

CHAPTER VI
DEVISE FORMULATION
AND
CHARACTERIZATION
FABRICATION AND I-V CHARACTERISTICS
RESULTS AND DISCUSSION

DEWISE FABRICATION

The figure below shows the devise architecture:

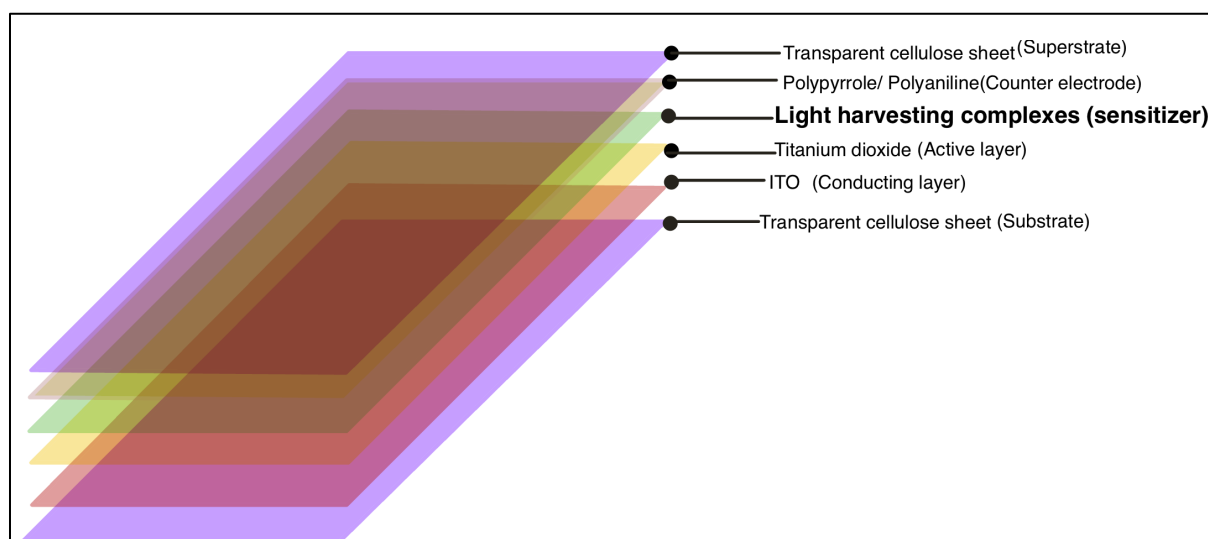


Figure 47: Devise Architecture

FABRICATION PROCESS

The fabrication of the device involved the following steps.

Sheet A

A1. The cellulose sheet made from plant residues, to be used as substrate for the working electrode was cleaned and coated with ITO using RF magnetron sputtering.

A2. The ITO coated cellulose sheet was washed thoroughly with water and then with acetone followed by ethyl cellulose to eliminate the contaminants.

A3. A TiO_2 ink was formulated by dissolving 2 grams of TiO_2 in an ethyl cellulose solution containing 5 ml Isopropyl alcohol and 2 grams of ethyl cellulose. The mixture was vigorously stirred to form a TiO_2 paste. 2 ml of Terpeneol was added to this paste to achieve a proper colloidal solution with the desired viscosity for spin coating.

A4. This ink was then spin-coated onto the cellulose sheet at a speed of 5000 rpm for 1 minute and allowed to dry at room temperature.

A5. The dried films were then dipped in a solution containing light-harvesting complexes (LHCs) for 4 hours to ensure sufficient absorption of complexes

Sheet B

B1. Another sheet of cellulose, to be used as counter electrode, was cleaned and coated with the synthesized polymer using the spin coating technique.

B2. An electrolyte solution was prepared by first dissolving 0.127 grams of Iodine (I_2) in 10 ml of ethylene glycol. Subsequently, 0.83 grams of Potassium Iodide (**KI**) were added to the solution and stirred for a few minutes.

