Least Power	LP	Lowest Power of the Average Daily Power
Beginning Power	BP	Average Power produced in the first daylight cycle
Ending Power	EP	Average Power produced in the last daylight cycle
Total Power Change	TPC	Difference between Beginning Power and the Ending Power

RESULTS AND DISCUSSION

Resistance Tables

Values and calculations used to determine voltage, current, and maximum power for each solar cell can be found in the appendix. Appendix I includes data used to construct beginning power curves. Appendix II includes data used to construct ending power curves. Data reported in the appendices were used to show values and calculations for voltage, current, and power production using Ohm's Law, so that power curves could be constructed.

Description of Power Curves

In this investigation, power curves (I-V curves) were used to show the power production (in Watts) of photovoltaic cells. The curves represent the maximum power that could be generated by a solar cell when comparing the voltage and current as the resistance was changed from a short circuit (low resistance) to an open circuit (high resistance) (Nelson 2008). A point exists on the graph that represents the maximum power that each solar cell can produce, called a maximum power point (P_{max}). This point is a balance of the maximum current flow to maximum voltage output (Nelson 2008). A model power curve (Figure 5) has an I-V graph that maintains high current from the highest short circuit current location on the Y-axis. The graph line remains nearly linear on the Y-axis as the voltage increases on the X-axis until reaching the P_{max}. At this point, the line on the graph falls sharply to the point on the X-axis that represents the open circuit voltage. The variations of voltage to current maximums in solar cells represent the ability of the photon-excited pigments to overcome the internal resistances of the energy gap between pigment and the substrate (Peter et al. 2002). In this investigation, it was assumed that photovoltaic cells demonstrate unique power curves for different pigment treatments and other factors that may have varied in the construction of individual cells.

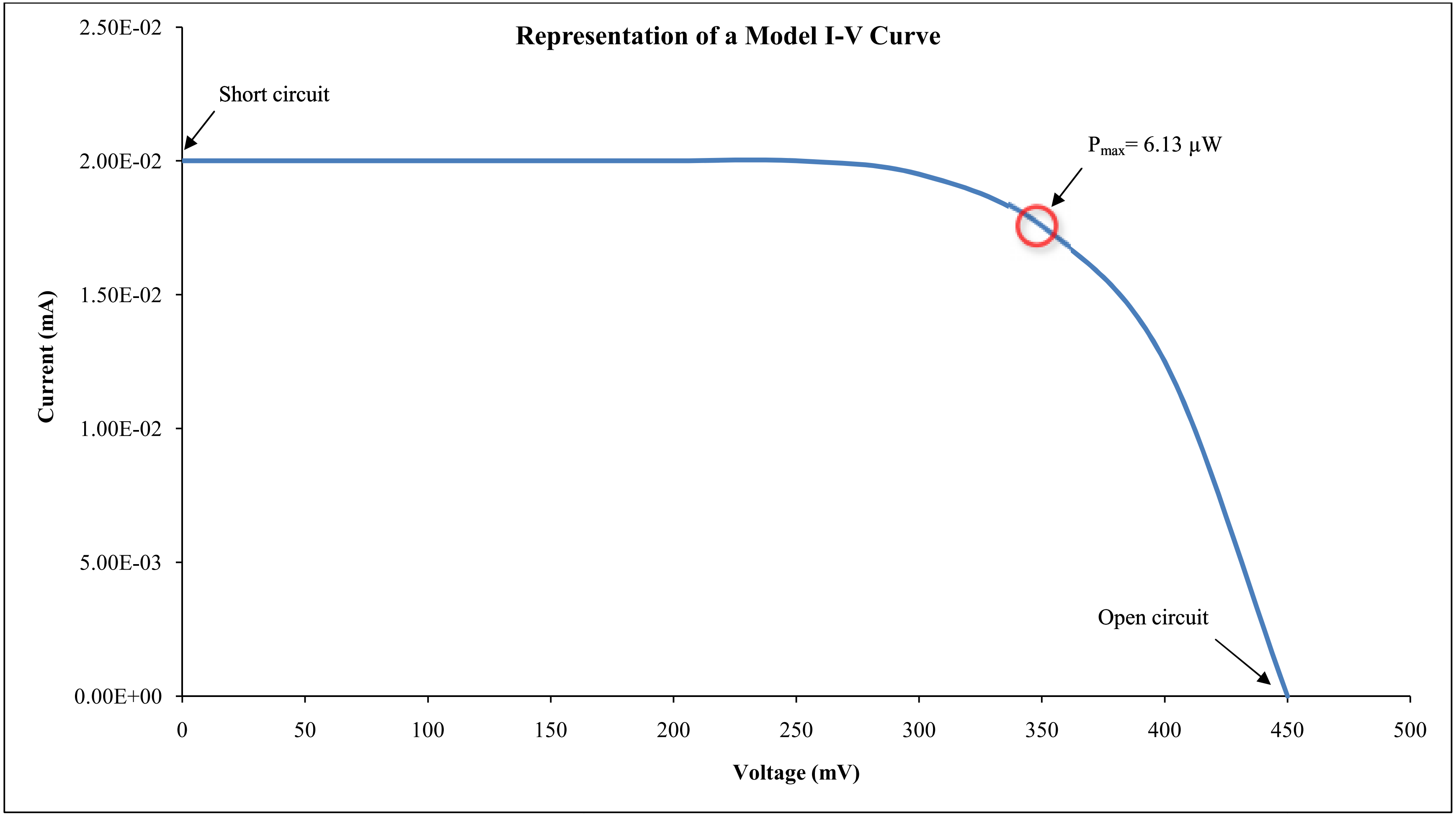

Figure 5: A model power curve that demonstrates open circuit voltage, closed circuit voltage and the maximum power (P_{max}) locations. This power curve represents an ideal shape of an I-V curve, but does not represent the ideal voltage to current characteristics.

Power Curves

The beginning power curves were constructed from voltages produced from the DSSCs while increasing the resistance applied to the solar cell. This was performed prior to the 10-day experiment. The ending power curves were performed after the 10-day experiment using the same techniques that were used to perform the beginning power curves.

Beginning Power Curves

Chlorophyll *a*

Of the chlorophyll *a* treatments, chlorophyll *a*-4 had the greatest maximum power with 4.80 microwatts (μW) at 219 millivolts (mV). Chlorophyll *a*-1 showed a power production of 2.67 μW at a voltage of 116 mV. Chlorophyll *a*-3 demonstrated a lower power production of 0.610 μW at 96.2 mV. The lowest power-producing chlorophyll *a* cell was chlorophyll *a*-2, with only 0.180 μW at a voltage of 73.5 mV (Figure 6). It has been suggested that adsorption of chlorophyll *a* onto the substrate is through the carboxyl group of the molecules that spontaneously shed their phytol tail (Kathiravan et al. 2009). Though with a tail, the pigment can adhere to the substrate, and the electron injection rate into the TiO_2 is much slower and less efficient. This may help to explain the low power productions of solar cells constructed with chlorophyll *a* as their primary pigment.

Chlorophyll *b*

Of the chlorophyll *b* treatments, chlorophyll *b*-1 had the greatest maximum power production of 0.949 μW at a voltage of 119 mV (Figure 7). Previous work with chlorophyll *b* demonstrated energy transfers from the excited pigment to the substrate in several hundred femtoseconds as opposed to chlorophyll *a* that demonstrated energy transfers in several picoseconds (Gradinaru et al. 2003). Chlorophyll *b*'s ability to transfer excitable energy to a substrate faster than chlorophyll *a* may have allowed chlorophyll *b* to return to the ground state in a shorter period of time. This potentially facilitated chlorophyll *b* to be excited by a photon at a

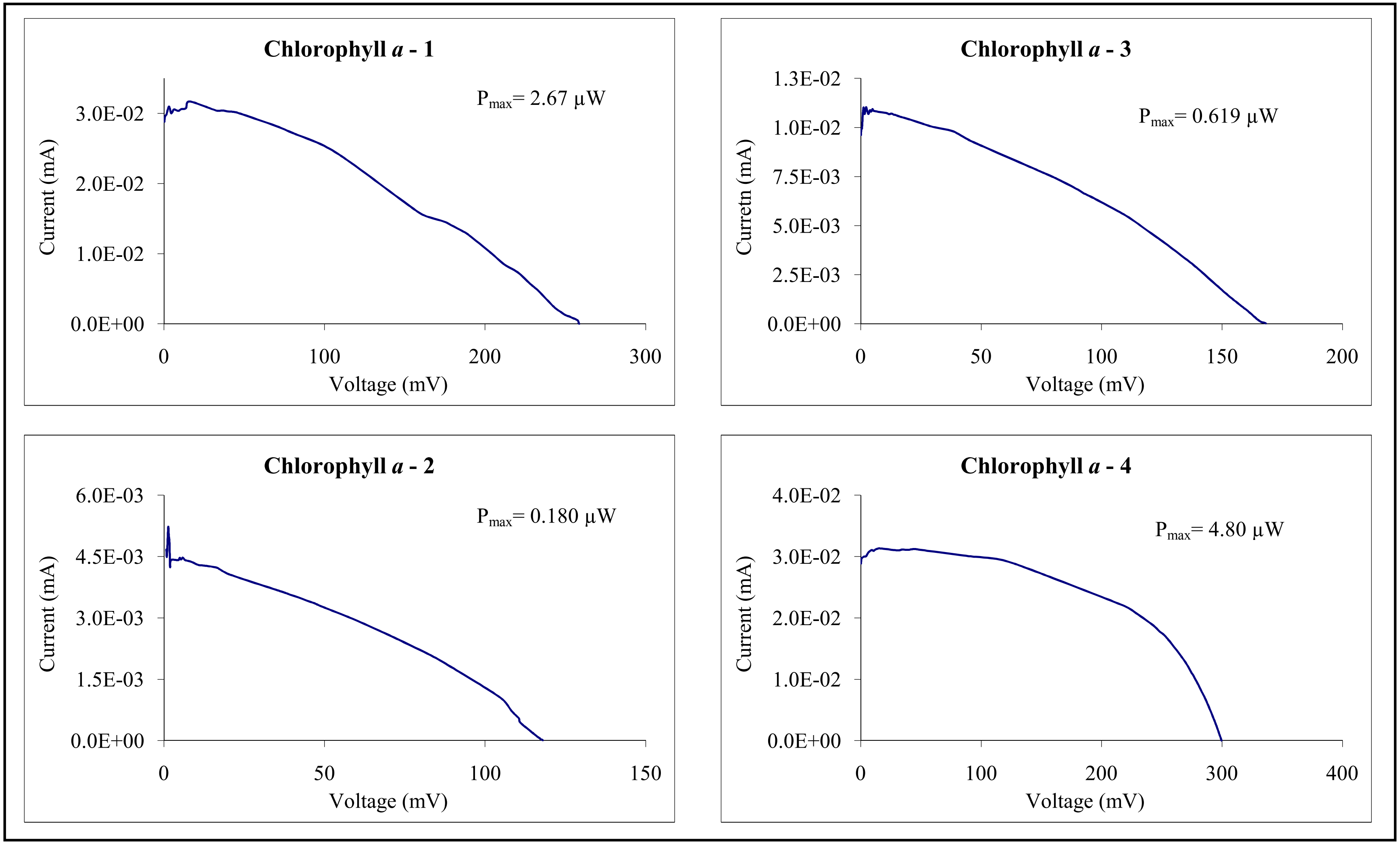

Figure 6: The beginning power curves of chlorophyll *a*.

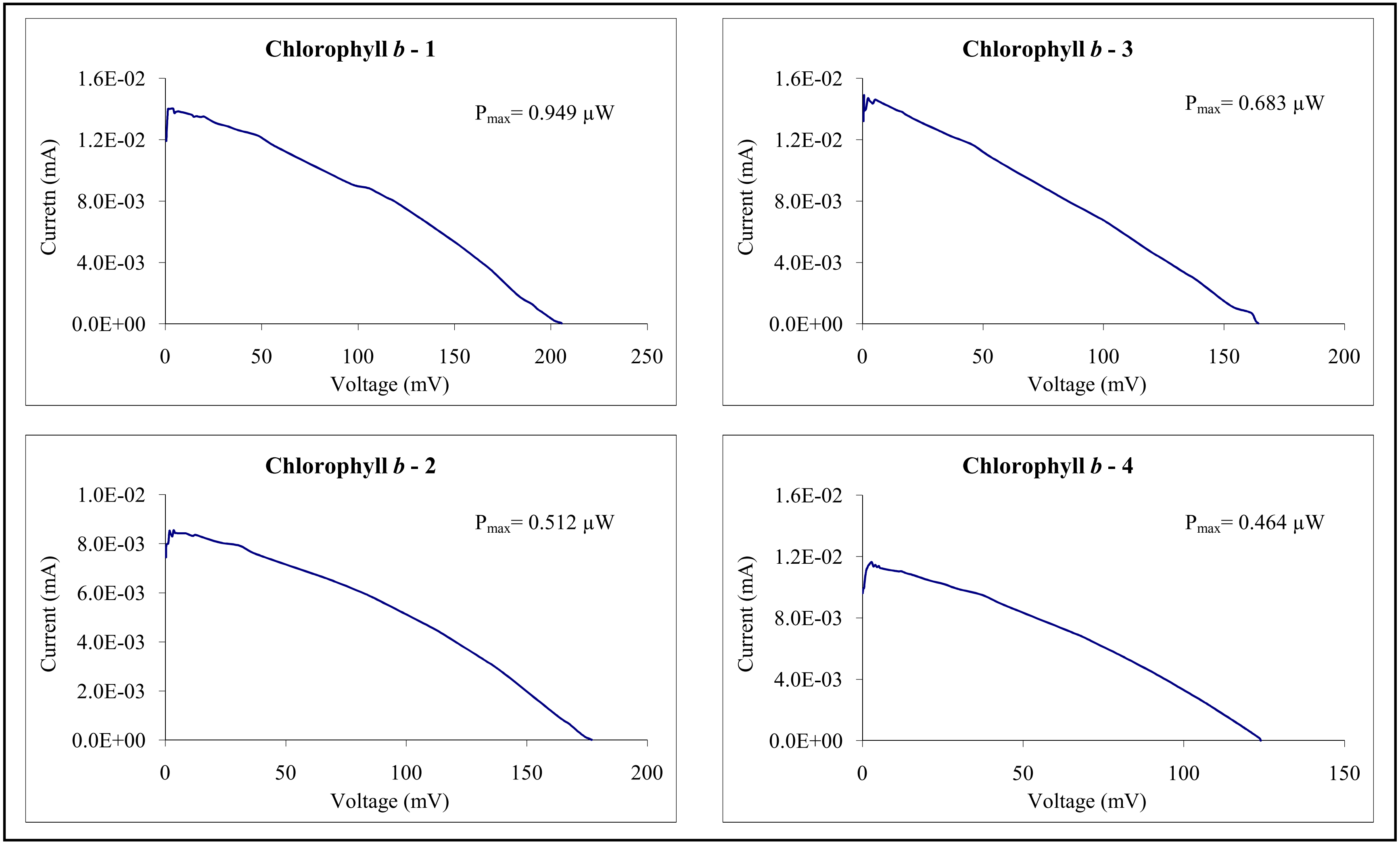

Figure 7: The beginning power curves of chlorophyll *b*.

faster rate than chlorophyll *a* despite also having a phytol tail. Power production for chlorophyll b-3 demonstrated a P_{max} of 0.683 μW at 90.4 mV. Chlorophyll b-2 had a lower power production of 0.512 μW with a voltage of 101 mV. The solar cell chlorophyll *b*-4 produced the least power with 0.464 μW at a voltage of 68.0 mV.

Chlorophyll *a/b*

The solar cells pigmented with chlorophyll *a/b* demonstrated large variations of maximum power production (Figure 8). The most power was produced by chlorophyll *a/b*-4 with a P_{max} of 3.05 μW at 214 mV. Power production dropped rapidly with the next productive cell (a/b-3), demonstrating a P_{max} of 0.277 μW at 74.4 mV. The P_{max} was lower in the remaining solar cells, with 0.236 μW at 68.6 mV from chlorophyll *a/b*-2 and only 0.0974 μW at 49.3 mV from chlorophyll *a/b*-1. The large variation could be related to differing amounts of pigments *a* or *b* that adhered to the titanium dioxide surface, although the pigment concentration was equal to that of the crude extract. There may have also been competition between the two pigments adherence to the substrate that may have prevented the most efficient transfer of electrons to the substrate.

Crude Extract

The crude extracts of spinach showed substantially higher P_{max} values than those observed for the chlorophyll *a*, *b*, and *a/b* treatments. It is thought that a synergistic effect of different photosensitive compounds is responsible for the increased voltages when compared to individual pigments in DSSCs (Amao et al. 2006, De Padova et al. 2009). The highest P_{max} occurred with solar cell crude extract-4 demonstrating a power production of 5.68 μW at 337 mV. Crude extract-2 had a P_{max} of 5.68 μW at 291 mV. The solar cell crude extract-1 demonstrated a P_{max} of 3.75 μW at a voltage of 237 mV. The lowest maximum power of the crude extract solar cells was crude extract-3. This cell had a P_{max} of 3.10 μW at 249 mV (Figure 9).

Phycocyanin

Phycocyanin demonstrated responses to light (Figure 10) that were more typical of the model power curve see (Figure 5) than those obtained for purified chlorophyll and crude extract

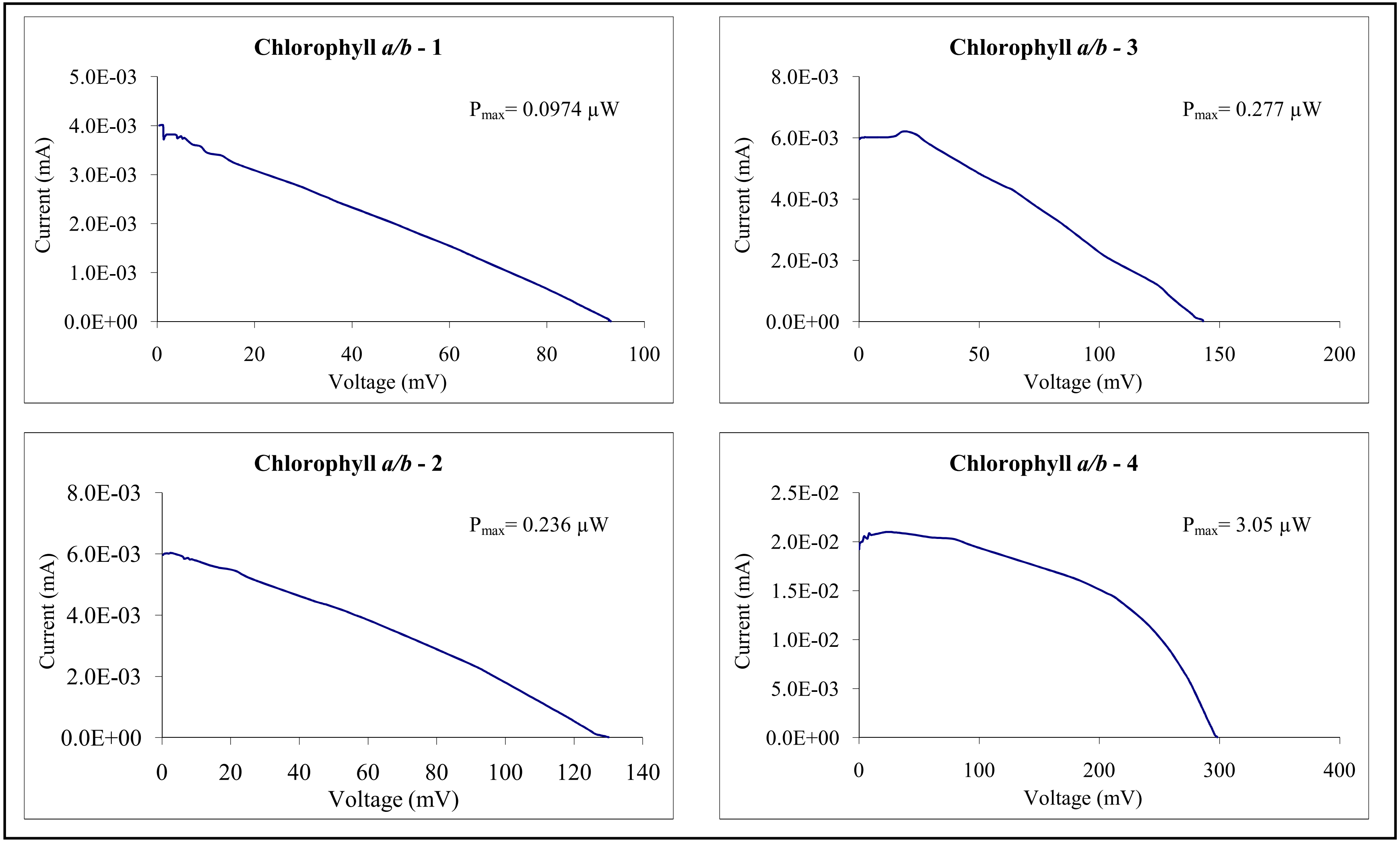

Figure 8: The beginning power curves of chlorophyll *a/b*.

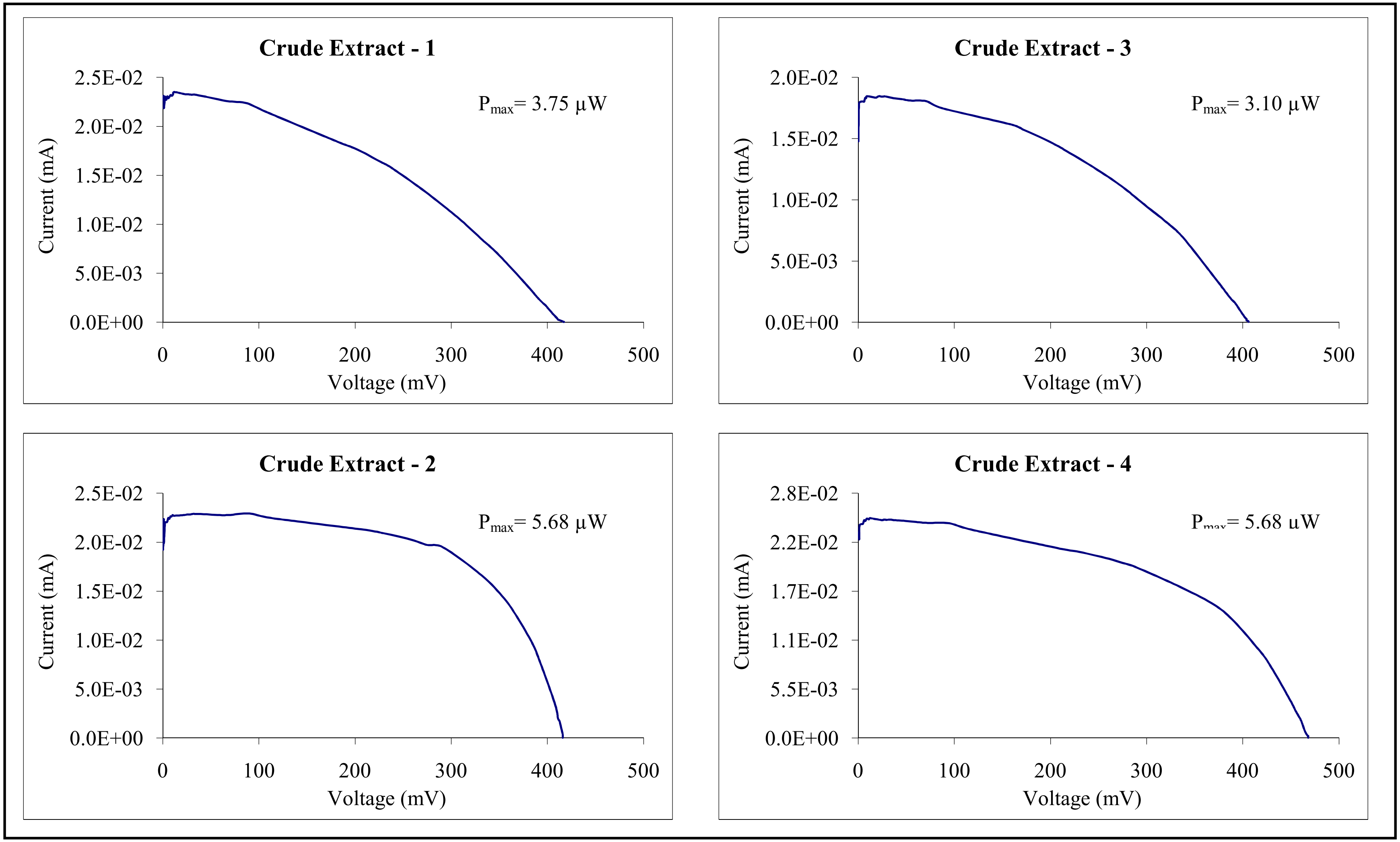

Figure 9: The beginning power curves of crude extract.

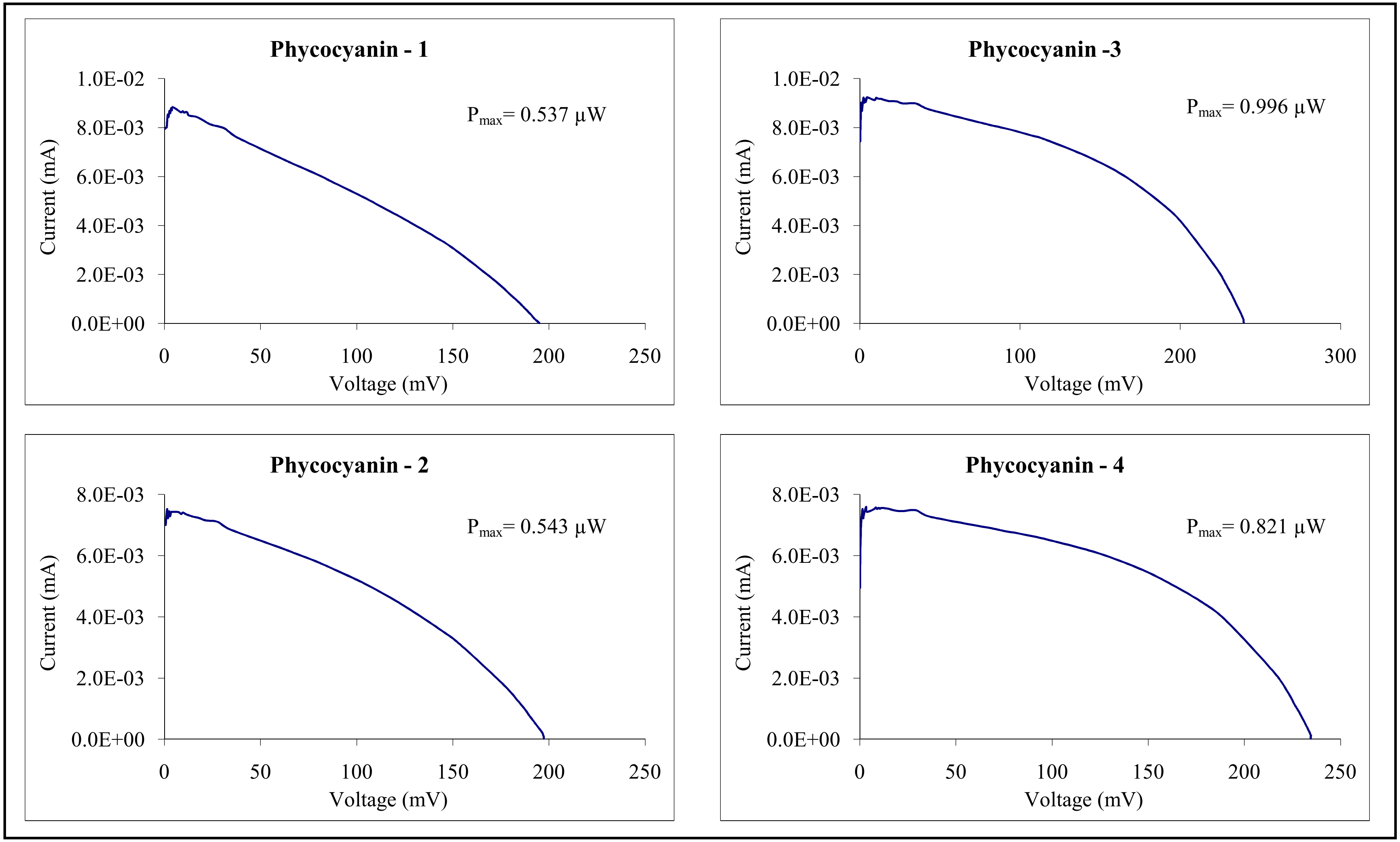

Figure 10: The beginning power curves of phycocyanin.

treatments. Phycocyanin exhibited lower P_{max} values when compared to either crude extract (see Figure 9) or chlorophyllin (Figure 11) and possessed similar values as demonstrated by the solar cells pigmented with chlorophyll *b* (see Figure 7). The linear shape of the phycocyanin molecule may possibly have led to slower electron injection rates into the TiO_2 substrate, limiting the P_{max} (Myahkostupov et al. 2007). Maximum power produced from phycocyanin-treated cells peaked in phycocyanin-3 with a P_{max} of 0.996 µW at 158 mV. The solar cell phycocyanin-4 demonstrated a P_{max} of 0.821 µW at 157 mV. Phycocyanin-2 had a maximum power of 0.543 µW at 166 mV. The least maximum power producing phycocyanin-treated cell was phycocyanin-1 at 0.537 µW and a voltage of 156 mV.

Chlorophyllin

Chlorophyllin demonstrated the highest maximum power production of any of the other pigmented treatments being tested (Figure 11). Even though chlorophyllin was the most productive of the pigments tested, the open circuit photo-voltages for this experiment were all lower than what were initially observed by Kay and Grätzel (1993) of 520 mV. This may be due to the lower light intensities from the four 39 W fluorescent bulbs that were used in this investigation compared to the 450 W xenon lamp that Kay and Grätzel (1993) used to illuminate their cells. Solar cell chlorophyllin-3 had the highest P_{max} value of 7.88 µW at 198 mV. Chlorophyllin-1 had a P_{max} value of 6.79 µW at 184 mV. Chlorophyllin-4 and chlorophyllin-1 had P_{max} values of 5.01 µW at 223 mV and 6.79 µW at 184 mV, respectively. These P_{max} values were higher than other treatments tested, but lower than the 58.6 µW value reported for similar photovoltaic cells in the literature (Amao and Komori 2004).

Control

Control treatments demonstrated variable I-V curves in response to illumination (Figure 12). One of the treatments, control-4, demonstrated some response to the light, which was suggested by the close similarity to the model I-V curve graph (Figure 5) when compared

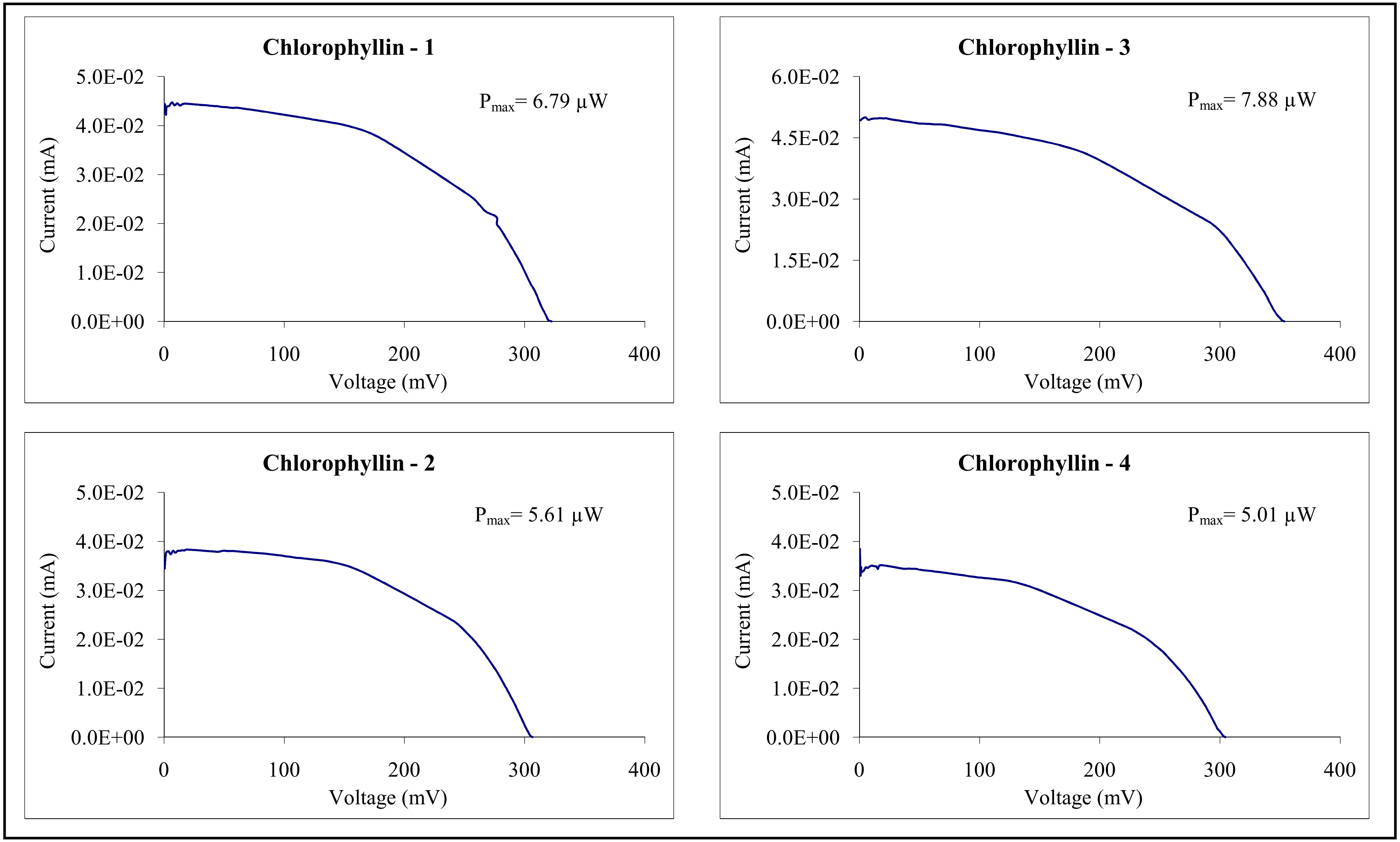

Figure 11: The beginning power curves of chlorophyllin.

