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Characterization of Natural Peruvian Dyes on Dye-Sensitized Solar Cells

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Committee of Tropical Ecology
Uppsala University, Sweden

Minor Field Study 207
ISSN 1653-5634

September 2017 Uppsala

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Abstract

Dye sensitized solar cells (DSSCs) are the third generation of solar cells and are thinner and cheaper than conventional silicon solar cells. The purpose of the project is to study purple corn as a photosensitizer and compare it to airampo which is another photosensitizor. To achieve this purpose the solar cells need to be manufactured and optimal solution for purple corn needs to be found. Current density-voltage (J-V) and incident photon to current conversion efficiency (IPCE) are measured and solar-to-electrical conversion efficiency and fill factor is calculated from the measurements.

The results showed that purple corn work better as a photosensitizer than airampo since the maximal solar-to-electrical energy conversion efficiency for purple corn was 0.2425 procent and for airampo was it 0.06127 procent. The maximal open circuit voltage was higher for airampo than purple corn but the other measurements were higher for purple corn. The optimal solution for purple corn ended up to 20:1 for the amount of purple corn and distilled water in the solution. The LED-measurements and the halogen measurements showed that purple corn is neither water sensitive nor sensitive to the amount of purple corn in the solution. The IPCE measurements for purple corn had strangely high values and the curve showed slopes around 480 nm and 490 nm and peaks around 540 nm and 625 nm. For airampo was the IPCE measurements not translatable.

More measurements need to be done to establish if purple corn is sensitive to water and amount of purple corn in the solution due to measuring errors. The reduction of IPCE, for purple corn, at 475 nm shows surface recombination in the DSSCs and a dip around 580 nm could be an indicator of activity in the bulk, such as short diffusion lengths. Due to low values even for DSSCs dyed with purple corn, it is unclear if the dye is fit for use outside a laboratory, further research on both dyes are therefore suggested. Continued work could be to study cells with polymer paper, do measurements with closed cells, use another electrolyte and other measurement devices that have a sun simulator.

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Granting Institution:
Arbetsgruppen för Tropisk Ekologi, ATE

Key words:
DSSC, renewable resource, solar energy

Acknowledgments

We would like to give special thanks to

Prof. Dr. Maria Quintana for her guidance and support as our supervisor at Universidad National de Ingenieria.

Dr. Erik Johansson for his feedback and assistance as our supervisor at Uppsala University.

Prof. Dr. Walter Estrada for arranging for us to come to Universidad National de Ingenieria.

Russell Nazario Ticse for all his help in manufacturing, measuring and analyzing the solar cells.

Pierre Ramos Apestegui for his help with the measurement apparatuses and his general help in the thin film lab.

Harry Anderson Rivera Tito for his help with all the chemical questions that developed during the project.

The thin films group for their hospitality and support through the project.

Prof. Dr. Mikael Sternad for his feedback on the physical and technical aspects of our project.

Dr. Roger Herbert for his support and feedback on the structure and relevance of our project.

Arbetsgruppen för Tropisk Ekologi, Uppsala University, och **Ronny Alexandersson** for choosing us as MFS candidates for the SIDA sponsorship.

SIDA for the sponsorship and preparatory course for minor field studies.

Abbreviations

CB	Conduction Band
DSSC	Dye-Sensitized Solar Cell
EQE	External Quantum Efficiency
FF	Fill Factor
IPCE	Incident Photon to Converted Electron
IQE	Internal Quantum Efficiency
PV	Photovoltaic
QE	Quantum Efficiency
UNI	Universidad Nacional de Ingeniería

Nomenclature

η	Solar-to-electrical energy conversion efficiency
J_{MP}	Maximum power output current density [A/m^2]
J_{SC}	Short-circuit current density [A/m^2]
P_{IN}	Input power [W]
V_{OC}	Open-circuit voltage [V]
V_{MP}	Maximum power output voltage [V]

Units

AU	Astronomical Unit	1 AU = 149597870700 m
deg C	Degrees Celsius	1 deg C = -273.15 K
J	Joule	1 J = 1 kg*m^{2}s^2
K	Kelvin	1 K = 273.15 deg C
W	Watt	1 W = 1 J/s

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1 Introduction

Combating climate change will be one of the greatest challenges mankind has ever faced. In order to honor the Paris Agreement and thus limiting global average temperature rise to below 2° C compared to preindustrial levels, the world's countries must move from non-renewable energy sources, such as fossil fuels, to renewable energy sources to power our civilization (United Nations, 2017).

The sun is the most prominent source of renewable energy (Dr. Stern, 2006). Solar cells have historically been inefficient, but new generations of cells are changing this. Modern thin-film solar cells are lighter, less expensive than their precursors, giving solar energy potential to power much of the future world. One type of thin-film cell is the dye-sensitized solar cell (DSSC). The DSSCs have several advantages to more conventional silicon cells, which makes them an interesting subject for research (Jacoby, 2016). They are semi-transparent and semi-flexible, unlike solid conventional solar cells, giving them potential for a wide range of uses. They can convert any visible light to electricity, making them fit both for outside as well as inside applications as well as low-light weather conditions, and the performance-to-price ratio of DSSCs is one of the most favorable of the third generation cells (Gcell, 2017a).

At the Universidad Nacional de Ingeniería (UNI) in Lima, Peru, the Thin Films Group is working with DSSCs at the Faculty of Science. The handmade solar cells are manufactured and evaluated by the group, aiming to find more efficient cells using natural Peruvian dyes as sensitizers (Quintana, 2017).

1.1 Project Purpose

The purpose of the project is to characterize the natural Peruvian dye purple corn as photosensitizer for DSSCs at UNI and compare its properties to another natural Peruvian dye, airampo.

1.2 Project Goals

The goal of the project is to manufacture, measure and analyze the performance of DSSCs with two natural Peruvian dyes as photosensitizers. In order to achieve this, the work has been divided in tasks.

- Manufacture DSSCs
- Finding the optimal solution for the extraction of purple corn as a dye
- Measuring current density-voltage (J-V) ratio for DSSCs sensitized with purple corn and airampo
- Measuring incident photon to current conversion efficiency (IPCE) for DSSCs sensitized with purple corn
- Analyzing solar-to-electrical energy conversion efficiency η and fill factor (FF) for DSSCs sensitized with purple corn and airampo

1.3 Limitations

During the course of the project limitations to the work was encountered.

The project spans 9 weeks in the laboratory at UNI. No more experimental data can be generated after the 9 week deadline, and any further investigations into findings will be left to other projects.

At UNI resources are limited. Regarding characterizations, J-V curve and IPCE can be measured, and fill factor and efficiency calculated with the existing measuring equipment. The equipment is built in the laboratory. The J-V measurements are done with an LED or halogen based apparatus, since there is no sun simulator. Fourier transform infrared spectroscopy (FTIR) was not possible to measure. Other resources such as FTO-glasses, ovens and cups are also limited, prompting reuse of resources or bottlenecks in the project. Chemicals are also limited, affecting what kind of electrolyte for the DSSCs that can be manufactured.

Sharing a laboratory with a group of 10 people leads to sharing machines and other resources like cups, scissors and ethanol. When a machine is needed to be on overnight it is important to leave a note on the machine telling to leave it on, otherwise it happens that someone in the group turns it off. Language barriers can cause difficulties and delays in the project.

2 Background and Theory

The history, the advantages and the disadvantages of DSSCs are presented and the transformation of solar energy to electricity and properties of the dyes are presented in this section.

2.1 A Brief History of Solar Cells

The first silicon PV cells were developed by Bell labs in 1954 after decades of experiments with low efficient solar cells made from selenium. A year later, the first commercial licenses for silicon PV cells where sold, and in 1958 the first silicon PV cells were used in satellites (U.S. Department of Energy, 2001). This continued to be the main area of use for PV cells during the 1960s, but new improvements of the cells in the 1970s increased quality and performance, and reduced costs, resulting in PV cells entering new markets such as telecommunications aids, navigation equipment, and other low-power usages (Florida Solar Energy Center, 2014).

The energy crises during the 1970s increased efforts to develop PV systems for big scale use, and further improvements made PV cells enter the consumer electronics as well as off-grid solutions in the 1980s. Thin film solar cells were developed, the first solar powered aircraft flew over the English Channel and the first solar powered car drove between Sydney and Perth. The total worldwide installed PV power was 9.3 megawatts (MV) in 1982 (U.S. Department of Energy, 2001), which can be compared to the generating capacity of a nuclear power plant, which lies in the span of 500-4000 MW (PVeducation,

2017a).

During the 1990s the efficiency of PV cells continued to increase, and in 1999 the total installed PV power reached 1000 MW (U.S. Department of Energy, 2001). The 2000s meant a continued exponential growth in the installation of PV power (Figure 1), and a sharp drop in prices (Fraas, 2014).

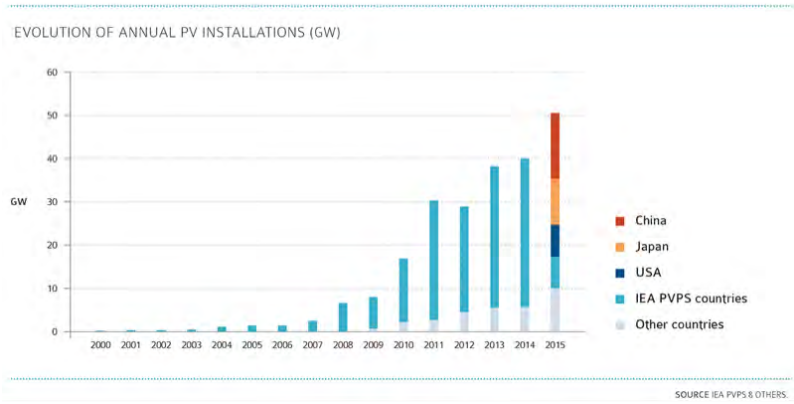


Figure 1. *Evolution of annual installed PV power 2000-2015, with portion of installation per top installer country/region marked for 2015.* Source: *Trends 2016 in Photovoltaic Applications*, International Energy Agency

Increasing understanding of man-made climate change further advanced the PV cell market, and PV cells are today seen as a key factor to halt fossil fuel growth (The Guardian, 2017). As can be seen in Figure 1, installation of PV power has been on a steady rise since it was first developed. A few countries dominates the new installations, with China leading the way, but installations are increasing also outside the IEA membership countries, which incorporates the developing world.

2.2 DSSCs: Advantages and Disadvantages

Silicon solar cells has shown the maximal efficiency of 26.3 procent which is close to the maximal theoretical efficincy that is 29 procent (Boyd, 2017). The lifespan is 25 years and after that the cells still produce 80 procent of their original power. Today is approximatly 90 procent of the sold solar cells silicon based (Energy, 2013). The cost of the balance of the system (BOS), which is hardware, invertes, installation, inspections, finances and so on, is high for silicon solar cells. The cells need a thick layer of glass and are therefore heavy and robust which limits the area of use (Stauffer, 2015).