B3. A drop of this electrolyte solution was then placed on the polymer electrode surface.

GENERAL WORKING MECHANISM OF DEVICE

The device uses a photosensitive dye to absorb photons and generate an electric current. TiO_2 and polymer electrodes are commonly used to serve as the electron transport layer and hole transport layer, respectively.

1. Absorption of light

The first step is the absorption of light by the LHC constituent molecules, which serve as the dye. These dye molecules are typically organic molecules that contain a chromophore, which is responsible for absorbing light. The absorption of light by the dye molecules leads to the excitation of an electron to a higher energy level.

2. Injection of electrons into the active layer

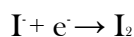
The next step is the injection of electrons from the excited dye molecules into the active layer, which is the TiO_2 layer. The TiO_2 layer serves as the electron transport layer. When the excited electrons are injected into the TiO_2 layer, they are free to move through the material.

3. Transport of Electrons through the TiO_2 Layer

Once the electrons are injected into the TiO_2 layer, they are transported through the material by hopping from one TiO_2 molecule to another. The TiO_2 layer is a porous material that provides a large surface area for the electrons to move through. This makes it an efficient material for transporting electrons.

4. Reduction of Iodide ions at the TiO_2 - Polymer interface

The excited electrons that are transported through the TiO_2 layer reduce the iodide (I^-) ions present in the electrolyte, to iodine molecules (I_2) at the interface between the TiO_2 layer and the polymer electrode. This reaction can be facilitated by a catalyst such as platinum or palladium.



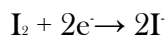
5. Diffusion of Iodine molecules into the polymer electrode

The iodine molecules that are formed at the TiO_2 - polymer interface diffuse into the polymer electrode, which serves as the hole transport layer in DSSCs. The polymer electrode

is made of a conductive polymer such as polyaniline, polypyrrole or poly (3, 4-ethylenedioxythiophene) (PEDOT).

6. Oxidation of Iodine molecules at the polymer electrode

At the polymer electrode, the iodine molecules are oxidized back to iodide ions. This reaction is facilitated by a redox couple such as the tri-iodide ion (I_3^-), which is present in the electrolyte.



7. Regeneration of dye molecules

The oxidized dye molecules that are formed during the injection of electrons into the TiO_2 layer are regenerated by the reduction of the redox couple at the polymer electrode. This reaction completes the cycle and allows the device to continue generating electricity.

I –V CHARACTERISTICS OF FABRICATED DEVICES

The performance i.e. efficiency of devices was evaluated by measuring the short circuit current (I_{SC}) and open circuit voltage (V_{OC}) under AM 1.5 conditions.

Short Circuit Current (I_{SC}): The short circuit current corresponds to short circuit condition and it is calculated when the voltage is 0. For an ideal cell, I_{SC} is the maximum current or total current produced in the solar cell by photon excitation.

Open Circuit Voltage (V_{OC}): Open circuit voltage occurs when there is no current passing through the cell. V_{OC} is also the maximum voltage difference across the cell.

Fill Factor (FF): The fill factor is the ratio of the maximum obtainable power to theoretical power. When the fill factor value is close to 1, it can be considered as an efficient cell. It is given by the following relation.

$$FF = \frac{J_{max} * V_{max}}{J_{sc} * V_{oc}}$$

Power Conversion Efficiency (η): The power conversion efficiency of the cells was calculated by the relation given below.

$$\eta = \frac{J_{sc} * V_{oc} * FF}{P_{in}}$$

Where P_{in} = Input power (power of light source)

The I-V characteristic curves are presented below in terms of sets. The constitution of a set is

LHC from one particular plant specie

with

1. Counter electrode layer of Polypyrrole synthesized by Method 1 [PP1]
2. Counter electrode layer of Polypyrrole synthesized by Method 2 [PP2]
3. Counter electrode layer of Polyaniline synthesized by Method 1 [PA1]
4. Counter electrode layer of Polyaniline synthesized by Method 2 [PA2]

For each electrode, the cell was investigated for its efficiency for consecutive three weeks (0, 1, 2 and 3 weeks – total 4 durations). With LHC's from 20 plant species, 80 sets of curves have been presented.