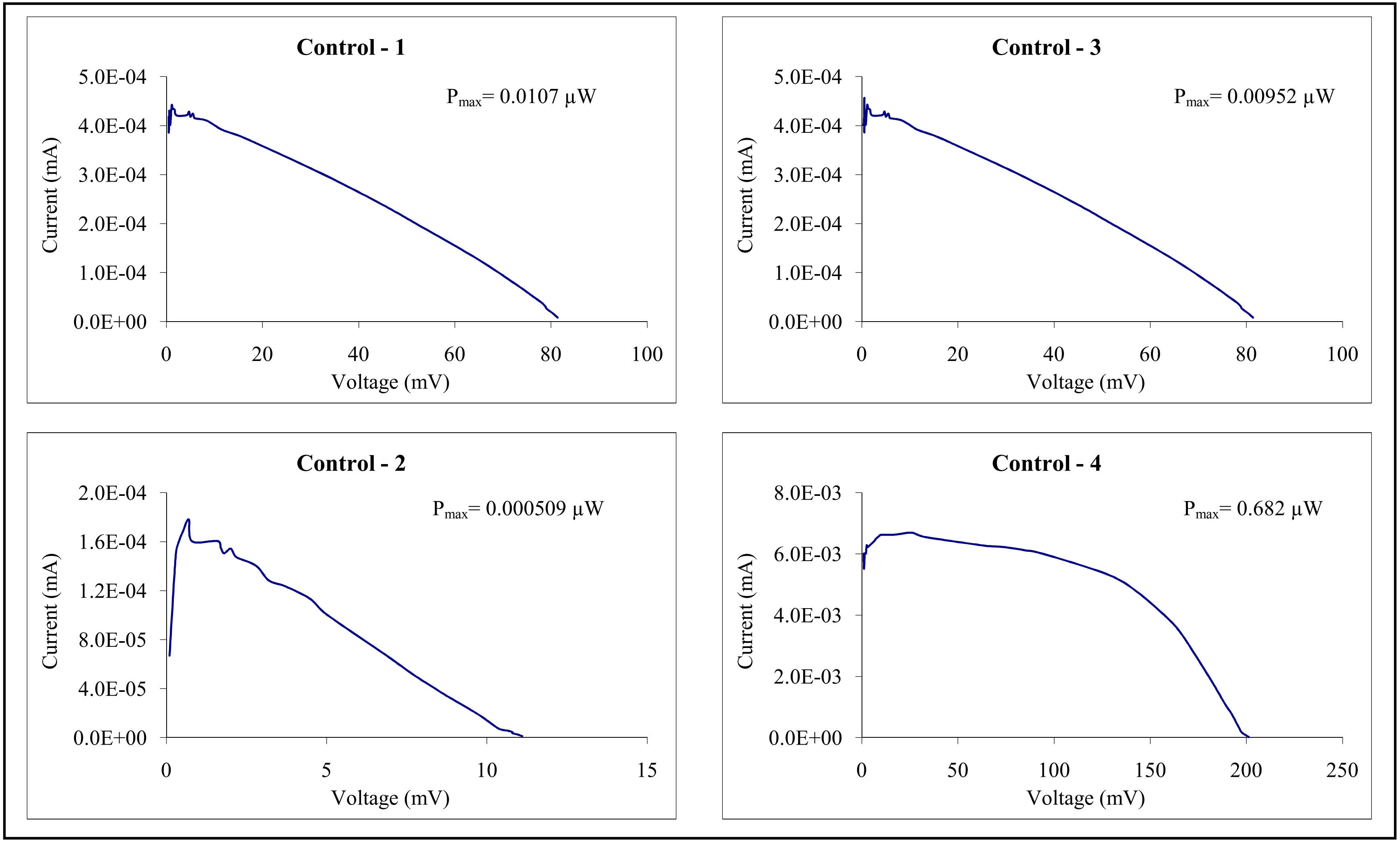

Figure 12: The beginning power curves of the control.

to graphs for the other control treatments. Iodine can act as a limited photo-sensitizer for a short period of time due to its absorption of light at near 500 nm and impedance on the TiO_2 substrate (Hoshikawa et al. 2006). Maximum power production was 0.687 μW at 131 mV with this cell. The remaining control cells failed to demonstrate the power productions that occurred with control-4. Control-1 and control-3 demonstrated similar P_{max} values of 0.0107 μW at 46.3 mV and 0.0101 μW at 44.2 mV, respectively. The lowest producing control-2 had a P_{max} of .000509 μW at a voltage of 4.50 mV.

Ending Power Curves

The ending power curves helped to demonstrate the longevity of a solar cell. Generally, a solar cell with an ending power curve resembling that of the beginning power curve indicates a useful solar cell. DSSCs properly sealed and protected from UV light were expected to demonstrate losses of over 15% as they age (Hinsch et al. 2000).

The majority of the experimental solar cells demonstrated reductions in the power curve voltages and currents produced. A decline in voltage production of a DSSC may be due to several conditions. UV light can destroy pigments rapidly; however the UV light from the fluorescent lamps may not have been a factor in reducing molecular stability of the pigments as there is very low UV amounts emitted (Lytle et al. 1992). It is more likely that a breach in the solar cell's seal may have been responsible for the decreased voltage productions. A compromised seal would allow evaporation of the electrolyte and oxidation of the pigment to occur (Hinsch et al. 2001). Other factors that may degrade the production of the DSSC according to Hinsch and his team (2001) include:

1. Photo-oxidation of the electrolyte solvent, propylene glycol, leading to a pH change of the electrolyte from proton increases in solution.
2. Oxidation of the pigments from the strong valence band-gap of TiO_2 and weakly attached pigments.
3. Structural changes in the TiO_2 leading to a decreased surface area to be photo-active.
4. Chemical changes of the pigments due to desorption of dye molecules to the substrate or reactions with oxidizing species of the electrolyte.

The solar cells were not tested to determine which of these factors, or combinations thereof, may have been responsible for the voltage decreases.

Chlorophyll *a*

The highest P_{max} obtained with chlorophyll *a* at the end of the experiment was from chlorophyll *a*-1, with a value of 0.000536 μW. Chlorophyll *a*-2 had a P_{max} measurement of

0.000102 μW. Chlorophyll *a*-4 had an atypical power curve and showed a P_{max} of 0.000000252 μW. Chlorophyll *a*-3 did not have any measurable voltage production, and therefore did not have any production of power coming from the cell (Figure 13). The electrolyte in solar cells chlorophyll *a*-3 and *a*-4 was near absent possibly the result of a compromised seal. However, the large decrease in voltage production indicated that chlorophyll *a* would not be a good candidate for a DSSC pigment.

Chlorophyll *b*

The DSSCs pigmented with chlorophyll *b* exhibited drops in voltage productions in three of the cells. One cell, chlorophyll *b*-3, experienced an increase in the P_{max} to 2.55 μW when compared to the beginning power curves (Figure 14). This increase could not be fully determined from the literature. Chlorophyll *b*-1 had a P_{max} of 0.632 μW. The solar cell chlorophyll *b*-4 had a P_{max} of 0.00423 μW, and chlorophyll *b*-2 had a P_{max} of 0.00193 μW. The pigment chlorophyll *b* appeared to be more resistant to the degradation that occurred with chlorophyll *a* since the ending voltage values were relatively larger.

Chlorophyll *a/b*

The DSSCs pigmented with chlorophylls *a/b* resulted in two cells that failed to produce voltage, namely, cells *a/b*-1 and *a/b*-4 (Figure 15). These two solar cells exhibited electrolyte loss, indicating a compromised seal. The maximum power was produced from solar cell chlorophyll *a/b*-2 with 0.890 μW. This cell experienced an increase of maximum power when compared to the beginning power curve (Figure 8). The other power producing cell was *a/b*-3 with a lower power production when compared to the beginning power curve of 0.00115 μW. The ending power curve results were not comparable enough to make a decision on the pigment's longevity due the seals. Chlorophyll *a/b*, though, did not exhibit ending voltage productions as high as chlorophyllin or crude extract.

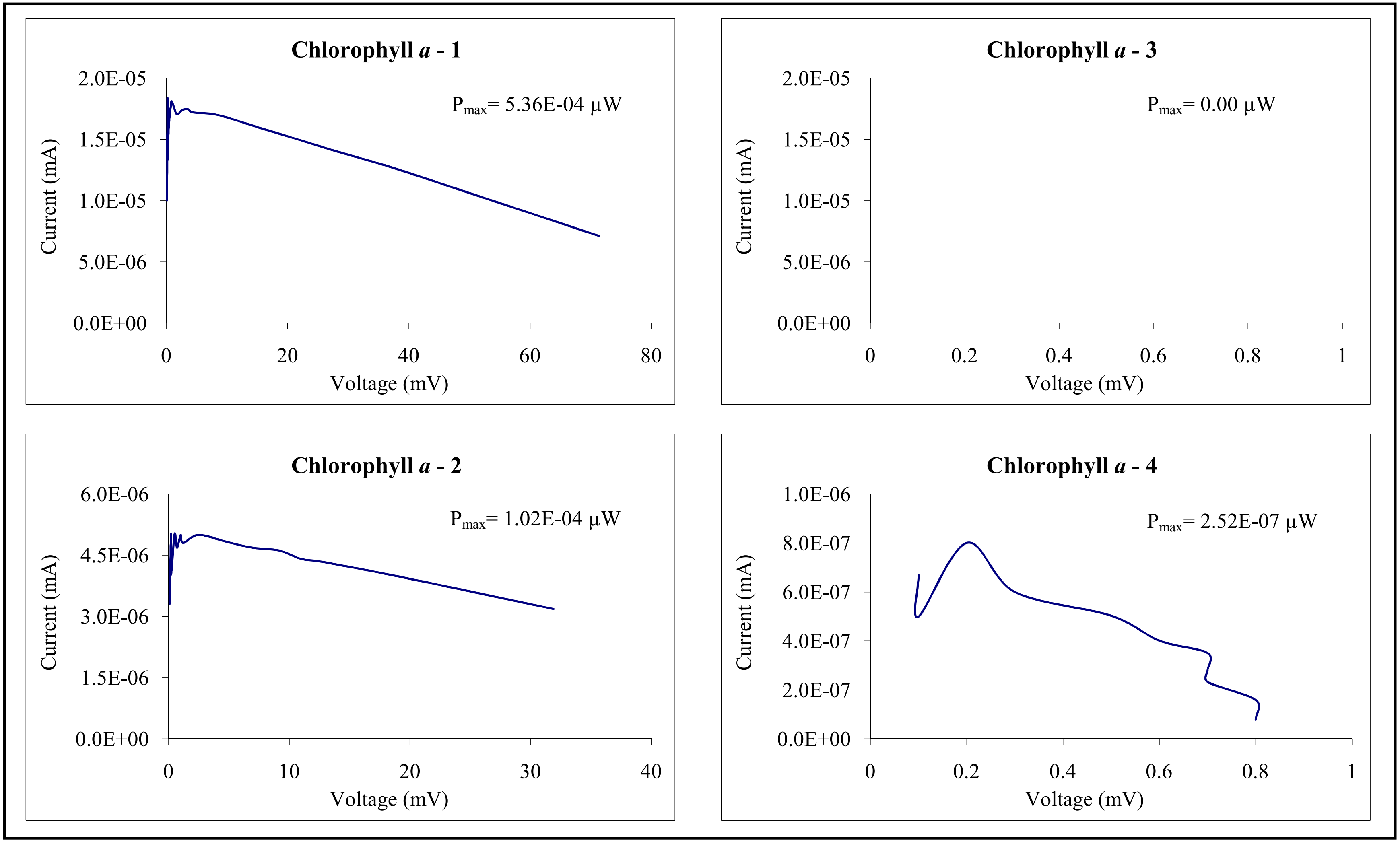

Figure 13: The ending power curves of chlorophyll *a*.

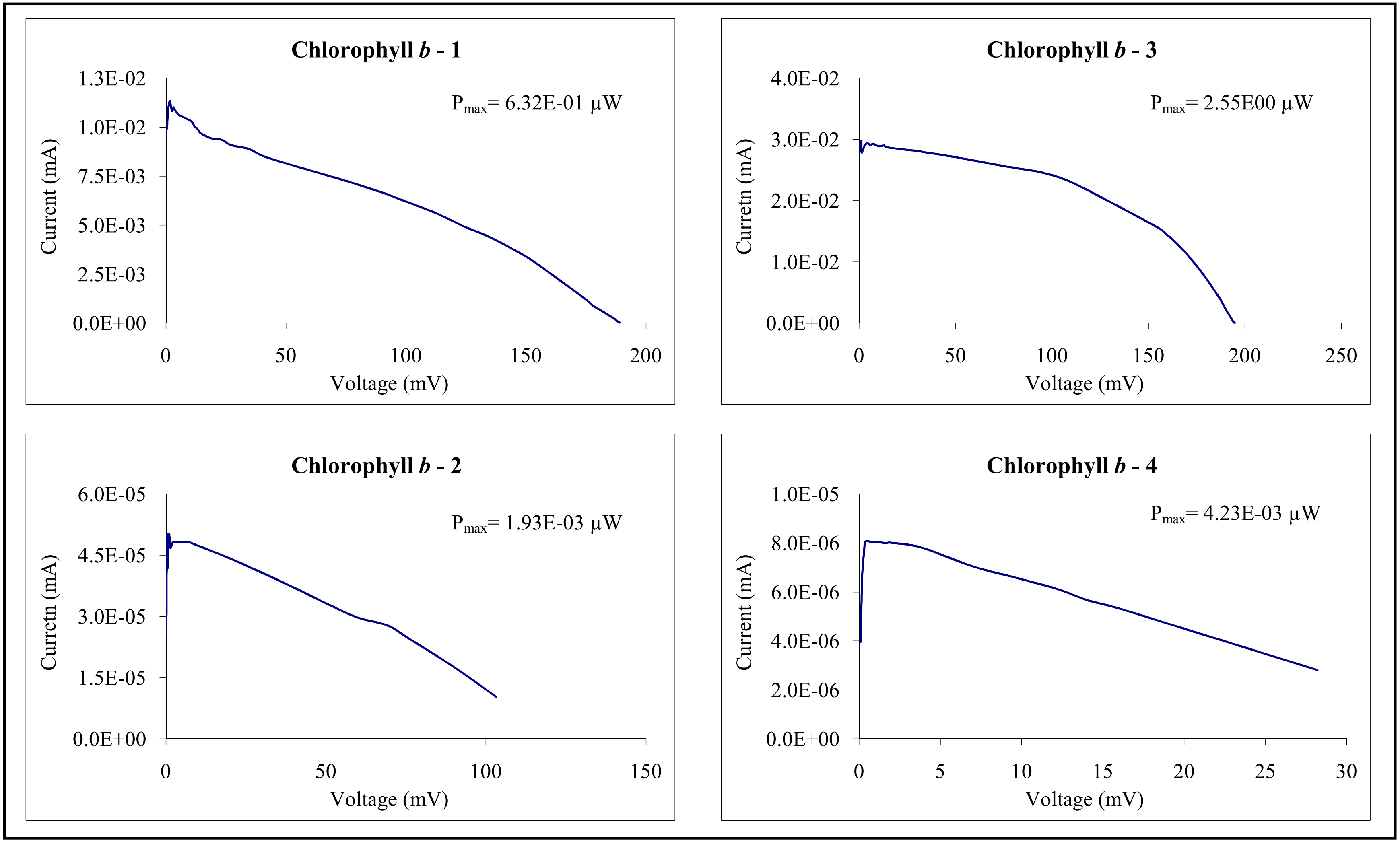

Figure 14: The ending power curves of chlorophyll *b*.

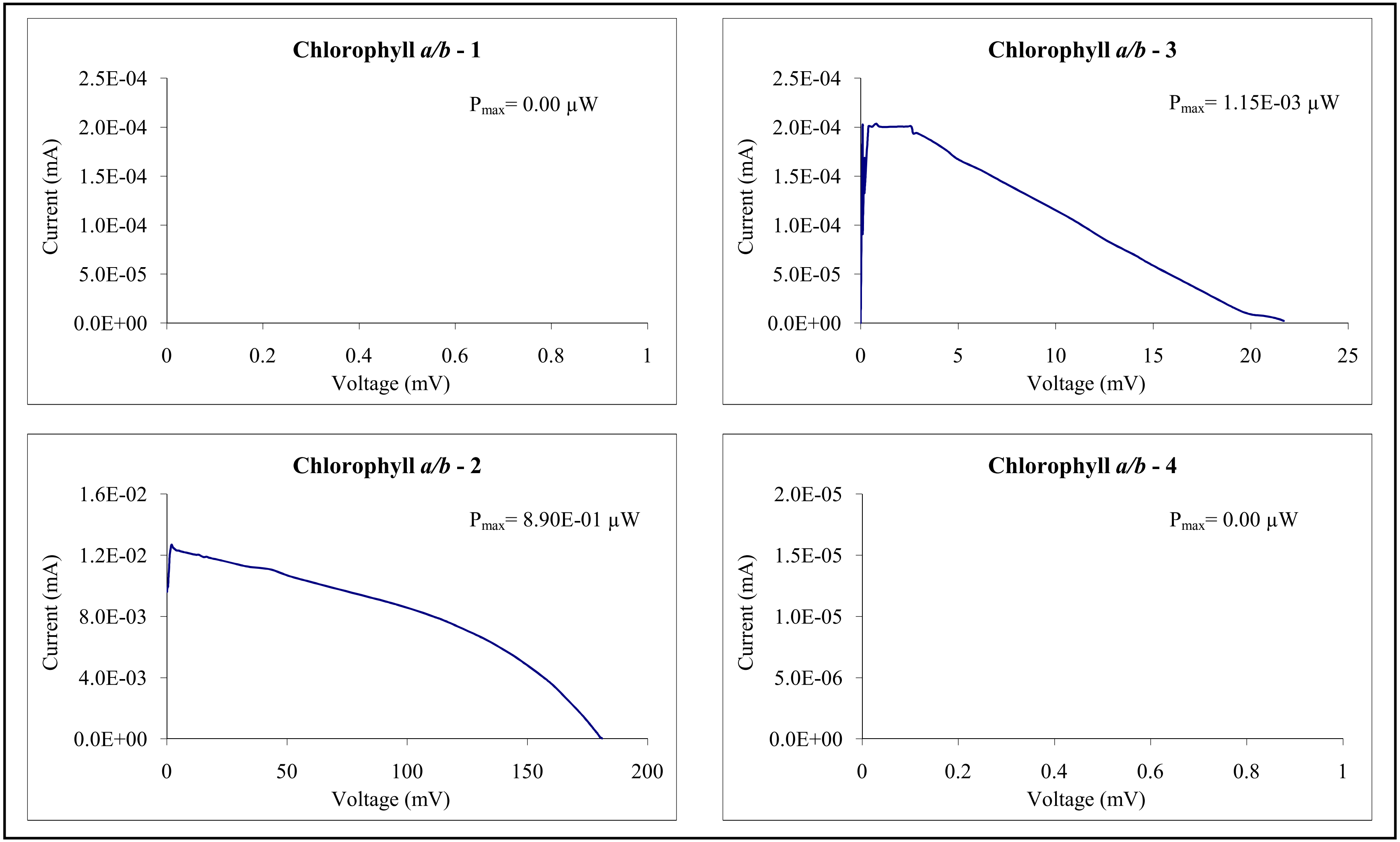

Figure 15: The ending power curves of chlorophyll *a/b*.

Crude Extract

The crude extract solar cells exhibited a significant drop in power production compared to the beginning power curves (Figure 16). Few of the solar cells retained the curved I-V line observed in a model power curve. Crude extract-4 demonstrated the highest P_{max} of 0.125 μW, and had a much higher voltage than the other cells. Crude extract-3 demonstrated a P_{max} of 0.0471 μW. Crude extract-2 had a maximum power production of 0.0114 μW. The lowest producing cell, crude extract-1 with 0.00318 μW had a linear-shaped power curve and very little voltage production when compared to the other three cells, suggesting that this cell may have had a compromised seal, as well as experiencing electrolyte evaporation or pigment degradation (Matsui et al. 2009). The higher ending voltages produced by the crude extract when compared to pigments of chlorophyll *a* and chlorophyll *b* suggested a possibility of some resistance to the degradation that occurred with the other pigments. The crude extract may have had antioxidants in the methanol solvent and as a result, these antioxidants may have assisted in protecting the pigments from degradation.

Phycocyanin

Phycocyanin exhibited two solar cells that did not produce any voltage, phycocyanin-2 and phycocyanin-3 (Figure 17). These two cells appeared to have a lack of electrolyte in the cell, which suggested a compromised seal. The highest P_{max} of the phycocyanin pigmented solar cells was solar cell phycocyanin-4 with 0.369 μW. This compared to the peak P_{max} of 0.996 μW demonstrated in the beginning power curves (Figure 10). Phycocyanin-1 demonstrated a production of 0.255 μW of power. Based upon the similarity of the two solar cells that produced ending voltages, it is assumed that phycocyanin was a more stable pigment when compared to chlorophyll *a* or *b*.

Chlorophyllin

Two of the chlorophyllin solar cells experienced an increase in the P_{max} in relation to the beginning power curves. The reason for this could not be adequately explained in the literature.

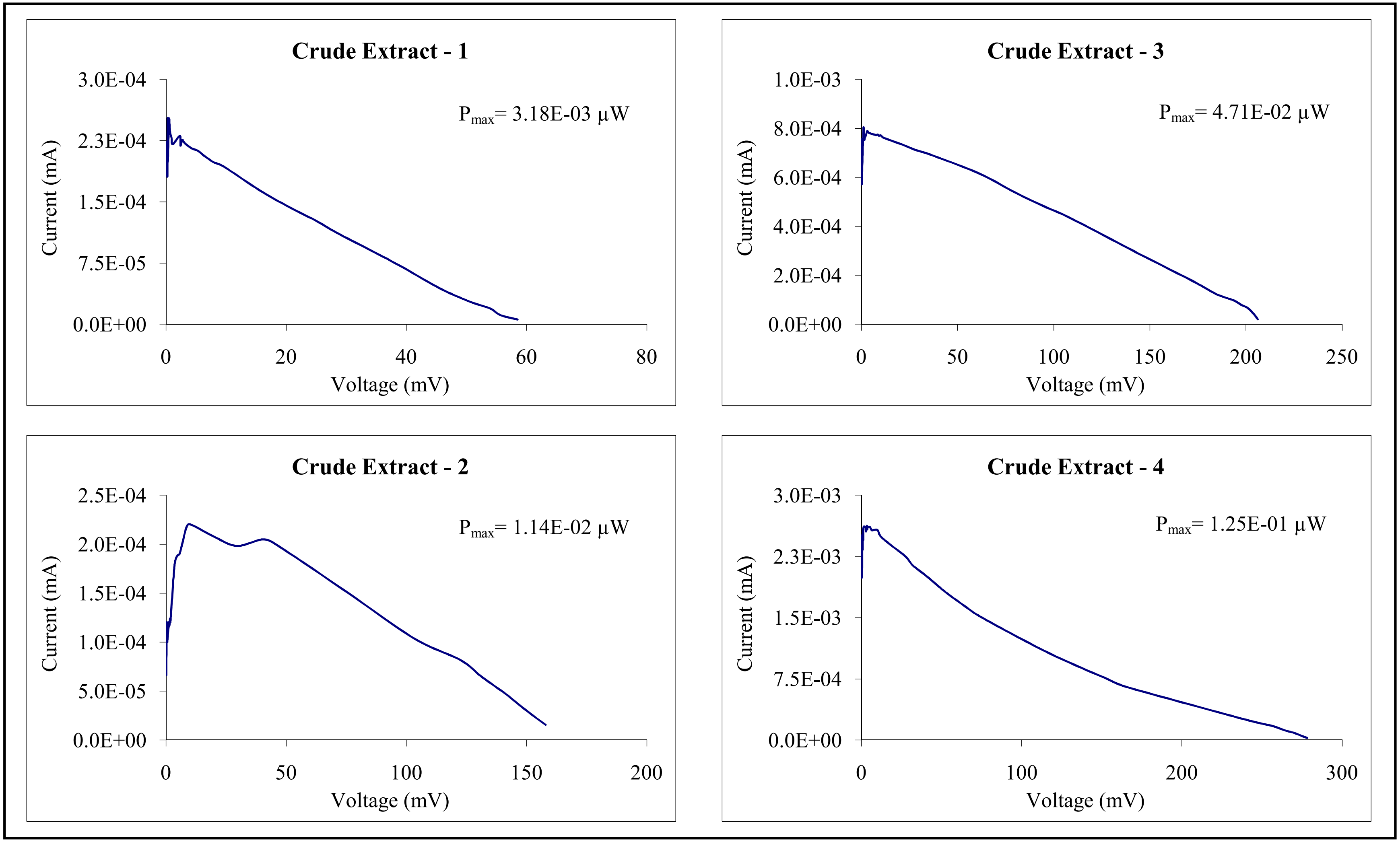

Figure 16: The ending power curves of crude extract.

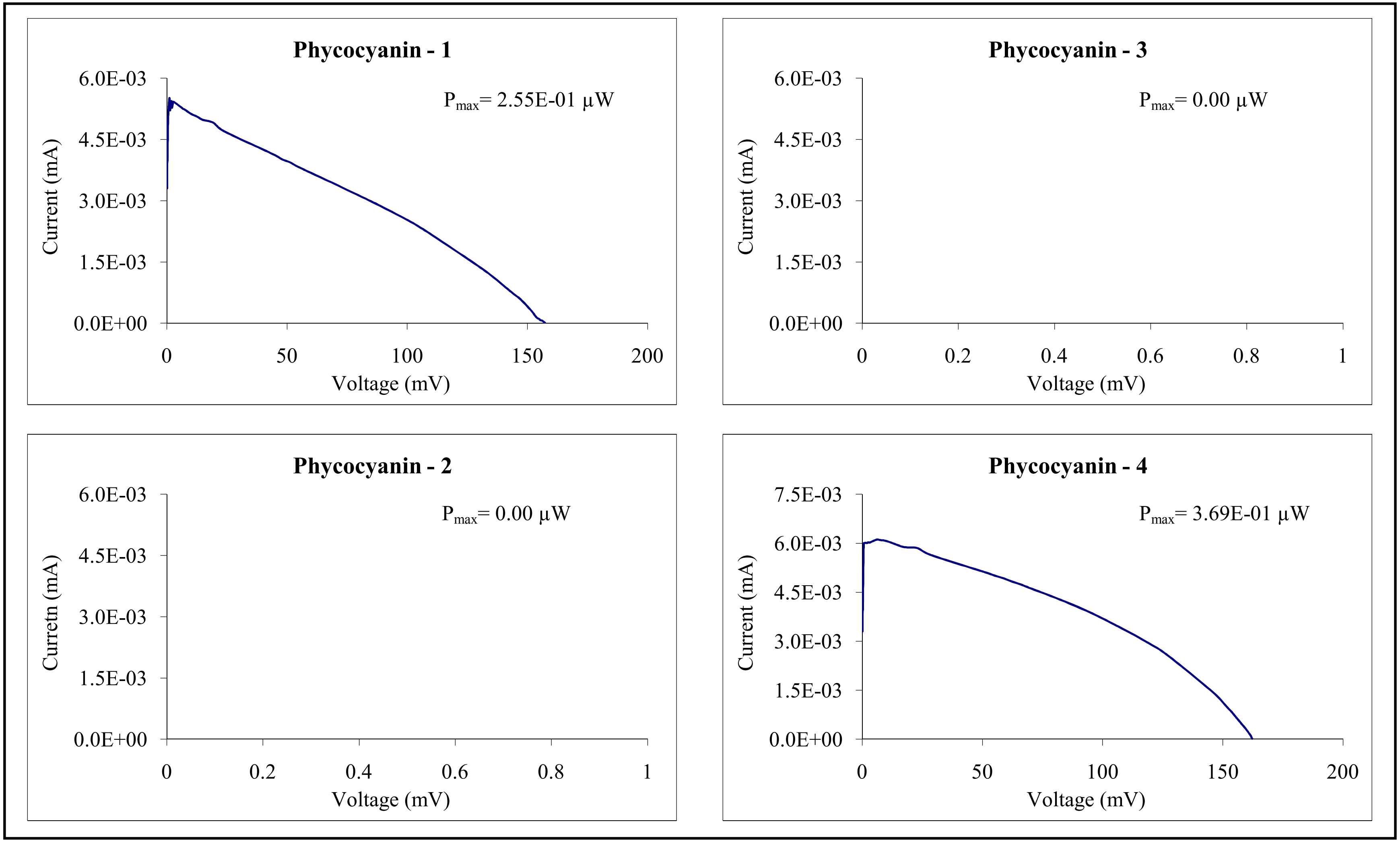

Figure 17: The ending power curves of phycocyanin.

Chlorophyllin-1 demonstrated an ending P_{max} of 26.0 μW (Figure 18), compared to the beginning P_{max} of 6.79 μW (Figure 11), a 283% increase. Chlorophyllin-2 experienced an increase in power production from a beginning P_{max} of 5.61 μW (Figure 11) to an ending P_{max} of 21.8 μW (Figure 43), a 289% increase. Chlorophyllin-4 demonstrated a drop in the P_{max} with 3.13 μW. Chlorophyllin-3 had the lowest power production and P_{max} of the chlorophyllin solar cells with a power maximum of 0.00322 μW. The iodide electrolyte in this cell was still present, but at reduced levels than what was originally injected into the cell. The higher power values of chlorophyllin compared to the other pigments may be due, in part, to the carboxylic anchoring group to the TiO_2 surface, proving a better electron flow from pigment to substrate (Ernstorfer et al. 2006). Chlorophyllin demonstrated the highest ending voltage productions when compared to the other pigments tested.

Control

The control solar cells failed to produce voltage at the end of the experiment, and therefore, no power production was observed (Figure 19). The rapid drop in power production of the control from the beginning power curves (Figure 12) was due to the lack of a pigment. As the light was emitted upon the electrolyte, some iodine molecules were degraded and the resulting compounds may have started to react with other iodide molecules within the solvent (Junghänel and Tributsch 2005). In a short time, the iodine became clear and nonfunctioning as a photo-excitable pigment. This demonstrated the importance of providing adequate ratios of pigment to iodide to accept the electron within the closed system of the solar cell to prevent iodide degradation and voltage drop.

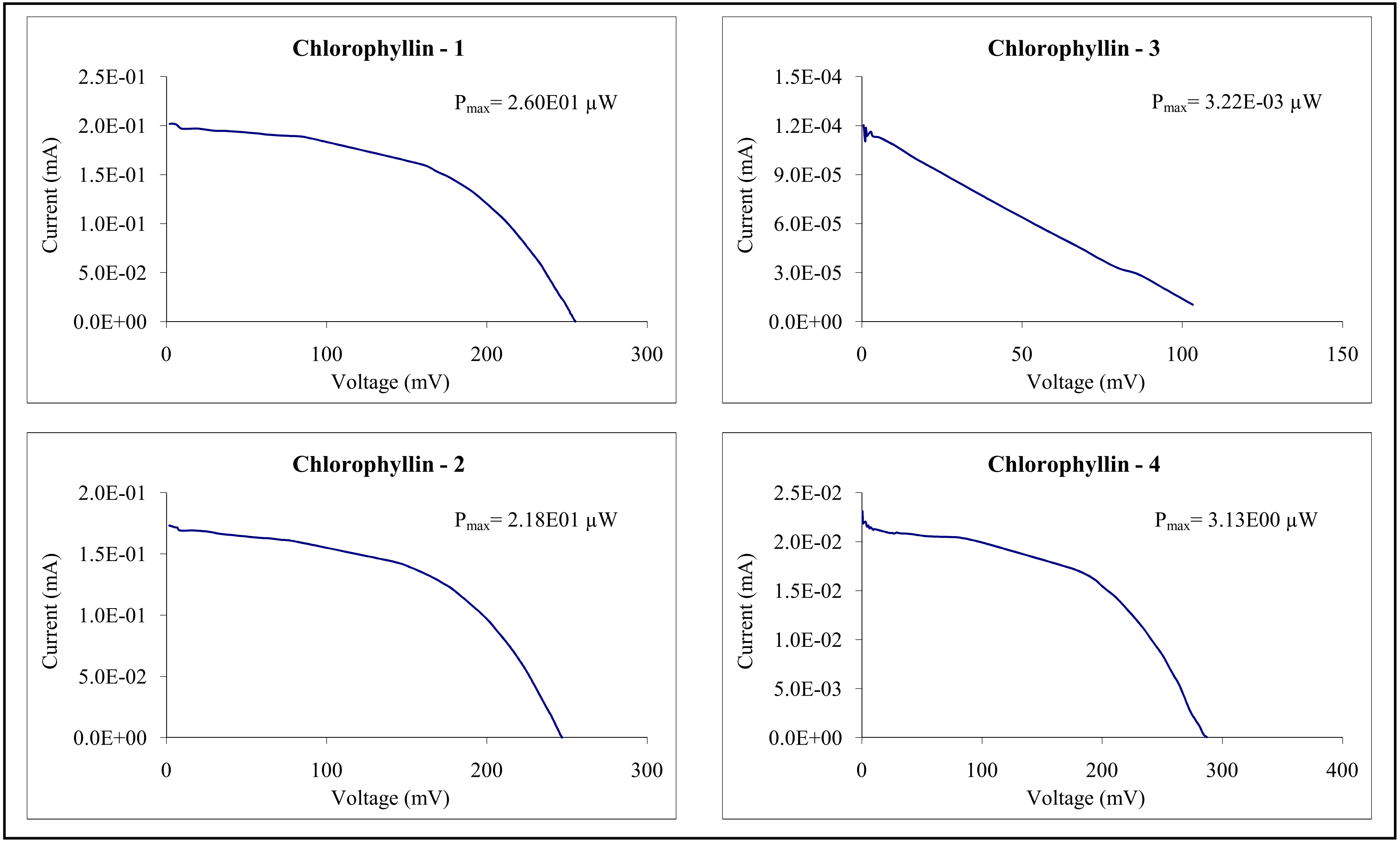

Figure 18: The ending power curves of chlorophyllin.