The maximal efficiency for DSSCs is 14.1 procent and the theoretical maximal efficiency is 32 procent under standard conditions (Gcell, 2017b). The maximal open circuit voltage is 0.85-0.9 V and the maximal current is approximately 22 mA/cm^2. A normal value for the fill factor (FF) is 0.75 for DSSCs (Soga, 2006). Even though the efficiency is lower for DSSCs than conventional silicon solar cells and they use less expensive materials and can therefore be more convenient to use in larger volumes (Energy, 2013). One of the main difficulties with DSSCs are their longterm stability issues. The lifespan is 5-10 years (Solar Energy, 2016). Using natural sensitizers such as betalains the lifespan is only one

year. Another difficulty with DSSCs is the liquid electrolyte which brings problems with leakage and contamination. And at higher temperatures there are stability issues (Hug et al., 2013).

The main advantages are that they are light and thin and can absorb all visible light and can therefore be installed in windows and other new areas of use. They are also easy to transport and to be installed (Stauffer, 2015).

2.3 The Sun and the Solar Radiation

In the center of our solar system there is a yellow dwarf star: the Sun. In its core, at a temperature of 15 million degrees Celsius, a thermonuclear fusion process produces enormous amounts of energy in the form of electromagnetic radiation (Nasa Science, 2017). This electromagnetic radiation is then uniformly radiated from the Sun out in space.

The Sun has a luminosity of $3.83*10^{26}$ W, of which $1.75*10^{17}$ W hits the Earth (Williams, 2016). This can be compared to the total human energy yearly energy consumption of $6.21*10^{20}$ J (U. S Energy Information Administration, 2017), translating to $1.97*10^{13}$ W over the year. The solar constant is another way of measuring the power of the Sun at Earth, being the electromagnetic radiation from the Sun going through a square meter incident perpendicular to the radiation, at one astronomical unit (AU) from the Sun - approximately the distance between the Sun and Earth. Despite its name, the solar constant is not constant, but varies historically and with solar minimums and maximums. Therefore, an approximate value of 1370 W/m^2 is used to express the solar constant (Nasa Science Beta, 2003).

The Sun's radiation lies predominantly in the visible and infrared spectrum (Figure 2), and behaves similarly to a 5250 °C (5525 K) blackbody.

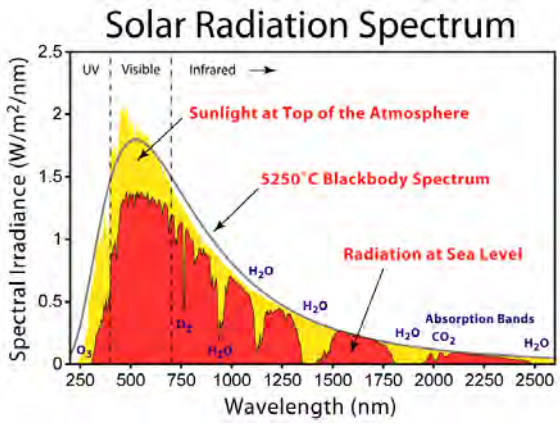


Figure 2. *Solar radiation spectrum for direct light for at sea level, the top of Earth's atmosphere and a 5525 K blackbody. Source: Global Warming Art, based on American Society for Testing and Materials, 2007-08-25.*

This is not surprising seeing the Sun's surface temperature is 5772 K. A portion of the Sun's electromagnetic radiation passing through Earth's atmosphere is absorbed by gases.

2.4 Dye-Sensitized Solar Cells

In 1839, French scientist Edmond Becquerel discovered the photovoltaic (PV) effect. During experiments, Becquerel noticed that a voltage and electric current could be created in materials when exposed to light. This became the first step in the development of today's solar cells (U.S. Department of Energy, 2001).

Dye-sensitized solar cells (DSSCs) use the PV effect to convert visible light to electricity through a special bond between a sensitized dye and a semiconductor. Titanium dioxide (TiO_2) is used as semiconductor with its n-type wide band gap (Soga, 2006). The special bond is created by the carboxylic groups on the dye that adsorb to the surface of TiO_2 and makes electron injection effective and fast (Lalander, 2009). Electrons are mobile charge carriers, and their movement create an electric current (Encyclopædia Britannica, 2017).

The electron energy in the DSSC is different for the different parts of the cell (Figure 3). When a photon meet the sensitized dye in the cell an electron excites and injects into the conduction band (CB) of the TiO_2 due to the carboxylic groups on the dye. The lowest unoccupied molecular orbital (LUMO) of the dye is the electron energy for the exited electron and the highest unoccupied molecule orbital (HOMO) of the dye is the electron energy when the electron is not excited. Inside the semiconductor the electron diffuses to the electrode and travels through the fluorine doped tin oxide (FTO) glasses towards the counter electrode where the platinum is. The electron diffuses from the platinum to the electrolyte, iodide, then goes to the dye and the circle is complete (Lalander, 2009).

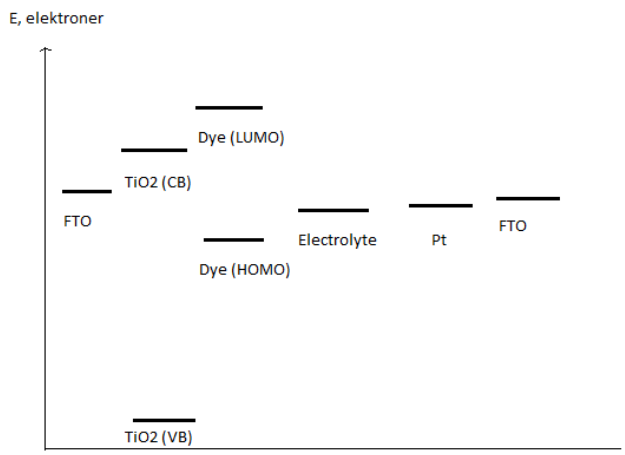


Figure 3. *A simplified example how the electron energy levels for FTO, TiO_2, the dye, electrolyte and the platinum in the DSSC are placed (Johansson, 2016).*

The most important thing with the energy levels are the difference between the excited electron in the dye, the CB for the TiO_2 and the electrolyte. If the energy level for the electrolyte is too close to the energy level for the excited electron in the dye the electron

can go there instead, it recombinates instead of injects into the semiconductor (Lalander, 2009). Recombination of electrons annihilates the carriers, and losses due to recombination affects the currents and voltages produced by the cell. Recombination can be classified by where in the cell it occurs, with surface- and bulk recombination being the most common in solar cells (PVeducation, 2017b). Diffusion length is the length a carrier travels on average between generation and recombination. Short diffusion lengths indicate high recombination rates, and vice versa. Long diffusion lengths are associated with long lifetimes for the material in question, and is therefore of importance when evaluating a semiconductor material (PVeducation, 2017a).

2.4.1 The Properties of Dyes

Airampo and purple corn come from natural plants and are thereby organic dyes and have similar properties such as being able to solve in water. To get better results of the cells it is important to know and understand the properties of the dyes. Airampo (*Opuntia soehrensii*) comes from the cactus family and are famous in the Andean region for its antioxidant capacity. In the seeds of airampo betacyanin can be found (Figure 4) (Caldas-Cueva et al., 2015).

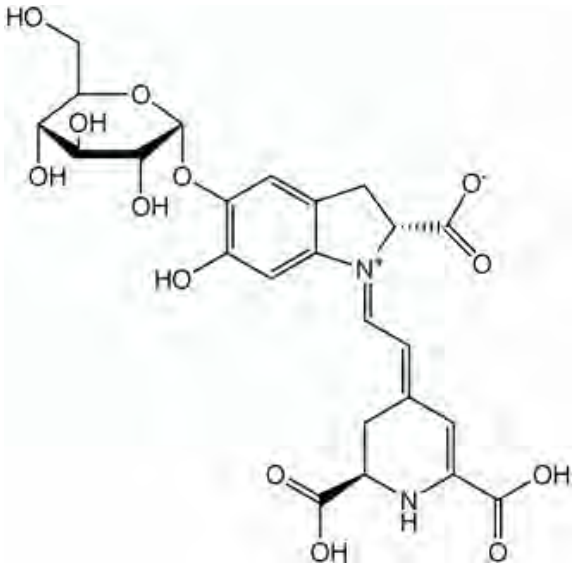


Figure 4. *The chemical structure of betanin.*

Betacyanin can be found in most red plants and contain nitrogen and glycosylated combounds. Betaxanthins are chemically similar but generate yellow pigments and these two groups are classed as betalains. The most studied betalain is betanin (Figure 4) (A Dictionary of Biology, 2004). The color of the purple corn has a more purple color than the dark pink color from airampo (Figure 5).

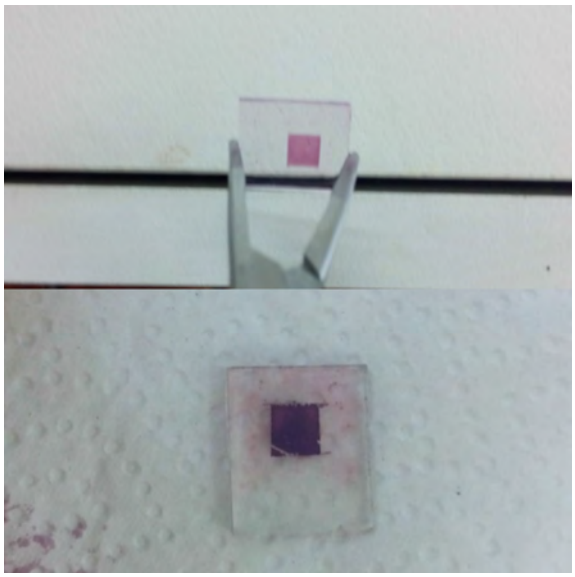


Figure 5. *Above: The color of airampo with handmade TiO_2-film. Lower: The color of purple corn with handmade TiO_2-film.*

Purple corn or maíz morado (Spanish) is native to Peru and is used for the popular drink chicha morada. The color from the purple corn is so intense that it is used for coloring rise for example (Peru Delights, 2013). Both airampo and purple corn are being used and have being used by the Peruvians in Cusco to color the alpaca wool they are using to make clothes and blankets (Anderson Rivera Tito, 2017).

2.4.2 Solvents of Dyes

Distilled water and ethanol are the solvents for the dyes. When a ZnO based dye-sensitized solar cells been studied with different sensitizing dyes, with and without including water to the dye solution it showed that water in the dye solution reduces surface dye aggregation for one of the sensitizing dyes. The solar cell performance for one of the sensitizing dye was thereby showing better results (Schölin et al., 2011).

2.4.3 Measurement Techniques for Characterizations of Dye-Sensitized Solar Cells

In order to evaluate the performance of solar cells a characterization of the cells is made, taking several properties into consideration. In this project current density-voltage J-V characterization, fill factor, efficiency, and quantum efficiency will be used to evaluate the performance of the differently dyed cells.

One of the most fundamental characterizations is the current-voltage (I-V) characterization, where voltage V and current I of the illuminated solar cell is measured cite. The measurements are used to calculate the output power P according to (Hyper Physics, 2017).

$$P = IV \tag{1}$$

In order to make the measurements independent of cell size, current density J is often considered instead of current I, using the relation

$$J = I/a \tag{2}$$

with a being the area of the cell (Elert, 2017). Any equation describing the solar cell's current can thus be modified to instead describe the cell's current density, and the I-V characterization thus becomes a J-V characterization. A solar cell can operate at a range of voltages and currents. The short-circuit current density J_{SC} is the maximum possible current density the cell can produce, and the open circuit voltage V_{OC} the highest voltage. A maximum power P_{MP} output is given by a cell specific current density-voltage ratio, the voltage V_{MP} and the current density J_{MP}. The fill factor (FF) is the ratio between the maximum obtainable power output P_{MP} and the ideal maximum power output:

$$FF = \frac{J_{MP}V_{MP}}{J_{SC}V_{OC}} \tag{3}$$

with J_{MP} and V_{MP} being the current density and voltage respectively for the maximum power output P_{MP} (Tupta, 2017). Thus, the fill factor provides insight in the internal efficiency of the solar cell, being a measurement on how close the cell is to its highest possible performance.