The I-V characteristic of each cell has been presented separately to make it distinct and avoid any overlap. The values of J_{sc} , V_{oc} , Fill Factor and efficiency have been given in the table accompanying the curves.

Plant Specie:

Spinach

Electrode:

PP1

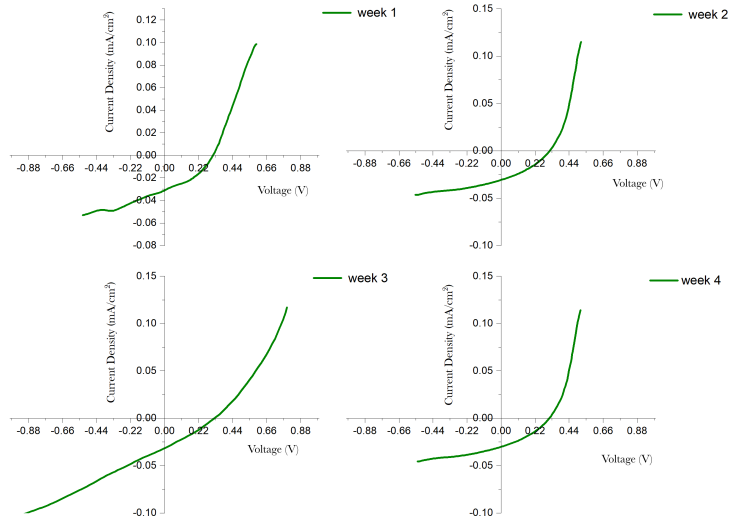


Figure 48

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	31	314	0.47	4.6
7	30.9	313.8	0.46	4.5
14	30.7	313.6	0.46	4.4
21	30.5	313.9	0.44	4.2

Plant Specie:

Spinach

Electrode:

PP2

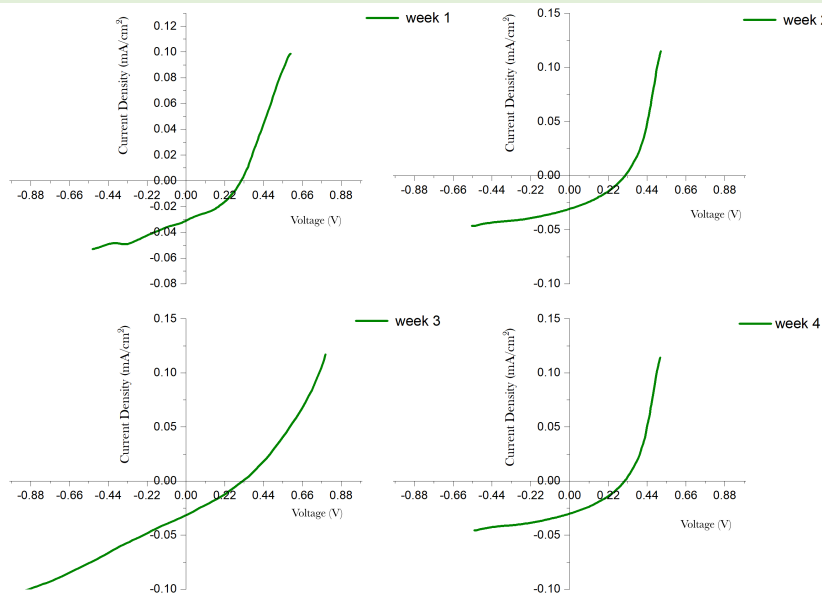


Figure 49

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	38	423	0.32	5.1
7	37.8	422.9	0.31	5
14	37.6	422.7	0.31	4.9
21	37.4	422.5	0.30	4.7