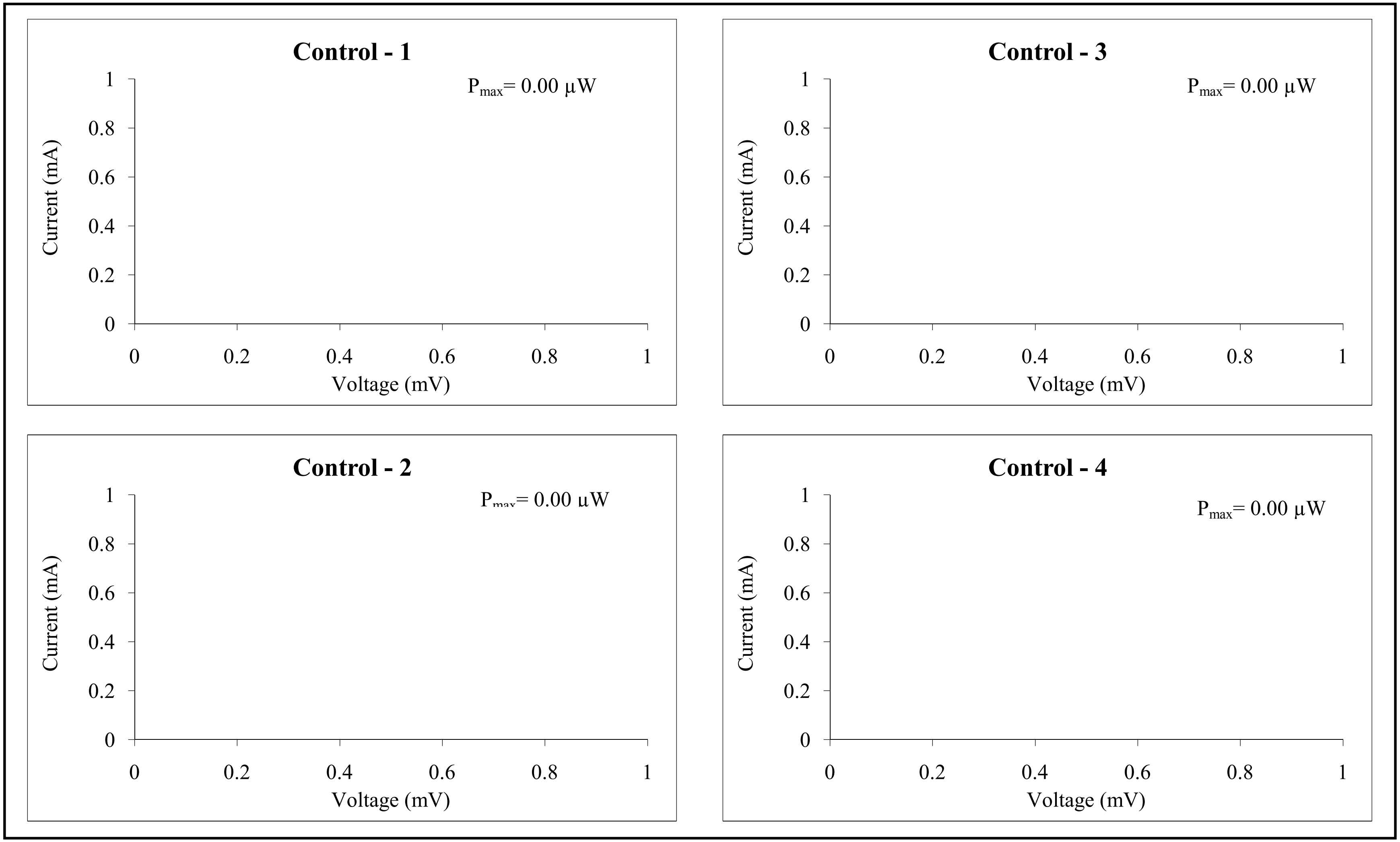

Figure 19: The ending power curves of the control.

Response to Light

Voltages were calculated for each replication and averages among replications were reported for each treatment over the course of the 10-day experiment. All solar cells, except for the control, demonstrated a response to light and achieved substantially higher voltages during the day compared with those obtained at night (Figure 20). Hereafter, solar cell performance focused on daylight measurements.

Time Study of Voltages

Voltage values decreased over the course of the experiment (Figure 20), suggesting that cells may not have been as photo-stable as anticipated. Previous work by Patrocinio et al. (2009) suggests that natural pigments can be photo-stable for more than 14 weeks. Since the pigments did not demonstrate the same longevity as Patrocino and his team, it may be concluded that the pigments were undergoing degradation factors as described by Hinsch et al. (2009). The different reagents and sealing procedures used by Patrocinio and coworkers (2009) may improve upon the stability of cells demonstrated in this investigation.

Solar cells that are properly sealed and shielded from UV light are photo-stable (Tennakone et al. 1997). Shielding of the cells to protect them from UV radiation was not performed during this experiment. Previous work has shown that use of a UV filter for fluorescent bulbs is not necessary due to the very low UV emitted (Lytle et al. 1992). Yet, UV light can be detrimental to both the stability of the pigments (Tennakone et al. 1997) and the electrolyte (Hinsch et al. 2001). For DSSCs to be productive in UV rich environments, proper UV protection may help to maintain long-term voltage productions of solar cells.

Throughout the 10-day experiment, photovoltaic cells constructed with chlorophyllin demonstrated significantly higher voltages than those of other pigments (Figure 20). These solar cells of chlorophyllin did not exhibit the same decrease in voltage production as other pigments. These higher voltages suggest that chlorophyllin can be a useful natural pigment for solar cell research.

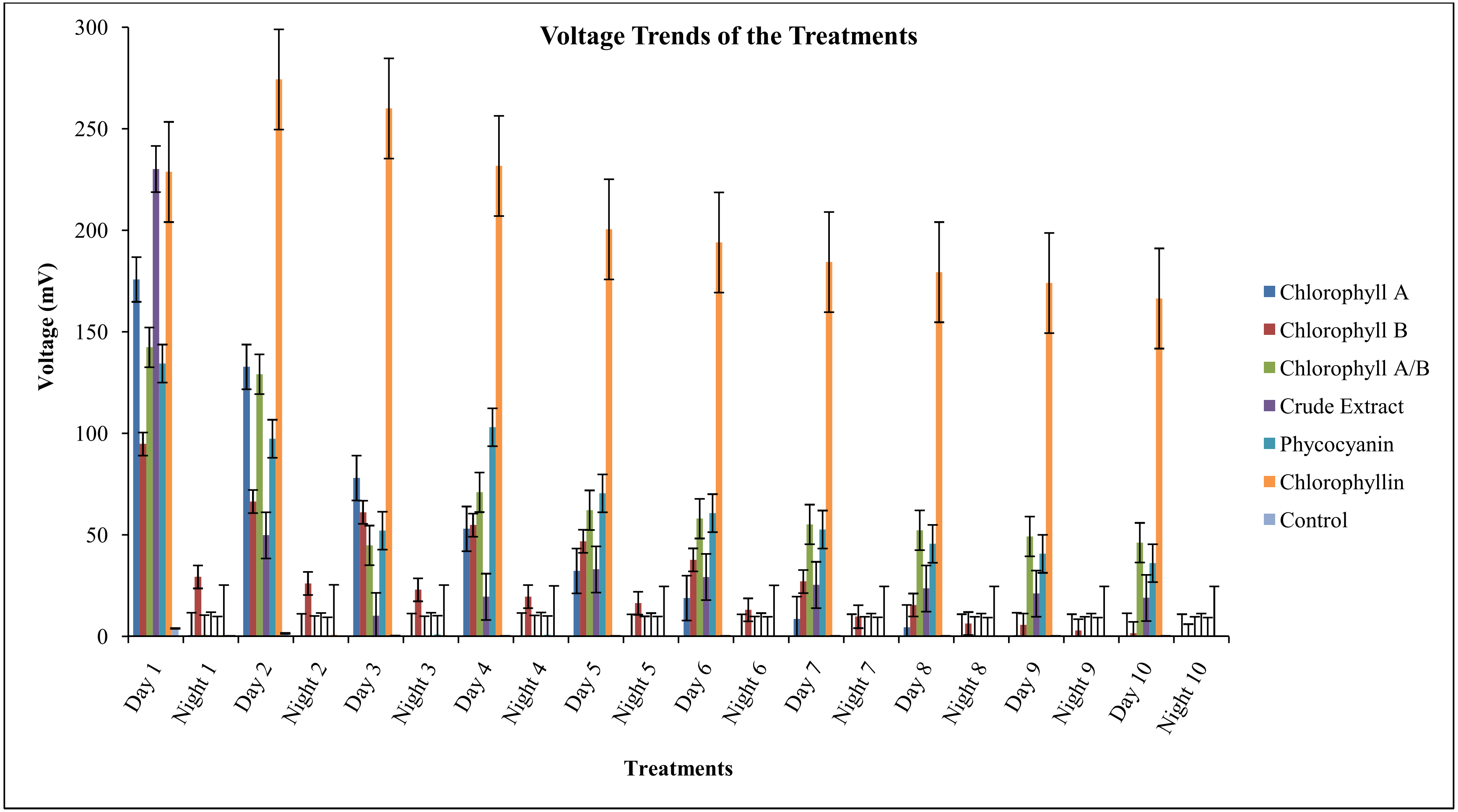

Figure 20: The average voltage of the treatments expressed in millivolts (mV) for the course of the 10-day experiment. Bars represent the standard error of each treatment.

The increased voltage production of chlorophyll *a/b* when compared to chlorophyll *a* or *b* alone supports previous investigations that have shown that the use of multiple pigments or dyes on the TiO_2 surface leads to higher voltages due to broader wavelength capture of the light (Amao et al. 2006, De Padova et al. 2009). It was noted that, although cells treated with some pigments achieved higher voltages than others, all cells experienced decreases in voltage values over the course of the experiment possibly due to reasons presented by Hinsch and his team (2001).

Voltage

The voltages observed, and calculations thereof, varied significantly among treatments during the experimental trial. Observed changes were seen in the total average voltage (TAV), average daily voltage (ADV), median daily voltage (MDV), peak voltage (PV), least voltage (LV), beginning voltage (BV), ending voltage (EV), and total voltage change (TVC). Results from analysis of variance (ANOVA) of all voltage measurements, and calculations thereof, showed significant differences at the 0.05 probability level (or even more significant) among treatments (Table 6). Statistical rankings were determined from the least significant difference (LSD) of each value seen in Table 7.

Total Average Voltage (TAV)

The TAV was the average of the voltages accumulated throughout the 10-day experimental trial. Total average voltage varied significantly ($p < 0.001$) among the different pigments (Tables 6 and 7). Chlorophyllin demonstrated the highest TAV with a mean value of 2,094 mV. The TAVs for chlorophyll *a/b* and phycocyanin were statistically similar to each other with values of 711 and 691 mV, respectively, and ranked together (Table 7). The TAVs of chlorophyll *b,* chlorophyll *a*, and the crude extract were also statistically ranked with values of 505 mV, 461 mV and 412 mV, respectively. The control demonstrated a TAV production of 6.60 mV.

Average Daily Voltage (ADV)

The ADV of the pigmented solar cells were used to determine the mean expectancy of voltage from each pigment over the course of the experiment. The ADV varied significantly ($p < 0.001$) among treatments, with chlorophyllin demonstrating the highest value of 209 mV, suggesting that is was the most stable pigment (Table 7). Chlorophyll *a/b* with a value of 71.0 m and phycocyanin with a value of 69.4 mV, were statistically similar. The grouped ranking of chlorophyll *a/b* and phycocyanin suggested moderate stability of these pigments throughout the experiment. A third statistical ranking occurred with chlorophyll *a* at 50.5 mV,

Table 6: ANOVA test results for the voltage calculations.

Source	df	TAV	ADV	MDV	PV	LV	BV	EV	TVC
Treatment	6	***	***	*	***	**	***	*	*
Rep	3	NS	NS	NS	NS	NS	NS	NS	NS
Error	18								

***, **, * Significant at the 0.001, 0.01, 0.05 probability levels, respectively; NS = Not significant

Table 7: Voltage values and calculations (in millivolts) for different pigments (treatments) used to construct photovoltaic cells during a 10-day experiment in the environmental chamber.

Treatment	TAV	ADV	MDV	PV	LV	BV	EV	TVC
Chlorophyll *a*	461 bc*	50.5 bc	21.2 b	179 bc	0.400 b	176 ab	0.470 b	175 ab
Chlorophyll *b*	505 bc	41.2 bc	55.1 b	94.8 d	1.53 b	94.8 b	36.1 b	63.9 c
Chlorophyll *a/b*	711 b	71.0 b	55.6 b	162 bcd	16.0 b	142 bc	46.2 b	98.2 bc
Crude Extract	412 bc	46.1 bc	23.1 b	230 ab	7.80 b	230 a	19.0 b	211 a
Phycocyanin	691 b	69.4 b	57.1 b	149 cd	26.7 b	134 bc	36.1 b	98.3 bc
Chlorophyllin	2,093 a	209 a	197 a	274 a	161 a	229 a	166 a	67.7 bc
Control	6.60 c	0.66 c	0.13 b	3.99 e	0.0900 b	3.97 d	0.140 b	3.83 c
LSD (0.05)	681	68.1	101.6	78.6	70.9	79.7	98.0	108

*Means within a column followed by the same letter are not significantly different. TAV = total average accumulated voltage; ADV = average daily voltage; MDV = median daily voltage; PV = peak voltage; LV = least voltage; BV = beginning voltage; EV = ending voltage; TVC = total voltage change; LSD = least significant difference at the 0.05 probability level. This table shows that all values and calculations, except those for TVC, were significantly higher for the chlorophyllin treatment, compared to other pigments used in photovoltaic cells. Other values and calculations varied among pigment treatments, and those followed by same letter(s) within a column were not significantly different, whereas those followed by different letter(s) were significantly different.

crude extract with 46.1 mV, and chlorophyll *b* with 41.2 mV, demonstrating these as the least stable pigments over the course of the experiment.. The control had the lowest ADV with only 0.66 mV. The higher ranking of chlorophyll *a/b* compared to pure chlorophyll pigment lends credence to previous work suggesting that combined pigments would be better photo-sensitizer pigments an individual pigments alone (Amao et al. 2006, De Padova et al. 2009). But the ranking of phycocyanin with chlorophyll *a/b* suggests that phycocyanin may be more efficient than either chlorophyll.

Median Daily Voltage (MDV)

The MDV was used to determine the voltage half-life production of the pigment during the experiment. Chlorophyllin pigmented solar cells demonstrated a significantly higher ($p < 0.05$) MDV when compared to the other pigments with a MDV value of 197 mV (Table 7). The remaining treatments were not significantly different from each other and were ranked together. The higher MDV value for chlorophyllin when compared to the other pigments suggested that chlorophyllin may be more stable as a photo-sensitizer, assuming all possible degradation factors are excluded. The MDV production of the remaining treatments were phycocyanin with 57.1 mV, chlorophyll *a/b* with 55.6 mV, chlorophyll *b* with 55.1 mV, crude extract with 23.1 mV, chlorophyll *a* with 21.2 mV, and the control with a MDV production of 0.13 mV.

Peak Voltage (PV)

The PV of the solar cell determined the maximum voltage that could be produced from the pigment. Chlorophyllin demonstrated the highest significant ($p < 0.001$) PV production with a mean value of 274 mV (Table 7). The crude extract, with a mean PV of 230 mV was statistically similar to chlorophyllin as well as chlorophylls *a* and *a/b* with mean PVs of 179 and 162 mV, respectively. The similarity of crude extract and chlorophyllin PV values suggested that the pigments were both good producers of electricity, initially. Peak voltages of chlorophylls *a* and *a/b* were statistically similar to those of phycocyanin, which had a PV of 149 mV. However, only chlorophyll *a/b* and phycocyanin were statistically similar to chlorophyll *b* with a mean PV production of 94.8 mV. The control demonstrated the lowest PV of the treatments with a mean of 3.99 mV.

Least Voltage (LV)

The LV value was useful to determine the endurance of a solar cell as the experiment continued. The observed LV means demonstrated a large disparity ($p < 0.01$) in voltage production among the treatments (Table 7). The LV mean for the four replications of chlorophyllin was 161 mV making it the highest value among the treatments and suggested that chlorophyllin was the most stable pigment. The means for the remaining treatments were all statistically similar to each other ($p < 0.01$). The similar rankings and LV values of the remaining pigments suggest that the cells were not able to act as efficient photo-sensitizers for a more than a few days. The LVs produced by each pigment were phycocyanin with 26.7 mV, chlorophyll *a/b* with 16.0 mV, crude extract with 7.80 mV, chlorophyll *b* with 1.53 mV, chlorophyll *a* with 0.400 mV, and the control with 0.0900 mV.

Beginning Voltage (BV)

The BV was used to show the voltage productions of a newly-made cell that could be compared to ending values. The BVs for crude extract, chlorophyllin, and chlorophyll *a* were statistically higher ($p < 0.001$) than those of other treatments, with mean voltages of 230, 229, and 176 mV, respectively (Table 7). This similarity suggested that initially, degradation products were not an issue for the solar cells, and further investigations should be pursued to possibly enhance these BV values. The high value of the crude extract suggested that the pigments in the solar cell were capturing a wider spectrum of light than chlorophyll *a* or *b* could do. Chlorophyll *a* though, was statistically similar and grouped with chlorophyll *a/b*, and phycocyanin with BV values of 142 and 134 mV, respectively. Chlorophyll *b* had a BV of 94.8 mV and was statistically similar to phycocyanin. The control demonstrated the lowest BV of 3.97 mV. The beginning voltages were assumed to be high because these cells had not experienced the photo-degradation, oxidation processes, or sealant issues that may occur as DSSCs age during time-study experiments (Hinsch et al. 2001). It is notable that extraction of pigments from living tissues with certain solvents, such as methanol, could result in degradation of chlorophylls *a* and *b* (Heaton et al. 1996). In this experiment, the differences in the voltages as the experiment continued may be due to photo-degradation of the pigments and/or oxidation, as well as sealant failure of DSSCs.

Ending Voltage (EV)

The EV was also used to determine the production capacity of the solar cell. An EV similar to the BV indicated that degradation of the pigments would be limited and that they could maintain similarly high voltage production. Voltage produced by all pigments decreased during the 10-day experiment when compared to the BV. Chlorophyllin demonstrated the highest significant ending voltages ($p < 0.05$), when compared to the other treatments, with a mean of 166 mV (Table 7). The remaining treatments were statistically similar in their mean values and grouped together. The EVs of chlorophyll *a,* chlorophyll *a/b*, phycocyanin, chlorophyll *b*, crude extract, and control were 46.2, 36.1, 36.1, 19.0, 0.47 and 0.140 mV, respectively.

Total Voltage Change (TVC)

The TVC was the difference between the BV and the EV. The higher the voltage values from this calculation, the worse the pigment was expected to perform as a photo-sensitizer. The TVC from photovoltaic cells constructed with crude extract had a mean value of 211 mV, which was significantly higher ($p < 0.05$) than the TVC from cells constructed with other pigments (Table 7). The large drop of crude extract voltage production suggested that there may have been a large number of impurities in the crude extracts that sped up degradation factors of the solar cell. The TVC of chlorophyll *a* was similar to the crude extract with a mean of 175 mV, but was also statistically similar to phycocyanin, chlorophyll *a/b* and chlorophyllin with TVCs of 98.3, 98.2, and 67.7 mV respectively. Phycocyanin, chlorophyll *a/b* and chlorophyllin were also statistically similar to chlorophyll *b* with a mean TVC of 63.9 mV and the control with 3.83 mV.

However, the control and chlorophyll *b* were not statistically different from each other and grouped together.

Analysis of Voltage Data and Calculations

Differences in behavior of photovoltaic cells as they aged were suggested through a comparison of BV and EV (Table 7). For instance, cells treated with chlorophyllin had the lowest voltage decrease, with a loss of 27.5%. The multiple carboxylic side chains of chlorophyllin may have increased the stability of the molecule (Doss and Ulshöfer 1971). Photovoltaic cells constructed with chlorophyll *b* and *a/b* demonstrated voltage changes of 61.9% and 67.5%, respectively, while cells constructed with chlorophyll *a* decreased 73.3%. The stability of the chlorophyll *b* molecule (Thomas 1997) could explain lower TVC values of chlorophyll *b* and chlorophyll *a/b*, when compared to chlorophyll *a* alone, which demonstrated a voltage decrease of nearly 100% (Table 7). Cells constructed with phycocyanin demonstrated a voltage drop of 73.1%. Of the two subunits of phycocyanin, alpha-phycocyanin and beta-phycocyanin (Schirmer et al. 1985), the alpha subunit is more sensitive to degradation (Renalducci et al. 2006) which may have accelerated the pigment's degradation in DSSCs. The crude extract had a voltage decrease of 91.7%, and the control had a voltage decrease of 96.5%. The high voltage decreases of crude extract may have been due to the increased competition of available substrate anchoring sites between the various photo-sensitive pigments and non-photo-sensitive molecules in the crude extract solution. Degradation of these non-photo-sensitive molecules may have accelerated the destruction of functioning pigments leading to the voltage decreases.

Photovoltaic cells constructed with crude extract had the highest TVC when compared to the other treatments (Table 7). The photovoltaic cells constructed with crude extract may have experienced pigment degradation and photo-oxidation. This may have occurred because the DSSCs were made with methanol-soluble chlorophyll extracts from spinach that was not freshly cut from the plant. It is likely that spinach leaves in this investigation included denatured proteins and pigments that were not as productive as those obtain from fresh samples (Thomas 1997) and explains, to some extent, why DSSCs constructed from crude extracts did not perform as well as anticipated. Chlorophyll *a* is not as photo-stable as chlorophyll *b in vivo* (Thomas 1997), which would explain the lower TVC of chlorophyll *b* in this experiment. However, chlorophyll *b* is not as efficient a solar energy converter as suggested by the low PV value from these cells (Table 7). This may explain why DSSCs constructed with chlorophyll *a* demonstrated higher initial voltage, but cells constructed with chlorophyll *b* maintained voltage for a longer period of time. Chlorophyllin demonstrated a low TVC (Table 7) when compared to the crude extract and chlorophyll *a*. This may be due to the increased number of carboxylic side chains in chlorophyllin that promote stability (Doss and Ulshöfer 1971). It has been reported that the phytol tail of chlorophylls in crude extracts and chlorophylls *a, b,* and, *a/b* hamper the pigment from anchoring efficiently to the TiO_2 substrate (Kathiravan et al. 2009).

Current

Current for each photovoltaic cell was calculated from the voltage produced divided by the resistance of the resistor in the circuit. Observed changes were seen in the total average accumulated current (TAC), average daily current (ADC), median daily current (MDC), peak current (PC), least current (LC), beginning current (BC), and ending current (EC). Results from analysis of variance (ANOVA) of all current measurements and calculations thereof, except total current change (TCC), showed significant differences at the 0.05 probability level (or even more significant) among treatments (Table 8). Statistical rankings were determined from the LSD of each value seen in Table 9.

Total Average Current (TAC)

Chlorophyllin demonstrated the highest significant TAC of 295 microamps (µA), when compared to the other treatments ($p < 0.001$) (Tables 8 and 9). Comparison of TAV (Table 7) to TAC (Table 9) suggested that the relative performance of cells among treatments maintained the same ranking of most efficient to least efficient in solar energy conversion. In other words, cells with higher TAVs usually produced higher TACs. This is generality the predicted behavior of solar cells (Nelson 2008). As chlorophyllin had the highest TAC value compared to the other pigments, it was considered the most efficient of the pigments for current. The TACs of all other treatments were not significantly different from each other (Table 9). Chlorophylls *a*, *b*, and *a/b* demonstrated currents of 38.6, 29.7, and 32.0 µA respectively. Crude extracts and phycocyanin had TAC means of 27.9 µA and 26.1 µA. The control exhibited a TAC mean of 0.0300 µA.

Average Daily Current (ADC)

The ADC of the pigmented solar cells determined the mean expectancy of current from each pigment over the course of the experiment. Chlorophyllin produced the highest significant ADC ($p < 0.001$) of all the treatments with a mean current of 29.9 µA (Table 9). The higher value of chlorophyllin compared to the other pigments suggested that it was a better photo-

Table 8: ANOVA test results for the current calculations.

Source	df	TAC	ADC	MDC	PC	LC	BC	EC	TCC
Treatment	6	***	***	**	***	**	***	*	NS
Rep	3	NS	NS	NS	NS	NS	NS	NS	NS
Error	18								

***, **, * Significant at the 0.001, 0.01, 0.05 probability levels, respectively; NS = Not significant.

Table 9: Current values and calculations (in microamps) for different pigments (treatments) used to construct photovoltaic cells during a 10-day experiment in an environmental chamber.

Treatment	TAC	ADC	MDC	PC	LC	BC	EC	TCC
Chlorophyll *a*	38.6 b*	3.86 b	1.52 b	14.2 b	0.019 b	13.9 bc	0.025 b	13.9 ab
Chlorophyll *b*	29.7 b	2.95 b	4.38 b	6.92 bc	0.136 b	6.92 bcd	3.59 b	3.84 ab
Chlorophyll *a/b*	32.0 b	3.23 b	2.53 b	7.36 bc	0.725 b	6.47 bcd	2.10 b	4.46 ab
Crude Extract	27.9 b	2.87 b	1.18 b	16.1 b	0.402 b	16.1 b	0.910 b	15.2 a
Phycocyanin	26.1 b	2.674 b	2.24 b	5.66 bc	1.08 b	5.00 cd	1.36 b	3.64 ab
Chlorophyllin	295 a	29.9 a	26.7 a	41.9 a	21.8 a	33.8 a	23.0 a	12.0 ab
Control	0.03 b	0.003 b	0.13 b	0.018 c	0.00 b	3.97 d	0.001 b	0.017 b
LSD (0.05)	91.0	8.95	12.7	12.3	10.4	10.3	12.7	14.3

*Means within a column followed by the same letter are not significantly different. TAC = total average accumulated current; ADC = average daily current; MDC = median daily current; PC = peak current; LC = least current; BC = beginning current; EC = ending current; TCC = total current change; LSD = least significant difference at the 0.05 probability level. This table shows that all values and calculations, except those for TCC, were significantly higher for the chlorophyllin treatment, compared to other pigments used in photovoltaic cells. Other values and calculations varied among pigment treatments, and those followed by same letter(s) within a column were not significantly different, whereas those followed by different letter(s) were significantly different.

sensitizer than the other pigments. The other treatments did not demonstrate significant differences among each other. Chlorophylls *a*, *b*, and *a*/*b* demonstrated only 3.86 µA, 3.23 µA, and 2.95 µA of ADC production, respectively. Crude extract and phycocyanin had ADC productions of 2.87 µA and 2.67 µA. The close similarity of ADC values for many pigments (Table 9) suggests that, although the pigments are capable of producing voltage (Table 7), they are not very efficient at moving the excited electron into the substrate. The control had the lowest ADC of 0.00300 µA.

Median Daily Current (MDC)

The MDC was used to determine the current half-life production of the pigment during the 10-day experiment. Chlorophyllin demonstrated the highest significant MDC ($p < 0.01$) with a value of 26.7 µA (Table 9). The remaining treatments were statistically similar. The higher value for chlorophyllin suggested that the pigment was more stable at producing current compared to the other pigments. The other pigments were possibly hampered more by degradation factors (Hinsch et al. 2009). Chlorophyll *b*, *a/b*, and phycocyanin had MDCs of 4.38, 2.53, and 2.24 µA per day. Chlorophyll *a* showed a lower MDC of 1.52 µA, followed by the crude extract with a value of 1.18 µA. The control demonstrated the least MDC over the course of the experiment with a value of 0.00100 µA.

Peak Current (PC)

The PC determined the maximum current produced from the solar cell. A high PC indicated that the cell was readily converting solar energy into current. Solar cells pigmented with chlorophyllin demonstrated the highest PC values ($p < 0.001$) with a mean of 41.9 µA (Table 9). Crude extract, chlorophyll *a,* chlorophyll *a/b*, chlorophyll *b,* and phycocyanin pigments were statistically ranked with each other, and had currents of 16.1, 14.2, 7.36, 6.92, and 5.66 µA, respectively. Chlorophyll *a/b,* chlorophyll *b*, and the phycocyanin pigments were statistically similar to the control, which demonstrated a PC of 0.0180 µA.

Chang et al. (2010) reported on the short circuit current of spinach crude extracts with a value of 0.460 mA per square centimeter, which was higher than what was demonstrated in this experiment (cells used in Chang's investigation were 0.88 cm^2, and for comparison purposes, this relates to 0.405 mA for this experiment). The higher short circuit current from Chang's work was the result of a decrease in the pH of the pigment solvents that led to better efficiencies of the dye to substrate energy transfer. Experiments for this thesis investigation did not examine the relationships of pH to pigment efficiencies.

Least Current (LC)

The LC of a solar cell was the least current produced under daylight conditions by the solar cells. The cells experienced a decrease in current production as the experiment progressed. The loss of current in the DSSCs may have been the result of several factors mentioned previously (Hinsch et al 2001) including degradation of the pigment (Le et al. 2010), a bad seal that allowed for the evaporation of the electrolyte (Hinsch et al. 2001), or introduction of oxygen into the cell that leads to oxidation of the pigments (Hinsch et al. 2001, Matsui et al. 2009).

The chlorophyllin pigment demonstrated the highest ($p < 0.01$) LC with 21.8 μA (Table 9) and was ranked higher in LC production compared to the other pigments. The higher value of chlorophyllin may indicate its ability to resist degradation as opposed to the other pigments. The remaining treatments were all ranked similarly, suggesting a strong reaction to degradation factors. Phycocyanin had a LC value of 1.08 μA, chlorophyll *a*/*b* with 0.725 μA, crude extract with 0.402 μA, chlorophyll *b* with 0.136 μA and chlorophyll *a* with 0.0190 μA. The control's LC production was negligible.

Beginning Current (BC)

The BC of a solar cell was useful to determine the initial current that the solar cell could produce before degradation occurred. The BC had more statistical rankings than those encountered in most of the other current variables (Table 9). Chlorophyllin had the highest BC mean ($p < 0.001$) of 33.8 μA, more than double the production of crude extract with a BC of 16.1

μA. The higher value of chlorophyllin suggested that it was the most efficient pigment for current production. The crude extract was also similar to chlorophyll *a*, chlorophyll *b,* and chlorophyll *a/b* with BC means of 13.9, 6.92, and 6.47 μA, respectively. Statistically similar to the chlorophyll pigments was phycocyanin and the control with BCs of 5.00 and 0.0180 μA (Table 9). Values for BC produced by chlorophylls *b* and *a/b* were also statistically similar to phycocyanin and the control, but only phycocyanin shared similarity with the BC values of chlorophyll *a*. The close similarity of several pigment's values indicated that they had undergone little degradation by the time that the experiment began. This can be inferred from the higher levels of current produced when compared to the ending current.

Ending Current (EC)

The EC was used to determine the endurance of the pigments when used in photovoltaic devices. An EC that more resembled the BC would be better suited as a pigment in a DSSC. Chlorophyllin demonstrated the highest EC among the treatments ($p < 0.05$) with a mean of 23.0 μA (Table 9). The remaining treatments failed to demonstrate significant differences among themselves when comparing ECs and were ranked together. The similarity of the other treatments compared to chlorophyllin suggested that chlorophyllin was the most stable pigment of those tested as it was able to maintain current productions closer to what was achieved in the BC. Chlorophyll *b* had an EC of 3.59 μA, chlorophyll *a/b* with 2.01 μA, phycocyanin with 1.36 μA, crude extract with 0.910 μA, chlorophyll *a* with 0.0250 μA, and the control produced an EC of only 0.00100 μA.