The solar-to-electrical energy conversion efficiency η of the cell can then be calculated using

$$\eta = \frac{J_{SC}V_{OC}FF}{P_{IN}} \tag{4}$$

P_{IN} is the solar power input (Tupta, 2017).

The quantum efficiency (QE) of a solar cell is the ratio of the total amount of carriers collected by the cell to the amount of incident photons by a given energy on the cell (PVeducation, 2017d). QE can be defined in two ways.

- External quantum efficiency (EQE). EQE includes optical losses due to phenomena such as transmission and reflection.
- Internal quantum efficiency (IQE). IQE excludes optical losses, but only considers the QE with regard to photons that are not transmitted or reflected out of the cell. To obtain the IQE of a solar cell, the EQE is measured, and the reflection and transmission is then subtracted from the EQE curve (PVeducation, 2017d).

In the particular case of DSSCs, QE is often referred to as the incident photon to current conversion efficiency, IPCE, and then specifically means the EQE. When the DSSC is illuminated by an monochromatic source, the IPCE gives the ratio between the photocurrent density in the external circuit and the incident photon flux (Hagfeldt et al., 2010).

$$IPCE = \frac{J_{SC(\lambda)}}{e}\frac{1}{\phi(\lambda)} = \frac{hc}{e}\frac{J_{SC(\lambda)}}{P_{IN(\lambda)}\lambda} = 1240\frac{J_{SC(\lambda)}}{P_{IN(\lambda)}\lambda} \tag{5}$$

with *e* being the elementary charge, *h* the Planck's constant, *c* the speed of light and λ the light's wavelength in nanometer (Hagfeldt et al., 2010). An IPCE curve for ideal solar cell is square, meaning the IPCE is at a 100% through the whole wavelength spectrum. Depending on where in the cell the electromagnetic radiation is being absorbed, different spans of wavelengths of electromagnetic radiation in the IPCE will affected (PVeducation, 2017c). Recombination effects and diffusion lengths in particular parts of the solar cell will reduce the IPCE for the corresponding wavelengths of radiation. Visible blue light with a wavelength of 475 nm (Madigan, 2017) is absorbed close to the surface of the cell,

and surface recombination will reduce the IPCE around the 475 nm wavelength. Green light on the other hand, with a wavelength of 510 nm, is absorbed in the cell's bulk, and low diffusion lengths will reduce the IPCE around the 510 nm wavelength. For photons with energy below the bandgap the IPCE is zero (PVeducation, 2017c). IPCE typically peak around 10-50% for DSSCs (Zimmermann et al., 2014).

3 Method

Preparing the solar cells and the measurements are presented in this section.

3.1 Manufacture DSSCs

To manufacture DSSC two FTO-glasses are needed. One of the glasses is treated with TiO_2 and the other is treated with platinum. Both glasses are painted with silver on one side and thereafter is usual paper placed between the glasses. Clamps are used to keep the cell together and an open cell is created.

3.1.1 Cleaning FTO-glass

The FTO-glasses are scrubbed with washing-up liquid and a sponge and thereafter washed with distilled water that is created at the laboratory. The scrubbed FTO-glasses are placed in a beaker that fills up with distilled water and placed in to a sonicator for 20 minutes. After 20 minutes is the distilled water replaced with ethanol and placed in the sonicator for another 20 minutes. To finish the cleaning process the FTO-glasses are placed in a oven in 60-120 degrees until the ethanol has evaporated.

3.1.2 TiO_2 Film

Two grams of pure TiO_2 is scaled in a cleaned cup with a cleaned magnet inside that acts as a stirrer. Thereafter eight grams of ethanol is scaled and a plastic-paper is placed on top of the cup to avoid evaporation of the ethanol. For 12 hours is the stirrer on and then is the TiO_2 film ready to be used.

3.1.3 Applying TiO_2 Film on FTO-glas

Cleaned FTO-glasses are placed on a pane of glass with a graphed paper glued under it (Figure 6).

Figure 6. *The 5*5 millimeter square of the TiO_2 is created with four pieces of tape. The white TiO_2 film covers the square.*

A 5*5 millimeter square is created with four pieces of tape. One drop of the TiO_2-solution is placed on the tape on the FTO-glass near the square and the TiO_2-solution wipes over the square with a smooth tool. This method is called doctor blading and the purpose is to get a homogeneous TiO_2 film over the entire square. After a few minutes when the TiO_2 film has dried can the pieces of tape be removed and the TiO_2-glasses is places in a cold oven. The TiO_2-glasses are in the oven for 50 minutes in 450 degrees and then the oven turns off and the glasses need to cool down for two hours before they can leave the oven.

3.1.4 Counter Electrodes

The cleaning process of FTO-glass are made the same way as is described in the section *4.1.1 Cleaning of FTO-glass*. One to three drops of liquid platinum are placed on each FTO-glass with a pipette. It is important to cover the entire surface but also to not let the platinum liquid to pour over the surface. The FTO-glasses are thereafter placed in a cold oven and after 30 minutes in 450 degrees the oven turns off. After two hours of cooling in the oven the counter electrodes are ready to be used.

3.1.5 Electrolyte

The electrolyte that is used in this project is taken from the course *Oorganiskt kemi*, 3B1781, at Uppsala University used in Laboration 2: *Dye Sensitized Nanostructured Solar cells*. The amount of electrolyte that is created is 50 ml and the concentration of litium iodide (LiI) is 0.5 M and the concentration of iodide (I_2) is 50 mM. The mass for the substances are calculated with equation 6 and 7.

$$n[mol] = \frac{m[g]}{M[g/mol]} \tag{6}$$

with *n* being the amount of solute, *m* the mass and *M* the mass per amount of substance called the molar mass (Mills & Milton, 2009).

$$c[M] = \frac{n[mol]}{V[L]} \tag{7}$$

with c being the molar concentration which is the amount of a solute present in one unit of a solution and V the volume (Sigma-Aldrich, 2017). 3.349 g of LiI and 0.635 g of I_2 is scaled into a beaker and thereafter is the solution 3-metoxypropionitrile added until 50 ml is accomplished.

3.1.6 Finished DSSC

When both the TiO_2-glasses and the counter electrodes are made a thin line with a silver conductive paint is painted on one side of the glasses with a toothpick made of wood (Figure 7).

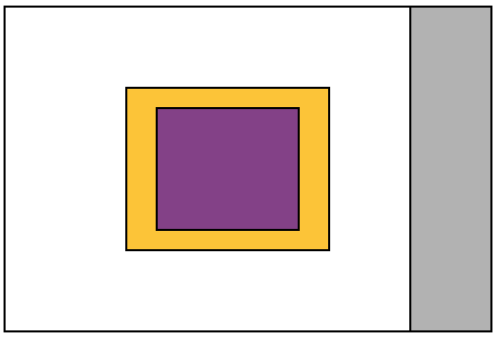


Figure 7. *A TiO_2-glass with a silver line and a normal paper over the 5*5 square that is colored yellow from the electrolyte.*

A piece of tissue paper is placed over the 5*5 square and after a few minutes when the silver has dried the electrodes are putted together. For an open cell the electrodes are putted together with clamps and 1-2 drops of electrolyte is being dropped between the glasses (Figure 8).

Figure 8. *A finished handmade solar cell with a dyed TiO_2-glass and a counter electrode together thanks to the clamps. The painted silver lines on each electrode are placed so that cables can be connected and measurements can be done.*

For a closed cell the electrodes are glued together. For all measurements in this project were only open cells used. After all the measurements were done the cells were picked apart and the FTO-glasses were washed clean and were used again for new handmade solar cells.

3.2 Manufacturing of Natural Peruvian Dyes

Airampo and purple corn are the two different natural Peruvian dyes that are studied as photosensitizers for DSSCs.

3.2.1 Airampo

Seeds from airampo are scaled in a cup and desired amount of distilled water and ethanol are added. The optimal concentration of seeds, distilled water and ethanol is used from earlier studies of airampo (Nazario Ticse, 2017). Optimal concentration for a dye means that it dissolves and can dye the TiO_2 film effectively so that the DSSC reaches as high efficiency, P, as possible. After one test session the same optimal concentration was achieved to 1:1:5 for seeds, distilled water and ethanol as earlier studies showed. If 5 g of seeds from airampo is used, 5 g of distilled water and 25 g of ethanol are added.

The beaker with the optimal concentration of seeds, distilled water and ethanol are placed in a sonicator for 20 minutes. Thereafter is the dye-solution ready to dye the TiO_2 film on the FTO-glass. When finished TiO_2-glasses are placed in the cup with dye-solution it is important to have the TiO_2 film facing up so it can get dyed correctly. The TiO_2-glasses should be in the dye-solution for two days to achieve the most efficient color of the TiO_2

film (Nazario Ticse, 2017). A plastic paper is used to avoid evaporation and tinfoil is used to cover the dye-solution from light because the dye is sensitive to light.

3.2.2 Purple Corn

Purple corn that is a few days old are wiped from the corn so that only the stem of the purple corn is left (Figure 9). The stem is divided into smaller parts and placed in a cup that thereafter is filled with distilled water. Since purple corn has not been studied earlier the optimal concentration of corn, distilled water and ethanol is unknown and in section *4.2.3 Finding Optimal Solution* this part is described. Desired amount of the stem parts are scaled in a new cup and desired amount of distilled water and ethanol are thereafter added.

Figure 9. *Purple corn that is wiped from the corn so that only the stem of the purple corn is left.*

The beaker with the optimal concentration for the purple corn was placed in a sonicator for 20 minutes. Finished TiO_2-glasses was placed in the beaker and the same procedure as for airampos was performed.

3.2.3 Finding Optimal Solution

To investigate if purple corn is sensitive to the amount of distilled water in the solvent five different cups were used and the only difference was the amount of distilled water (Table 1 in section *5.1.1 Finding Optimal Solution*). The same method were used to investigate if purple corn is sensitive to the amount of purple corn in the solvent (Table 2 in section *5.1.1 Finding Optimal Solution*). The only factor that is studied is the maximal efficiency not fill factor.

3.3 Measurements

The performance of the dyes on the DSSCs are evaluated with J-V and IPCE measurements. Calculations and processing of the measurement data are made in Matlab.

3.3.1 Current-Voltage Measurements

The J-V measurements are done using two measurement apparatuses, refered to as the LED based J-V measurement apparatus (Figure 10) and the halogen based measurement apparatus (Figure 11).