Plant Specie:

Spinach

Electrode:

PA1

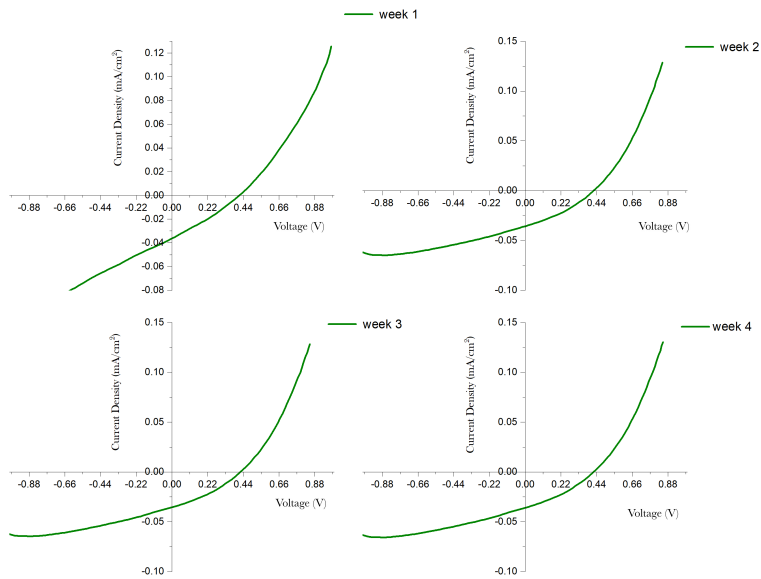


Figure 50

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	36	423	0.37	5.6
7	35.8	422.8	0.36	5.4
14	35.7	422.6	0.35	5.3
21	35.5	422.4	0.37	5.5

Plant Specie:

Spinach

Electrode:

PA2

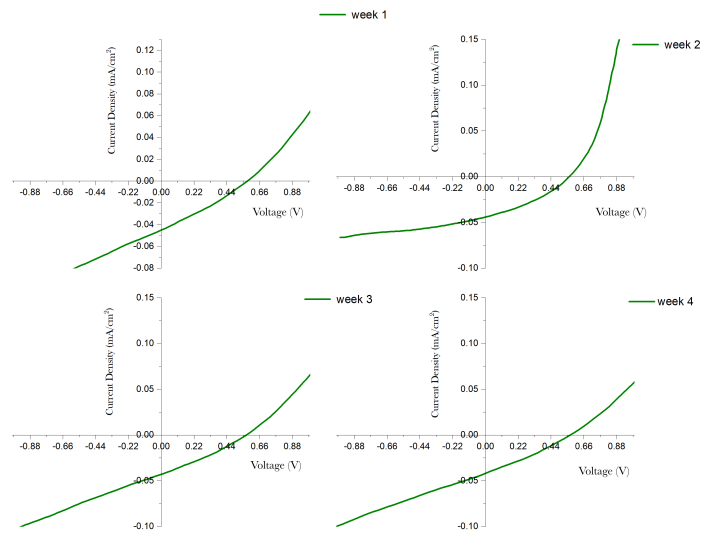


Figure 51

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	44	563	0.20	5
7	43.9	562.9	0.19	4.8
14	43.6	562.7	0.19	4.7
21	43.4	562.5	0.19	4.6