Total Current Change (TCC)

The TCC was determined by comparing the beginning current to the ending currents. The higher the current results for this calculation, the worse the pigment is expected to perform as a photo-sensitizer. The ANOVA failed to show differences at the 0.05 probability level among TCC values, although general trends of TCC were observed from the LSD analysis (Table 9).

Crude extract demonstrated the highest TCC value of 15.2 μA, but this was similar to all the remaining treatments except the control. Chlorophyll *a*, chlorophyllin, chlorophyll *a/b*, chlorophyll *b*, and phycocyanin had TCC values of 13.9, 12.0, 4.46, 3.84, and 3.64 μA, respectively. The control had the lowest TCC value of 0.0170 μA, and displayed statistical similarities with all treatments except the crude extract. The similar LSD rankings and the ANOVA failure at 0.05 suggested that the pigments all experienced a decrease in current production over the 10-day experiment, but crude extract had the highest change suggesting degradation was more rapid with this pigment than the others.

Analysis of Current Data and Calculations

Photovoltaic cells constructed with chlorophyll *a/b* and *b* failed to demonstrate large differences between the BC and EC values (Table 9) when compared to those of chlorophyll *a* and the crude extract. As suggested by previous investigators, the photo-stability of chlorophyll *b* (and possibly chlorophyll *a/b*) helped to prevent significant losses due to degradation (Thomas 1997), but possible leaks in the DSSC seals may have lowered their performance (Matsui et al. 2009).

Chlorophyllin's EC was higher than the other treatments (Table 9), but exhibited reductions in current production as noted from comparison of BC to EC. The high ECs of chlorophyllin cells suggested that this pigment was more stable as a photo-sensitizer in DSSCs, perhaps due to more side chains of this molecule (Doss and Ulshöfer 1971). Chlorophyll *a* had the largest reduction in current production of 99.7%, when comparing BC to EC. The crude extract and the control both had reductions of 94.4%. The differences for phycocyanin, chlorophyll *a/b*, chlorophyll *b*, and chlorophyllin were 72.8%, 68.9%, 48.1%, and 32.0%, respectively.

The low EC value obtained from cells constructed with chlorophyll *a* further suggests the sensitivity of chlorophyll *a* when compared to similar isolated pigments such as chlorophyll *b.* The phytol tail may explain decreases in current for the crude extract and chlorophylls *a, b,* and *a/b*, as the tails hamper the pigment from anchoring well to the TiO_2 substrate (Kathiravan et al. 2009), and chlorophyllin has no such tail. The low differences between the BC and the EC values (and relatively lower TCC value) of chlorophyll *b* compared to chlorophyll *a* suggest the resistance of chlorophyll *b* to degradation when compared to chlorophyll *a* (Thomas 1997), and similar current characteristics demonstrated by chlorophyll *a/b*.

Power

Treatments were also evaluated for several power measurements and calculations thereof. The power was calculated from the current multiplied by the voltage. Changes were observed in the total average accumulated power (TAP), average daily power (ADP), median daily power (MDP), peak power (PP), least power (LP), beginning power (BP), and ending power (EP). The results from analysis of variance (ANOVA) of all power measurements and calculations thereof, except total power change (TPC), showed significant differences at the 0.05 probability level (or even more significant level) among treatments (Table 10). Statistical rankings were determined from the LSD of each value seen in Table 11.

Total Average Power (TAP)

Chlorophyllin displayed the highest TAP values ($p < 0.001$) in comparison to the other treatments (Table 11). Chlorophyllin had a TAP production of 673 microwatts (μW). This corresponded to the similar findings of the TAV (see Table 7) and the TAC (see Table 9), and as predicted by Ohm's law, would correspond to a higher TAP. The higher TAP production of chlorophyllin suggested it was more efficient as a photo-sensitizer than the other pigments. The remaining treatments failed to exhibit any statistical differences among each other. Chlorophyll *a/b* TAP was observed at 31.7 μW, chlorophyll *a* at 23.5 μW, phycocyanin at 20.9 μW, chlorophyll *b* at 19.6 μW, and crude extract at 12.8 μW. The control demonstrated negligible power production.

Average Daily Power (ADP)

The ADP of the solar cells determined the mean expectancy of power produced from each pigment over the course of the experiment. Chlorophyllin pigmented solar cells displayed the highest ADP value among all treatments (Table 11). This coincided with previous investigations that demonstrated chlorophyllin as a highly effective DSSC pigment (Amao and Komori 2004). Chlorophyllin had an ADP of 6.81 μW. The remaining treatments were

Table 10: ANOVA test results for the power calculations.

Source	df	TAP	ADP	MDP	PP	LP	BP	EP	TPC
Treatment	6	***	***	**	***	**	***	*	NS
Rep	3	NS	NS	NS	NS	NS	NS	NS	NS
Error	18								

***, **, * Significant at the 0.001, 0.01, 0.05 probability levels, respectively; NS = Not significant.

Table 11: Power values and calculations (in microwatts) for different pigments (treatments) used to construct photovoltaic cells during a 10-day experiment in the environmental chamber.

Treatment	TAP	ADP	MDP	PP	LP	BP	EP	TPC
Chlorophyll *a*	23.5 b*	0.235 b	0.061 b	3.13 b	0.00 b	3.01 bc	0.00 b	3.00 ab
Chlorophyll *b*	19.6 b	0.195 b	0.548 bc	0.894 bc	0.001 b	0.894 cd	0.510 b	0.525 ab
Chlorophyll *a/b*	31.7 b	0.319 b	0.340 b	1.36 bc	0.023 b	1.135 cd	0.288 b	0.842 ab
Crude Extract	12.8 b	0.134 b	0.041 b	3.74 b	0.005 b	3.74 b	0.030 b	3.32 a
Phycocyanin	20.9 b	0.214 b	0.183 b	0.865 bc	0.054 b	0.667 cd	0.084 b	0.397 ab
Chlorophyllin	673 a	6.81 a	6.75 a	11.3 a	4.84 a	7.56 a	5.33 a	1.96 ab
Control	0.00 b	0.00 b	0.00 b	0.00 c	0.00 b	0.00 cd	0.00 b	0.00 b
LSD (0.05)	270	2.67	3.06	3.09	2.43	2.50	2.92	3.22

*Means within a column followed by the same letter are not significantly different. TAP = total average accumulated power; ADP = average daily power; MDP = median daily power; PP = peak power; LP = least power; BP = beginning power; EP = ending power; TPC = total power change; LSD = least significant difference at the 0.05 probability level. This table shows that all values and calculations, except those for TPC, were significantly higher for the chlorophyllin treatment, compared to other pigments used in photovoltaic cells. Other values and calculations varied among pigment treatments, and those followed by same letter(s) within a column were not significantly different, whereas those followed by different letter(s) were significantly different.

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statistically similar and ranked accordingly. Chlorophyll *a/b* had an ADP production of 0.319 μW, chlorophyll *a* at 0.235μW; phycocyanin at 0.214 μW, crude extract at 0.134 μW, and chlorophyll *b* at 0.195 μW. The control ADP value was negligible.

Median Daily Power (MDP)

The MDP was used to determine the power half-life production of the pigment during the 10-day experiment. The MDP of the treatments identified chlorophyllin with the highest value ($p < 0.01$) compared to the other treatments (Table 11). Chlorophyllin had a MDP production of 6.75 μW. The remaining treatments were statistically similar and ranked together. Chlorophyll *b* produced 0.548 μW, chlorophyll *a/b* produced 0.340 μW, phycocyanin produced 0.183 μW, chlorophyll *a* produced 0.061 μW, and crude extract produced only 0.041 μW. The control had a MDP that was negligible.

Peak Power (PP)

The PP determined the maximum power produced from the solar cell. A high PP indicated that the cell was readily converting light energy into electrical power. Chlorophyllin exhibited the highest PP production of 11.3 μW ($p < 0.001$) and the most effective at converting light into electricity (Table 11). The crude extract and chlorophyll *a* pigmented solar cells were statistically similar to each other and ranked together with PP values of 3.74 and 3.13 μW. Chlorophyll *a/b,* chlorophyll *b,* and phycocyanin had PP productions of 3.74, 3.13, 1.36, 0.894, and 0.865 μW, respectively, and were statistically similar to crude extract and chlorophyll *a,* as well as the control which had a negligible PP. The close similarity of chlorophyll *a/b*, chlorophyll *b*, phycocyanin, and the control suggested that these pigments were not efficient producers of power.

In previous studies (Chang et al. 2010), crude extracts of spinach demonstrated a maximum power production of 250 μW/cm^2 (cells used in Chang's study were 0.88 cm^2, and for comparison purposes, this relates to 220 μW in this experiment). The PP produced by DSSCs in

Chang's experiment was substantially higher than the PP produced from DSSCs in this investigation, which may be explained by the different methodologies in preparation of DSSCs. For instance, the results that Chang and coworkers (2010) published facilitated the use of ethanol and a hot water bath to assist in the extraction of chlorophyll, which may have possibly removed more of the chlorophyll from the leaves. However, in Chang's investigation, the hot ethanol may have also removed the phytol tails (Gaur et al. 2007) and the lack of a tail would have led to a better adherence to the substrate (Kathiravan et al. 2009). Further investigations are needed to better understand why these types of differences exist in performance of DSSCs.

Least Power (LP)

The LP of a solar cell was the least power produced under daylight conditions. The pigmented solar cells experienced a decrease in power production as the experiment continued, which suggests possible degradation factors as mentioned by Hinsch and his team (2009). Chlorophyllin had the highest LP value when compared to the other treatments ($p < 0.01$) with 4.84 μW (Table 11). Chlorophyllin was the most efficient and possibly the most stable of the pigments that were used in this investigation due to its much higher LP values when compared to the other pigments. The remaining treatments were statistically similar to each other and ranked accordingly. Phycocyanin demonstrated a LP production of 0.054 μW, chlorophyll *a/b* with 0.023 μW, crude extract with 0.005 μW, and chlorophyll *b* with 0.001 μW. The control and chlorophyll *a* both had LPs of 0.000 μW.

Beginning Power (BP)

The BP of a solar cell was useful to determine the initial power that the solar cell could produce before degradation occurred. Chlorophyllin exhibited the highest BP value with a mean of 7.56 μW ($p < 0.001$) (Table 11). Crude extract and chlorophyll *a* were statistically grouped with BPs of 3.74 and 3.01 μW. However, chlorophyll *a* was statistically similar to chlorophyll *a/b,* chlorophyll *b,* and phycocyanin, with BPs of 1.14, 0.894, and 0.667 μW, respectively. The control demonstrated a BP of 0.000 μW. The control BP was statistically similar to that of chlorophylls *a/b, b,* and phycocyanin suggesting that the pigments were not efficient producers of electrical power.

Ending Power (EP)

The EP was used to determine the power production endurance of the solar cells. Chlorophyllin had the highest EP value ($p < 0.05$) of 5.33 µW and, compared to the EP of the other pigments, was the most efficient power producer (Table 11). The remaining treatments were statistically similar and ranked together. Chlorophyll *b* had an EP of 0.510 µW, chlorophyll *a/b* at 0.288 µW, phycocyanin 0.084 at µW, and the crude extract at 0.030 µW. The higher EPs of chlorophyll *b* and chlorophyll *a/b* further demonstrated the stability of the chlorophyll *b* molecule when compared to the chlorophyll *a* molecule (Thomas 1997). The control and chlorophyll *a* treatments both had EP production means of 0.000 µW.

Total Power Change (TPC)

The TPC was the difference between the BC and the EP and was used to determine the endurance and the viability of the pigments in DSSCs. The TPC of the treatments demonstrated no statistical differences at the 0.05 probability level from the ANOVA (Table 11). The LSD suggested that statistical rankings did exist between the different pigments. Crude extract demonstrated the highest TPC with a mean of 3.32 µW. The use of multiple pigments may have initially helped in developing modest power results (Dürr et al. 2004), but the potential deterioration of pigments may have resulted in power loss in DSSCs constructed with crude extract. Values from the crude extract were statistically similar to the other treatments, but ranked higher than the control according to the LSD. Chlorophyll *a* had a TPC mean of 3.00 µW, chlorophyllin at 1.96 µW, chlorophyll *a/b* at 0.840 µW, chlorophyll *b* at 0.530 µW, and phycocyanin at 0.400 µW. The control had a mean TPC of 0.000 µW, and was statistically similar to other treatments from the ANOVA, but was not ranked with the crude extract according to the LSD.

Analysis of Power Data and Calculations

The near 100% power reduction of chlorophyll *a* and, as indicated from observation of the BP and EP (Table 11), suggest the instability of the chlorophyll *a* molecule when compared to chlorophyll *b* (Thomas 1997) or chlorophyll *a/b*, with power losses of 44.0% and 74.6%, respectively. The control's initial power production may be attributed to the iodine absorbing some of the light spectrum (Hoshikawa et al. 2006), but the breakdown of the iodine molecules (Junghänel and Tributsch 2005) may have prevented the cells from generating power as the experiment continued. Chlorophyllin had a power loss of 29.5%, making it the most stable of the treatments, possibly due to better bonding with the TiO_2 substrate through the carboxylic side chains (Doss and Ulshöfer 1971) or a lack of a phytol tail (Kathiravan et al. 2009). Conversely, lower stability of the crude extract may explain why these DSSCs demonstrated a 99.2% power loss. In previous studies with crude extracts, this drop in power production has been attributed to degradation of pigments (Thomas 1997). Phycocyanin had an 88.0% power loss, which affirms instability of the pigment due to the alpha subunit (Renalducci et al. 2006), but the beta-subunit could have been producing power for a longer period of time.

Efficiencies

The calculated efficiency of each DSSC is presented in Tables 12 and 13. Table 12 shows beginning efficiency of each DSSC treatment and Table 13 shows ending efficiency of each DSSC treatment. Efficiencies were calculated using the following formula:

$$((P_{max} \text{ of the Solar Cell}) / (\text{Power of Light})) * 100$$

Beginning Efficiencies

The efficiencies of the different pigments were compared using the LSD values (Figure 21). The results indicated that chlorophyllin was the most efficient photo-sensitizer with a mean efficiency of 0.0217%. Crude extract was significantly higher with a mean efficiency of 0.0156%. Chlorophyll *a* had an efficiency of 0.00710% and other pigment efficiencies were as follows: chlorophyll *a/b* with 0.00314%; phycocyanin with 0.00249%; and chlorophyll *b* with 0.00224%. Efficiency values for chlorophyll *a/b*, phycocyanin, and chlorophyll *b* were statistically similar to both chlorophyll *a* and the control. The control had an efficiency of 0.000595%. The lack of a phytol tail and the multiple carboxyl groups of the chlorophyllin may have been responsible for the stability of the chlorophyllin (Doss and Ulshöfer 1971). This may have led to a better injection rate of excited electrons into the TiO_2 compared to the other treatments and ultimately a better pigment for a DSSC.

Ending Efficiencies

The ending efficiencies (Figure 22) were generally lower than the beginning efficiencies (see Figure 21). Some exceptions occurred with chlorophyllin and chlorophyll *b.* Chlorophyllin demonstrated the highest value with an efficiency mean of 0.0437% ($p < 0.05$), more than 15 times more efficient than chlorophyll *b,* the next closest efficiency value, making chlorophyllin an exceptional photo-sensitizer, compared with the other treatments. The stability of the chlorophyllin molecule in a DSSC may have been observed because of its lack of degradation

Table 12: Efficiencies of the solar cells calculated from the beginning power curves.

Treatment	Power of light (W/m^2)	P_{max} of cells (W/m^2)	Efficiency
Chlorophyll *a*-1	2.91E-02	2.67E-06	9.17E-03
Chlorophyll *a*-2	2.91E-02	6.19E-07	2.13E-03
Chlorophyll *a*-3	2.91E-02	1.80E-07	6.18E-04
Chlorophyll *a*-4	2.91E-02	4.80E-06	1.65E-02
Chlorophyll *b*-1	2.91E-02	9.49E-08	3.26E-03
Chlorophyll *b*-2	2.91E-02	5.12E-07	1.76E-03
Chlorophyll *b*-3	2.91E-02	6.83E-07	2.34E-03
Chlorophyll *b*-4	2.91E-02	4.64E-07	1.59E-03
Chlorophyll *a/b*-1	2.91E-02	9.74E-08	3.34E-04
Chlorophyll *a/b*-2	2.91E-02	2.36E-07	8.10E-04
Chlorophyll *a/b*-3	2.91E-02	2.77E-07	9.51E-04
Chlorophyll *a/b*-4	2.91E-02	3.05E-06	1.05E-02
Crude Extract-1	2.91E-02	3.75E-06	1.29E-02
Crude Extract-2	2.91E-02	5.68E-06	1.95E-02
Crude Extract-3	2.91E-02	3.10E-06	1.06E-02
Crude Extract-4	2.91E-02	5.68E-06	1.95E-02
Phycocyanin-1	2.91E-02	5.37E-07	1.84E-03
Phycocyanin-2	2.91E-02	5.43E-07	1.86E-03
Phycocyanin-3	2.91E-02	9.96E-07	3.42E-03
Phycocyanin-4	2.91E-02	8.21E-07	2.82E-03
Chlorophyllin-1	2.91E-02	6.79E-06	2.33E-02
Chlorophyllin-2	2.91E-02	5.61E-06	1.93E-02
Chlorophyllin-3	2.91E-02	7.88E-06	2.71E-02
Chlorophyllin-4	2.91E-02	5.01E-06	1.72E-02
Control-1	2.91E-02	1.07E-08	3.67E-05
Control-2	2.91E-02	5.09E-10	1.75E-07
Control-3	2.91E-02	9.52E-10	3.27E-06
Control-4	2.91E-02	6.82E-07	2.34E-03

Table 13: Efficiencies of the solar cells calculated from the ending power curves.

Treatment	Power of light (W/m^2)	P_{max} of cells (W/m^2)	Efficiency
Chlorophyll *a*-1	2.91E-02	5.36E-10	1.84E-06
Chlorophyll *a*-2	2.91E-02	1.02E-10	3.50E-07
Chlorophyll *a*-3	2.91E-02	0	0
Chlorophyll *a*-4	2.91E-02	2.52E-13	8.65E-10
Chlorophyll *b*-1	2.91E-02	6.32E-07	2.17E-03
Chlorophyll *b*-2	2.91E-02	1.93E-09	6.63E-06
Chlorophyll *b*-3	2.91E-02	2.55E-06	8.75E-03
Chlorophyll *b*-4	2.91E-02	4.23E-09	1.45E-05
Chlorophyll *a/b*-1	2.91E-02	0	0
Chlorophyll *a/b*-2	2.91E-02	8.90E-07	3.06E-03
Chlorophyll *a/b*-3	2.91E-02	1.15E-10	3.95E-07
Chlorophyll *a/b*-4	2.91E-02	0	0
Crude Extract-1	2.91E-02	3.18E-09	1.09E-05
Crude Extract-2	2.91E-02	1.14E-08	3.91E-05
Crude Extract-3	2.91E-02	4.71E-08	1.62E-04
Crude Extract-4	2.91E-02	1.25E-07	4.29E-04
Phycocyanin-1	2.91E-02	2.55E-07	8.75E-04
Phycocyanin-2	2.91E-02	0	0
Phycocyanin-3	2.91E-02	0	0
Phycocyanin-4	2.91E-02	3.69E-07	1.27E-03
Chlorophyllin-1	2.91E-02	2.60E-05	8.93E-02
Chlorophyllin-2	2.91E-02	2.18E-05	7.47E-02
Chlorophyllin-3	2.91E-02	3.22E-09	1.11E-05
Chlorophyllin-4	2.91E-02	3.13E-06	1.07E-02
Control-1	2.91E-02	0	0
Control-2	2.91E-02	0	0
Control-3	2.91E-02	0	0
Control-4	2.91E-02	0	0

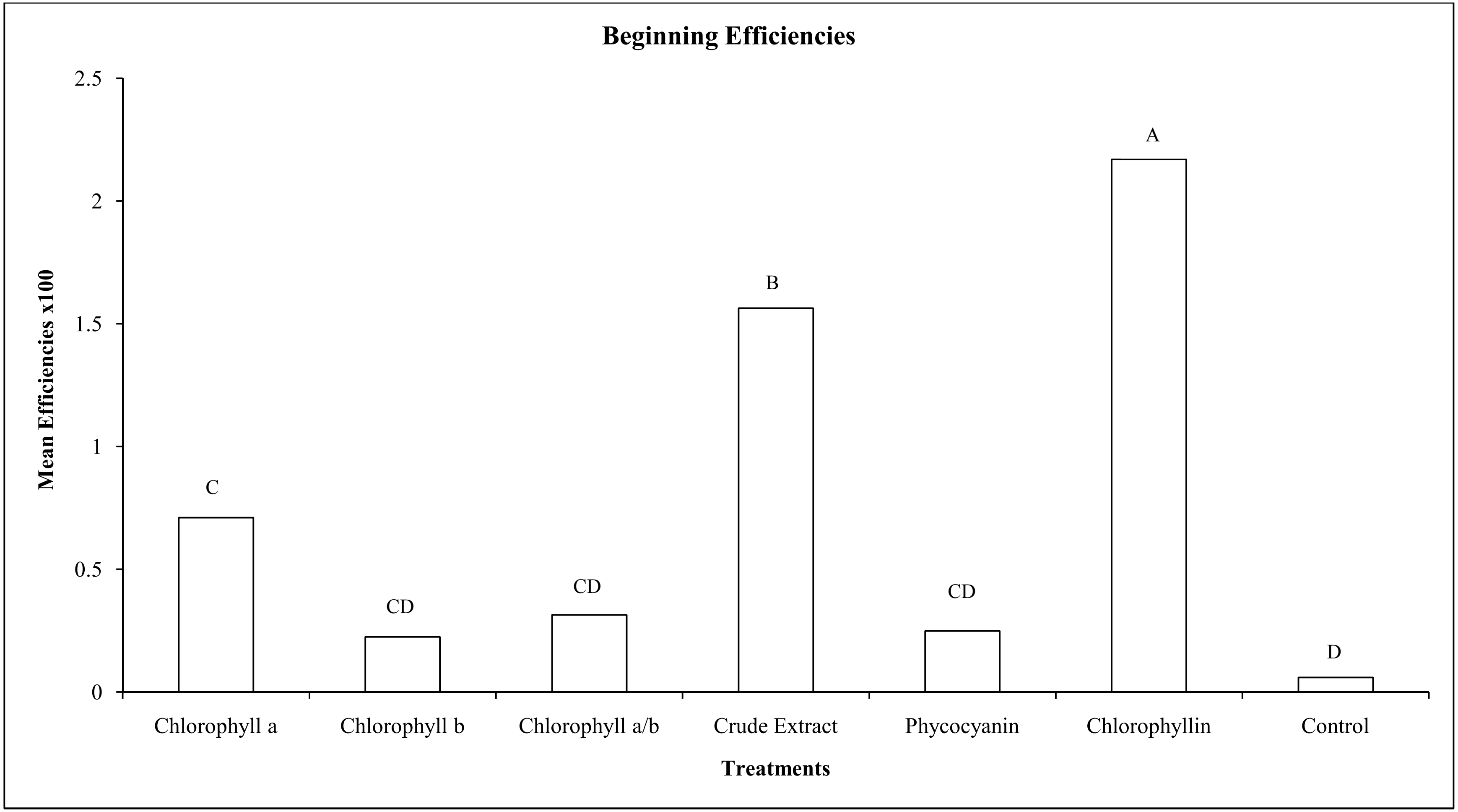

Figure 21: The mean beginning efficiencies of the treatments multiplied by 100. Letters indicated the ranking of the treatments from the least significant difference at the 0.05 probability level. Bars with the same letter displayed are not significantly different. This figure shows that beginning mean efficiency of the chlorophyllin treatment was higher than that of all other pigment treatments.

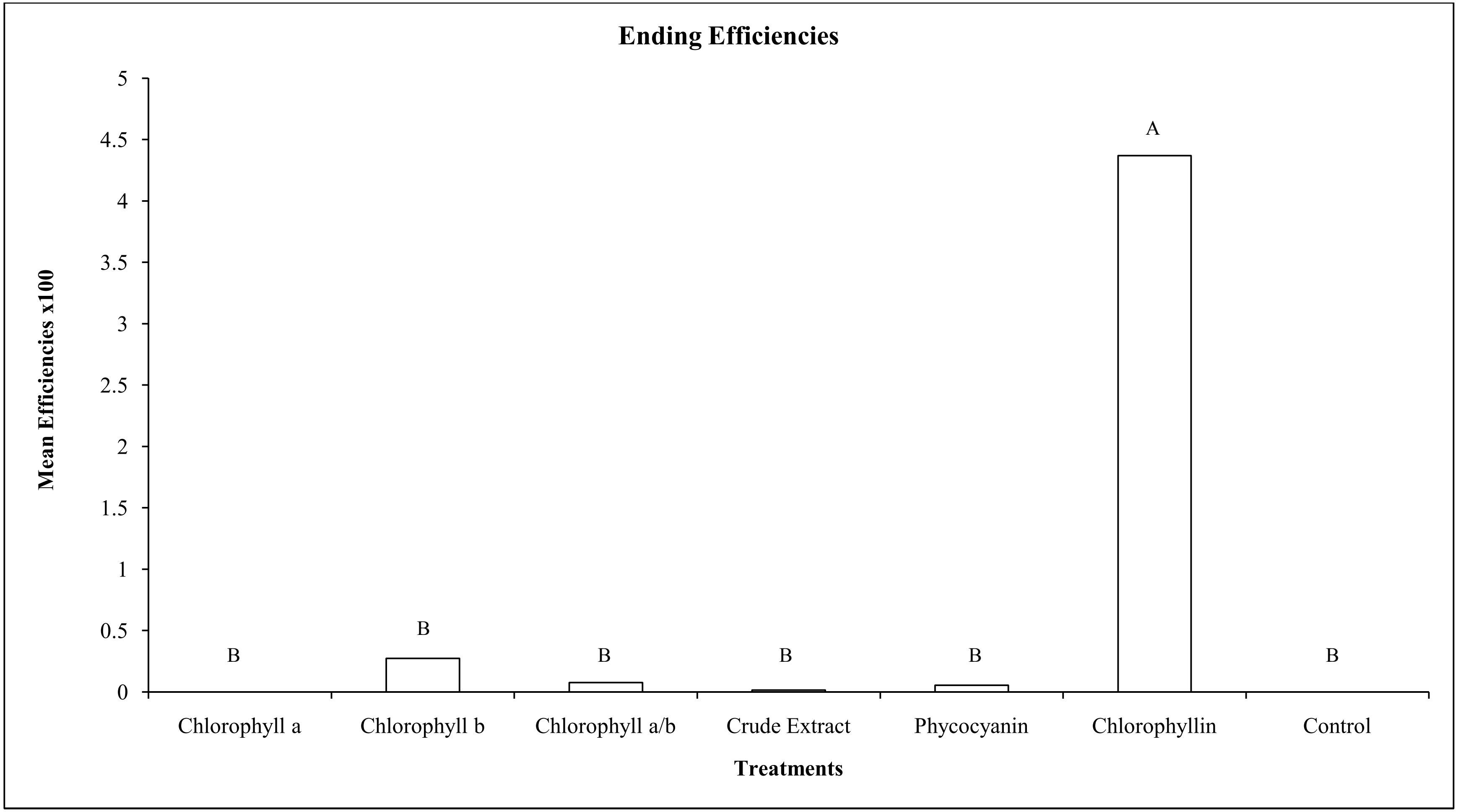

Figure 22: The mean ending efficiencies of the treatments multiplied by 100. Letters indicated the ranking of the treatments from the least significant difference at the 0.05 probabilty level. Bars with the same letter displayed are not significantly different. This figure shows that the ending mean efficiency of the chlorophyllin treatment was higher than that of all other pigment treatments.

compared to the other cells. None of the other treatments were significantly different from each other. Chlorophyll b had an efficiency of 0.00274%, chlorophyll a/b at 0.00760%, phycocyanin at 0.000540%, and crude extract at 0.000160%. The control and chlorophyll *a* had efficiencies of zero.

Two treatments had increases in efficiencies at the end of the experiment; chlorophyllin demonstrated a 101% increase and chlorophyll *b* had a 22.4% increase, contrary to the expected 15.0% decrease presented by Hinsch and coworkers (2001). These increases in efficiency could be the result of the pigments establishing better contact with the TiO_2 substrate as the experiment progressed, resulting in lower internal resistances, although no measurements were made to support that theory. Evaluation of cell performance for a longer period of time would be necessary to determine the true longevity of these pigments in DSSCs.

The remaining pigments performed at levels lower than the 15.0% decrease in efficiencies proposed by Hinsch and coworkers (2001). Chlorophyll *a*/b had a decrease of 75.8%, phycocyanin demonstrated a decrease of 78.3%, and the crude extract had a decrease of 99.0%. Chlorophyll *a* and the control had 100% efficiency reductions. The high decreases in efficiency encountered in this experiment may be attributed to several reasons as stated by Hinsch et al (2001). As to why chlorophyllin was not affected by the same factors was not determined.

Analysis of Pigment Efficiencies

Chlorophyll *a*

Chlorophyll *a* demonstrated an average beginning efficiency of only 0.00709% and an ending average efficiency of essentially zero (0.000000548%). Few literature papers were found that show the efficiencies of the pigment, chlorophyll *a*. Kay and Grätzel (2005) determined that the incident photon conversion efficiency (IPCE) of chlorophyll *a* was 3.50%. However, the chlorophyll in Kay and Grätzel's investigation was dissolved in either diethyl ether or hexane, potentially allowing more of the dye to adhere onto the TiO_2 substrate.

Chlorophyll *b*

The pigment chlorophyll *b* demonstrated an average efficiency of only 0.00224% and an average ending efficiency of 0.00274%. This is an increase in efficiency due to one solar cell's improvement in performance following the experimental day/night cycle. The increase in efficiency may be the result of better iodide interactions with chlorophyll *b* (Junghänel and Tributsch 2005) or better interactions with the substrate. Limited information is available in the literature to compare the efficiencies of chlorophyll *b*.

. **Chlorophyll *a/b***

Chlorophylls *a/b* together demonstrated an average efficiency of 0.00314% and an ending average efficiency of 0.000764%. The efficiency for the combination of pure chlorophyll *a* and chlorophyll *b* is not well-documented in the literature. However, it is known that effect of multiple pigments on the DSSC helps them capture more of the light spectrum than one pigment alone (Amao et al. 2006, De Padova et al. 2009). In this investigation, the combination of pigments was more effective than chlorophyll *b* as a photo-sensitizer, but less effective than chlorophyll *a* alone.

Crude Extract

The crude extract demonstrated a beginning efficiency of 0.0156% and an ending efficiency of 0.000160%. The beginning efficiency of these cells was relatively low when compared to the efficiency of 0.131% reported by Chang and coworkers in 2010. However, the efficiency of the crude extract was significantly higher than any of the purified pigment preparations of chlorophyll *a*, *b*, and *a/b*. This may be the result of the synergistic effect of multiple pigments, which were combined in the crude extract, covering a larger portion of the light spectrum (Amao et al. 2006, De Padova et al. 2009).

Phycocyanin

Phycocyanin had a beginning average efficiency of only 0.00249% and an ending efficiency of 0.000536%. Limited information is available to describe the efficiency of phycocyanin as a solar energy converter, although it does appear that the phycocyanin could be a good photosensitizing agent (Liu 2008). The results do not fully support the findings by Liu, as some pigments (chlorophyllin) produced much better efficiencies.

Chlorophyllin

The average beginning efficiency of chlorophyllin at 0.0217% was the highest among all treatments. The ending solar cell efficiency was 0.0437%, which is an increase compared with the beginning efficiency. These efficiency levels are similar to those of previous investigations that show efficiencies of chlorophyllin ranging from 0.0290 to 0.400% (Amao and Komori 2004, Amao et al. 2006). It was noted that results from Amao and coworkers did not include ending efficiencies, but rather, one measurement of the solar cells after construction, similar to what was performed to determine the beginning power curves in this experiment. An increase in the efficiencies of the ending solar cells made with chlorophyllin show a potential improvement compared to what has been demonstrated in these previous investigations.

Control

The control treatments had relatively low efficiencies with the exception of one cell. The average beginning efficiency was 0.000595% due to one DSSC. Iodine can act as a slight photo-sensitizer due to its color and impedance on the TiO_2 substrate (Hoshikawa et al. 2006). The ending efficiencies of all control treatments were zero, which showed that, although slight power was observed in the beginning of the experiment values for power quickly declined. It was predicted that the control would not have any measurable voltage over the course of the experiment, however the voltage that was produced was minute compared to the values produced by the other pigments.

CONCLUSIONS

Power Curves Obtained From Different Pigments Used in Photovoltaic Cells

The shape and values obtained for beginning and ending power curves of DSSCs using different pigments varied. In general, beginning power curves of most DSSCs were curvilinear and representative of what was expected for photovoltaic cells (see Figure 5). However, ending power curves of some DSSCs were less curvilinear and not as representative of what was expected for photovoltaic cells. Beginning and ending power curves varied among pigments used to construct DSSCs, supporting the alternate hypothesis that pigment types result in photovoltaic cells that produce different voltage, current, and power values. These results further indicated that performance of DSSCs may not always be stable over time, supporting the alternate hypothesis, that age of the photovoltaic cell and its components will have significant effects upon the voltage, current and power values. These results indicate that further research is needed to evaluate the voltage, current, and power produced by different pigments used to construct DSSCs, as well as their performance as they age.