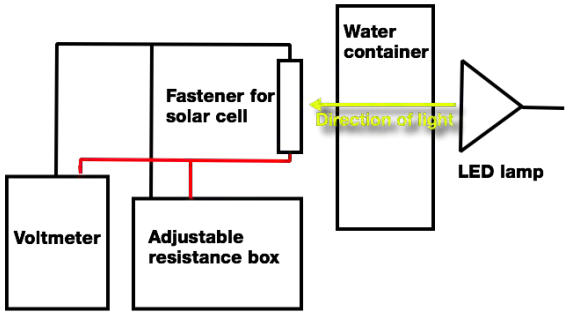


Figure 10. *Schematic of measurement apparatus for J-V measurements of DSSCs using a LED as a light source, at the Faculty of Science, Universidad Nacional de Ingeniería.*

The LED based measurement apparatus has a MR16 LED lamp as light source (Figure 10, Appendix A), operating on 20 V. The lamp is facing a plastic container filled with water, used to filter out infrared light. Behind the container, there is a fastener on which a solar cell can be attached, so that the light from the overhead filtered through the water is incident. At this distance from the LED lamp the intensity of the light is 1000 W/m^2. Two wires are attached to an adjustable resistance box and a voltmeter. A resistance sweep can be made with the resistance box with a range of 999 999-0 Ohm [Ω], with respective voltages shown on the voltmeter. The wires can be attached to the solar cell to do measurements. Currents corresponding to resistances and voltages can be calculated from the measurement data (Equation 1).

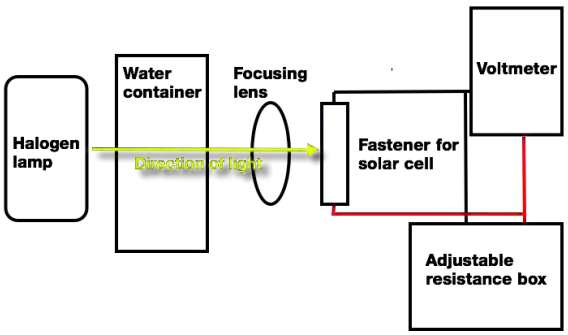


Figure 11. *Schematic of measurement apparatus for J-V measurements of DSSCs using an oat the Faculty of Science, Universidad Nacional de Ingeniería.*

The halogen based measurement apparatus has an overhead projector with a halogen lamp as light source (Figure 27, Appendix A). It is facing a plastic container filled with water, filtering out infrared light. Behind the container a lens focuses the light on a fastener on which solar cells can be attached for measurements. The intensity of the light hitting the solar cell at this distance form the halogen light source is 1000 W/m^2. Just as for the LED based apparatus, two wires are attached to an adjustable resistance box (range of

999 999-0 (Ω), and a voltmeter for reading the voltages over the cell.

The halogen based measurement apparatus has a spectrum more like the Sun's spectrum (Figure 2), compared to the LED based measurement apparatus (Quintana, 2017). The exact spectrum of the two apparatuses are not known.

3.3.2 IPCE

The measurement apparatus for IPCE measurements (Figure 28, Appendix A) utilizes a xenon light as light source.

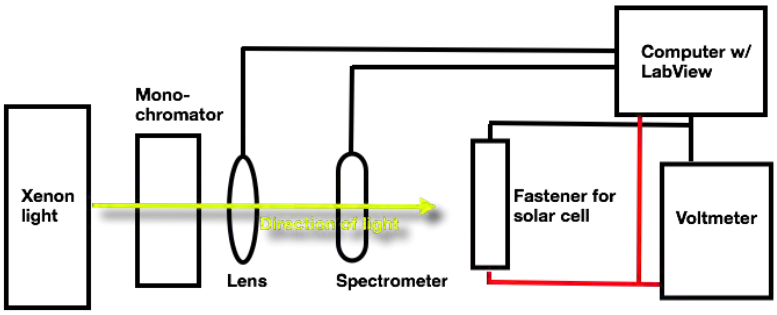


Figure 12. *Schematic of measurement apparatus for IPCE measurements of DSSCs, at the Faculty of Science, Universidad Nacional de Ingeniería.*

The light is filtered through a monochromator to narrow the range of wavelengths in the light to 300-800 nanometer (nm) in order for different wavelengths to be evaluated separately on the cell. The light goes through a focus lens and then a lens that separates 50% of the light to a sensor in a PC and 50% of the light to a optical ultraviolet-visible (UV-Vis) spectrometer. The spectrometer measures the light absorption of the solar cell. The UV-Vis measurements are also sent to the PC, where light absorption by the cell for the wavelength tested can be seen. Measurements are made in the range 400-700 nm, with 20 nm steps. The solar cell is wired to a voltmeter, where the voltage of the cell can be seen.

4 Results

The results of the study of purple corn and airampo as sensitizers for DSSCs are presented in this section.

4.1 Finding Optimal Solution for Purple Corn

To find the optimal solution for purple corn one factor at a time was studied, first the amount of distilled water and then the amount of purple corn in the solution.

4.1.1 Sensitivity to Amount of Distilled Water

Different solutions were made where only the amount of the water solution was changed (Table 1). The current density-voltage curves for the different solutions are presented with

possible measurement error and without them (Figure 13 and 14).

Table 1. *The different concentrations of purple corn that were used to study water sensitivity*

Concentration	Purple Corn (g)	Water solution (g)	Ethanol (g)
1:1	10	10	25
2:1	10	5	25
4:1	10	2,5	25
5:1	10	2	25
10:1	10	1	25
20:1	10	0,5	25

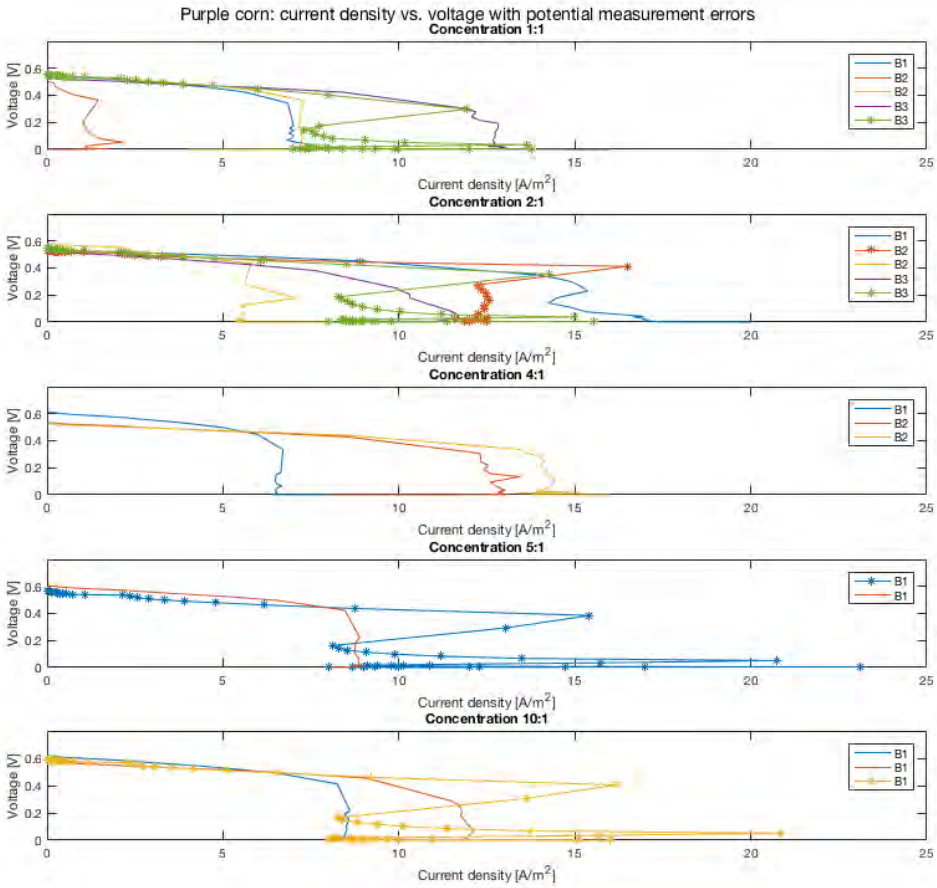


Figure 13. *Current density-voltage curve with possible measurement error curves for different concentrations of solvent for purple corn, with the level of the highest power output. B1, B2, B3 stand for different batches.*

The curves with the dots are the curves with the possible measurement error (Figure 13). Concentration 1:1 and 2:1 have measurements from five different handmade solar cells

from three different batches. Concentration 4:1 has measurements from three different handmade solar cells from two different batches. Concentration 5:1 has measurements from two different handmade solar cells from only one batch. Concentration 10:1 has three different handmade solar cells from only one batch as well (Figure 13). Without the possible measurement error has 1:1 four different curves, 2:1 and 4:1 have three, 5:1 has only one and 10:1 has measurement from two different handmade solar cells (Figure 14).

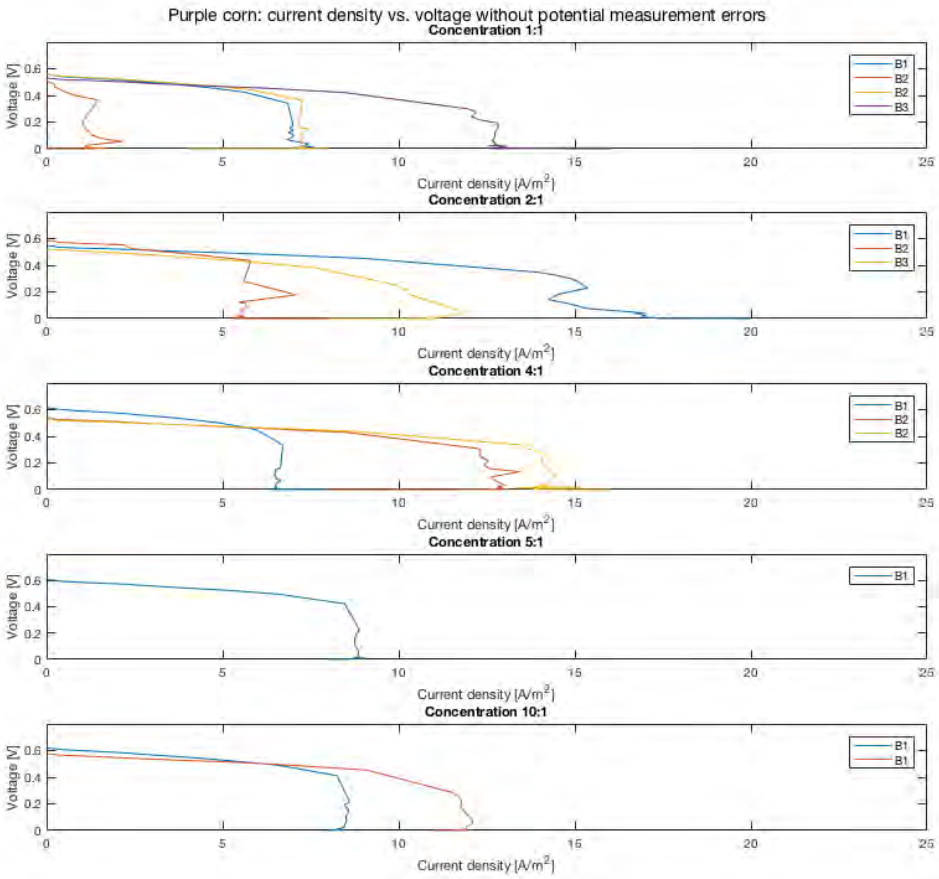


Figure 14. *Current density-voltage curve without possible measurement error curves for different concentrations of solvent for purple corn, with the level of the highest power output. B1, B2 and B3 are different batches.*

The current density-output power curves for the different concentrations are presented with and without possible measurement error (Figure 15 and 16).