Plant Specie: Dill Leaves Electrode: PP1

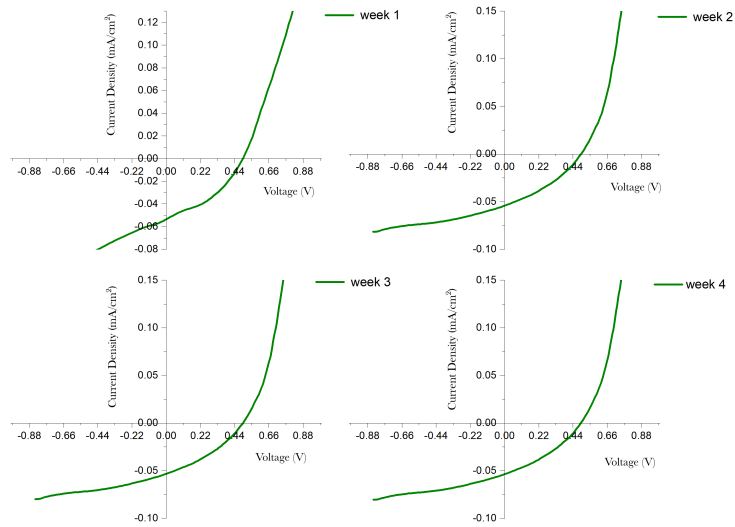


Figure 52

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	54	494	0.08	2.1
7	53.8	493.9	0.08	2
14	53.7	493.7	0.07	1.9
21	53.4	493.5	0.06	1.7

Plant Specie: Dill Leaves Electrode: PP2

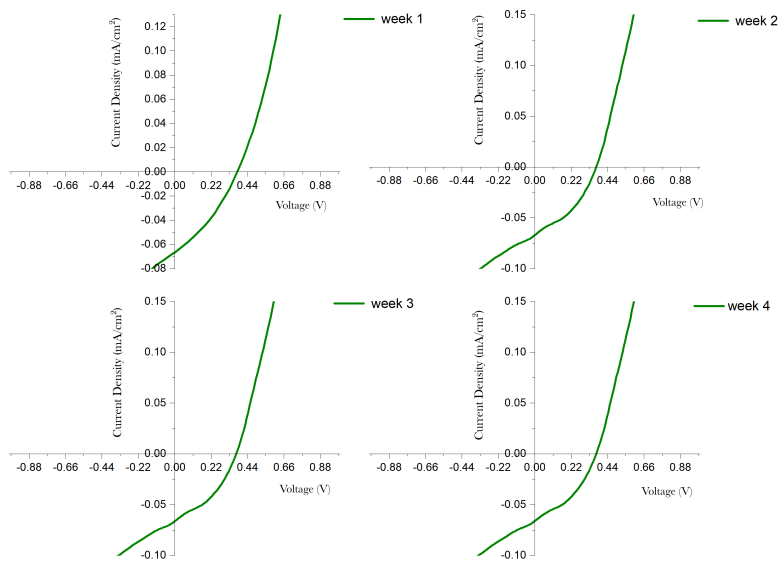


Figure 53

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	67	373	0.12	2.9
7	66.9	372.9	0.11	2.8
14	66.6	372.6	0.10	2.6
21	66.5	372.4	0.10	2.5

Plant Specie: **Dill Leaves** Electrode: **PA1**

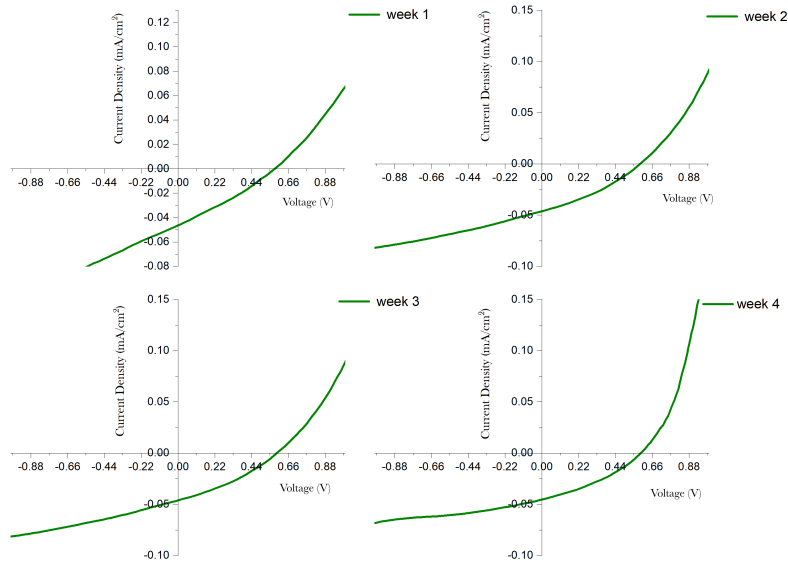


Figure 54

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	46	592	0.12	3.4
7	45.8	591.8	0.12	3.3
14	45.7	591.7	0.11	3.1
21	45.4	591.5	0.11	2.9