Response of Photovoltaic Cells to Light

When comparing performances during the day and at night (Figure 20), DSSCs demonstrated substantial differences in measurements and calculations thereof. The differences among voltage, current, and power values obtained at night and the day demonstrated that the DSSCs were directly responding to the light. Chlorophyll *b* was the only treatment that had voltage production during the nighttime hours. This night production was not substantial when compared to voltage productions during the day.

Variation Among Voltage, Current, and Power Values Obtained from Different Pigments Used in Photovoltaic Cells

The ANOVA tests for voltage measurements and calculations were significantly different for all values at the 0.05 probability level or better (Table 6). This supports the alternate hypothesis of the pigments demonstrating different voltage values. The differences in the LSD rankings also suggested different performance of individual pigments as photo-sensitizers. This was expected, as each pigment absorbs light at a different wavelength. Chlorophyllin and crude extract demonstrated the highest PV values (Table 7), suggesting that these pigments were initially the most productive of all treatments. All pigments experienced voltage decreases at end of the experiment; with the crude extract undergoing the largest decrease among all the treatments. The EV of the treatments suggests that chlorophyllin was at least three times as effective a photo-sensitizer as any of the treatments (Table 7); the EV of the crude extract was substantially lower, suggesting the longevity of chlorophyllin in DSSCs is superior to that of crude extract.

The ANOVA tests for current production, with the exception for TCC, demonstrated significant differences among pigments in the DSSCs (Table 8). The current is calculated from the voltage and provided further support for the alternate hypothesis that the pigments would exhibit different voltages from DSSCs. The higher ADC of chlorophyllin (Table 9) and the statistically similar TCC rankings among all other treatments suggested that, if the experiment were to continue, the ADC of chlorophyllin may remain significantly higher than other treatments for more than ten days. The EV of chlorophyllin was significantly higher than that of all other treatments (Table 9).

The ANOVA comparison of power values obtained from DSSCs indicated statistical differences among all the calculations except for TPC (Table 10). This supports the alternate hypothesis that the pigments would each possess different voltages in DSSCs as the power was calculated from the voltage. The statistical differences in many of the ANOVA calculations also showed downward trends of power production when comparing the BP and the EP (Table 11). Chlorophyll *a* and crude extract were similarly ranked for PP, but as suggested by the EP, both were producing less observable power, but not statistically different, than chlorophylls *b,* and *a/b,* as well as phycocyanin. The lower TPC rankings of chlorophyllin and the observed stabilization of its voltages after seven days (Figure 20) suggested that the deterioration of chlorophyllin was beginning to slow. A longer experiment cycle could reveal more differences between chlorophyllin and the other treatments.

Calculated Rankings Based on Data from Time Study

This investigation demonstrated that photosynthetic and organic pigments can be used successfully in DSSCs. Indeed, differences were detected among values obtained for different pigments in this experiment, suggesting there is potential for selection of better performing DSSCs using natural pigments. Better dye extractions, improved pigment/substrate adhesion, and enhanced sealing techniques have potential to improve a natural pigment's performance in DSSCs.

Different voltages, current, and power values at the end of the experiment, compared to beginning values, supported the alternate hypothesis that the pigments would exhibit different voltage, current, and power characteristics. To evaluate overall the performance of DSSCs in this experiment, peak voltage (PV) values were assumed to be the best single measurement of solar cell optimum performance; whereas least voltage (LV) values were assumed to be a good indicator of the longevity of solar cell performance. With these assumptions in mind, the following rankings of solar cell performance were obtained as follows:

Peak and Least Voltage

Peak voltage ranged from 3.99 to 274 mV, with chlorophyllin ranked as the highest and control ranked as the lowest voltage producers near the beginning of the experiment:

Chlorophyllin = Crude Extract ≥ Chlorophyll *a* ≥ Chlorophyll *a/b* ≥ Phycocyanin ≥ Chlorophyll *b* > Control

Least voltage ranged from 0.09 to 161 mV, with chlorophyllin ranked as the highest and control ranked as the lowest voltage producers at the end of the experiment:

Chlorophyllin > Phycocyanin ≥ Chlorophyll *a/b* ≥ Crude Extract ≥ Chlorophyll *b* ≥ Chlorophyll *a* ≥ Control

Peak and Least Current

Peak current ranged from 0.0180 to 41.9 µA, with chlorophyllin ranked as the highest and control ranked as the lowest current producers near the beginning of the experiment:

Chlorophyllin > Crude Extract = Chlorophyll *a* ≥ Chlorophyll *a/b* = Chlorophyll *b* = Phycocyanin ≥ Control

Least current ranged from 0.019 to 21.8 µA, with chlorophyllin ranked as the highest and control ranked as the lowest current producers at the end of the experiment:

Chlorophyllin > Phycocyanin ≥ Chlorophyll *a/b* ≥ Crude Extract ≥ Chlorophyll *b* ≥ Chlorophyll *a* ≥ Control

Peak and Least Power

Power ranged from 0.000 to 11.3 μW, with chlorophyllin ranked as the highest and control ranked as the lowest power producers near the beginning of the experiment:

Chlorophyllin > Crude Extract = Chlorophyll *a* ≥ Chlorophyll *a/b* = Chlorophyll *b* = Phycocyanin ≥ Control

Least power ranged from 0.000 to 4.84 μW, with chlorophyllin ranked as the highest and chlorophyll *a* and the control ranked among the lowest power producers at the end of the experiment:

Chlorophyllin > Phycocyanin ≥ Chlorophyll *a/b* ≥ Crude Extract ≥ Chlorophyll *b* ≥ Chlorophyll *a* = Control

Based on these rankings from peak and least voltage values, it was concluded that the DSSCs pigmented with chlorophyllin performed the best and lasted the longest as photo-sensitizers. The DSSCs constructed with crude extract performed as well as those constructed with chlorophyllin at the beginning of the experiment, but degradation of this pigment prevented these cells from sustaining solar energy conversion for more than a few days. Other DSSCs constructed with pigments such as chlorophyll *b*, chlorophyll *a/b*, phycocyanin, and chlorophyll *a* all achieved higher performances for a longer period of time as photo-sensitizers when compared with the control DSSCs which contained no pigments.

Efficiency Rankings

Although a pigment may demonstrate higher productions of voltage production in a DSSC, it is also important to examine the efficiency that the cell is capable of converting available light into electrical energy. The solar cells in this experiment had the efficiencies tested twice, once in the beginning and again at the end, to determine the quality of the pigments conversion abilities. The results from the beginning and the ending solar cells indicated that chlorophyllin overwhelmingly was the most efficient of the pigments tested.

Beginning of Experiment

Chlorophyllin > Crude Extract > Chlorophyll *a* > Chlorophyll *a/b* = Phycocyanin = Chlorophyll *b* ≥ Control

End of Experiment

Chlorophyllin > Chlorophyll *b* ≥ Chlorophyll *a/b* = Phycocyanin ≥ Crude Extract ≥ Chlorophyll *a* = Control

Concluding Remarks

As societies strive to be more industrial, more energy will be necessary to accommodate human needs. Progress has been made to extend our current finite reserves of fossil fuels, but time needs to be well spent on researching alternate energy resources. Solar energy has the potential to facilitate current electrical needs by acting as either a bridge to another stable energy source or as the source itself. Dye sensitized solar cells are yet another step towards the goal of stable energy production. The utilization of natural pigments already supplied by photosynthetic organisms could provide a stable supply of DSSC pigments.

Based upon the results of this experiment, slightly modified natural pigments (chlorophyllin) work better as photo-sensitizers in DSSCs. However, further research should focus on extending the life of these pigmented DSSCs by limiting pigment degradation. Additionally, a multitude of other natural pigments exist that could potentially be better photo-sensitizers than what has been studied in this investigation. More research will be necessary to conclude whether natural pigments are as good as synthetic dyes currently used. It is possible that incorporation of pigment complexes, such as those found in thylakoid membranes, may allow for more efficient DSSCs when these complexes are left intact. Careful extraction, preservation, and implantation of photosystems in semiconductors such as TiO_2 is one approach that may enhance the efficiency and longevity of DSSCs when photosynthetic pigments are used.

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APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0003	2.88E-05	8.65E-09	5000	4990	0.1155	2.31E-05	2.67E-06
20	20.3	0.0006	2.96E-05	1.77E-08	10000	9970	0.1586	1.59E-05	2.52E-06
30	30.3	0.0009	2.97E-05	2.67E-08	11000	10970	0.1662	1.52E-05	2.52E-06
40	40.3	0.0012	2.98E-05	3.57E-08	12000	11960	0.1745	1.46E-05	2.55E-06
50	50.3	0.0015	2.98E-05	4.47E-08	13000	12960	0.1803	1.39E-05	2.51E-06
100	100	0.0031	3.10E-05	9.61E-08	14000	13960	0.1855	1.33E-05	2.46E-06
150	149.8	0.0045	3.00E-05	1.35E-07	15000	14960	0.1898	1.27E-05	2.41E-06
200	199.5	0.0061	3.06E-05	1.87E-07	20000	19960	0.2033	1.02E-05	2.07E-06
250	249.3	0.0076	3.05E-05	2.32E-07	25000	24950	0.2119	8.49E-06	1.80E-06
300	299.5	0.0091	3.04E-05	2.76E-07	30000	29930	0.2203	7.36E-06	1.62E-06
350	349.3	0.0107	3.06E-05	3.28E-07	40000	39800	0.228	5.73E-06	1.31E-06
400	398	0.0122	3.07E-05	3.74E-07	50000	49700	0.2333	4.69E-06	1.1E-06
450	448	0.0138	3.08E-05	4.25E-07	100000	99600	0.2428	2.44E-06	5.92E-07
500	498	0.0158	3.17E-05	5.01E-07	150000	149400	0.2474	1.66E-06	4.10E-07
1000	997	0.0305	3.06E-05	9.33E-07	200000	200100	0.2501	1.25E-06	3.13E-07
1100	1096	0.0333	3.04E-05	1.01E-06	250000	249800	0.2529	1.01E-06	2.56E-07
1200	1196	0.0364	3.04E-05	1.11E-06	500000	500000	0.2576	5.15E-07	1.33E-07
1300	1296	0.0393	3.03E-05	1.19E-06	1000000	994000	0.2582	2.6E-07	6.71E-08
1400	1394	0.0422	3.03E-05	1.28E-06	1500000	1495000	0.2582	1.73E-07	4.46E-08
1500	1495	0.0451	3.02E-05	1.36E-06	2000000	1994000	0.2583	1.30E-07	3.35E-08
2000	1992	0.0581	2.92E-05	1.69E-06	2500000	2494000	0.2583	1.04E-07	2.68E-08
2500	2490	0.0702	2.82E-05	1.98E-06	3000000	3005000	0.2584	8.60E-08	2.22E-08
3000	2992	0.0812	2.71E-05	2.20E-06	5000000	5030000	0.2585	5.14E-08	1.33E-08
4000	3930	0.0998	2.54E-05	2.53E-06	10000000	10020000	0.2586	2.58E-08	6.67E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0576	1.15E-05	6.65E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.0929	9.32E-06	8.66E-07
30	30.3	0.0003	9.9E-06	2.97E-09	11000	10970	0.0988	9.01E-06	8.90E-07
40	40.3	0.0004	9.93E-06	3.97E-09	12000	11960	0.1057	8.84E-06	9.34E-07
50	50.3	0.0006	1.19E-05	7.16E-09	13000	12960	0.1105	8.53E-06	9.42E-07
100	100	0.0014	1.40E-05	1.96E-08	14000	13960	0.1149	8.23E-06	9.46E-07
150	149.8	0.0021	1.40E-05	2.94E-08	15000	14960	0.1192	7.97E-06	9.50E-07
200	199.5	0.0028	1.40E-05	3.93E-08	20000	19960	0.1342	6.72E-06	9.02E-07
250	249.3	0.0035	1.40E-05	4.91E-08	25000	24950	0.1448	5.80E-06	8.40E-07
300	299.5	0.0042	1.40E-05	5.89E-08	30000	29930	0.1527	5.10E-06	7.79E-07
350	349.3	0.0048	1.37E-05	6.60E-08	40000	39800	0.1631	4.10E-06	6.68E-07
400	398	0.0055	1.38E-05	7.60E-08	50000	49700	0.1698	3.42E-06	5.80E-07
450	448	0.0062	1.38E-05	8.58E-08	100000	99600	0.1831	1.84E-06	3.37E-07
500	498	0.0069	1.39E-05	9.56E-08	150000	149400	0.1903	1.27E-06	2.42E-07
1000	997	0.0136	1.36E-05	1.86E-07	200000	200100	0.193	9.65E-07	1.86E-07
1100	1096	0.0148	1.35E-05	2.00E-07	250000	249800	0.1952	7.81E-07	1.53E-07
1200	1196	0.0162	1.35E-05	2.19E-07	500000	500000	0.1995	3.99E-07	7.96E-08
1300	1296	0.0175	1.35E-05	2.36E-07	1000000	994000	0.2018	2.03E-07	4.10E-08
1400	1394	0.0188	1.35E-05	2.54E-07	1500000	1495000	0.2032	1.36E-07	2.76E-08
1500	1495	0.0202	1.35E-05	2.73E-07	2000000	1994000	0.2039	1.02E-07	2.09E-08
2000	1992	0.0261	1.31E-05	3.42E-07	2500000	2494000	0.2045	8.20E-08	1.68E-08
2500	2490	0.0321	1.29E-05	4.14E-07	3000000	3005000	0.205	6.82E-08	1.40E-08
3000	2992	0.0378	1.26E-05	4.78E-07	5000000	5030000	0.2055	4.09E-08	8.40E-09
4000	3930	0.0482	1.23E-05	5.91E-07	10000000	10020000	0.2056	2.05E-08	4.22E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0161	3.23E-03	5.19E-02
20	20.3	0	0	0	10000	9970	0.028	2.81E-03	7.86E-02
30	30.3	0.0001	3.30E-03	3.30E-04	11000	10970	0.030	2.73E-03	8.20E-02
40	40.3	0.0001	2.48E-03	2.48E-04	12000	11960	0.0318	2.66E-03	8.46E-02
50	50.3	0.0001	1.99E-03	1.99E-04	13000	12960	0.0335	2.58E-03	8.66E-02
100	100	0.0004	4.00E-03	1.60E-03	14000	13960	0.0352	2.52E-03	8.88E-02
150	149.8	0.0006	4.01E-03	2.40E-03	15000	14960	0.0367	2.45E-03	9.00E-02
200	199.5	0.0008	4.01E-03	3.21E-03	20000	19960	0.0437	2.19E-03	9.57E-02
250	249.3	0.001	4.01E-03	4.01E-03	25000	24950	0.0493	1.98E-03	9.74E-02
300	299.5	0.0012	4.01E-03	4.81E-03	30000	29930	0.0537	1.79E-03	9.63E-02
350	349.3	0.0013	3.72E-03	4.84E-03	40000	39800	0.0606	1.52E-03	9.23E-02
400	398	0.0015	3.77E-03	5.65E-03	50000	49700	0.0653	1.31E-03	8.58E-02
450	448	0.0017	3.79E-03	6.45E-03	100000	99600	0.0776	7.79E-04	6.05E-02
500	498	0.0019	3.82E-03	7.25E-03	150000	149400	0.0825	5.52E-04	4.56E-02
1000	997	0.0038	3.81E-03	1.45E-02	200000	200100	0.0851	4.25E-04	3.62E-02
1100	1096	0.0041	3.74E-03	1.53E-02	250000	249800	0.0866	3.47E-04	3.00E-02
1200	1196	0.0045	3.76E-03	1.69E-02	500000	500000	0.090	1.80E-04	1.62E-02
1300	1296	0.0049	3.78E-03	1.85E-02	1000000	994000	0.0918	9.24E-05	8.48E-03
1400	1394	0.0052	3.73E-03	1.94E-02	1500000	1495000	0.0924	6.18E-05	5.71E-03
1500	1495	0.0056	3.75E-03	2.10E-02	2000000	1994000	0.0927	4.65E-05	4.31E-03
2000	1992	0.0072	3.61E-03	2.60E-02	2500000	2494000	0.0928	3.72E-05	3.45E-03
2500	2490	0.0089	3.57E-03	3.18E-02	3000000	3005000	0.0927	3.08E-05	2.86E-03
3000	2992	0.0103	3.44E-03	3.55E-02	5000000	5030000	0.0929	1.85E-05	1.72E-03
4000	3930	0.0133	3.38E-03	4.50E-02	10000000	10020000	0.0931	9.29E-06	8.65E-04

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0002	1.92E-05	3.85E-09	5000	4990	0.1072	2.15E-05	2.30E-06
20	20.3	0.0004	1.97E-05	7.88E-09	10000	9970	0.1831	1.84E-05	3.36E-06
30	30.3	0.0007	2.31E-05	1.62E-08	11000	10970	0.1962	1.79E-05	3.51E-06
40	40.3	0.0009	2.23E-05	2.01E-08	12000	11960	0.2077	1.74E-05	3.61E-06
50	50.3	0.0011	2.19E-05	2.41E-08	13000	12960	0.218	1.68E-05	3.67E-06
100	100	0.0023	2.30E-05	5.29E-08	14000	13960	0.2277	1.63E-05	3.71E-06
150	149.8	0.0034	2.27E-05	7.72E-08	15000	14960	0.2368	1.58E-05	3.75E-06
200	199.5	0.0046	2.31E-05	1.06E-07	20000	19960	0.2701	1.35E-05	3.66E-06
250	249.3	0.0057	2.29E-05	1.30E-07	25000	24950	0.2933	1.18E-05	3.45E-06
300	299.5	0.0069	2.30E-05	1.59E-07	30000	29930	0.3105	1.04E-05	3.22E-06
350	349.3	0.0081	2.32E-05	1.88E-07	40000	39800	0.3328	8.36E-06	2.78E-06
400	398	0.0092	2.31E-05	2.13E-07	50000	49700	0.3481	7.00E-06	2.44E-06
450	448	0.0104	2.32E-05	2.41E-07	100000	99600	0.3785	3.80E-06	1.44E-06
500	498	0.0117	2.35E-05	2.75E-07	150000	149400	0.3889	2.60E-06	1.01E-06
1000	997	0.0232	2.33E-05	5.40E-07	200000	200100	0.3952	1.98E-06	7.81E-07
1100	1096	0.0255	2.33E-05	5.93E-07	250000	249800	0.3992	1.60E-06	6.38E-07
1200	1196	0.0278	2.32E-05	6.46E-07	500000	500000	0.406	8.12E-07	3.30E-07
1300	1296	0.0301	2.32E-05	6.99E-07	1000000	994000	0.410	4.12E-07	1.69E-07
1400	1394	0.0324	2.32E-05	7.53E-07	1500000	1495000	0.411	2.75E-07	1.13E-07
1500	1495	0.0347	2.32E-05	8.05E-07	2000000	1994000	0.413	2.07E-07	8.55E-08
2000	1992	0.0458	2.30E-05	1.05E-06	2500000	2494000	0.414	1.66E-07	6.87E-08
2500	2490	0.0567	2.28E-05	1.29E-06	3000000	3005000	0.415	1.38E-07	5.73E-08
3000	2992	0.0675	2.26E-05	1.52E-06	5000000	5030000	0.416	8.27E-08	3.44E-08
4000	3930	0.0878	2.23E-05	1.96E-06	10000000	10020000	0.417	4.16E-08	1.74E-08

Ohm's law states that $V = I*R$ (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from $V*I$. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0379	7.6E-06	2.88E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.0655	6.57E-06	4.30E-07
30	30.3	0.0002	6.60E-06	1.32E-09	11000	10970	0.0703	6.41E-06	4.51E-07
40	40.3	0.0003	7.44E-06	2.23E-09	12000	11960	0.0748	6.25E-06	4.68E-07
50	50.3	0.0004	7.95E-06	3.18E-09	13000	12960	0.0791	6.1E-06	4.83E-07
100	100	0.0008	8.00E-06	6.40E-09	14000	13960	0.0831	5.95E-06	4.95E-07
150	149.8	0.0012	8.01E-06	9.61E-09	15000	14960	0.0868	5.8E-06	5.04E-07
200	199.5	0.0017	8.52E-06	1.45E-08	20000	19960	0.1032	5.17E-06	5.34E-07
250	249.3	0.0021	8.42E-06	1.77E-08	25000	24950	0.1158	4.64E-06	5.37E-07
300	299.5	0.0026	8.68E-06	2.26E-08	30000	29930	0.126	4.21E-06	5.30E-07
350	349.3	0.003	8.59E-06	2.58E-08	40000	39800	0.1408	3.54E-06	4.98E-07
400	398	0.0035	8.79E-06	3.08E-08	50000	49700	0.1508	3.03E-06	4.58E-07
450	448	0.0039	8.71E-06	3.40E-08	100000	99600	0.1722	1.73E-06	2.98E-07
500	498	0.0044	8.84E-06	3.89E-08	150000	149400	0.1796	1.20E-06	2.16E-07
1000	997	0.0086	8.63E-06	7.42E-08	200000	200100	0.1837	9.18E-07	1.69E-07
1100	1096	0.0095	8.67E-06	8.23E-08	250000	249800	0.1859	7.44E-07	1.38E-07
1200	1196	0.0103	8.61E-06	8.87E-08	500000	500000	0.1904	3.81E-07	7.25E-08
1300	1296	0.0112	8.64E-06	9.68E-08	1000000	994000	0.1925	1.94E-07	3.73E-08
1400	1394	0.012	8.61E-06	1.03E-07	1500000	1495000	0.1934	1.29E-07	2.50E-08
1500	1495	0.0127	8.49E-06	1.08E-07	2000000	1994000	0.194	9.73E-08	1.89E-08
2000	1992	0.0168	8.43E-06	1.42E-07	2500000	2494000	0.1941	7.78E-08	1.51E-08
2500	2490	0.0206	8.27E-06	1.70E-07	3000000	3005000	0.1944	6.47E-08	1.26E-08
3000	2992	0.0243	8.12E-06	1.97E-07	5000000	5030000	0.1947	3.87E-08	7.54E-09
4000	3930	0.0313	7.96E-06	2.49E-07	10000000	10020000	0.195	1.95E-08	3.79E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

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Chlorophyllin-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0005	4.81E-05	2.40E-08	5000	4990	0.184	3.69E-05	6.78E-06
20	20.3	0.0009	4.43E-05	3.99E-08	10000	9970	0.255	2.56E-05	6.52E-06
30	30.3	0.0013	4.29E-05	5.58E-08	11000	10970	0.2621	2.39E-05	6.26E-06
40	40.3	0.0017	4.22E-05	7.17E-08	12000	11960	0.2679	2.24E-05	6.00E-06
50	50.3	0.0022	4.37E-05	9.62E-08	13000	12960	0.2766	2.13E-05	5.90E-06
100	100	0.0044	4.4E-05	1.94E-07	14000	13960	0.277	1.98E-05	5.50E-06
150	149.8	0.0067	4.47E-05	3.00E-07	15000	14960	0.2803	1.87E-05	5.25E-06
200	199.5	0.0088	4.41E-05	3.88E-07	20000	19960	0.2906	1.46E-05	4.23E-06
250	249.3	0.0111	4.45E-05	4.94E-07	25000	24950	0.2967	1.19E-05	3.53E-06
300	299.5	0.0132	4.41E-05	5.82E-07	30000	29930	0.3004	1.00E-05	3.02E-06
350	349.3	0.0155	4.44E-05	6.88E-07	40000	39800	0.3051	7.67E-06	2.34E-06
400	398	0.0177	4.45E-05	7.87E-07	50000	49700	0.3086	6.21E-06	1.92E-06
450	448	0.0199	4.44E-05	8.84E-07	100000	99600	0.3138	3.15E-06	9.89E-07
500	498	0.0221	4.44E-05	9.81E-07	150000	149400	0.316	2.12E-06	6.68E-07
1000	997	0.0438	4.39E-05	1.92E-06	200000	200100	0.317	1.58E-06	5.02E-07
1100	1096	0.048	4.38E-05	2.1E-06	250000	249800	0.3178	1.27E-06	4.04E-07
1200	1196	0.0523	4.37E-05	2.29E-06	500000	500000	0.3189	6.38E-07	2.03E-07
1300	1296	0.0565	4.36E-05	2.46E-06	1000000	994000	0.3196	3.22E-07	1.03E-07
1400	1394	0.0608	4.36E-05	2.65E-06	1500000	1495000	0.3201	2.14E-07	6.85E-08
1500	1495	0.065	4.35E-05	2.83E-06	2000000	1994000	0.3203	1.61E-07	5.15E-08
2000	1992	0.0852	4.28E-05	3.64E-06	2500000	2494000	0.3209	1.29E-07	4.13E-08
2500	2490	0.1046	4.20E-05	4.39E-06	3000000	3005000	0.3213	1.07E-07	3.44E-08
3000	2992	0.1234	4.12E-05	5.09E-06	5000000	5030000	0.322	6.40E-08	2.06E-08
4000	3930	0.1561	3.97E-05	6.20E-06	10000000	10020000	0.3223	3.22E-08	1.04E-08

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

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Control-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0
20	20.3	0	0	0
30	30.3	0	0	0
40	40.3	0	0	0
50	50.3	0	0	0
100	100	0	0	0
150	149.8	0	0	0
200	199.5	0	0	0
250	249.3	0.0001	4.01E-07	4.01E-11
300	299.5	0.0001	3.34E-07	3.34E-11
350	349.3	0.0001	2.86E-07	2.86E-11
400	398	0.0001	2.51E-07	2.51E-11
450	448	0.0001	2.23E-07	2.23E-11
500	498	0.0002	4.02E-07	8.03E-11
1000	997	0.0004	4.01E-07	1.60E-10
1100	1096	0.0005	4.56E-07	2.28E-10
1200	1196	0.0005	4.18E-07	2.09E-10
1300	1296	0.0005	3.86E-07	1.93E-10
1400	1394	0.0006	4.30E-07	2.58E-10
1500	1495	0.0006	4.01E-07	2.41E-10
2000	1992	0.0008	4.02E-07	3.21E-10
2500	2490	0.0011	4.42E-07	4.86E-10
3000	2992	0.0013	4.34E-07	5.65E-10
4000	3930	0.0017	4.33E-07	7.35E-10
5000	4990	0.0021	4.21E-07	8.84E-10
10000	9970	0.0042	4.21E-07	1.77E-09
11000	10970	0.0047	4.28E-07	2.01E-09
12000	11960	0.005	4.18E-07	2.09E-09
13000	12960	0.0055	4.24E-07	2.33E-09
14000	13960	0.0058	4.15E-07	2.41E-09
15000	14960	0.0062	4.14E-07	2.57E-09
20000	19960	0.0082	4.11E-07	3.37E-09
25000	24950	0.01	4.01E-07	4.01E-09
30000	29930	0.0117	3.91E-07	4.57E-09
40000	39800	0.0151	3.79E-07	5.73E-09
50000	49700	0.0182	3.66E-07	6.66E-09
100000	99600	0.0308	3.09E-07	9.52E-09
150000	149400	0.0397	2.66E-07	1.05E-08
200000	200100	0.0463	2.31E-07	1.07E-08
250000	249800	0.0511	2.05E-07	1.05E-08
500000	500000	0.0645	1.29E-07	8.32E-09
1000000	994000	0.0731	7.35E-08	5.38E-09
1500000	1495000	0.0763	5.10E-08	3.89E-09
2000000	1994000	0.078	3.91E-08	3.05E-09
2500000	2494000	0.0788	3.16E-08	2.49E-09
3000000	3005000	0.0791	2.63E-08	2.08E-09
5000000	5030000	0.0805	1.60E-08	1.29E-09
10000000	10020000	0.0814	8.12E-09	6.61E-10

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0203	4.07E-06	8.26E-08
20	20.3	0	0	0	10000	9970	0.0364	3.65E-06	1.33E-07
30	30.3	0	0	0	11000	10970	0.0392	3.57E-06	1.40E-07
40	40.3	0.0001	2.48E-06	2.48E-10	12000	11960	0.0419	3.50E-06	1.47E-07
50	50.3	0.0002	3.98E-06	7.95E-10	13000	12960	0.0444	3.43E-06	1.52E-07
100	100	0.0004	4.00E-06	1.60E-09	14000	13960	0.0469	3.36E-06	1.58E-07
150	149.8	0.0007	4.67E-06	3.27E-09	15000	14960	0.0491	3.28E-06	1.61E-07
200	199.5	0.0009	4.51E-06	4.06E-09	20000	19960	0.0592	2.97E-06	1.76E-07
250	249.3	0.0013	5.21E-06	6.78E-09	25000	24950	0.0671	2.69E-06	1.80E-07
300	299.5	0.0015	5.01E-06	7.51E-09	30000	29930	0.0735	2.46E-06	1.80E-07
350	349.3	0.0017	4.87E-06	8.27E-09	40000	39800	0.0831	2.09E-06	1.74E-07
400	398	0.0018	4.52E-06	8.14E-09	50000	49700	0.0895	1.80E-06	1.61E-07
450	448	0.0019	4.24E-06	8.06E-09	100000	99600	0.1048	1.05E-06	1.10E-07
500	498	0.0022	4.42E-06	9.72E-09	150000	149400	0.1083	7.25E-07	7.85E-08
1000	997	0.0044	4.41E-06	1.94E-08	200000	200100	0.1105	5.52E-07	6.10E-08
1100	1096	0.0049	4.47E-06	2.19E-08	250000	249800	0.111	4.44E-07	4.93E-08
1200	1196	0.0053	4.43E-06	2.35E-08	500000	500000	0.1143	2.29E-07	2.61E-08
1300	1296	0.0058	4.48E-06	2.60E-08	1000000	994000	0.116	1.17E-07	1.35E-08
1400	1394	0.0062	4.45E-06	2.76E-08	1500000	1495000	0.1167	7.81E-08	9.11E-09
1500	1495	0.0066	4.41E-06	2.91E-08	2000000	1994000	0.1171	5.87E-08	6.88E-09
2000	1992	0.0087	4.37E-06	3.80E-08	2500000	2494000	0.1172	4.70E-08	5.51E-09
2500	2490	0.0107	4.30E-06	4.60E-08	3000000	3005000	0.1173	3.90E-08	4.58E-09
3000	2992	0.0128	4.28E-06	5.48E-08	5000000	5030000	0.1178	2.34E-08	2.76E-09
4000	3930	0.0166	4.22E-06	7.01E-08	10000000	10020000	0.118	1.18E-08	1.39E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0378	7.58E-06	2.86E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.066	6.62E-06	4.37E-07
30	30.3	0.0002	6.60E-06	1.32E-09	11000	10970	0.0707	6.44E-06	4.56E-07
40	40.3	0.0003	7.44E-06	2.23E-09	12000	11960	0.0751	6.28E-06	4.72E-07
50	50.3	0.0004	7.95E-06	3.18E-09	13000	12960	0.0792	6.11E-06	4.84E-07
100	100	0.0008	8.00E-06	6.40E-09	14000	13960	0.0831	5.95E-06	4.95E-07
150	149.8	0.0012	8.01E-06	9.61E-09	15000	14960	0.0866	5.79E-06	5.01E-07
200	199.5	0.0017	8.52E-06	1.45E-08	20000	19960	0.1011	5.07E-06	5.12E-07
250	249.3	0.0021	8.42E-06	1.77E-08	25000	24950	0.1122	4.50E-06	5.05E-07
300	299.5	0.0025	8.35E-06	2.09E-08	30000	29930	0.1202	4.02E-06	4.83E-07
350	349.3	0.0029	8.30E-06	2.41E-08	40000	39800	0.1317	3.31E-06	4.36E-07
400	398	0.0034	8.54E-06	2.90E-08	50000	49700	0.1394	2.80E-06	3.91E-07
450	448	0.0038	8.48E-06	3.22E-08	100000	99600	0.1554	1.56E-06	2.42E-07
500	498	0.0042	8.43E-06	3.54E-08	150000	149400	0.1615	1.08E-06	1.75E-07
1000	997	0.0084	8.43E-06	7.08E-08	200000	200100	0.165	8.25E-07	1.36E-07
1100	1096	0.0092	8.39E-06	7.72E-08	250000	249800	0.1675	6.71E-07	1.12E-07
1200	1196	0.01	8.36E-06	8.36E-08	500000	500000	0.1714	3.43E-07	5.88E-08
1300	1296	0.0108	8.33E-06	9.00E-08	1000000	994000	0.1736	1.75E-07	3.03E-08
1400	1394	0.0116	8.32E-06	9.65E-08	1500000	1495000	0.1745	1.17E-07	2.04E-08
1500	1495	0.0125	8.36E-06	1.05E-07	2000000	1994000	0.1753	8.79E-08	1.54E-08
2000	1992	0.0164	8.23E-06	1.35E-07	2500000	2494000	0.1757	7.04E-08	1.24E-08
2500	2490	0.0202	8.11E-06	1.64E-07	3000000	3005000	0.1761	5.86E-08	1.03E-08
3000	2992	0.024	8.02E-06	1.93E-07	5000000	5030000	0.1765	3.51E-08	6.19E-09
4000	3930	0.0311	7.91E-06	2.46E-07	10000000	10020000	0.1769	1.77E-08	3.12E-09