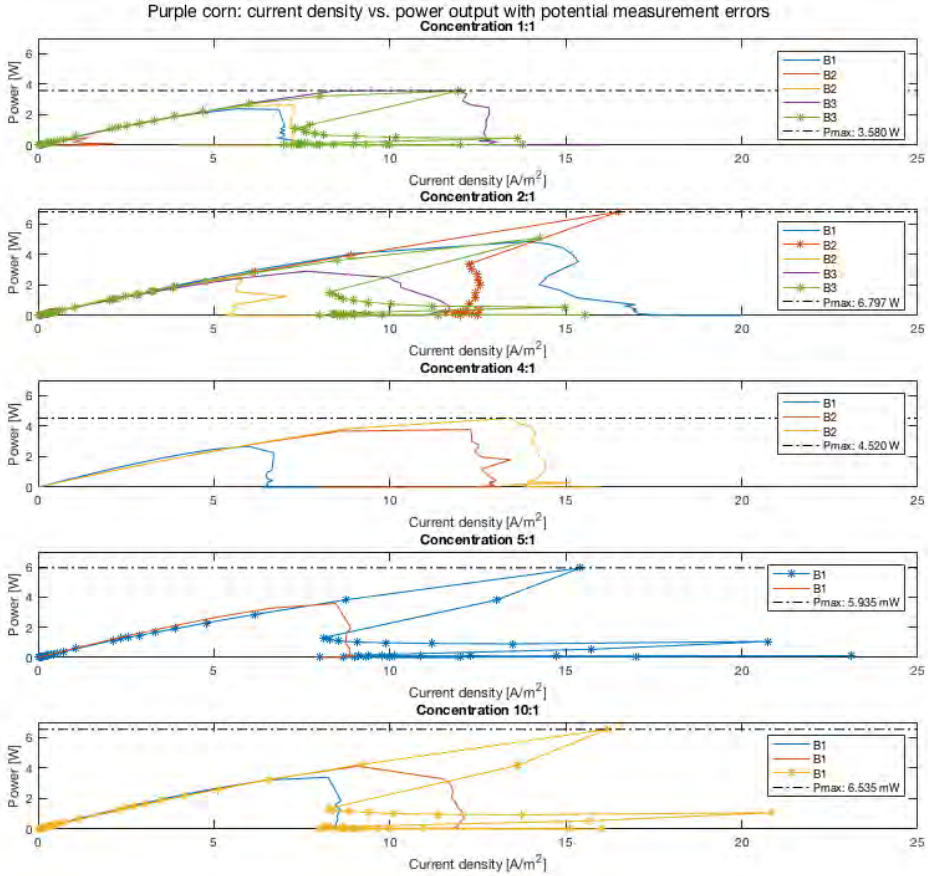


Figure 15. *Current density-output power curve with possible measurement error curves for different concentrations of solvent for purple corn. The maximal output power is presented for each concentration.*

The maximal output power for the concentrations 1:1, 2:1, 4:1, 5:1 and 10:1 are 3.530 W, 8.793 W, 4.520 W, 5.995 W and 5.535 W respectively (Figure 15).

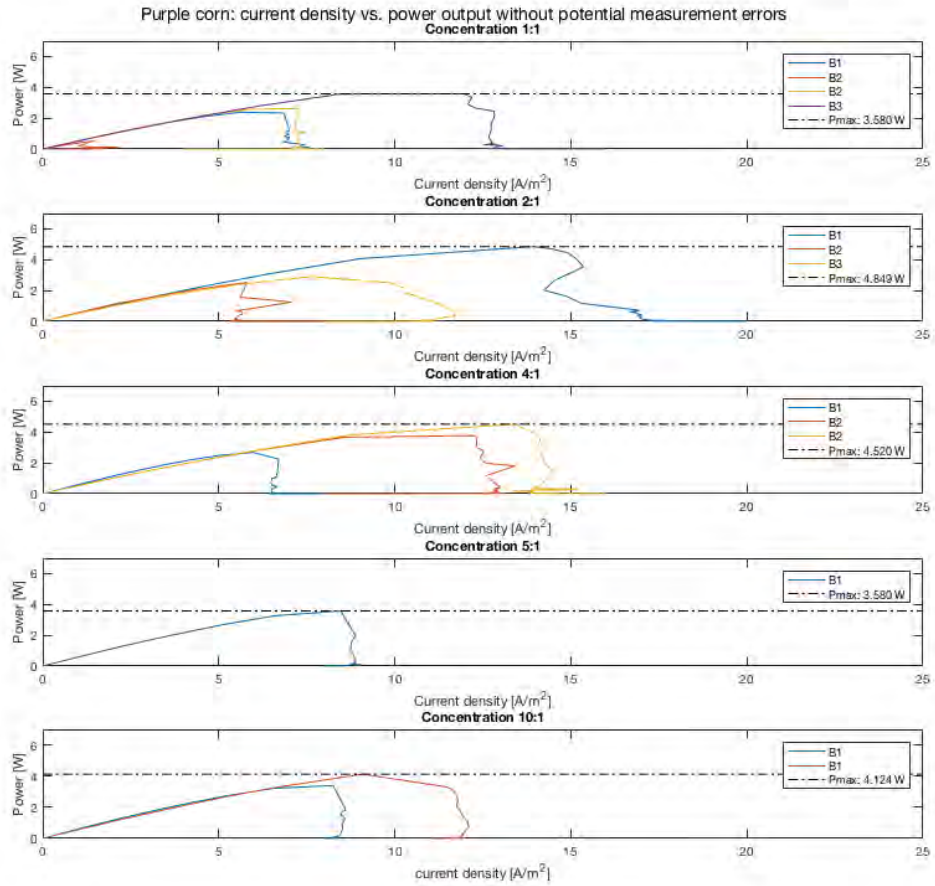


Figure 16. *Current density-output power curve without possible measurement error curves for different concentrations of solvent for purple corn.*

The maximal output power for the concentrations 1:1, 2:1, 4:1, 5:1 and 10:1 are now 3.580 W, 4.549 W, 4.520 W, 3.580 W and 4.124 W respectively (Figure 16). The relationship between the maximal output power and the different concentrations using a LED lamp and using an overhead are illustrated (Figure 17, Figure 18).

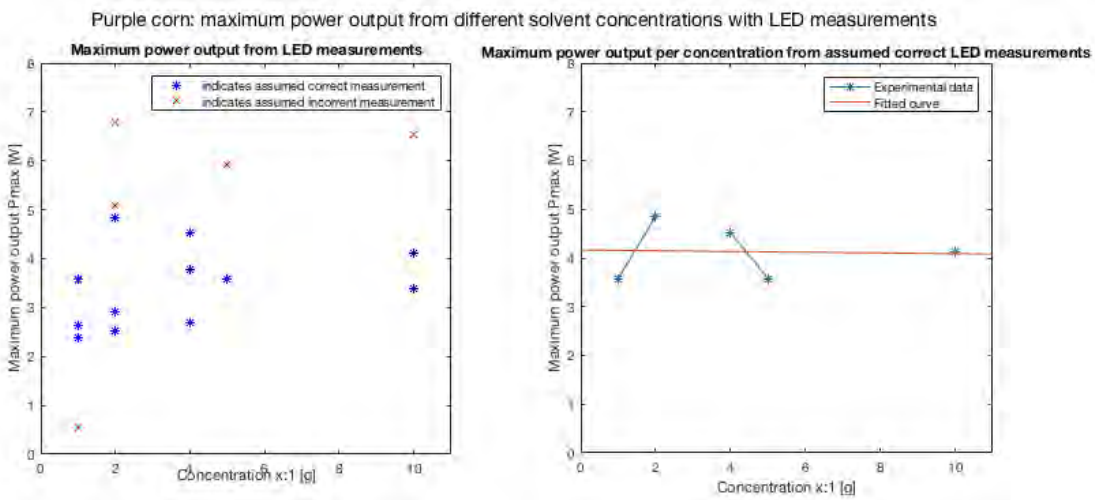


Figure 17. *(Left) Maximum power output for in relation to solvent concentration and (right) maximum power output per solvent concentration with fitted curve for LED measurements on purple corn.*

With the results from LED measurements the purple corn is not sensitive to the amount of water solution. The fitted curve has the gradient -0.0076 (Figure 17).

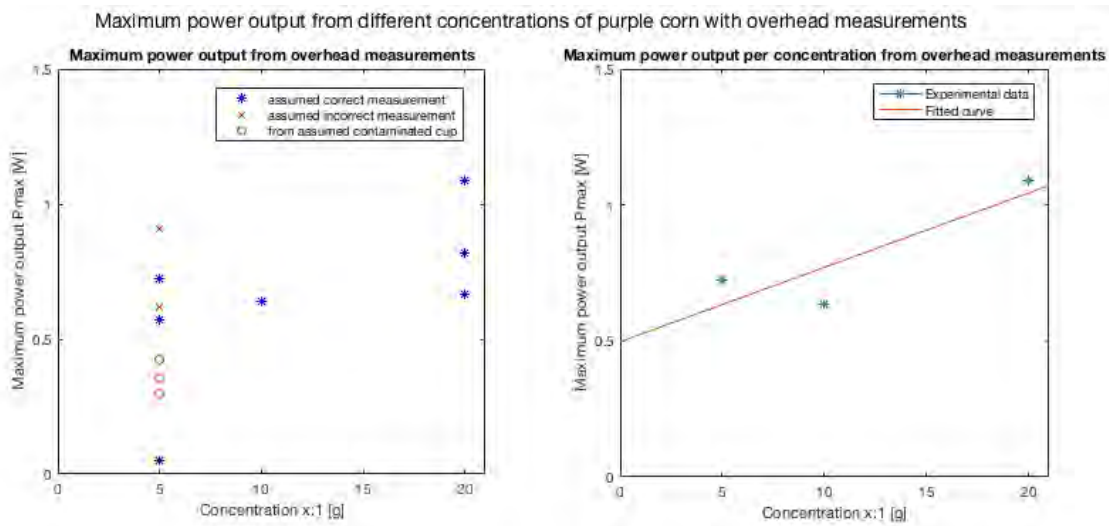


Figure 18. *(Left) Maximum power output for in relation to solvent concentration and (right) maximum power output per solvent concentration with fitted curve for overhead measurements on purple corn.*

The measurements from the LED lamp show that purple corn is not sensitive to changes of the amount of water in the solution and the measurements from the halogen lamp show the same. The fitted curve has the gradient 0.027 (Figure 18).

4.1.2 Sensitivity to Amount of Purple Corn

The concentrations with different amount of purple corn were studied to analyze if purple corn is sensitive to the amount of purple corn in the solution (Table 2).

Table 2. *The different concentrations of purple corn that were used to study sensitivity to the amount of purple corn in the solution*

Concentration	Purple Corn (g)	Water solution (g)	Ethanol (g)
5:1	15	3	25
5:1	20	4	25
5:1	25	5	25

Three different beakers were used with 15 g, 20 g and 25 g of purple corn in each respectively (Table 2). The current density-voltage curve and the current density-power output are illustrated for these three quantities of purple corn (Figure 19).