Plant Specie: **Dill Leaves** Electrode: **PA2**

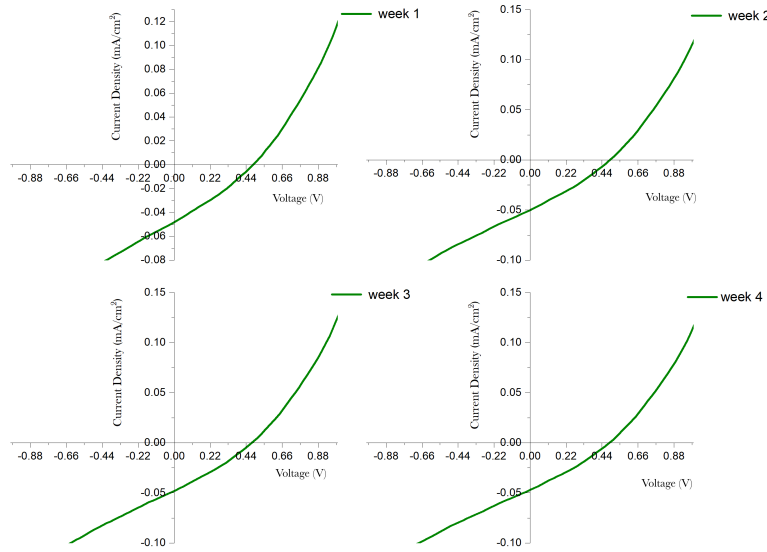


Figure 55

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	48	483	0.12	2.8
7	47.8	482.9	0.12	2.7
14	47.6	482.6	0.11	2.6
21	47.5	482.4	0.10	2.3

Plant Specie: Aegle Marmelos Electrode: PP1

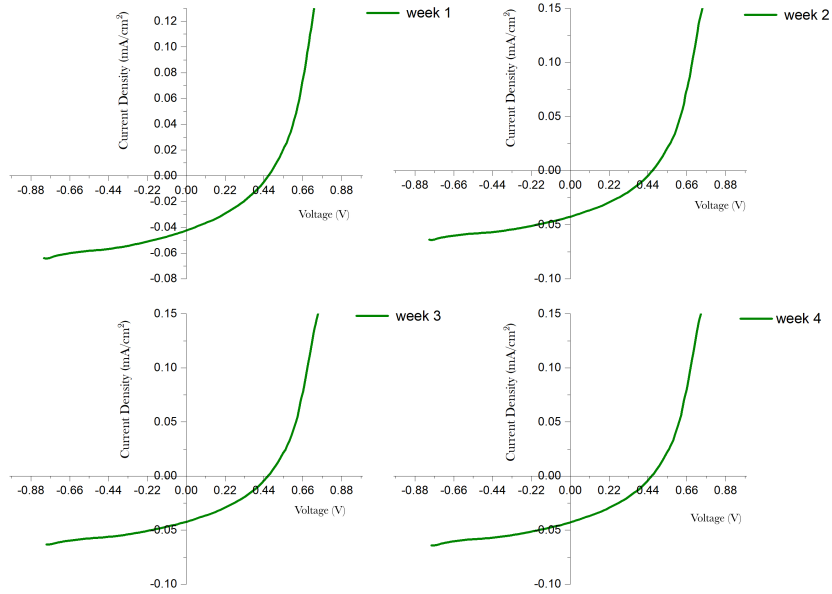


Figure 56

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	43	465	0.12	2.3
7	42.9	464.8	0.11	2.2
14	42.6	464.6	0.11	2.1
21	42.5	464.4	0.10	1.9