Ohm's law states that $V = I*R$ (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0259	5.19E-06	1.34E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.0444	4.45E-06	1.98E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.0477	4.35E-06	2.07E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0507	4.24E-06	2.15E-07
50	50.3	0.0003	5.96E-06	1.79E-09	13000	12960	0.0535	4.13E-06	2.21E-07
100	100	0.0006	6.00E-06	3.60E-09	14000	13960	0.056	4.01E-06	2.25E-07
150	149.8	0.0009	6.01E-06	5.41E-09	15000	14960	0.0585	3.91E-06	2.29E-07
200	199.5	0.0012	6.02E-06	7.22E-09	20000	19960	0.0686	3.44E-06	2.36E-07
250	249.3	0.0015	6.02E-06	9.03E-09	25000	24950	0.0764	3.06E-06	2.34E-07
300	299.5	0.0018	6.01E-06	1.08E-08	30000	29930	0.0826	2.76E-06	2.28E-07
350	349.3	0.0021	6.01E-06	1.26E-08	40000	39800	0.0917	2.30E-06	2.11E-07
400	398	0.0024	6.03E-06	1.45E-08	50000	49700	0.0974	1.96E-06	1.91E-07
450	448	0.0027	6.03E-06	1.63E-08	100000	99600	0.111	1.11E-06	1.24E-07
500	498	0.003	6.02E-06	1.81E-08	150000	149400	0.1163	7.78E-07	9.05E-08
1000	997	0.0059	5.92E-06	3.49E-08	200000	200100	0.1192	5.96E-07	7.10E-08
1100	1096	0.0064	5.84E-06	3.74E-08	250000	249800	0.1208	4.84E-07	5.84E-08
1200	1196	0.007	5.85E-06	4.10E-08	500000	500000	0.1244	2.49E-07	3.10E-08
1300	1296	0.0076	5.86E-06	4.46E-08	1000000	994000	0.1261	1.27E-07	1.60E-08
1400	1394	0.0081	5.81E-06	4.71E-08	1500000	1495000	0.1274	8.52E-08	1.09E-08
1500	1495	0.0087	5.82E-06	5.06E-08	2000000	1994000	0.1282	6.43E-08	8.24E-09
2000	1992	0.0114	5.72E-06	6.52E-08	2500000	2494000	0.1288	5.16E-08	6.65E-09
2500	2490	0.014	5.62E-06	7.87E-08	3000000	3005000	0.1292	4.30E-08	5.55E-09
3000	2992	0.0166	5.55E-06	9.21E-08	5000000	5030000	0.1296	2.58E-08	3.34E-09
4000	3930	0.0214	5.45E-06	1.17E-07	10000000	10020000	0.1301	1.30E-08	1.69E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0002	1.92E-05	3.85E-09	5000	4990	0.1121	2.25E-05	2.52E-06
20	20.3	0.0004	1.97E-05	7.88E-09	10000	9970	0.2117	2.12E-05	4.50E-06
30	30.3	0.0006	1.98E-05	1.19E-08	11000	10970	0.2294	2.09E-05	4.80E-06
40	40.3	0.0009	2.23E-05	2.01E-08	12000	11960	0.2459	2.06E-05	5.06E-06
50	50.3	0.001	1.99E-05	1.99E-08	13000	12960	0.2613	2.02E-05	5.27E-06
100	100	0.0022	2.20E-05	4.84E-08	14000	13960	0.2751	1.97E-05	5.42E-06
150	149.8	0.0033	2.20E-05	7.27E-08	15000	14960	0.2914	1.95E-05	5.68E-06
200	199.5	0.0044	2.21E-05	9.70E-08	20000	19960	0.3316	1.66E-05	5.51E-06
250	249.3	0.0056	2.25E-05	1.26E-07	25000	24950	0.3552	1.42E-05	5.06E-06
300	299.5	0.0067	2.24E-05	1.50E-07	30000	29930	0.3688	1.23E-05	4.54E-06
350	349.3	0.0079	2.26E-05	1.79E-07	40000	39800	0.3845	9.66E-06	3.71E-06
400	398	0.009	2.26E-05	2.04E-07	50000	49700	0.392	7.89E-06	3.09E-06
450	448	0.0102	2.28E-05	2.32E-07	100000	99600	0.406	4.08E-06	1.65E-06
500	498	0.0113	2.27E-05	2.56E-07	150000	149400	0.41	2.74E-06	1.13E-06
1000	997	0.0227	2.28E-05	5.17E-07	200000	200100	0.411	2.05E-06	8.44E-07
1100	1096	0.025	2.28E-05	5.70E-07	250000	249800	0.413	1.65E-06	6.83E-07
1200	1196	0.0273	2.28E-05	6.23E-07	500000	500000	0.415	8.30E-07	3.44E-07
1300	1296	0.0296	2.28E-05	6.76E-07	1000000	994000	0.416	4.19E-07	1.74E-07
1400	1394	0.0319	2.29E-05	7.30E-07	1500000	1495000	0.416	2.78E-07	1.16E-07
1500	1495	0.0342	2.29E-05	7.82E-07	2000000	1994000	0.416	2.09E-07	8.68E-08
2000	1992	0.0455	2.28E-05	1.04E-06	2500000	2494000	0.416	1.67E-07	6.94E-08
2500	2490	0.0567	2.28E-05	1.29E-06	3000000	3005000	0.416	1.38E-07	5.76E-08
3000	2992	0.0681	2.28E-05	1.55E-06	5000000	5030000	0.416	8.27E-08	3.44E-08
4000	3930	0.0901	2.29E-05	2.07E-06	10000000	10020000	0.416	4.15E-08	1.73E-08

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0342	6.85E-06	2.34E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.062	6.22E-06	3.86E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.0669	6.10E-06	4.08E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0716	5.99E-06	4.29E-07
50	50.3	0.0003	5.96E-06	1.79E-09	13000	12960	0.0762	5.88E-06	4.48E-07
100	100	0.0007	7.0E-06	4.90E-09	14000	13960	0.0805	5.77E-06	4.64E-07
150	149.8	0.0011	7.34E-06	8.08E-09	15000	14960	0.0846	5.66E-06	4.78E-07
200	199.5	0.0015	7.52E-06	1.13E-08	20000	19960	0.1025	5.14E-06	5.26E-07
250	249.3	0.0018	7.22E-06	1.30E-08	25000	24950	0.1164	4.67E-06	5.43E-07
300	299.5	0.0022	7.35E-06	1.62E-08	30000	29930	0.1273	4.25E-06	5.41E-07
350	349.3	0.0026	7.44E-06	1.94E-08	40000	39800	0.1431	3.60E-06	5.15E-07
400	398	0.0029	7.29E-06	2.11E-08	50000	49700	0.1538	3.09E-06	4.76E-07
450	448	0.0033	7.37E-06	2.43E-08	100000	99600	0.1765	1.77E-06	3.13E-07
500	498	0.0037	7.43E-06	2.75E-08	150000	149400	0.1841	1.23E-06	2.27E-07
1000	997	0.0074	7.42E-06	5.49E-08	200000	200100	0.1879	9.39E-07	1.76E-07
1100	1096	0.0081	7.39E-06	5.99E-08	250000	249800	0.1899	7.60E-07	1.44E-07
1200	1196	0.0088	7.36E-06	6.47E-08	500000	500000	0.1944	3.89E-07	7.56E-08
1300	1296	0.0096	7.41E-06	7.11E-08	1000000	994000	0.1966	1.98E-07	3.89E-08
1400	1394	0.0103	7.39E-06	7.61E-08	1500000	1495000	0.1969	1.32E-07	2.59E-08
1500	1495	0.011	7.36E-06	8.09E-08	2000000	1994000	0.1972	9.89E-08	1.95E-08
2000	1992	0.0145	7.28E-06	1.06E-07	2500000	2494000	0.1972	7.91E-08	1.56E-08
2500	2490	0.018	7.23E-06	1.30E-07	3000000	3005000	0.1972	6.56E-08	1.29E-08
3000	2992	0.0214	7.15E-06	1.53E-07	5000000	5030000	0.1972	3.92E-08	7.73E-09
4000	3930	0.0279	7.1E-06	1.98E-07	10000000	10020000	0.1972	1.97E-08	3.88E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0004	3.85E-05	1.54E-08	5000	4990	0.1673	3.35E-05	5.61E-06
20	20.3	0.0007	3.45E-05	2.41E-08	10000	9970	0.2393	2.40E-05	5.74E-06
30	30.3	0.0011	3.63E-05	3.99E-08	11000	10970	0.2471	2.25E-05	5.57E-06
40	40.3	0.0015	3.72E-05	5.58E-08	12000	11960	0.2527	2.11E-05	5.34E-06
50	50.3	0.0019	3.78E-05	7.18E-08	13000	12960	0.2577	1.99E-05	5.12E-06
100	100	0.0038	3.80E-05	1.44E-07	14000	13960	0.2615	1.87E-05	4.90E-06
150	149.8	0.0056	3.74E-05	2.09E-07	15000	14960	0.2649	1.77E-05	4.69E-06
200	199.5	0.0076	3.81E-05	2.90E-07	20000	19960	0.2759	1.38E-05	3.81E-06
250	249.3	0.0094	3.77E-05	3.54E-07	25000	24950	0.2819	1.13E-05	3.19E-06
300	299.5	0.0114	3.81E-05	4.34E-07	30000	29930	0.2859	9.55E-06	2.73E-06
350	349.3	0.0133	3.81E-05	5.06E-07	40000	39800	0.2908	7.31E-06	2.12E-06
400	398	0.0152	3.82E-05	5.81E-07	50000	49700	0.2936	5.91E-06	1.73E-06
450	448	0.0171	3.82E-05	6.53E-07	100000	99600	0.2991	3.00E-06	8.98E-07
500	498	0.0191	3.84E-05	7.33E-07	150000	149400	0.301	2.01E-06	6.06E-07
1000	997	0.0379	3.80E-05	1.44E-06	200000	200100	0.3021	1.51E-06	4.56E-07
1100	1096	0.0416	3.80E-05	1.58E-06	250000	249800	0.3028	1.21E-06	3.67E-07
1200	1196	0.0453	3.79E-05	1.72E-06	500000	500000	0.3041	6.08E-07	1.85E-07
1300	1296	0.0494	3.81E-05	1.88E-06	1000000	994000	0.3048	3.07E-07	9.35E-08
1400	1394	0.053	3.80E-05	2.02E-06	1500000	1495000	0.3054	2.04E-07	6.24E-08
1500	1495	0.0569	3.81E-05	2.17E-06	2000000	1994000	0.3057	1.53E-07	4.69E-08
2000	1992	0.0751	3.77E-05	2.83E-06	2500000	2494000	0.3058	1.23E-07	3.75E-08
2500	2490	0.0928	3.73E-05	3.46E-06	3000000	3005000	0.306	1.02E-07	3.12E-08
3000	2992	0.1098	3.67E-05	4.03E-06	5000000	5030000	0.3066	6.10E-08	1.87E-08
4000	3930	0.1405	3.58E-05	5.02E-06	10000000	10020000	0.3067	3.06E-08	9.39E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0008	1.60E-07	1.28E-10
20	20.3	0	0	0	10000	9970	0.0016	1.60E-07	2.57E-10
30	30.3	0	0	0	11000	10970	0.0017	1.55E-07	2.63E-10
40	40.3	0	0	0	12000	11960	0.0018	1.51E-07	2.71E-10
50	50.3	0	0	0	13000	12960	0.002	1.54E-07	3.09E-10
100	100	0	0	0	14000	13960	0.0021	1.50E-07	3.16E-10
150	149.8	0	0	0	15000	14960	0.0022	1.47E-07	3.24E-10
200	199.5	0	0	0	20000	19960	0.0028	1.40E-07	3.93E-10
250	249.3	0	0	0	25000	24950	0.0032	1.28E-07	4.10E-10
300	299.5	0	0	0	30000	29930	0.0037	1.24E-07	4.57E-10
350	349.3	0	0	0	40000	39800	0.0045	1.13E-07	5.09E-10
400	398	0	0	0	50000	49700	0.005	1.01E-07	5.03E-10
450	448	0	0	0	100000	99600	0.0068	6.83E-08	4.64E-10
500	498	0	0	0	150000	149400	0.0077	5.15E-08	3.97E-10
1000	997	0	0	0	200000	200100	0.0083	4.15E-08	3.44E-10
1100	1096	0	0	0	250000	249800	0.0087	3.48E-08	3.03E-10
1200	1196	0	0	0	500000	500000	0.0097	1.94E-08	1.88E-10
1300	1296	0	0	0	1000000	994000	0.0102	1.03E-08	1.05E-10
1400	1394	0	0	0	1500000	1495000	0.0104	6.96E-09	7.23E-11
1500	1495	0.0001	6.69E-08	6.69E-12	2000000	1994000	0.0107	5.37E-09	5.74E-11
2000	1992	0.0003	1.51E-07	4.52E-11	2500000	2494000	0.0108	4.33E-09	4.68E-11
2500	2490	0.0004	1.61E-07	6.43E-11	3000000	3005000	0.0108	3.59E-09	3.88E-11
3000	2992	0.0005	1.67E-07	8.36E-11	5000000	5030000	0.011	2.19E-09	2.41E-11
4000	3930	0.0007	1.78E-07	1.25E-10	10000000	10020000	0.0111	1.11E-09	1.23E-11

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0463	9.28E-06	4.30E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.0764	7.66E-06	5.85E-07
30	30.3	0.0003	9.90E-06	2.97E-09	11000	10970	0.0812	7.40E-06	6.01E-07
40	40.3	0.0004	9.93E-06	3.97E-09	12000	11960	0.0854	7.14E-06	6.10E-07
50	50.3	0.0005	9.94E-06	4.97E-09	13000	12960	0.0893	6.89E-06	6.15E-07
100	100	0.0011	1.10E-05	1.21E-08	14000	13960	0.0927	6.64E-06	6.16E-07
150	149.8	0.0016	1.07E-05	1.71E-08	15000	14960	0.0962	6.43E-06	6.19E-07
200	199.5	0.0022	1.10E-05	2.43E-08	20000	19960	0.11	5.51E-06	6.06E-07
250	249.3	0.0027	1.08E-05	2.92E-08	25000	24950	0.1188	4.76E-06	5.66E-07
300	299.5	0.0032	1.07E-05	3.42E-08	30000	29930	0.1254	4.19E-06	5.25E-07
350	349.3	0.0038	1.09E-05	4.13E-08	40000	39800	0.1342	3.37E-06	4.53E-07
400	398	0.0043	1.08E-05	4.65E-08	50000	49700	0.1399	2.81E-06	3.94E-07
450	448	0.0049	1.09E-05	5.36E-08	100000	99600	0.1518	1.52E-06	2.31E-07
500	498	0.0054	1.08E-05	5.86E-08	150000	149400	0.1566	1.05E-06	1.64E-07
1000	997	0.0107	1.07E-05	1.15E-07	200000	200100	0.1592	7.96E-07	1.27E-07
1100	1096	0.0117	1.07E-05	1.25E-07	250000	249800	0.1608	6.44E-07	1.04E-07
1200	1196	0.0128	1.07E-05	1.37E-07	500000	500000	0.1637	3.27E-07	5.36E-08
1300	1296	0.0138	1.06E-05	1.47E-07	1000000	994000	0.1653	1.66E-07	2.75E-08
1400	1394	0.0148	1.06E-05	1.57E-07	1500000	1495000	0.166	1.11E-07	1.84E-08
1500	1495	0.0158	1.06E-05	1.67E-07	2000000	1994000	0.1665	8.35E-08	1.39E-08
2000	1992	0.0207	1.04E-05	2.15E-07	2500000	2494000	0.1671	6.70E-08	1.12E-08
2500	2490	0.0254	1.02E-05	2.59E-07	3000000	3005000	0.1675	5.57E-08	9.34E-09
3000	2992	0.03	1.00E-05	3.01E-07	5000000	5030000	0.168	3.34E-08	5.61E-09
4000	3930	0.0385	9.80E-06	3.77E-07	10000000	10020000	0.1682	1.68E-08	2.82E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0539	1.08E-05	5.82E-07
20	20.3	0.0003	1.48E-05	4.43E-09	10000	9970	0.0823	8.25E-06	6.79E-07
30	30.3	0.0004	1.32E-05	5.28E-09	11000	10970	0.0865	7.89E-06	6.82E-07
40	40.3	0.0006	1.49E-05	8.93E-09	12000	11960	0.0904	7.56E-06	6.83E-07
50	50.3	0.0007	1.39E-05	9.74E-09	13000	12960	0.094	7.25E-06	6.82E-07
100	100	0.0014	1.40E-05	1.96E-08	14000	13960	0.0973	6.97E-06	6.78E-07
150	149.8	0.0022	1.47E-05	3.23E-08	15000	14960	0.1004	6.71E-06	6.74E-07
200	199.5	0.0029	1.45E-05	4.22E-08	20000	19960	0.1113	5.58E-06	6.21E-07
250	249.3	0.0036	1.44E-05	5.20E-08	25000	24950	0.1189	4.77E-06	5.67E-07
300	299.5	0.0043	1.44E-05	6.17E-08	30000	29930	0.1251	4.18E-06	5.23E-07
350	349.3	0.0051	1.46E-05	7.45E-08	40000	39800	0.1334	3.35E-06	4.47E-07
400	398	0.0058	1.46E-05	8.45E-08	50000	49700	0.1391	2.80E-06	3.89E-07
450	448	0.0065	1.45E-05	9.43E-08	100000	99600	0.1498	1.50E-06	2.25E-07
500	498	0.0072	1.45E-05	1.04E-07	150000	149400	0.1545	1.03E-06	1.60E-07
1000	997	0.0139	1.39E-05	1.94E-07	200000	200100	0.1598	7.99E-07	1.28E-07
1100	1096	0.0152	1.39E-05	2.11E-07	250000	249800	0.1618	6.48E-07	1.05E-07
1200	1196	0.0165	1.38E-05	2.28E-07	500000	500000	0.1628	3.26E-07	5.30E-08
1300	1296	0.0177	1.37E-05	2.42E-07	1000000	994000	0.1633	1.64E-07	2.68E-08
1400	1394	0.0189	1.36E-05	2.56E-07	1500000	1495000	0.1636	1.09E-07	1.79E-08
1500	1495	0.0201	1.34E-05	2.70E-07	2000000	1994000	0.1638	8.21E-08	1.35E-08
2000	1992	0.0259	1.30E-05	3.37E-07	2500000	2494000	0.1639	6.57E-08	1.08E-08
2500	2490	0.0314	1.26E-05	3.96E-07	3000000	3005000	0.1641	5.46E-08	8.96E-09
3000	2992	0.0366	1.22E-05	4.48E-07	5000000	5030000	0.1642	3.26E-08	5.36E-09
4000	3930	0.0458	1.17E-05	5.34E-07	10000000	10020000	0.1643	1.64E-08	2.69E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*/*b*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.029	5.81E-06	1.69E-07
20	20.3	0	0	0	10000	9970	0.0488	4.89E-06	2.39E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.0521	4.75E-06	2.47E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0553	4.62E-06	2.56E-07
50	50.3	0.0003	5.96E-06	1.79E-09	13000	12960	0.0584	4.51E-06	2.63E-07
100	100	0.0006	6.00E-06	3.60E-09	14000	13960	0.0613	4.39E-06	2.69E-07
150	149.8	0.0009	6.01E-06	5.41E-09	15000	14960	0.0642	4.29E-06	2.76E-07
200	199.5	0.0012	6.02E-06	7.22E-09	20000	19960	0.0744	3.73E-06	2.77E-07
250	249.3	0.0015	6.02E-06	9.03E-09	25000	24950	0.0825	3.31E-06	2.73E-07
300	299.5	0.0018	6.01E-06	1.08E-08	30000	29930	0.0885	2.96E-06	2.62E-07
350	349.3	0.0021	6.01E-06	1.26E-08	40000	39800	0.0971	2.44E-06	2.37E-07
400	398	0.0024	6.03E-06	1.45E-08	50000	49700	0.1035	2.08E-06	2.16E-07
450	448	0.0027	6.03E-06	1.63E-08	100000	99600	0.1234	1.24E-06	1.53E-07
500	498	0.003	6.02E-06	1.81E-08	150000	149400	0.1289	8.63E-07	1.11E-07
1000	997	0.006	6.02E-06	3.61E-08	200000	200100	0.1319	6.59E-07	8.69E-08
1100	1096	0.0066	6.02E-06	3.97E-08	250000	249800	0.1338	5.36E-07	7.17E-08
1200	1196	0.0072	6.02E-06	4.33E-08	500000	500000	0.1381	2.76E-07	3.81E-08
1300	1296	0.0078	6.02E-06	4.69E-08	1000000	994000	0.1399	1.41E-07	1.97E-08
1400	1394	0.0084	6.03E-06	5.06E-08	1500000	1495000	0.1414	9.46E-08	1.34E-08
1500	1495	0.009	6.02E-06	5.42E-08	2000000	1994000	0.1426	7.15E-08	1.02E-08
2000	1992	0.012	6.02E-06	7.23E-08	2500000	2494000	0.1428	5.73E-08	8.18E-09
2500	2490	0.0151	6.06E-06	9.16E-08	3000000	3005000	0.1431	4.76E-08	6.81E-09
3000	2992	0.0186	6.22E-06	1.16E-07	5000000	5030000	0.1431	2.84E-08	4.07E-09
4000	3930	0.024	6.11E-06	1.47E-07	10000000	10020000	0.1431	1.43E-08	2.04E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0002	1.92E-05	3.85E-09	5000	4990	0.0873	1.75E-05	1.53E-06
20	20.3	0.0003	1.48E-05	4.43E-09	10000	9970	0.1608	1.61E-05	2.59E-06
30	30.3	0.0005	1.65E-05	8.25E-09	11000	10970	0.1724	1.57E-05	2.71E-06
40	40.3	0.0007	1.74E-05	1.22E-08	12000	11960	0.1834	1.53E-05	2.81E-06
50	50.3	0.0009	1.79E-05	1.61E-08	13000	12960	0.1939	1.50E-05	2.90E-06
100	100	0.0018	1.80E-05	3.24E-08	14000	13960	0.2035	1.46E-05	2.97E-06
150	149.8	0.0027	1.80E-05	4.87E-08	15000	14960	0.2124	1.42E-05	3.02E-06
200	199.5	0.0036	1.80E-05	6.50E-08	20000	19960	0.2488	1.25E-05	3.10E-06
250	249.3	0.0045	1.81E-05	8.12E-08	25000	24950	0.2754	1.10E-05	3.04E-06
300	299.5	0.0054	1.80E-05	9.74E-08	30000	29930	0.2943	9.83E-06	2.89E-06
350	349.3	0.0063	1.80E-05	1.14E-07	40000	39800	0.3221	8.09E-06	2.61E-06
400	398	0.0073	1.83E-05	1.34E-07	50000	49700	0.3391	6.82E-06	2.31E-06
450	448	0.0082	1.83E-05	1.50E-07	100000	99600	0.3702	3.72E-06	1.38E-06
500	498	0.0092	1.85E-05	1.70E-07	150000	149400	0.3816	2.55E-06	9.75E-07
1000	997	0.0183	1.84E-05	3.36E-07	200000	200100	0.3876	1.94E-06	7.51E-07
1100	1096	0.0202	1.84E-05	3.72E-07	250000	249800	0.3922	1.57E-06	6.16E-07
1200	1196	0.0221	1.85E-05	4.08E-07	500000	500000	0.3988	7.98E-07	3.18E-07
1300	1296	0.0239	1.84E-05	4.41E-07	1000000	994000	0.4023	4.05E-07	1.63E-07
1400	1394	0.0257	1.84E-05	4.74E-07	1500000	1495000	0.404	2.70E-07	1.09E-07
1500	1495	0.0276	1.85E-05	5.10E-07	2000000	1994000	0.404	2.03E-07	8.19E-08
2000	1992	0.0365	1.83E-05	6.69E-07	2500000	2494000	0.404	1.62E-07	6.54E-08
2500	2490	0.0454	1.82E-05	8.28E-07	3000000	3005000	0.405	1.35E-07	5.46E-08
3000	2992	0.0542	1.81E-05	9.82E-07	5000000	5030000	0.406	8.07E-08	3.28E-08
4000	3930	0.071	1.81E-05	1.28E-06	10000000	10020000	0.406	4.05E-08	1.65E-08

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0436	8.74E-06	3.81E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.0809	8.11E-06	6.56E-07
30	30.3	0.0002	6.60E-06	1.32E-09	11000	10970	0.0879	8.01E-06	7.04E-07
40	40.3	0.0003	7.44E-06	2.23E-09	12000	11960	0.0946	7.91E-06	7.48E-07
50	50.3	0.0004	7.95E-06	3.18E-09	13000	12960	0.101	7.79E-06	7.87E-07
100	100	0.0009	9.00E-06	8.10E-09	14000	13960	0.1072	7.68E-06	8.23E-07
150	149.8	0.0013	8.68E-06	1.13E-08	15000	14960	0.1133	7.57E-06	8.58E-07
200	199.5	0.0018	9.02E-06	1.62E-08	20000	19960	0.1383	6.93E-06	9.58E-07
250	249.3	0.0023	9.23E-06	2.12E-08	25000	24950	0.1576	6.32E-06	9.96E-07
300	299.5	0.0027	9.02E-06	2.43E-08	30000	29930	0.1717	5.74E-06	9.85E-07
350	349.3	0.0032	9.16E-06	2.93E-08	40000	39800	0.1905	4.79E-06	9.12E-07
400	398	0.0036	9.05E-06	3.26E-08	50000	49700	0.2017	4.06E-06	8.19E-07
450	448	0.0041	9.15E-06	3.75E-08	100000	99600	0.2228	2.24E-06	4.98E-07
500	498	0.0046	9.24E-06	4.25E-08	150000	149400	0.2291	1.53E-06	3.51E-07
1000	997	0.0091	9.13E-06	8.31E-08	200000	200100	0.2323	1.16E-06	2.70E-07
1100	1096	0.0101	9.22E-06	9.31E-08	250000	249800	0.2339	9.36E-07	2.19E-07
1200	1196	0.011	9.20E-06	1.01E-07	500000	500000	0.2374	4.75E-07	1.13E-07
1300	1296	0.0119	9.18E-06	1.09E-07	1000000	994000	0.239	2.40E-07	5.75E-08
1400	1394	0.0128	9.18E-06	1.18E-07	1500000	1495000	0.2395	1.60E-07	3.84E-08
1500	1495	0.0137	9.16E-06	1.26E-07	2000000	1994000	0.2396	1.20E-07	2.88E-08
2000	1992	0.0181	9.09E-06	1.64E-07	2500000	2494000	0.2396	9.61E-08	2.30E-08
2500	2490	0.0226	9.08E-06	2.05E-07	3000000	3005000	0.2396	7.97E-08	1.91E-08
3000	2992	0.0269	8.99E-06	2.42E-07	5000000	5030000	0.2396	4.76E-08	1.14E-08
4000	3930	0.0353	8.98E-06	3.17E-07	10000000	10020000	0.2397	2.39E-08	5.73E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0005	4.81E-05	2.40E-08	5000	4990	0.1983	3.97E-05	7.88E-06
20	20.3	0.001	4.93E-05	4.93E-08	10000	9970	0.2729	2.74E-05	7.47E-06
30	30.3	0.0015	4.95E-05	7.43E-08	11000	10970	0.2826	2.58E-05	7.28E-06
40	40.3	0.002	4.96E-05	9.93E-08	12000	11960	0.2912	2.43E-05	7.09E-06
50	50.3	0.0025	4.97E-05	1.24E-07	13000	12960	0.2973	2.29E-05	6.82E-06
100	100	0.005	5.00E-05	2.50E-07	14000	13960	0.3018	2.16E-05	6.52E-06
150	149.8	0.0074	4.94E-05	3.66E-07	15000	14960	0.3055	2.04E-05	6.24E-06
200	199.5	0.0099	4.96E-05	4.91E-07	20000	19960	0.3171	1.59E-05	5.04E-06
250	249.3	0.0124	4.97E-05	6.17E-07	25000	24950	0.3239	1.30E-05	4.20E-06
300	299.5	0.0149	4.97E-05	7.41E-07	30000	29930	0.3285	1.10E-05	3.61E-06
350	349.3	0.0174	4.98E-05	8.67E-07	40000	39800	0.3341	8.39E-06	2.80E-06
400	398	0.0198	4.97E-05	9.85E-07	50000	49700	0.3376	6.79E-06	2.29E-06
450	448	0.0223	4.98E-05	1.11E-06	100000	99600	0.3435	3.45E-06	1.18E-06
500	498	0.0247	4.96E-05	1.23E-06	150000	149400	0.3458	2.31E-06	8.00E-07
1000	997	0.0484	4.85E-05	2.35E-06	200000	200100	0.3471	1.73E-06	6.02E-07
1100	1096	0.0531	4.84E-05	2.57E-06	250000	249800	0.3481	1.39E-06	4.85E-07
1200	1196	0.0579	4.84E-05	2.80E-06	500000	500000	0.3503	7.01E-07	2.45E-07
1300	1296	0.0626	4.83E-05	3.02E-06	1000000	994000	0.3512	3.53E-07	1.24E-07
1400	1394	0.0673	4.83E-05	3.25E-06	1500000	1495000	0.3517	2.35E-07	8.27E-08
1500	1495	0.072	4.82E-05	3.47E-06	2000000	1994000	0.3521	1.77E-07	6.22E-08
2000	1992	0.0939	4.71E-05	4.43E-06	2500000	2494000	0.3525	1.41E-07	4.98E-08
2500	2490	0.1153	4.63E-05	5.34E-06	3000000	3005000	0.3529	1.17E-07	4.14E-08
3000	2992	0.1352	4.52E-05	6.11E-06	5000000	5030000	0.3531	7.02E-08	2.48E-08
4000	3930	0.169	4.30E-05	7.27E-06	10000000	10020000	0.3535	3.53E-08	1.25E-08

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0021	4.21E-07	8.84E-10
20	20.3	0	0	0	10000	9970	0.0042	4.21E-07	1.77E-09
30	30.3	0	0	0	11000	10970	0.0047	4.28E-07	2.01E-09
40	40.3	0	0	0	12000	11960	0.005	4.18E-07	2.09E-09
50	50.3	0	0	0	13000	12960	0.0055	4.24E-07	2.33E-09
100	100	0	0	0	14000	13960	0.0058	4.15E-07	2.41E-09
150	149.8	0	0	0	15000	14960	0.0062	4.14E-07	2.57E-09
200	199.5	0	0	0	20000	19960	0.0082	4.11E-07	3.37E-09
250	249.3	0.0001	4.01E-07	4.01E-11	25000	24950	0.01	4.01E-07	4.01E-09
300	299.5	0.0001	3.34E-07	3.34E-11	30000	29930	0.0117	3.91E-07	4.57E-09
350	349.3	0.0001	2.86E-07	2.86E-11	40000	39800	0.0151	3.79E-07	5.73E-09
400	398	0.0001	2.51E-07	2.51E-11	50000	49700	0.0182	3.66E-07	6.66E-09
450	448	0.0001	2.23E-07	2.23E-11	100000	99600	0.0308	3.09E-07	9.52E-09
500	498	0.0002	4.02E-07	8.03E-11	150000	149400	0.0397	2.66E-07	1.05E-08
1000	997	0.0004	4.01E-07	1.60E-10	200000	200100	0.0463	2.31E-07	1.07E-08
1100	1096	0.0005	4.56E-07	2.28E-10	250000	249800	0.0511	2.05E-07	1.05E-08
1200	1196	0.0005	4.18E-07	2.09E-10	500000	500000	0.0645	1.29E-07	8.32E-09
1300	1296	0.0005	3.86E-07	1.93E-10	1000000	994000	0.0731	7.35E-08	5.38E-09
1400	1394	0.0006	4.30E-07	2.58E-10	1500000	1495000	0.0763	5.10E-08	3.89E-09
1500	1495	0.0006	4.01E-07	2.41E-10	2000000	1994000	0.078	3.91E-08	3.05E-09
2000	1992	0.0008	4.02E-07	3.21E-10	2500000	2494000	0.0788	3.16E-08	2.49E-09
2500	2490	0.0011	4.42E-07	4.86E-10	3000000	3005000	0.0791	2.63E-08	2.08E-09
3000	2992	0.0013	4.34E-07	5.65E-10	5000000	5030000	0.0805	1.60E-08	1.29E-09
4000	3930	0.0017	4.33E-07	7.35E-10	10000000	10020000	0.0814	8.12E-09	6.61E-10