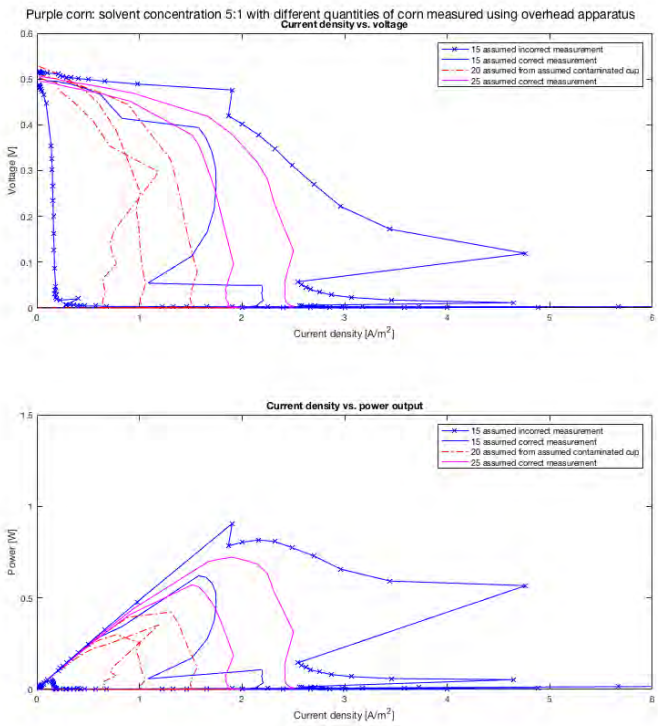
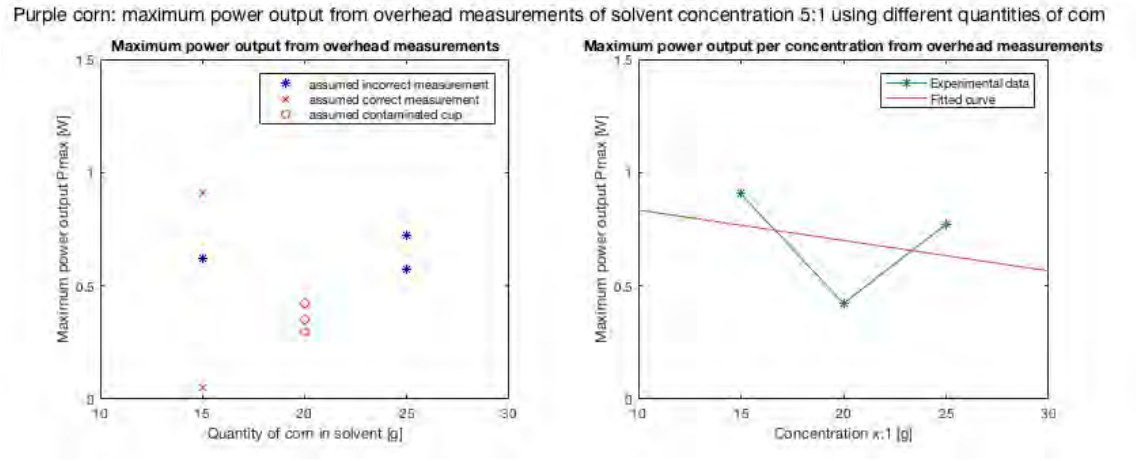


Figure 19. *(Above) Current density vs. voltage and (below) current density vs. power output for solvent concentration 5:1 with different quantities of purple corn, of using overhead measurements.*

Three handmade solar cells were in each cup. Two cells with 15 g of purple corn are assumed incorrect measurements (Figure 19). The relationship between the maximal output power and the different concentrations of amount of purple corn using a halogen lamo are illustrated (Figure 20).



m

Figure 20. *(Left) Solvent concentration 5:1 plotted for different quantities of purple corn in solvent and (right) maximum power output per quantity with fitted curve, of using overhead measurements.*

One solar cell with 15 g of the purple corn is assumed having incorrect measurements. All measurements from the cup having 20 g of purple corn are assumed having a contaminated cup. The purple corn does not seem to be sensitive to the amount of purple corn in the solution. The fitted curve has the gradient -0.013 (Figure 20).

4.2 Final Results with Optimal Solutions

The final results for purple corn and airampo are presented.

4.2.1 Purple corn

The optimal solution for purple corn decided to be 20:1 with 10 g of purple corn. The results of J-V measurements using both LED and halogen based measurement apparatuses are presented, with open circuit voltage V_{OC}, short circuit current density J_{SC} (compare to short circuit current, Equation 2), maximum power output P_{MAX}, fill factor and efficiency (Table 3).

Table 3. *Results of J-V measurements on machine and handmade purple corn cells*

Measurement type	V_{OC} [V]	J_{SC} [A/m2]	P_{MAX} [W]	Fill factor	Efficiency [%]
Machine made LED no. 1	454.0	7.158	2.425	0.7337	0.2425%
Machine made LED no. 2	532.0	8.667	2.328	0.7364	0.2328%
Handmade halogen no. 1	520.0	3.368	1.088	0.7261	0.1088%
Handmade halogen no. 2	520.0	3.034	0.8162	0.7233	0.08162%
Handmade halogen no. 3	503.0	2.526	0.6646	0.6258	0.06646%

The current density-voltage curve and the current density-power curve for the optimal solution are illustrated with handmade TiO_2 film of the handmade solar cells using halogen based measurement apparatus (Figure 21).

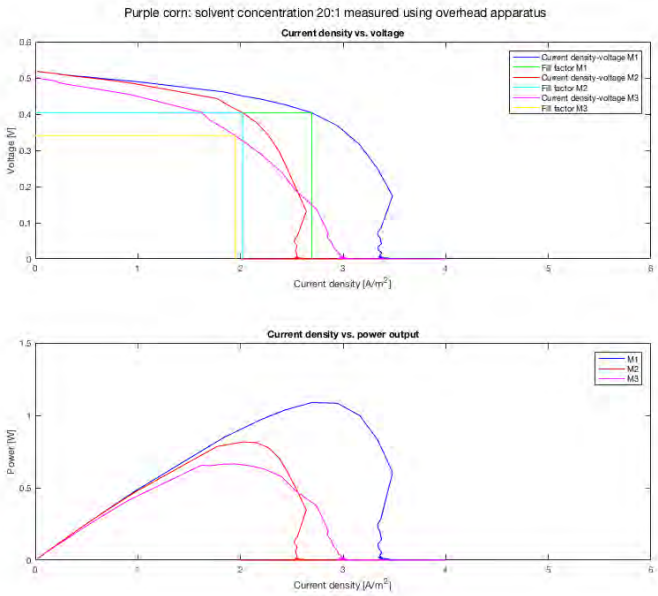


Figure 21. *(Above) current density-voltage curve and (below) current density-power curve for solvent concentration 20:1 for purple corn of using overhead measurements with handmade TiO_2 film for the solar cells.*

The curves have 0.53 V, 3.4 A/m2 and 1.2 W as the highest values with handmade TiO_2 film to the handmade solar cells using halogen measurements (Figure 21). The current density-voltage curve and the current density-power curve for the optimal solution using LED measurements with machine made FTO-glasses with TiO_2 film for handmade solar cells are presented (Figure 22).

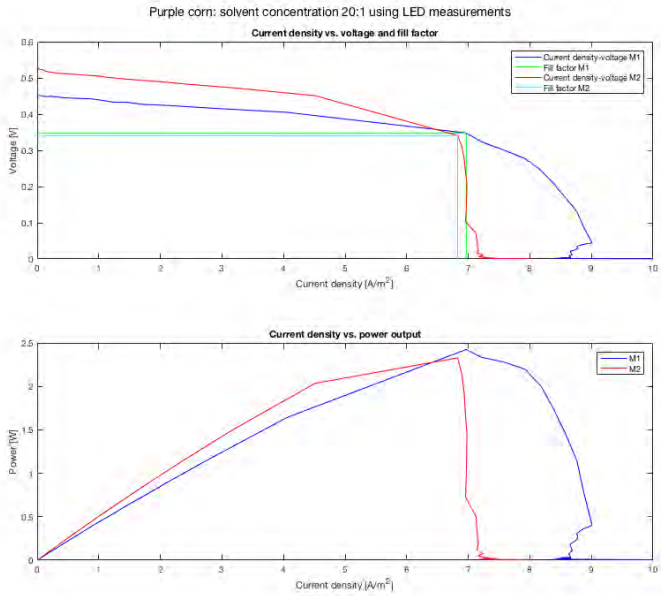


Figure 22. *(Above) current density-voltage curve with marked fill factors and (below) current density-power curve for solvent concentration 20:1 for purple corn of using LED measurements with machine made FTO-glasses with TiO_2 film.*

The curves with machine made FTO-glasses with TiO_2 film using the LED measurements have 0.53 V, 0.88 A/m2 and 2.4 * 10-4 as the highest values. The IPCE measurements for the optimal solution with machine made FTO-glasses with TiO_2film for the handmade solar cells are presented (Figure 23)

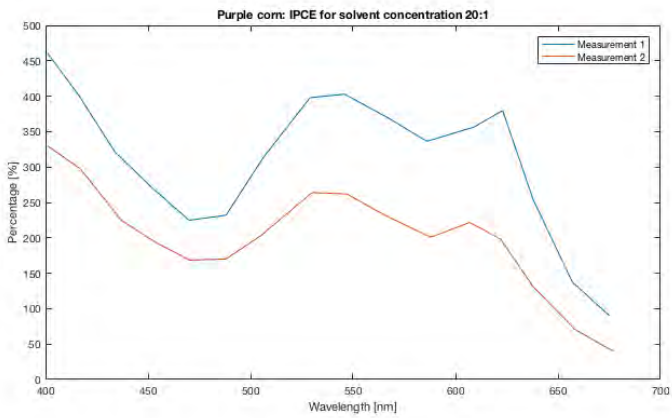


Figure 23. *IPCE measurements for purple corn using solvent concentration 20:1 with percentage plotted against wavelength in nanometer.*

The two curves are following a similar path for purple corn with two decreases around 480 nm and 590 nm and two peaks around 540 nm and 625 nm (Figure 23).

4.2.2 Airampo

The optimal solution for airampo is 1:1:5 with seeds from airampo, distilled water and ethanol. The results of J-V measurements on handmade cells using the LED based measurement apparatus are presented, with open circuit voltage V_{OC}, short circuit current density J_{SC}, maximum power output P_{MAX}, fill factor and efficiency (Table 4).

Table 4. *Results of J-V measurements on handmade airampo cells*

Measurement type	V_{OC} [V]	J_{SC} [A/m2]	P_{MAX} [W]	Fill factor	Efficiency [%]
LED no. 1	550.0	1.795	0.6127	0.7270	0.06127%
LED no. 2	477.0	1.949	0.5646	0.7246	0.05646%
LED no. 3	451.0	1.079	0.2711	0.6982	0.02711%

The current density-voltage curve and the current density-power curve for the optimal solution with machine made FTO-glasses with TiO_2 film for the handmade solar cells are illustrated (Figure 24).