Ohm’s law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0003	2.88E-05	8.65E-09	5000	4990	0.1396	2.80E-05	3.91E-06
20	20.3	0.0006	2.96E-05	1.77E-08	10000	9970	0.2188	2.19E-05	4.80E-06
30	30.3	0.0009	2.97E-05	2.67E-08	11000	10970	0.2283	2.08E-05	4.75E-06
40	40.3	0.0012	2.98E-05	3.57E-08	12000	11960	0.2362	1.97E-05	4.66E-06
50	50.3	0.0015	2.98E-05	4.47E-08	13000	12960	0.243	1.88E-05	4.56E-06
100	100	0.003	3.00E-05	9.00E-08	14000	13960	0.2482	1.78E-05	4.41E-06
150	149.8	0.0045	3.00E-05	1.35E-07	15000	14960	0.2533	1.69E-05	4.29E-06
200	199.5	0.0061	3.06E-05	1.87E-07	20000	19960	0.2674	1.34E-05	3.58E-06
250	249.3	0.0077	3.09E-05	2.38E-07	25000	24950	0.2749	1.10E-05	3.03E-06
300	299.5	0.0093	3.11E-05	2.89E-07	30000	29930	0.2796	9.34E-06	2.61E-06
350	349.3	0.0108	3.09E-05	3.34E-07	40000	39800	0.2852	7.17E-06	2.04E-06
400	398	0.0124	3.12E-05	3.86E-07	50000	49700	0.2884	5.80E-06	1.67E-06
450	448	0.014	3.13E-05	4.38E-07	100000	99600	0.2943	2.95E-06	8.70E-07
500	498	0.0156	3.13E-05	4.89E-07	150000	149400	0.2961	1.98E-06	5.87E-07
1000	997	0.0309	3.10E-05	9.58E-07	200000	200100	0.297	1.48E-06	4.41E-07
1100	1096	0.0341	3.11E-05	1.06E-06	250000	249800	0.2975	1.19E-06	3.54E-07
1200	1196	0.0372	3.11E-05	1.16E-06	500000	500000	0.2986	5.97E-07	1.78E-07
1300	1296	0.0403	3.11E-05	1.25E-06	1000000	994000	0.2991	3.01E-07	9.00E-08
1400	1394	0.0435	3.12E-05	1.36E-06	1500000	1495000	0.2992	2.00E-07	5.99E-08
1500	1495	0.0466	3.12E-05	1.45E-06	2000000	1994000	0.2993	1.50E-07	4.49E-08
2000	1992	0.0613	3.08E-05	1.89E-06	2500000	2494000	0.2993	1.20E-07	3.59E-08
2500	2490	0.0757	3.04E-05	2.30E-06	3000000	3005000	0.2993	9.96E-08	2.98E-08
3000	2992	0.0899	3.00E-05	2.70E-06	5000000	5030000	0.2995	5.95E-08	1.78E-08
4000	3930	0.1159	2.95E-05	3.42E-06	10000000	10020000	0.2995	2.99E-08	8.95E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0441	8.84E-06	3.90E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.068	6.82E-06	4.64E-07
30	30.3	0.0003	9.90E-06	2.97E-09	11000	10970	0.0712	6.49E-06	4.62E-07
40	40.3	0.0004	9.93E-06	3.97E-09	12000	11960	0.0741	6.20E-06	4.59E-07
50	50.3	0.0005	9.94E-06	4.97E-09	13000	12960	0.0768	5.93E-06	4.55E-07
100	100	0.0011	1.10E-05	1.21E-08	14000	13960	0.0792	5.67E-06	4.49E-07
150	149.8	0.0017	1.13E-05	1.93E-08	15000	14960	0.0814	5.44E-06	4.43E-07
200	199.5	0.0023	1.15E-05	2.65E-08	20000	19960	0.0899	4.50E-06	4.05E-07
250	249.3	0.0029	1.16E-05	3.37E-08	25000	24950	0.0956	3.83E-06	3.66E-07
300	299.5	0.0034	1.14E-05	3.86E-08	30000	29930	0.0997	3.33E-06	3.32E-07
350	349.3	0.004	1.15E-05	4.58E-08	40000	39800	0.1053	2.65E-06	2.79E-07
400	398	0.0045	1.13E-05	5.09E-08	50000	49700	0.1088	2.19E-06	2.38E-07
450	448	0.0051	1.14E-05	5.81E-08	100000	99600	0.1164	1.17E-06	1.36E-07
500	498	0.0056	1.12E-05	6.30E-08	150000	149400	0.1191	7.97E-07	9.49E-08
1000	997	0.011	1.10E-05	1.21E-07	200000	200100	0.1205	6.02E-07	7.26E-08
1100	1096	0.0121	1.10E-05	1.34E-07	250000	249800	0.1213	4.86E-07	5.89E-08
1200	1196	0.0131	1.10E-05	1.43E-07	500000	500000	0.123	2.46E-07	3.03E-08
1300	1296	0.0141	1.09E-05	1.53E-07	1000000	994000	0.1237	1.24E-07	1.54E-08
1400	1394	0.0151	1.08E-05	1.64E-07	1500000	1495000	0.1238	8.28E-08	1.03E-08
1500	1495	0.0161	1.08E-05	1.73E-07	2000000	1994000	0.1238	6.21E-08	7.69E-09
2000	1992	0.0208	1.04E-05	2.17E-07	2500000	2494000	0.1238	4.96E-08	6.15E-09
2500	2490	0.0254	1.02E-05	2.59E-07	3000000	3005000	0.1238	4.12E-08	5.10E-09
3000	2992	0.0296	9.89E-06	2.93E-07	5000000	5030000	0.1238	2.46E-08	3.05E-09
4000	3930	0.0373	9.49E-06	3.54E-07	10000000	10020000	0.1239	1.24E-08	1.53E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0002	1.92E-05	3.85E-09	5000	4990	0.0972	1.95E-05	1.89E-06
20	20.3	0.0004	1.97E-05	7.88E-09	10000	9970	0.1671	1.68E-05	2.80E-06
30	30.3	0.0006	1.98E-05	1.19E-08	11000	10970	0.1786	1.63E-05	2.91E-06
40	40.3	0.0008	1.99E-05	1.59E-08	12000	11960	0.1887	1.58E-05	2.98E-06
50	50.3	0.001	1.99E-05	1.99E-08	13000	12960	0.1977	1.53E-05	3.02E-06
100	100	0.002	2.00E-05	4.00E-08	14000	13960	0.2059	1.47E-05	3.04E-06
150	149.8	0.003	2.00E-05	6.01E-08	15000	14960	0.2135	1.43E-05	3.05E-06
200	199.5	0.0041	2.06E-05	8.43E-08	20000	19960	0.2374	1.19E-05	2.82E-06
250	249.3	0.0051	2.05E-05	1.04E-07	25000	24950	0.2511	1.01E-05	2.53E-06
300	299.5	0.0061	2.04E-05	1.24E-07	30000	29930	0.2599	8.68E-06	2.26E-06
350	349.3	0.0071	2.03E-05	1.44E-07	40000	39800	0.2699	6.78E-06	1.83E-06
400	398	0.0083	2.09E-05	1.73E-07	50000	49700	0.2758	5.55E-06	1.53E-06
450	448	0.0093	2.08E-05	1.93E-07	100000	99600	0.2862	2.87E-06	8.22E-07
500	498	0.0103	2.07E-05	2.13E-07	150000	149400	0.2896	1.94E-06	5.61E-07
1000	997	0.0209	2.10E-05	4.38E-07	200000	200100	0.2915	1.46E-06	4.25E-07
1100	1096	0.023	2.10E-05	4.83E-07	250000	249800	0.2927	1.17E-06	3.43E-07
1200	1196	0.0251	2.10E-05	5.27E-07	500000	500000	0.2949	5.90E-07	1.74E-07
1300	1296	0.0272	2.10E-05	5.71E-07	1000000	994000	0.2959	2.98E-07	8.81E-08
1400	1394	0.0292	2.09E-05	6.12E-07	1500000	1495000	0.2965	1.98E-07	5.88E-08
1500	1495	0.0313	2.09E-05	6.55E-07	2000000	1994000	0.297	1.49E-07	4.42E-08
2000	1992	0.0414	2.08E-05	8.60E-07	2500000	2494000	0.2974	1.19E-07	3.55E-08
2500	2490	0.0513	2.06E-05	1.06E-06	3000000	3005000	0.2977	9.91E-08	2.95E-08
3000	2992	0.0611	2.04E-05	1.25E-06	5000000	5030000	0.298	5.92E-08	1.77E-08
4000	3930	0.0796	2.03E-05	1.61E-06	10000000	10020000	0.2981	2.98E-08	8.87E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0002	1.92E-05	3.85E-09	5000	4990	0.1169	2.34E-05	2.74E-06
20	20.3	0.0004	1.97E-05	7.88E-09	10000	9970	0.2117	2.12E-05	4.50E-06
30	30.3	0.0007	2.31E-05	1.62E-08	11000	10970	0.2295	2.09E-05	4.80E-06
40	40.3	0.0009	2.23E-05	2.01E-08	12000	11960	0.2455	2.05E-05	5.04E-06
50	50.3	0.0012	2.39E-05	2.86E-08	13000	12960	0.2609	2.01E-05	5.25E-06
100	100	0.0024	2.40E-05	5.76E-08	14000	13960	0.2747	1.97E-05	5.41E-06
150	149.8	0.0036	2.40E-05	8.65E-08	15000	14960	0.2878	1.92E-05	5.54E-06
200	199.5	0.0048	2.41E-05	1.15E-07	20000	19960	0.3368	1.69E-05	5.68E-06
250	249.3	0.0061	2.45E-05	1.49E-07	25000	24950	0.3714	1.49E-05	5.53E-06
300	299.5	0.0073	2.44E-05	1.78E-07	30000	29930	0.3912	1.31E-05	5.11E-06
350	349.3	0.0086	2.46E-05	2.12E-07	40000	39800	0.413	1.04E-05	4.29E-06
400	398	0.0098	2.46E-05	2.41E-07	50000	49700	0.426	8.57E-06	3.65E-06
450	448	0.011	2.46E-05	2.70E-07	100000	99600	0.448	4.50E-06	2.02E-06
500	498	0.0123	2.47E-05	3.04E-07	150000	149400	0.455	3.05E-06	1.39E-06
1000	997	0.0244	2.45E-05	5.97E-07	200000	200100	0.459	2.29E-06	1.05E-06
1100	1096	0.0269	2.45E-05	6.60E-07	250000	249800	0.461	1.85E-06	8.51E-07
1200	1196	0.0293	2.45E-05	7.18E-07	500000	500000	0.464	9.28E-07	4.31E-07
1300	1296	0.0318	2.45E-05	7.80E-07	1000000	994000	0.466	4.69E-07	2.18E-07
1400	1394	0.0342	2.45E-05	8.39E-07	1500000	1495000	0.467	3.12E-07	1.46E-07
1500	1495	0.0366	2.45E-05	8.96E-07	2000000	1994000	0.468	2.35E-07	1.10E-07
2000	1992	0.0486	2.44E-05	1.19E-06	2500000	2494000	0.468	1.88E-07	8.78E-08
2500	2490	0.0604	2.43E-05	1.47E-06	3000000	3005000	0.468	1.56E-07	7.29E-08
3000	2992	0.0723	2.42E-05	1.75E-06	5000000	5030000	0.468	9.30E-08	4.35E-08
4000	3930	0.0948	2.41E-05	2.29E-06	10000000	10020000	0.468	4.67E-08	2.19E-08

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0363	7.27E-06	2.64E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.0687	6.89E-06	4.73E-07
30	30.3	0.0002	6.60E-06	1.32E-09	11000	10970	0.0747	6.81E-06	5.09E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0807	6.75E-06	5.45E-07
50	50.3	0.0003	5.96E-06	1.79E-09	13000	12960	0.0865	6.67E-06	5.77E-07
100	100	0.0007	7.00E-06	4.90E-09	14000	13960	0.0922	6.60E-06	6.09E-07
150	149.8	0.0011	7.34E-06	8.08E-09	15000	14960	0.0976	6.52E-06	6.37E-07
200	199.5	0.0015	7.52E-06	1.13E-08	20000	19960	0.1221	6.12E-06	7.47E-07
250	249.3	0.0018	7.22E-06	1.30E-08	25000	24950	0.1416	5.68E-06	8.04E-07
300	299.5	0.0022	7.35E-06	1.62E-08	30000	29930	0.1568	5.24E-06	8.21E-07
350	349.3	0.0026	7.44E-06	1.94E-08	40000	39800	0.1781	4.47E-06	7.97E-07
400	398	0.003	7.54E-06	2.26E-08	50000	49700	0.191	3.84E-06	7.34E-07
450	448	0.0034	7.59E-06	2.58E-08	100000	99600	0.2157	2.17E-06	4.67E-07
500	498	0.0037	7.43E-06	2.75E-08	150000	149400	0.223	1.49E-06	3.33E-07
1000	997	0.0075	7.52E-06	5.64E-08	200000	200100	0.2261	1.13E-06	2.55E-07
1100	1096	0.0083	7.57E-06	6.29E-08	250000	249800	0.2282	9.14E-07	2.08E-07
1200	1196	0.009	7.53E-06	6.77E-08	500000	500000	0.232	4.64E-07	1.08E-07
1300	1296	0.0098	7.56E-06	7.41E-08	1000000	994000	0.2338	2.35E-07	5.50E-08
1400	1394	0.0105	7.53E-06	7.91E-08	1500000	1495000	0.2343	1.57E-07	3.67E-08
1500	1495	0.0113	7.56E-06	8.54E-08	2000000	1994000	0.2346	1.18E-07	2.76E-08
2000	1992	0.015	7.53E-06	1.13E-07	2500000	2494000	0.2344	9.40E-08	2.20E-08
2500	2490	0.0186	7.47E-06	1.39E-07	3000000	3005000	0.2345	7.80E-08	1.83E-08
3000	2992	0.0223	7.45E-06	1.66E-07	5000000	5030000	0.2344	4.66E-08	1.09E-08
4000	3930	0.0294	7.48E-06	2.20E-07	10000000	10020000	0.2345	2.34E-08	5.49E-09

Ohm’s law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0004	3.85E-05	1.54E-08	5000	4990	0.1499	3.00E-05	4.50E-06
20	20.3	0.0007	3.45E-05	2.41E-08	10000	9970	0.2234	2.24E-05	5.01E-06
30	30.3	0.001	3.30E-05	3.30E-08	11000	10970	0.2324	2.12E-05	4.92E-06
40	40.3	0.0014	3.47E-05	4.86E-08	12000	11960	0.2397	2.00E-05	4.80E-06
50	50.3	0.0017	3.38E-05	5.75E-08	13000	12960	0.2453	1.89E-05	4.64E-06
100	100	0.0034	3.40E-05	1.16E-07	14000	13960	0.2503	1.79E-05	4.49E-06
150	149.8	0.0052	3.47E-05	1.81E-07	15000	14960	0.2544	1.70E-05	4.33E-06
200	199.5	0.0069	3.46E-05	2.39E-07	20000	19960	0.2676	1.34E-05	3.59E-06
250	249.3	0.0087	3.49E-05	3.04E-07	25000	24950	0.2753	1.10E-05	3.04E-06
300	299.5	0.0105	3.51E-05	3.68E-07	30000	29930	0.2801	9.36E-06	2.62E-06
350	349.3	0.0122	3.49E-05	4.26E-07	40000	39800	0.2859	7.18E-06	2.05E-06
400	398	0.0139	3.49E-05	4.85E-07	50000	49700	0.2892	5.82E-06	1.68E-06
450	448	0.0154	3.44E-05	5.29E-07	100000	99600	0.2954	2.97E-06	8.76E-07
500	498	0.0175	3.51E-05	6.15E-07	150000	149400	0.2974	1.99E-06	5.92E-07
1000	997	0.0344	3.45E-05	1.19E-06	200000	200100	0.2989	1.49E-06	4.46E-07
1100	1096	0.0377	3.44E-05	1.30E-06	250000	249800	0.3	1.20E-06	3.60E-07
1200	1196	0.0412	3.44E-05	1.42E-06	500000	500000	0.3017	6.03E-07	1.82E-07
1300	1296	0.0446	3.44E-05	1.53E-06	1000000	994000	0.3026	3.04E-07	9.21E-08
1400	1394	0.0479	3.44E-05	1.65E-06	1500000	1495000	0.3031	2.03E-07	6.15E-08
1500	1495	0.0511	3.42E-05	1.75E-06	2000000	1994000	0.3033	1.52E-07	4.61E-08
2000	1992	0.0672	3.37E-05	2.27E-06	2500000	2494000	0.3037	1.22E-07	3.70E-08
2500	2490	0.0827	3.32E-05	2.75E-06	3000000	3005000	0.3042	1.01E-07	3.08E-08
3000	2992	0.0978	3.27E-05	3.20E-06	5000000	5030000	0.3042	6.05E-08	1.84E-08
4000	3930	0.1253	3.19E-05	3.99E-06	10000000	10020000	0.3045	3.04E-08	9.25E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX I: INITIAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0327	6.55E-06	2.14E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.0626	6.28E-06	3.93E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.0685	6.24E-06	4.28E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0744	6.22E-06	4.63E-07
50	50.3	0.0002	3.98E-06	7.95E-10	13000	12960	0.08	6.17E-06	4.94E-07
100	100	0.0005	5.00E-06	2.50E-09	14000	13960	0.0853	6.11E-06	5.21E-07
150	149.8	0.0009	6.01E-06	5.41E-09	15000	14960	0.0907	6.06E-06	5.50E-07
200	199.5	0.0011	5.51E-06	6.07E-09	20000	19960	0.1128	5.65E-06	6.37E-07
250	249.3	0.0015	6.02E-06	9.03E-09	25000	24950	0.1309	5.25E-06	6.87E-07
300	299.5	0.0018	6.01E-06	1.08E-08	30000	29930	0.1429	4.77E-06	6.82E-07
350	349.3	0.0021	6.01E-06	1.26E-08	40000	39800	0.1579	3.97E-06	6.26E-07
400	398	0.0025	6.28E-06	1.57E-08	50000	49700	0.1666	3.35E-06	5.58E-07
450	448	0.0028	6.25E-06	1.75E-08	100000	99600	0.1821	1.83E-06	3.33E-07
500	498	0.0031	6.22E-06	1.93E-08	150000	149400	0.1874	1.25E-06	2.35E-07
1000	997	0.0064	6.42E-06	4.11E-08	200000	200100	0.1904	9.52E-07	1.81E-07
1100	1096	0.0071	6.48E-06	4.60E-08	250000	249800	0.1924	7.70E-07	1.48E-07
1200	1196	0.0078	6.52E-06	5.09E-08	500000	500000	0.1956	3.91E-07	7.65E-08
1300	1296	0.0085	6.56E-06	5.57E-08	1000000	994000	0.1972	1.98E-07	3.91E-08
1400	1394	0.0092	6.60E-06	6.07E-08	1500000	1495000	0.1984	1.33E-07	2.63E-08
1500	1495	0.0099	6.62E-06	6.56E-08	2000000	1994000	0.1991	9.98E-08	1.99E-08
2000	1992	0.0132	6.63E-06	8.75E-08	2500000	2494000	0.1997	8.01E-08	1.60E-08
2500	2490	0.0165	6.63E-06	1.09E-07	3000000	3005000	0.2001	6.66E-08	1.33E-08
3000	2992	0.0199	6.65E-06	1.32E-07	5000000	5030000	0.2006	3.99E-08	8.00E-09
4000	3930	0.0263	6.69E-06	1.76E-07	10000000	10020000	0.2012	2.01E-08	4.04E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0.0001	1.00E-08	1.00E-12
30	30.3	0	0	0	11000	10970	0.0002	1.82E-08	3.65E-12
40	40.3	0	0	0	12000	11960	0.0002	1.67E-08	3.34E-12
50	50.3	0	0	0	13000	12960	0.0002	1.54E-08	3.09E-12
100	100	0	0	0	14000	13960	0.0002	1.43E-08	2.87E-12
150	149.8	0	0	0	15000	14960	0.0002	1.34E-08	2.67E-12
200	199.5	0	0	0	20000	19960	0.0003	1.50E-08	4.51E-12
250	249.3	0	0	0	25000	24950	0.0004	1.60E-08	6.41E-12
300	299.5	0	0	0	30000	29930	0.0005	1.67E-08	8.35E-12
350	349.3	0	0	0	40000	39800	0.0007	1.76E-08	1.23E-11
400	398	0	0	0	50000	49700	0.0009	1.81E-08	1.63E-11
450	448	0	0	0	100000	99600	0.0017	1.71E-08	2.90E-11
500	498	0	0	0	150000	149400	0.0026	1.74E-08	4.52E-11
1000	997	0	0	0	200000	200100	0.0035	1.75E-08	6.12E-11
1100	1096	0	0	0	250000	249800	0.0043	1.72E-08	7.40E-11
1200	1196	0	0	0	500000	500000	0.0085	1.70E-08	1.45E-10
1300	1296	0	0	0	1000000	994000	0.0158	1.59E-08	2.51E-10
1400	1394	0	0	0	1500000	1495000	0.0223	1.49E-08	3.33E-10
1500	1495	0	0	0	2000000	1994000	0.028	1.40E-08	3.93E-10
2000	1992	0	0	0	2500000	2494000	0.0332	1.33E-08	4.42E-10
2500	2490	0	0	0	3000000	3005000	0.0379	1.26E-08	4.78E-10
3000	2992	0	0	0	5000000	5030000	0.0519	1.03E-08	5.36E-10
4000	3930	0	0	0	10000000	10020000	0.0714	7.13E-09	5.09E-10

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0422	8.46E-06	3.57E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.0731	7.33E-06	5.36E-07
30	30.3	0.0003	9.90E-06	2.97E-09	11000	10970	0.0783	7.14E-06	5.59E-07
40	40.3	0.0004	9.93E-06	3.97E-09	12000	11960	0.0831	6.95E-06	5.77E-07
50	50.3	0.0005	9.94E-06	4.97E-09	13000	12960	0.0877	6.77E-06	5.93E-07
100	100	0.0011	1.10E-05	1.21E-08	14000	13960	0.092	6.59E-06	6.06E-07
150	149.8	0.0017	1.13E-05	1.93E-08	15000	14960	0.0958	6.40E-06	6.13E-07
200	199.5	0.0022	1.10E-05	2.43E-08	20000	19960	0.1123	5.63E-06	6.32E-07
250	249.3	0.0027	1.08E-05	2.92E-08	25000	24950	0.1237	4.96E-06	6.13E-07
300	299.5	0.0033	1.10E-05	3.64E-08	30000	29930	0.1336	4.46E-06	5.96E-07
350	349.3	0.0038	1.09E-05	4.13E-08	40000	39800	0.1461	3.67E-06	5.36E-07
400	398	0.0043	1.08E-05	4.65E-08	50000	49700	0.1538	3.09E-06	4.76E-07
450	448	0.0048	1.07E-05	5.14E-08	100000	99600	0.1695	1.70E-06	2.88E-07
500	498	0.0053	1.06E-05	5.64E-08	150000	149400	0.1753	1.17E-06	2.06E-07
1000	997	0.0103	1.03E-05	1.06E-07	200000	200100	0.1779	8.89E-07	1.58E-07
1100	1096	0.0112	1.02E-05	1.14E-07	250000	249800	0.1802	7.21E-07	1.30E-07
1200	1196	0.012	1.00E-05	1.20E-07	500000	500000	0.1849	3.70E-07	6.84E-08
1300	1296	0.0129	9.95E-06	1.28E-07	1000000	994000	0.1872	1.88E-07	3.53E-08
1400	1394	0.0137	9.83E-06	1.35E-07	1500000	1495000	0.1877	1.26E-07	2.36E-08
1500	1495	0.0145	9.70E-06	1.41E-07	2000000	1994000	0.1881	9.43E-08	1.77E-08
2000	1992	0.0188	9.44E-06	1.77E-07	2500000	2494000	0.1883	7.55E-08	1.42E-08
2500	2490	0.0233	9.36E-06	2.18E-07	3000000	3005000	0.1886	6.28E-08	1.18E-08
3000	2992	0.0272	9.09E-06	2.47E-07	5000000	5030000	0.1889	3.76E-08	7.09E-09
4000	3930	0.0349	8.88E-06	3.10E-07	10000000	10020000	0.1891	1.89E-08	3.57E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0011	2.20E-07	2.42E-10
20	20.3	0	0	0	10000	9970	0.0023	2.31E-07	5.31E-10
30	30.3	0	0	0	11000	10970	0.0024	2.19E-07	5.25E-10
40	40.3	0	0	0	12000	11960	0.0027	2.26E-07	6.10E-10
50	50.3	0	0	0	13000	12960	0.0029	2.24E-07	6.49E-10
100	100	0	0	0	14000	13960	0.0031	2.22E-07	6.88E-10
150	149.8	0	0	0	15000	14960	0.0033	2.21E-07	7.28E-10
200	199.5	0	0	0	20000	19960	0.0043	2.15E-07	9.26E-10
250	249.3	0	0	0	25000	24950	0.0053	2.12E-07	1.13E-09
300	299.5	0	0	0	30000	29930	0.0062	2.07E-07	1.28E-09
350	349.3	0	0	0	40000	39800	0.0079	1.98E-07	1.57E-09
400	398	0	0	0	50000	49700	0.0096	1.93E-07	1.85E-09
450	448	0.0001	2.23E-07	2.23E-11	100000	99600	0.0161	1.62E-07	2.60E-09
500	498	0.0001	2.01E-07	2.01E-11	150000	149400	0.0211	1.41E-07	2.98E-09
1000	997	0.0002	2.01E-07	4.01E-11	200000	200100	0.0252	1.26E-07	3.17E-09
1100	1096	0.0002	1.82E-07	3.65E-11	250000	249800	0.0282	1.13E-07	3.18E-09
1200	1196	0.0003	2.51E-07	7.53E-11	500000	500000	0.0379	7.58E-08	2.87E-09
1300	1296	0.0003	2.31E-07	6.94E-11	1000000	994000	0.0452	4.55E-08	2.06E-09
1400	1394	0.0003	2.15E-07	6.46E-11	1500000	1495000	0.0489	3.27E-08	1.60E-09
1500	1495	0.0003	2.01E-07	6.02E-11	2000000	1994000	0.0513	2.57E-08	1.32E-09
2000	1992	0.0005	2.51E-07	1.26E-10	2500000	2494000	0.0532	2.13E-08	1.13E-09
2500	2490	0.0006	2.41E-07	1.45E-10	3000000	3005000	0.0543	1.81E-08	9.81E-10
3000	2992	0.0007	2.34E-07	1.64E-10	5000000	5030000	0.0557	1.11E-08	6.17E-10
4000	3930	0.0009	2.29E-07	2.06E-10	10000000	10020000	0.0585	5.84E-09	3.42E-10

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0235	4.71E-06	1.11E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.0419	4.20E-06	1.76E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.0451	4.11E-06	1.85E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.048	4.01E-06	1.93E-07
50	50.3	0.0002	3.98E-06	7.95E-10	13000	12960	0.0511	3.94E-06	2.01E-07
100	100	0.0005	5.00E-06	2.50E-09	14000	13960	0.0538	3.85E-06	2.07E-07
150	149.8	0.0008	5.34E-06	4.27E-09	15000	14960	0.0565	3.78E-06	2.13E-07
200	199.5	0.0011	5.51E-06	6.07E-09	20000	19960	0.0687	3.44E-06	2.36E-07
250	249.3	0.0013	5.21E-06	6.78E-09	25000	24950	0.0788	3.16E-06	2.49E-07
300	299.5	0.0016	5.34E-06	8.55E-09	30000	29930	0.0873	2.92E-06	2.55E-07
350	349.3	0.0019	5.44E-06	1.03E-08	40000	39800	0.1003	2.52E-06	2.53E-07
400	398	0.0021	5.28E-06	1.11E-08	50000	49700	0.1093	2.20E-06	2.40E-07
450	448	0.0024	5.36E-06	1.29E-08	100000	99600	0.1315	1.32E-06	1.74E-07
500	498	0.0027	5.42E-06	1.46E-08	150000	149400	0.1398	9.36E-07	1.31E-07
1000	997	0.0053	5.32E-06	2.82E-08	200000	200100	0.1442	7.21E-07	1.04E-07
1100	1096	0.0058	5.29E-06	3.07E-08	250000	249800	0.1471	5.89E-07	8.66E-08
1200	1196	0.0063	5.27E-06	3.32E-08	500000	500000	0.1517	3.03E-07	4.60E-08
1300	1296	0.0068	5.25E-06	3.57E-08	1000000	994000	0.1536	1.55E-07	2.37E-08
1400	1394	0.0073	5.24E-06	3.82E-08	1500000	1495000	0.1549	1.04E-07	1.60E-08
1500	1495	0.0078	5.22E-06	4.07E-08	2000000	1994000	0.1553	7.79E-08	1.21E-08
2000	1992	0.0102	5.12E-06	5.22E-08	2500000	2494000	0.1562	6.26E-08	9.78E-09
2500	2490	0.0126	5.06E-06	6.38E-08	3000000	3005000	0.1564	5.20E-08	8.14E-09
3000	2992	0.0149	4.98E-06	7.42E-08	5000000	5030000	0.1569	3.12E-08	4.89E-09
4000	3930	0.0193	4.91E-06	9.48E-08	10000000	10020000	0.1573	1.57E-08	2.47E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0021	2.02E-04	4.24E-07	5000	4990	0.2376	4.76E-05	1.13E-05
20	20.3	0.0041	2.02E-04	8.28E-07	10000	9970	0.2462	2.47E-05	6.08E-06
30	30.3	0.0061	2.01E-04	1.23E-06	11000	10970	0.2473	2.25E-05	5.57E-06
40	40.3	0.008	1.99E-04	1.59E-06	12000	11960	0.2481	2.07E-05	5.15E-06
50	50.3	0.0099	1.97E-04	1.95E-06	13000	12960	0.2487	1.92E-05	4.77E-06
100	100	0.0197	1.97E-04	3.88E-06	14000	13960	0.2491	1.78E-05	4.44E-06
150	149.8	0.0292	1.95E-04	5.69E-06	15000	14960	0.2495	1.67E-05	4.16E-06
200	199.5	0.0388	1.94E-04	7.55E-06	20000	19960	0.2509	1.26E-05	3.15E-06
250	249.3	0.0482	1.93E-04	9.32E-06	25000	24950	0.2518	1.01E-05	2.54E-06
300	299.5	0.0575	1.92E-04	1.10E-05	30000	29930	0.252	8.42E-06	2.12E-06
350	349.3	0.0665	1.90E-04	1.27E-05	40000	39800	0.2531	6.36E-06	1.61E-06
400	398	0.0755	1.90E-04	1.43E-05	50000	49700	0.2534	5.10E-06	1.29E-06
450	448	0.0846	1.89E-04	1.60E-05	100000	99600	0.2542	2.55E-06	6.49E-07
500	498	0.0927	1.86E-04	1.73E-05	150000	149400	0.2545	1.70E-06	4.34E-07
1000	997	0.1598	1.60E-04	2.56E-05	200000	200100	0.2547	1.27E-06	3.24E-07
1100	1096	0.1683	1.54E-04	2.58E-05	250000	249800	0.2549	1.02E-06	2.60E-07
1200	1196	0.1764	1.47E-04	2.60E-05	500000	500000	0.2551	5.10E-07	1.30E-07
1300	1296	0.1829	1.41E-04	2.58E-05	1000000	994000	0.2551	2.57E-07	6.55E-08
1400	1394	0.1886	1.35E-04	2.55E-05	1500000	1495000	0.2552	1.71E-07	4.36E-08
1500	1495	0.1935	1.29E-04	2.50E-05	2000000	1994000	0.2552	1.28E-07	3.27E-08
2000	1992	0.21	1.05E-04	2.21E-05	2500000	2494000	0.2552	1.02E-07	2.61E-08
2500	2490	0.2194	8.81E-05	1.93E-05	3000000	3005000	0.2552	8.49E-08	2.17E-08
3000	2992	0.2256	7.54E-05	1.70E-05	5000000	5030000	0.2552	5.07E-08	1.29E-08
4000	3930	0.2332	5.93E-05	1.38E-05	10000000	10020000	0.2553	2.55E-08	6.50E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-1

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0.0001	4.01E-09	4.01E-13
300	299.5	0	0	0	30000	29930	0.0001	3.34E-09	3.34E-13
350	349.3	0	0	0	40000	39800	0.0002	5.03E-09	1.01E-12
400	398	0	0	0	50000	49700	0.0002	4.02E-09	8.05E-13
450	448	0	0	0	100000	99600	0.0005	5.02E-09	2.51E-12
500	498	0	0	0	150000	149400	0.0007	4.69E-09	3.28E-12
1000	997	0	0	0	200000	200100	0.001	5.00E-09	5.00E-12
1100	1096	0	0	0	250000	249800	0.0012	4.80E-09	5.76E-12
1200	1196	0	0	0	500000	500000	0.0025	5.00E-09	1.25E-11
1300	1296	0	0	0	1000000	994000	0.0048	4.83E-09	2.32E-11
1400	1394	0	0	0	1500000	1495000	0.007	4.68E-09	3.28E-11
1500	1495	0	0	0	2000000	1994000	0.0092	4.61E-09	4.24E-11
2000	1992	0	0	0	2500000	2494000	0.011	4.41E-09	4.85E-11
2500	2490	0	0	0	3000000	3005000	0.013	4.33E-09	5.62E-11
3000	2992	0	0	0	5000000	5030000	0.0198	3.94E-09	7.79E-11
4000	3930	0	0	0	10000000	10020000	0.0319	3.18E-09	1.02E-10

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0002	4.01E-08	8.02E-12
20	20.3	0	0	0	10000	9970	0.0005	5.02E-08	2.51E-11
30	30.3	0	0	0	11000	10970	0.0005	4.56E-08	2.28E-11
40	40.3	0	0	0	12000	11960	0.0005	4.18E-08	2.09E-11
50	50.3	0	0	0	13000	12960	0.0006	4.63E-08	2.78E-11
100	100	0	0	0	14000	13960	0.0007	5.01E-08	3.51E-11
150	149.8	0	0	0	15000	14960	0.0007	4.68E-08	3.28E-11
200	199.5	0	0	0	20000	19960	0.001	5.01E-08	5.01E-11
250	249.3	0	0	0	25000	24950	0.0012	4.81E-08	5.77E-11
300	299.5	0	0	0	30000	29930	0.0014	4.68E-08	6.55E-11
350	349.3	0	0	0	40000	39800	0.0019	4.77E-08	9.07E-11
400	398	0	0	0	50000	49700	0.0024	4.83E-08	1.16E-10
450	448	0	0	0	100000	99600	0.0048	4.82E-08	2.31E-10
500	498	0	0	0	150000	149400	0.0072	4.82E-08	3.47E-10
1000	997	0	0	0	200000	200100	0.0095	4.75E-08	4.51E-10
1100	1096	0	0	0	250000	249800	0.0117	4.68E-08	5.48E-10
1200	1196	0	0	0	500000	500000	0.0218	4.36E-08	9.50E-10
1300	1296	0	0	0	1000000	994000	0.0377	3.79E-08	1.43E-09
1400	1394	0	0	0	1500000	1495000	0.0498	3.33E-08	1.66E-09
1500	1495	0	0	0	2000000	1994000	0.0595	2.98E-08	1.78E-09
2000	1992	0.0001	5.02E-08	5.02E-12	2500000	2494000	0.0693	2.78E-08	1.93E-09
2500	2490	0.0001	4.02E-08	4.02E-12	3000000	3005000	0.0751	2.50E-08	1.88E-09
3000	2992	0.0001	3.34E-08	3.34E-12	5000000	5030000	0.0896	1.78E-08	1.60E-09
4000	3930	0.0001	2.54E-08	2.54E-12	10000000	10020000	0.1032	1.03E-08	1.06E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0001	9.62E-06	9.62E-10	5000	4990	0.0527	1.06E-05	5.57E-07
20	20.3	0.0002	9.85E-06	1.97E-09	10000	9970	0.09	9.03E-06	8.12E-07
30	30.3	0.0003	9.90E-06	2.97E-09	11000	10970	0.0961	8.76E-06	8.42E-07
40	40.3	0.0004	9.93E-06	3.97E-09	12000	11960	0.1016	8.49E-06	8.63E-07
50	50.3	0.0005	9.94E-06	4.97E-09	13000	12960	0.1067	8.23E-06	8.78E-07
100	100	0.0012	1.02E-05	1.44E-08	14000	13960	0.1113	7.97E-06	8.87E-07
150	149.8	0.0019	1.27E-05	2.41E-08	15000	14960	0.1156	7.73E-06	8.93E-07
200	199.5	0.0025	1.25E-05	3.13E-08	20000	19960	0.1315	6.59E-06	8.66E-07
250	249.3	0.0031	1.24E-05	3.85E-08	25000	24950	0.1417	5.68E-06	8.05E-07
300	299.5	0.0037	1.24E-05	4.57E-08	30000	29930	0.1486	4.96E-06	7.38E-07
350	349.3	0.0043	1.23E-05	5.29E-08	40000	39800	0.1573	3.95E-06	6.22E-07
400	398	0.0049	1.23E-05	6.03E-08	50000	49700	0.1623	3.27E-06	5.30E-07
450	448	0.0055	1.23E-05	6.75E-08	100000	99600	0.1718	1.72E-06	2.96E-07
500	498	0.0061	1.22E-05	7.47E-08	150000	149400	0.1749	1.17E-06	2.05E-07
1000	997	0.012	1.20E-05	1.44E-07	200000	200100	0.1764	8.82E-07	1.56E-07
1100	1096	0.0132	1.20E-05	1.59E-07	250000	249800	0.1773	7.10E-07	1.26E-07
1200	1196	0.0143	1.20E-05	1.71E-07	500000	500000	0.1791	3.58E-07	6.42E-08
1300	1296	0.0154	1.19E-05	1.83E-07	1000000	994000	0.1799	1.81E-07	3.26E-08
1400	1394	0.0166	1.19E-05	1.98E-07	1500000	1495000	0.1802	1.21E-07	2.17E-08
1500	1495	0.0177	1.18E-05	2.10E-07	2000000	1994000	0.1803	9.04E-08	1.63E-08
2000	1992	0.0232	1.16E-05	2.70E-07	2500000	2494000	0.1805	7.24E-08	1.31E-08
2500	2490	0.0285	1.14E-05	3.26E-07	3000000	3005000	0.1808	6.02E-08	1.09E-08
3000	2992	0.0337	1.13E-05	3.80E-07	5000000	5030000	0.181	3.60E-08	6.51E-09
4000	3930	0.0435	1.11E-05	4.81E-07	10000000	10020000	0.1811	1.81E-08	3.27E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0005	1.00E-07	5.01E-11
20	20.3	0	0	0	10000	9970	0.0012	1.20E-07	1.44E-10
30	30.3	0	0	0	11000	10970	0.0013	1.19E-07	1.54E-10
40	40.3	0	0	0	12000	11960	0.0014	1.17E-07	1.64E-10
50	50.3	0	0	0	13000	12960	0.0016	1.23E-07	1.98E-10
100	100	0	0	0	14000	13960	0.0017	1.22E-07	2.07E-10
150	149.8	0	0	0	15000	14960	0.0018	1.20E-07	2.17E-10
200	199.5	0	0	0	20000	19960	0.0036	1.80E-07	6.49E-10
250	249.3	0	0	0	25000	24950	0.0047	1.88E-07	8.85E-10
300	299.5	0	0	0	30000	29930	0.0057	1.90E-07	1.09E-09
350	349.3	0	0	0	40000	39800	0.0087	2.19E-07	1.90E-09
400	398	0	0	0	50000	49700	0.0109	2.19E-07	2.39E-09
450	448	0	0	0	100000	99600	0.0206	2.07E-07	4.26E-09
500	498	0	0	0	150000	149400	0.0296	1.98E-07	5.86E-09
1000	997	0.0001	1.00E-07	1.00E-11	200000	200100	0.041	2.05E-07	8.40E-09
1100	1096	0.0001	9.12E-08	9.12E-12	250000	249800	0.0487	1.95E-07	9.49E-09
1200	1196	0.0001	8.36E-08	8.36E-12	500000	500000	0.0754	1.51E-07	1.14E-08
1300	1296	0.0001	7.72E-08	7.72E-12	1000000	994000	0.1032	1.04E-07	1.07E-08
1400	1394	0.0001	7.17E-08	7.17E-12	1500000	1495000	0.1224	8.19E-08	1.00E-08
1500	1495	0.0001	6.69E-08	6.69E-12	2000000	1994000	0.1308	6.56E-08	8.58E-09
2000	1992	0.0002	1.00E-07	2.01E-11	2500000	2494000	0.1369	5.49E-08	7.51E-09
2500	2490	0.0003	1.20E-07	3.61E-11	3000000	3005000	0.1414	4.71E-08	6.65E-09
3000	2992	0.0003	1.00E-07	3.01E-11	5000000	5030000	0.1501	2.98E-08	4.48E-09
4000	3930	0.0004	1.02E-07	4.07E-11	10000000	10020000	0.1579	1.58E-08	2.49E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0018	1.73E-04	3.12E-07	5000	4990	0.22842	4.58E-05	1.05E-05
20	20.3	0.0035	1.72E-04	6.03E-07	10000	9970	0.2375	2.38E-05	5.66E-06
30	30.3	0.0052	1.72E-04	8.92E-07	11000	10970	0.2385	2.17E-05	5.19E-06
40	40.3	0.0069	1.71E-04	1.18E-06	12000	11960	0.2392	2.00E-05	4.78E-06
50	50.3	0.0085	1.69E-04	1.44E-06	13000	12960	0.2399	1.85E-05	4.44E-06
100	100	0.0169	1.69E-04	2.86E-06	14000	13960	0.2404	1.72E-05	4.14E-06
150	149.8	0.0252	1.68E-04	4.24E-06	15000	14960	0.2408	1.61E-05	3.88E-06
200	199.5	0.0332	1.66E-04	5.53E-06	20000	19960	0.2423	1.21E-05	2.94E-06
250	249.3	0.0412	1.65E-04	6.81E-06	25000	24950	0.2431	9.74E-06	2.37E-06
300	299.5	0.0492	1.64E-04	8.08E-06	30000	29930	0.2438	8.15E-06	1.99E-06
350	349.3	0.057	1.63E-04	9.30E-06	40000	39800	0.2445	6.14E-06	1.50E-06
400	398	0.0647	1.63E-04	1.05E-05	50000	49700	0.245	4.93E-06	1.21E-06
450	448	0.0723	1.61E-04	1.17E-05	100000	99600	0.2458	2.47E-06	6.07E-07
500	498	0.0798	1.60E-04	1.28E-05	150000	149400	0.2462	1.65E-06	4.06E-07
1000	997	0.1428	1.43E-04	2.05E-05	200000	200100	0.2464	1.23E-06	3.03E-07
1100	1096	0.1523	1.39E-04	2.12E-05	250000	249800	0.2465	9.87E-07	2.43E-07
1200	1196	0.1606	1.34E-04	2.16E-05	500000	500000	0.2468	4.94E-07	1.22E-07
1300	1296	0.1679	1.30E-04	2.18E-05	1000000	994000	0.2468	2.48E-07	6.13E-08
1400	1394	0.1741	1.25E-04	2.17E-05	1500000	1495000	0.2468	1.65E-07	4.07E-08
1500	1495	0.1796	1.20E-04	2.16E-05	2000000	1994000	0.2468	1.24E-07	3.05E-08
2000	1992	0.198	9.94E-05	1.97E-05	2500000	2494000	0.2468	9.90E-08	2.44E-08
2500	2490	0.2085	8.37E-05	1.75E-05	3000000	3005000	0.2468	8.21E-08	2.03E-08
3000	2992	0.2156	7.21E-05	1.55E-05	5000000	5030000	0.2469	4.91E-08	1.21E-08
4000	3930	0.2235	5.69E-05	1.27E-05	10000000	10020000	0.2469	2.46E-08	6.08E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-2

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0003	2.88E-05	8.65E-09	5000	4990	0.1128	2.26E-05	2.55E-06
20	20.3	0.0006	2.96E-05	1.77E-08	10000	9970	0.1551	1.56E-05	2.41E-06
30	30.3	0.0009	2.97E-05	2.67E-08	11000	10970	0.1593	1.45E-05	2.31E-06
40	40.3	0.0012	2.98E-05	3.57E-08	12000	11960	0.1626	1.36E-05	2.21E-06
50	50.3	0.0014	2.78E-05	3.90E-08	13000	12960	0.1654	1.28E-05	2.11E-06
100	100	0.0029	2.90E-05	8.41E-08	14000	13960	0.1677	1.20E-05	2.01E-06
150	149.8	0.0044	2.94E-05	1.29E-07	15000	14960	0.1697	1.13E-05	1.93E-06
200	199.5	0.0058	2.91E-05	1.69E-07	20000	19960	0.1763	8.83E-06	1.56E-06
250	249.3	0.0073	2.93E-05	2.14E-07	25000	24950	0.1801	7.22E-06	1.30E-06
300	299.5	0.0087	2.90E-05	2.53E-07	30000	29930	0.1826	6.10E-06	1.11E-06
350	349.3	0.0101	2.89E-05	2.92E-07	40000	39800	0.1856	4.66E-06	8.66E-07
400	398	0.0115	2.89E-05	3.32E-07	50000	49700	0.1875	3.77E-06	7.07E-07
450	448	0.013	2.90E-05	3.77E-07	100000	99600	0.1907	1.91E-06	3.65E-07
500	498	0.0143	2.87E-05	4.11E-07	150000	149400	0.192	1.29E-06	2.47E-07
1000	997	0.0281	2.82E-05	7.92E-07	200000	200100	0.1926	9.63E-07	1.85E-07
1100	1096	0.0308	2.81E-05	8.66E-07	250000	249800	0.193	7.73E-07	1.49E-07
1200	1196	0.0334	2.79E-05	9.33E-07	500000	500000	0.1936	3.87E-07	7.50E-08
1300	1296	0.036	2.78E-05	1.00E-06	1000000	994000	0.194	1.95E-07	3.79E-08
1400	1394	0.0386	2.77E-05	1.07E-06	1500000	1495000	0.1943	1.30E-07	2.53E-08
1500	1495	0.0412	2.76E-05	1.14E-06	2000000	1994000	0.1944	9.75E-08	1.90E-08
2000	1992	0.0536	2.69E-05	1.44E-06	2500000	2494000	0.1945	7.80E-08	1.52E-08
2500	2490	0.0653	2.62E-05	1.71E-06	3000000	3005000	0.1945	6.47E-08	1.26E-08
3000	2992	0.0765	2.56E-05	1.96E-06	5000000	5030000	0.1947	3.87E-08	7.54E-09
4000	3930	0.0962	2.45E-05	2.35E-06	10000000	10020000	0.1948	1.94E-08	3.79E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0
20	20.3	0	0	0
30	30.3	0	0	0
40	40.3	0	0	0
50	50.3	0	0	0
100	100	0	0	0
150	149.8	0	0	0
200	199.5	0	0	0
250	249.3	0	0	0
300	299.5	0	0	0
350	349.3	0	0	0
400	398	0	0	0
450	448	0	0	0
500	498	0.0001	2.01E-07	2.01E-11
1000	997	0.0001	1.00E-07	1.00E-11
1100	1096	0.0001	9.12E-08	9.12E-12
1200	1196	0.0002	1.67E-07	3.34E-11
1300	1296	0.0002	1.54E-07	3.09E-11
1400	1394	0.0002	1.43E-07	2.87E-11
1500	1495	0.0002	1.34E-07	2.68E-11
2000	1992	0.0004	2.01E-07	8.03E-11
2500	2490	0.0005	2.01E-07	1.00E-10
3000	2992	0.0006	2.01E-07	1.20E-10
4000	3930	0.0008	2.04E-07	1.63E-10

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
5000	4990	0.001	2.00E-07	2.00E-10
10000	9970	0.002	2.01E-07	4.01E-10
11000	10970	0.0022	2.01E-07	4.41E-10
12000	11960	0.0024	2.01E-07	4.82E-10
13000	12960	0.0026	2.01E-07	5.22E-10
14000	13960	0.0027	1.93E-07	5.22E-10
15000	14960	0.0029	1.94E-07	5.62E-10
20000	19960	0.0037	1.85E-07	6.86E-10
25000	24950	0.0044	1.76E-07	7.76E-10
30000	29930	0.005	1.67E-07	8.35E-10
40000	39800	0.0062	1.56E-07	9.66E-10
50000	49700	0.0072	1.45E-07	1.04E-09
100000	99600	0.0107	1.07E-07	1.15E-09
150000	149400	0.0126	8.43E-08	1.06E-09
200000	200100	0.014	7.00E-08	9.80E-10
250000	249800	0.0149	5.96E-08	8.89E-10
500000	500000	0.0173	3.46E-08	5.99E-10
1000000	994000	0.0188	1.89E-08	3.56E-10
1500000	1495000	0.0194	1.30E-08	2.52E-10
2000000	1994000	0.0198	9.93E-09	1.97E-10
2500000	2494000	0.0202	8.10E-09	1.64E-10
3000000	3005000	0.0208	6.92E-09	1.44E-10
5000000	5030000	0.0214	4.25E-09	9.10E-11
10000000	10020000	0.0217	2.17E-09	4.70E-11

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0039	7.82E-07	3.05E-09
20	20.3	0	0	0	10000	9970	0.0077	7.72E-07	5.95E-09
30	30.3	0	0	0	11000	10970	0.0085	7.75E-07	6.59E-09
40	40.3	0	0	0	12000	11960	0.0092	7.69E-07	7.08E-09
50	50.3	0	0	0	13000	12960	0.01	7.72E-07	7.72E-09
100	100	0	0	0	14000	13960	0.0107	7.66E-07	8.20E-09
150	149.8	0	0	0	15000	14960	0.0114	7.62E-07	8.69E-09
200	199.5	0	0	0	20000	19960	0.015	7.52E-07	1.13E-08
250	249.3	0	0	0	25000	24950	0.0185	7.41E-07	1.37E-08
300	299.5	0.0002	6.68E-07	1.34E-10	30000	29930	0.0219	7.32E-07	1.60E-08
350	349.3	0.0002	5.73E-07	1.15E-10	40000	39800	0.0283	7.11E-07	2.01E-08
400	398	0.0003	7.54E-07	2.26E-10	50000	49700	0.0346	6.96E-07	2.41E-08
450	448	0.0003	6.70E-07	2.01E-10	100000	99600	0.0613	6.15E-07	3.77E-08
500	498	0.0003	6.02E-07	1.81E-10	150000	149400	0.0802	5.37E-07	4.31E-08
1000	997	0.0007	7.02E-07	4.91E-10	200000	200100	0.0958	4.79E-07	4.59E-08
1100	1096	0.0008	7.30E-07	5.84E-10	250000	249800	0.1085	4.34E-07	4.71E-08
1200	1196	0.0009	7.53E-07	6.77E-10	500000	500000	0.1442	2.88E-07	4.16E-08
1300	1296	0.001	7.72E-07	7.72E-10	1000000	994000	0.1729	1.74E-07	3.01E-08
1400	1394	0.0011	7.89E-07	8.68E-10	1500000	1495000	0.1845	1.23E-07	2.28E-08
1500	1495	0.0012	8.03E-07	9.63E-10	2000000	1994000	0.1937	9.71E-08	1.88E-08
2000	1992	0.0015	7.53E-07	1.13E-09	2500000	2494000	0.1976	7.92E-08	1.57E-08
2500	2490	0.0019	7.63E-07	1.45E-09	3000000	3005000	0.2008	6.68E-08	1.34E-08
3000	2992	0.0023	7.69E-07	1.77E-09	5000000	5030000	0.2042	4.06E-08	8.29E-09
4000	3930	0.0031	7.89E-07	2.45E-09	10000000	10020000	0.2061	2.06E-08	4.24E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0006	1.20E-07	7.21E-11
20	20.3	0	0	0	10000	9970	0.0011	1.10E-07	1.21E-10
30	30.3	0	0	0	11000	10970	0.0013	1.19E-07	1.54E-10
40	40.3	0	0	0	12000	11960	0.0014	1.17E-07	1.64E-10
50	50.3	0	0	0	13000	12960	0.0015	1.16E-07	1.74E-10
100	100	0	0	0	14000	13960	0.0016	1.15E-07	1.83E-10
150	149.8	0	0	0	15000	14960	0.0017	1.14E-07	1.93E-10
200	199.5	0	0	0	20000	19960	0.0023	1.15E-07	2.65E-10
250	249.3	0	0	0	25000	24950	0.0029	1.16E-07	3.37E-10
300	299.5	0	0	0	30000	29930	0.0034	1.14E-07	3.86E-10
350	349.3	0	0	0	40000	39800	0.0045	1.13E-07	5.09E-10
400	398	0	0	0	50000	49700	0.0056	1.13E-07	6.31E-10
450	448	0	0	0	100000	99600	0.0107	1.07E-07	1.15E-09
500	498	0	0	0	150000	149400	0.0152	1.02E-07	1.55E-09
1000	997	0.0001	1.00E-07	1.00E-11	200000	200100	0.0194	9.70E-08	1.88E-09
1100	1096	0.0001	9.12E-08	9.12E-12	250000	249800	0.0232	9.29E-08	2.15E-09
1200	1196	0.0001	8.36E-08	8.36E-12	500000	500000	0.0382	7.64E-08	2.92E-09
1300	1296	0.0001	7.72E-08	7.72E-12	1000000	994000	0.0566	5.69E-08	3.22E-09
1400	1394	0.0001	7.17E-08	7.17E-12	1500000	1495000	0.0679	4.54E-08	3.08E-09
1500	1495	0.0001	6.69E-08	6.69E-12	2000000	1994000	0.075	3.76E-08	2.82E-09
2000	1992	0.0003	1.51E-07	4.52E-11	2500000	2494000	0.0806	3.23E-08	2.60E-09
2500	2490	0.0003	1.20E-07	3.61E-11	3000000	3005000	0.0865	2.88E-08	2.49E-09
3000	2992	0.0004	1.34E-07	5.35E-11	5000000	5030000	0.0955	1.90E-08	1.81E-09
4000	3930	0.0005	1.27E-07	6.36E-11	10000000	10020000	0.1033	1.03E-08	1.06E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-3

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that $V = I*R$ (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0.0001	1.00E-09	1.00E-13
500	498	0	0	0	150000	149400	0.0001	6.69E-10	6.69E-14
1000	997	0	0	0	200000	200100	0.0001	5.00E-10	5.00E-14
1100	1096	0	0	0	250000	249800	0.0002	8.01E-10	1.60E-13
1200	1196	0	0	0	500000	500000	0.0003	6.00E-10	1.80E-13
1300	1296	0	0	0	1000000	994000	0.0005	5.03E-10	2.52E-13
1400	1394	0	0	0	1500000	1495000	0.0006	4.01E-10	2.41E-13
1500	1495	0	0	0	2000000	1994000	0.0007	3.51E-10	2.46E-13
2000	1992	0	0	0	2500000	2494000	0.0007	2.81E-10	1.96E-13
2500	2490	0	0	0	3000000	3005000	0.0007	2.33E-10	1.63E-13
3000	2992	0	0	0	5000000	5030000	0.0008	1.59E-10	1.27E-13
4000	3930	0	0	0	10000000	10020000	0.0008	7.98E-11	6.39E-14

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *b*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0.0001	5.01E-09	5.01E-13
250	249.3	0	0	0	25000	24950	0.0001	4.01E-09	4.01E-13
300	299.5	0	0	0	30000	29930	0.0002	6.68E-09	1.34E-12
350	349.3	0	0	0	40000	39800	0.0003	7.54E-09	2.26E-12
400	398	0	0	0	50000	49700	0.0004	8.05E-09	3.22E-12
450	448	0	0	0	100000	99600	0.0008	8.03E-09	6.43E-12
500	498	0	0	0	150000	149400	0.0012	8.03E-09	9.64E-12
1000	997	0	0	0	200000	200100	0.0016	8.00E-09	1.28E-11
1100	1096	0	0	0	250000	249800	0.002	8.01E-09	1.60E-11
1200	1196	0	0	0	500000	500000	0.0039	7.80E-09	3.04E-11
1300	1296	0	0	0	1000000	994000	0.007	7.04E-09	4.93E-11
1400	1394	0	0	0	1500000	1495000	0.0098	6.56E-09	6.42E-11
1500	1495	0	0	0	2000000	1994000	0.0122	6.12E-09	7.46E-11
2000	1992	0	0	0	2500000	2494000	0.0141	5.65E-09	7.97E-11
2500	2490	0	0	0	3000000	3005000	0.016	5.32E-09	8.52E-11
3000	2992	0	0	0	5000000	5030000	0.0213	4.23E-09	9.02E-11
4000	3930	0	0	0	10000000	10020000	0.0282	2.81E-09	7.94E-11

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyll *a/b*-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Crude Extract-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0124	2.48E-06	3.08E-08
20	20.3	0	0	0	10000	9970	0.0231	2.32E-06	5.35E-08
30	30.3	0	0	0	11000	10970	0.0251	2.29E-06	5.74E-08
40	40.3	0	0	0	12000	11960	0.027	2.26E-06	6.10E-08
50	50.3	0.0001	1.99E-06	1.99E-10	13000	12960	0.0288	2.22E-06	6.40E-08
100	100	0.0002	2.00E-06	4.00E-10	14000	13960	0.0304	2.18E-06	6.62E-08
150	149.8	0.0003	2.00E-06	6.01E-10	15000	14960	0.032	2.14E-06	6.84E-08
200	199.5	0.0005	2.51E-06	1.25E-09	20000	19960	0.0402	2.01E-06	8.10E-08
250	249.3	0.0006	2.41E-06	1.44E-09	25000	24950	0.0473	1.90E-06	8.97E-08
300	299.5	0.0007	2.34E-06	1.64E-09	30000	29930	0.0537	1.79E-06	9.63E-08
350	349.3	0.0009	2.58E-06	2.32E-09	40000	39800	0.065	1.63E-06	1.06E-07
400	398	0.001	2.51E-06	2.51E-09	50000	49700	0.0748	1.51E-06	1.13E-07
450	448	0.0011	2.46E-06	2.70E-09	100000	99600	0.1115	1.12E-06	1.25E-07
500	498	0.0013	2.61E-06	3.39E-09	150000	149400	0.1351	9.04E-07	1.22E-07
1000	997	0.0026	2.61E-06	6.78E-09	200000	200100	0.1522	7.61E-07	1.16E-07
1100	1096	0.0028	2.55E-06	7.15E-09	250000	249800	0.1644	6.58E-07	1.08E-07
1200	1196	0.0031	2.59E-06	8.04E-09	500000	500000	0.2087	4.17E-07	8.71E-08
1300	1296	0.0034	2.62E-06	8.92E-09	1000000	994000	0.2415	2.43E-07	5.87E-08
1400	1394	0.0036	2.58E-06	9.30E-09	1500000	1495000	0.2568	1.72E-07	4.41E-08
1500	1495	0.0039	2.61E-06	1.02E-08	2000000	1994000	0.2626	1.32E-07	3.46E-08
2000	1992	0.0052	2.61E-06	1.36E-08	2500000	2494000	0.2666	1.07E-07	2.85E-08
2500	2490	0.0064	2.57E-06	1.64E-08	3000000	3005000	0.27	8.99E-08	2.43E-08
3000	2992	0.0077	2.57E-06	1.98E-08	5000000	5030000	0.2745	5.46E-08	1.50E-08
4000	3930	0.0101	2.57E-06	2.60E-08	10000000	10020000	0.2782	2.78E-08	7.72E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Phycocyanin-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0.0282	5.65E-06	1.59E-07
20	20.3	0.0001	4.93E-06	4.93E-10	10000	9970	0.051	5.12E-06	2.61E-07
30	30.3	0.0001	3.30E-06	3.30E-10	11000	10970	0.055	5.01E-06	2.76E-07
40	40.3	0.0002	4.96E-06	9.93E-10	12000	11960	0.0589	4.92E-06	2.90E-07
50	50.3	0.0002	3.98E-06	7.95E-10	13000	12960	0.0625	4.82E-06	3.01E-07
100	100	0.0006	6.00E-06	3.60E-09	14000	13960	0.0661	4.73E-06	3.13E-07
150	149.8	0.0009	6.01E-06	5.41E-09	15000	14960	0.0694	4.64E-06	3.22E-07
200	199.5	0.0012	6.02E-06	7.22E-09	20000	19960	0.0842	4.22E-06	3.55E-07
250	249.3	0.0015	6.02E-06	9.03E-09	25000	24950	0.0959	3.84E-06	3.69E-07
300	299.5	0.0018	6.01E-06	1.08E-08	30000	29930	0.105	3.51E-06	3.68E-07
350	349.3	0.0021	6.01E-06	1.26E-08	40000	39800	0.1184	2.97E-06	3.52E-07
400	398	0.0024	6.03E-06	1.45E-08	50000	49700	0.1272	2.56E-06	3.26E-07
450	448	0.0027	6.03E-06	1.63E-08	100000	99600	0.1455	1.46E-06	2.13E-07
500	498	0.003	6.02E-06	1.81E-08	150000	149400	0.1514	1.01E-06	1.53E-07
1000	997	0.0061	6.12E-06	3.73E-08	200000	200100	0.1544	7.72E-07	1.19E-07
1100	1096	0.0067	6.11E-06	4.10E-08	250000	249800	0.156	6.24E-07	9.74E-08
1200	1196	0.0073	6.10E-06	4.46E-08	500000	500000	0.1595	3.19E-07	5.09E-08
1300	1296	0.0079	6.10E-06	4.82E-08	1000000	994000	0.1611	1.62E-07	2.61E-08
1400	1394	0.0085	6.10E-06	5.18E-08	1500000	1495000	0.1616	1.08E-07	1.75E-08
1500	1495	0.0091	6.09E-06	5.54E-08	2000000	1994000	0.1618	8.11E-08	1.31E-08
2000	1992	0.012	6.02E-06	7.23E-08	2500000	2494000	0.1619	6.49E-08	1.05E-08
2500	2490	0.0148	5.94E-06	8.80E-08	3000000	3005000	0.1619	5.39E-08	8.72E-09
3000	2992	0.0176	5.88E-06	1.04E-07	5000000	5030000	0.1621	3.22E-08	5.22E-09
4000	3930	0.023	5.85E-06	1.35E-07	10000000	10020000	0.1622	1.62E-08	2.63E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Chlorophyllin-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0.0003	2.88E-05	8.65E-09	5000	4990	0.0995	1.99E-05	1.98E-06
20	20.3	0.0005	2.46E-05	1.23E-08	10000	9970	0.1729	1.73E-05	3.00E-06
30	30.3	0.0007	2.31E-05	1.62E-08	11000	10970	0.1843	1.68E-05	3.10E-06
40	40.3	0.0009	2.23E-05	2.01E-08	12000	11960	0.1934	1.62E-05	3.13E-06
50	50.3	0.0011	2.19E-05	2.41E-08	13000	12960	0.2001	1.54E-05	3.09E-06
100	100	0.0022	2.20E-05	4.84E-08	14000	13960	0.2066	1.48E-05	3.06E-06
150	149.8	0.0033	2.20E-05	7.27E-08	15000	14960	0.2124	1.42E-05	3.02E-06
200	199.5	0.0043	2.16E-05	9.27E-08	20000	19960	0.2314	1.16E-05	2.68E-06
250	249.3	0.0054	2.17E-05	1.17E-07	25000	24950	0.2425	9.72E-06	2.36E-06
300	299.5	0.0064	2.14E-05	1.37E-07	30000	29930	0.2504	8.37E-06	2.09E-06
350	349.3	0.0075	2.15E-05	1.61E-07	40000	39800	0.2587	6.50E-06	1.68E-06
400	398	0.0085	2.14E-05	1.82E-07	50000	49700	0.2643	5.32E-06	1.41E-06
450	448	0.0095	2.12E-05	2.01E-07	100000	99600	0.273	2.74E-06	7.48E-07
500	498	0.0106	2.13E-05	2.26E-07	150000	149400	0.2773	1.86E-06	5.15E-07
1000	997	0.0209	2.10E-05	4.38E-07	200000	200100	0.2797	1.40E-06	3.91E-07
1100	1096	0.0229	2.09E-05	4.78E-07	250000	249800	0.2811	1.13E-06	3.16E-07
1200	1196	0.025	2.09E-05	5.23E-07	500000	500000	0.2832	5.66E-07	1.60E-07
1300	1296	0.027	2.08E-05	5.63E-07	1000000	994000	0.2844	2.86E-07	8.14E-08
1400	1394	0.0292	2.09E-05	6.12E-07	1500000	1495000	0.2852	1.91E-07	5.44E-08
1500	1495	0.0312	2.09E-05	6.51E-07	2000000	1994000	0.2858	1.43E-07	4.10E-08
2000	1992	0.0414	2.08E-05	8.60E-07	2500000	2494000	0.2862	1.15E-07	3.28E-08
2500	2490	0.0513	2.06E-05	1.06E-06	3000000	3005000	0.2865	9.53E-08	2.73E-08
3000	2992	0.0614	2.05E-05	1.26E-06	5000000	5030000	0.2869	5.70E-08	1.64E-08
4000	3930	0.0803	2.04E-05	1.64E-06	10000000	10020000	0.2871	2.87E-08	8.23E-09

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.

APPENDIX II: FINAL PHOTOVOLTAIC CELL VOLTAGE, CURRENT, AND POWER

Control-4

Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)	Posted Resistance	True Resistance	Voltage (V)	Current (I)	Power (W)
10	10.4	0	0	0	5000	4990	0	0	0
20	20.3	0	0	0	10000	9970	0	0	0
30	30.3	0	0	0	11000	10970	0	0	0
40	40.3	0	0	0	12000	11960	0	0	0
50	50.3	0	0	0	13000	12960	0	0	0
100	100	0	0	0	14000	13960	0	0	0
150	149.8	0	0	0	15000	14960	0	0	0
200	199.5	0	0	0	20000	19960	0	0	0
250	249.3	0	0	0	25000	24950	0	0	0
300	299.5	0	0	0	30000	29930	0	0	0
350	349.3	0	0	0	40000	39800	0	0	0
400	398	0	0	0	50000	49700	0	0	0
450	448	0	0	0	100000	99600	0	0	0
500	498	0	0	0	150000	149400	0	0	0
1000	997	0	0	0	200000	200100	0	0	0
1100	1096	0	0	0	250000	249800	0	0	0
1200	1196	0	0	0	500000	500000	0	0	0
1300	1296	0	0	0	1000000	994000	0	0	0
1400	1394	0	0	0	1500000	1495000	0	0	0
1500	1495	0	0	0	2000000	1994000	0	0	0
2000	1992	0	0	0	2500000	2494000	0	0	0
2500	2490	0	0	0	3000000	3005000	0	0	0
3000	2992	0	0	0	5000000	5030000	0	0	0
4000	3930	0	0	0	10000000	10020000	0	0	0

Ohm's law states that V = I*R (Voltage = Current*Resistance). Voltages and true resistances are the known quantities from the experiments. The current was calculated from V/R. The power in watts (W) was calculated from V*I. Current and power have been rounded to 3 significant digits.