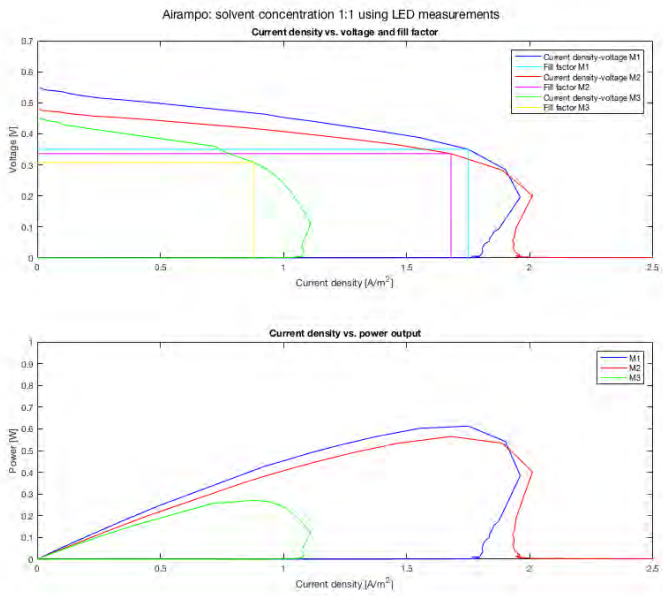


Figure 24. *(Above) current density-voltage curve with marked fill factors and (below) current density-power curve for solvent concentration 1:1 for airampo of using LED measurements.*

Three different solar cells were used and the maximal fill factor is 0.727 and maximal power is 550 (Figure 24).

4.3 Other Results

When IPCE measurements were done for airampo a equivocal result was obtained (Figure 25).

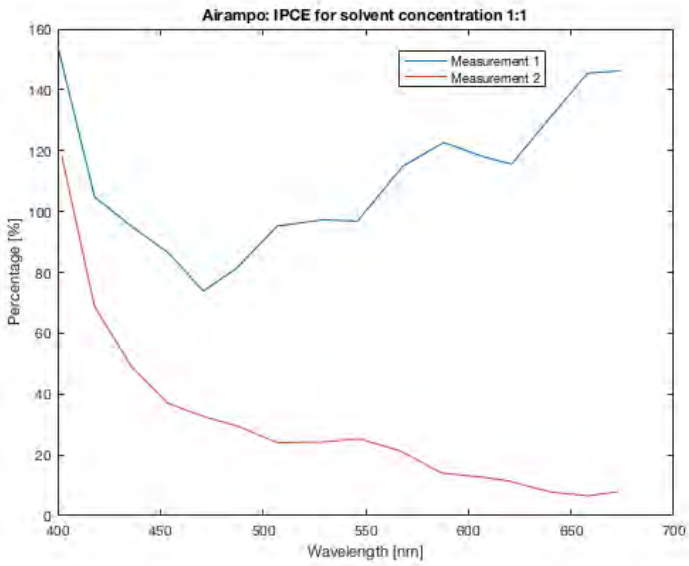


Figure 25. *IPCE measurements for airampo using solvent concentration 1:1 with percentage plotted against wavelength in nanometer.*

The two curves do not follow each other and show opposite behaviour for higher wavelengths (Figure 25).

5 Discussion

The analysis about how well purple corn and airampo are fitted to use as photosensitizers are discussed in this section.

5.1 Purple Corn

The results show that purple corn works as photosensitizer for DSSCs.

5.1.1 Finding Optimal Concentration

The optimal concentration for purple corn as a dye for DSSCs was decided to be 20:1 (20 g purple corn to 1 g of water). The results from LED versus halogen based measurements did not coincide. The LED based measurements showed a peak in efficiency in the concentration range 2:1 to 4:1, with a slight decline in efficiency for the higher concentration 10:1 (Figure 17). The halogen based measurements showed an opposite relationship, with the higher efficiency for concentration 20:1, compared to the lower concentration 5:1 and 10:1 (Figure 18). Since the spectrum of the halogen measurement apparatus is more similar to that of the sun with greater accuracy than the LED based ditto, the results from the halogen measurement were considered more accurate and 20:1 was chosen as the optimal solution for dye with purple corn.

Investigations into whether dyes with purple corn are sensitive to the quantity of purple corn and water in the solvent showed a negative relationship (Figure 19). Since few

data points were recorded and one of the batches of dye for the cells showed signes of being defect, further research would be needed to establish this. If the suspected defect dye batch was not taken into consideration, the relationship would be almost neutral, implying no sensitivity to quantity of seed and water for dyes with purple corn. The quantity 10 g of purple corn to 0.5 g of water was therefore chosen as the optimal quantity.

5.1.2 J-V Curve, Efficiency and Fill Factor

The obtained efficiencies, in the range 0.2328-0.2425% for LED based measurements and 0.06646-0.1088% for halogen based measurements, are very low. This could in part be due to low J_{SC}, in the range 7.158-8.667 A/m^2 for LED based measurements and 2.526-3.368 A/m^2 for halogen based measurements (Table 3), which in turn could be caused by evaporation of the cells' electrolyte since the cells are open.

The obtained V_{OC} for the DSSCs was also low, ranging 454.0-532.0 for all measurements (Table 3). This could be caused in part by the manufacturing technique of the cells, especially the doctor blading but also due to the reuse of FTO-glasses which reduces the glasses conductivity. Worth noting is that where both the efficiencies and J_{SC} differ significantly for LED versus halogen based measurements, the V_{OC} are similar. The fill factor for the measured DSSCs were mostly in the range 0.7233-0.7364, with one exception of 0.6646. The fill factors were without any significant difference between LED and halogen based measurements. Fill factors in this range are common for DSSCs.

5.1.3 IPCE

The IPCE measurements of dye concentration 20:1 of purple corn gave results that were strangely high (Figure 23). It is very unlikely that the IPCE for the measured cells actually exceeded 450%, and it is probable that measurement errors contributed to the high percentage. Considering the equation for IPCE 5, it seems likely that the J_{SC} was recorded as higher than its actual value, or the P_{IN} was recorded as lower than its actual value. This is discussed further in 5.4.9 *Improbable High IPCE Results*. The IPCE results for airampo dye also show improbable high results for short wavelenghths (Figure 25), but then contine to diverge (measurement 1) and converge to zero (measurement 2). The divergence and convergence to zero indicate faulty results, but the high IPCE for wavelengths around 400 nm shows that the measurement technique gives errors in the obtained data.

Apart from the unlikely high IPCE the curves has two coinciding dips, a major dip around 475 nm and smaller dip around 580 nm. The reduction of IPCE at 475 nm shows surface recombination in the DSSCs, and the dip around 580 nm could be an indicator of activity in the bulk, such as short diffusion lengths.

5.2 Airampo

The results show that airampo works as photosensitizer for DSSCs.

5.2.1 Optimal Concentration

The optimal concentration for the dye with airampo was chosen to be 1:1 (1 g airampo to 1 g of water), based on previous research from the Thin Films Group at UNI (Nazario

Ticse, 2017).

5.2.2 J-V Curve, Efficiency and Fill Factor

Two of three measured J-V curves for airampo are following a similar pattern, wheras the third curve shows significantly lower values (Figure 24). There is therefore reason to presume that the cell corresponding to the third, lower, curve was somehow faulty. This could be becuase of resued FTO-glasses or defects in the dye. The two measurements that are assumed correct has efficiencies of 0.06127 and 0.05646% respectivly, and the presumed faulty measurement 0.02711%. These efficiencies are all very low, and are caused by very low J_{SC}, with 1.795 and 1.949 A/m^2 for the presumed correct measurements, and 1.079 A/m^2 for the presumed faulty measurement. Just as in the case of purple corn, this could be caused by the cells being open and electrolyte evaoprating during the measurement process since DSSCs dyed with airampo also showed V_{OC}s that were in a low but acceptable range of 451.0-550.0 V (Table 4). The V_{OC} could, just as in the case of purple corn, be affected by the doctor blading of the cells as well as of the resuse of FTO-glasses, giving reduced conductivity. The fill factors for the measured DSSCs were in the range 0.6982-0.7270, and thus lie within the common range for DSSCs' fill factors.

5.2.3 IPCE

The IPCE measurements of DSSCs dyed with airampo showed faulty results (Figure 25). The two measurements did show a correlation in the range 400-450 nm, but did not in the range 450-700 nm. For higher wavelengths, measurement 1 seems to diverge to infinity and measurement 2 converges to zero. Despite of the IPCE being high for both of the measurements, this is probably a result of errors in the measurement technique as can be seen when comparing to the IPCE results of DSSCs dyed with purple corn. It is therefore safe to assume that the accurate IPCE of the two measurements are significantly lower than the obtained results.

Both the measurements show an intital decline, which ends at around 475 nm. This could indicate recombination effects in the cells' surface. For wavelengths higher than this, the curves seize to coincide. Both the divergence of measurement 1 and the convergence of measurement 2 are probable to be results of defective DSSCs, since the same measurement technique resulted in coinciding curves for purple corn. The voltage of measurement 1 increased significantly slower compared to other samples after the measurement apparatus was turned on and the cell exposed to light. This could be because of defect FTO-glasses used in the cell, as well as defect dying process. The converging curve of measurement 2 could be a result of reused FTO-glasses, unable to conduct properly for longer wavelengths with lower energies.

Due to time restrictions of the project, the measurements could not be redone.

5.3 Comparing Purple Corn and Airampo

If comparing LED based measurement results, DSSCs dyed with purple corn and DSSCs dyed with airampo had similar V_{OC} and fill factors, but DSSCs dyed with purple corn showed significantly higher J_{SC} and thus efficiency. Therefore the results suggest that purple corn is a preferred photosensitizer for DSSCs compared to airampo. Due to low

values even for DSSCs dyed with purple corn, it is unclear if the dye is fit for use outside a laboratory. Since the solar constant is higher than the intensities used for measurements slightly higher efficiencies could be expected, but the efficiencies remain very low. Because of suspected measurement errors the J-V measurements could have ended up lower than their actual values, and further research on both dyes are therefore suggested.

5.4 Sources of Errors in Manufacturing and Measurements

There is reason to believe that error sources in the manufacturing process and measurement equipment affected the measurements.

5.4.1 Washing of FTO-glasses

The FTO-glasses used for conduction in the DSSCs were reused and cleaned each time the cells were manufactured. The cleaning process impacted the FTO-glasses conduction ability, potentially reducing their conductivity for each wash. The reduction in conductivity was not of the same magnitude for each FTO-glass for every cleaning, meaning some cells went through the process with a maintained conductivity and some did not. If a glass had lost all conductivity this was noted and the glass discarded since this made DSSCs non-functioning during measurements, but otherwise it was not possible to know if the glass had reduced conductivity due to cleaning and how this affected the measurements on the finished DSSCs. There is therefore reason to believe that the later measurements - those of the optimal solutions - can have been lower due to lessened conductivity of the FTO-glasses compared to earlier measurements.

5.4.2 Different Results for Different Batches of Dye

The performance of DSSCs seem to be affected by which batch of dye they were dyed in, even if the dye and concentration were the same. The first batch of purple corn using concentration 4:1 for finding the optimal concentration show significantly lower performance compared to the second batch of the same concentration (Figure 14). When investigating if purple corn dye was amount sensitive, the cells dyed in dyes with 20 g purple corn had a lower performance compared to those dyed in dyes with 15 g and 25 g purple corn (Figure 19). This could be caused by a fault in the dye batch, since dyes with purple corn does not seem to have amount sensitive behavior seeing that the 15 g and 25 g purple corn dyes performed similarly.

5.4.3 Unevenness in TiO_2 Film Caused by Doctor Blading

Doctor blading can cause unevenness in the TiO_2 film, which can affect the performance of the finished DSSCs. Scratches and impurities can also be introduced to the film through doctor blading, further increasing the risk of affecting the performance of the DSSCs.

5.4.4 Unknown Manufacturing Technique for Machine Made Cells

The manufacturing technique for the machine made cells is unknown, other than that they were manufactured at Uppsala University using a manufacturing machine. This gives that they can have defects affecting the measurement results in unknown ways.

5.4.5 Spectrum and Intensity of J-V Measurements

The spectrum of the LED based and the halogen based measurement apparatuses are unknown, and it is unlikely that they match the solar spectrum (Figure 2), since the light generation processes differ greatly. This will affect the measurements, seeing that the DSSCs might absorb the solar light to a greater or lesser extent than the investigated spectrum. The intensity of both the measurement apparatuses is 1000 W/m^2, where the solar constant is 1370 W/m^2. This means that the DSSCs will produce higher current densities and voltages when using solar measurements compared to the used measurements apparatuses, seeing the higher input power per area unit.

5.4.6 Spikes in J-V Curves Caused by Adjustable Resistance Box

Several DSSCs showed spikes in J-V measurements (Figure 13, Figure 19), which all where in the 899-699 Ω and 99-79 Ω ranges. This implies that the adjustable resistance box used for measurements have some sort of defect in these ranges, rather than this being accurate measurements. Because of this, the data points in these spikes are seen as faulty result.

5.4.7 Evaporation of Electrolyte

Since the DSSCs measured where open and paper was used to keep the electrolyte in place, evaporation of electrolyte during the measurement process is probable. Because of this, there is reason to believe that the short circuit current density J_{SC} from the measurements is lower than it would be if the electrolyte did not evaporate during the measurements.

5.4.8 Usage of Two J-V Measurement Apparatuses

The usage of two different measurement apparatuses for J-V measurements was due to practicalities, and resulted in measurement data not being able to be translated directly between the apparatuses. This caused difficulties in evaluation of the obtained data. The obtained V_{OC} were of similar size, but the J_{SC} differed considerably (Table 3) between the measurement apparatuses. Since a LED spectrum has steep spikes for certain wavelengths of light, wheras a halogen lamp has a continous spectrum for visable wavelengths of light, the different ranges of J_{SC} for the two measurement apparatuses could be spectrum related. The halogen based measurements were assessed as more accurate, since previous experiments had showed its spectrum to be closer to the Sun's spectrum.

5.4.9 Improbable High IPCE Results

The results of the IPCE measurements came out suspiciously high. The measurements on DSSCs dyed with purple corn exceeded 450%, where DSSCs can generally be expected to have an IPCE under 100%. The high values could be caused by light pollution from the room. This would give higher J_{SC}, measured by the voltmeter, wheras the input power read from the PC would be lower than the actual provided power (Equation 5). Regardless of input power, the DSSCs' IPCE would still have reductions at the same wavelengths. Because of this, the reductions in teh measurements remain valid despite the improbable high IPCE results.

5.5 Continued Work

Several aspects of the project's results could be subject of continued work.

5.5.1 Optimal Concentration for Dye with Purple Corn

Because of the time restriction of the project, further investigations into the optimal solution for purple corn could not be conducted. Since measurements showed an increased efficiency for increased concentration, concentrations higher than 20:1 could be investigated. More measurements on lower concentrations in the range 2:1 to 4:1 could also be done, to better establish whether a higher concentration of purple corn in the dye gives higher efficiency of the DSSC.

5.5.2 Polymer Paper

Instead of using paper to keep the electrolyte in place on the DSSCs, polymer paper could be used. Polymer paper is placed around the DSSC's TiO_2 film, and the cell is then exposed to heat while the FTO-glass and the counter electrode are pressed together, causing the polymer paper to work as a glue between the two. This prevents the electrolyte from evaporating during measurements or employment.

5.5.3 Closed Cells

Open cells makes for less stable cells than closed dittos, since electrolyte and dye can evaporate or be contaminated by the surroundings. Therefore further measurements on closed cells would be advisable, since closed cells have potential to be more stable and produce higher measurement values.

5.5.4 Electrolyte

Improvements of the electrolyte could be made. The used electrolyte could for instance have 0.5 M of 4-tertbutylpyridine added for increased efficiency (Quintana, 2017).

5.5.5 Other Measurement Devices

Since it is not probable that J-V measurements apparatuses used has the same spectrum as the sun, and it is known that the intensity differs, it would be advisable to do measurements with a solar simulator as well. Measurements using a solar simulator would give an improved image of how the DSSCs would behave if employed in sunlight.

5.5.6 Further Measurements

As a complement to measuring J-V ratio and IPCE, further measurements could be done to analyze the DSSCs behavior. Recommended measurements are FTIR for dye properties, measurements in cell stability, and electron lifetime to understand recombination effects.

6 Conclusions

Both purple corn and airampo work as photosensitizers for DSSCs. With the used method and solvent DSSCs dyed with purple corn get higher results than DSSCs dyed with airampo for efficiency, short-circuit current density and fill factor, but not for open-circuit voltage. This implies that purple corn is better suited as a photosensitizer for DSSCs of the two natural Peruvian dyes.

The optimal solution for purple corn as a dye for DSSCs is 20:1, with 20 g purple corn to 1 g water, along with 25 g ethanol. Dyes with purple corn showed a negative relationship regarding quantity of seed and water in the solvent in relation to efficiency.

The fill factors for DSSCs dyed with the two dyes are within the range of what can be expected from DSSCs, but the rest of the measured values are not. Current-density measurement results were low or very low, and IPCE suspiciously high. This could in part be due to the respective dyes unsuitability as a photosensitizer for DSSCs, but also to several potential measurement errors resulting in inacurate measurement data. Further research into purple corn and airampo as photosensitizer for DSSCs could confirm or deny this, and would be desirable before any larger scale of use of either dye.

The open-circuit voltages were low for both dyes, and the short-circuit current densities were very low. This resulted in very low efficiencies. The current densities and efficiencies were particularily low for DSSCs dyed with airampo, where DSSCs dyed with purple corn gave more than four times the short-circuit current density compared to the same dyed with airampo. The open-circuit voltages were in the same range for both dyes, with airampo producing slightly higher results at max. Also the fill factors for the two dyes were in the same range.

The results of the IPCE measurements of DSSCs dyed with purple corn were suspiciously high. This was most likely due to measurement errors. They showed surface recombination in the cells, as well as indications of short diffusion lengths in the bulk. The IPCE measurements of airampo came out unclear, and could not be interpereted.

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Appendices

A Measurement Apparatuses

Photographs of the measurement apparatuses used for the project are presented.

A photograph of the LED based J-V measurement apparatus can be seen (Figure 26).

Figure 26. *Photograph of measurement apparatus for J-V measurements of DSSCs using a LED as a light source, at the Faculty of Science, Universidad Nacional de Ingeniería.*

A photograph of the halogen based J-V measurement apparatus can be seen (Figure 27).

A photograph of the IPCE measurement apparatus can be seen (Figure 28).

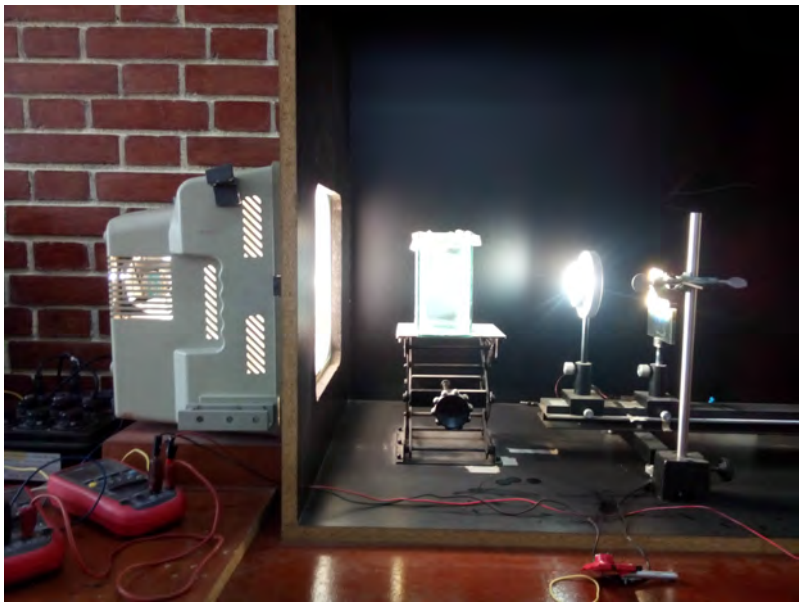

Figure 27. *Photograph of measurement apparatus for J-V measurements of DSSCs using an oat the Faculty of Science, Universidad Nacional de Ingeniería.*

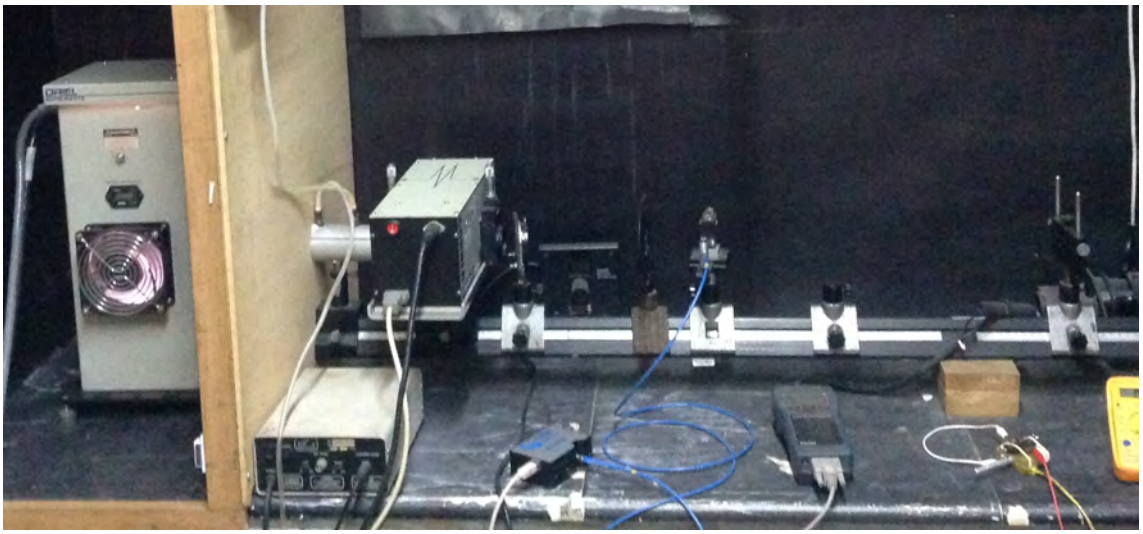

Figure 28. *Photograph of measurement apparatus for ICPE measurements of DSSCs, at the Faculty of Science, Universidad Nacional de Ingeniería.*