Plant Specie: Aegle Marmelos Electrode: PP2

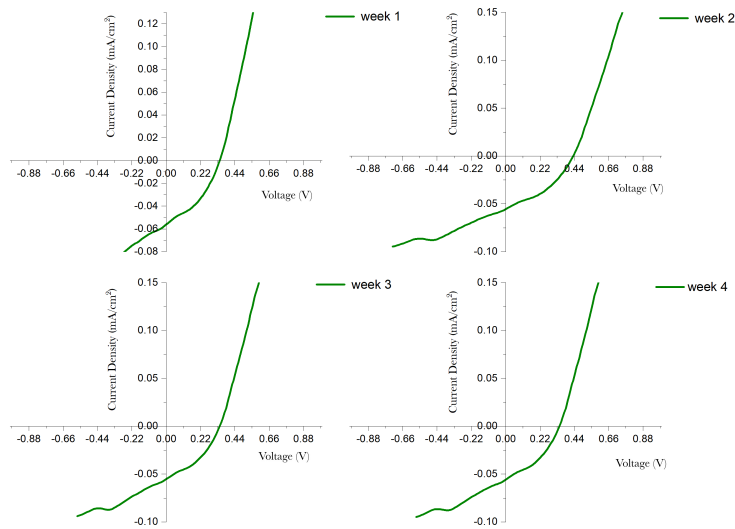


Figure 57

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	56	344	0.15	2.8
7	55.8	343.9	0.14	2.7
14	55.7	343.7	0.13	2.5
21	55.4	343.5	0.12	2.3

Plant Specie: Aegle Marmelos Electrode: PA1

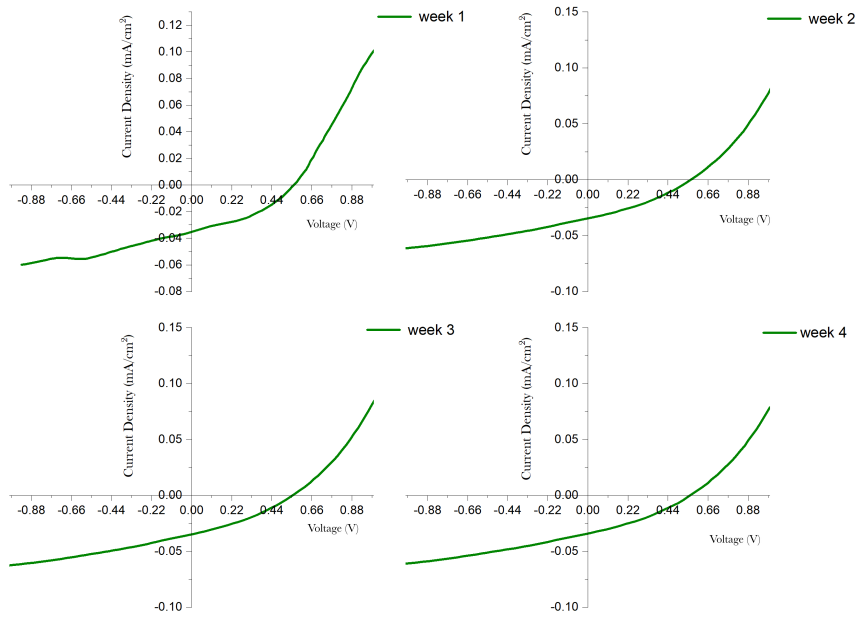


Figure 58

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	35	563	0.16	3.2
7	34.9	562.9	0.15	3
14	34.6	562.6	0.14	2.7
21	34.5	562.4	0.14	2.8

Plant Specie: Aegle Marmelos Electrode: PA2

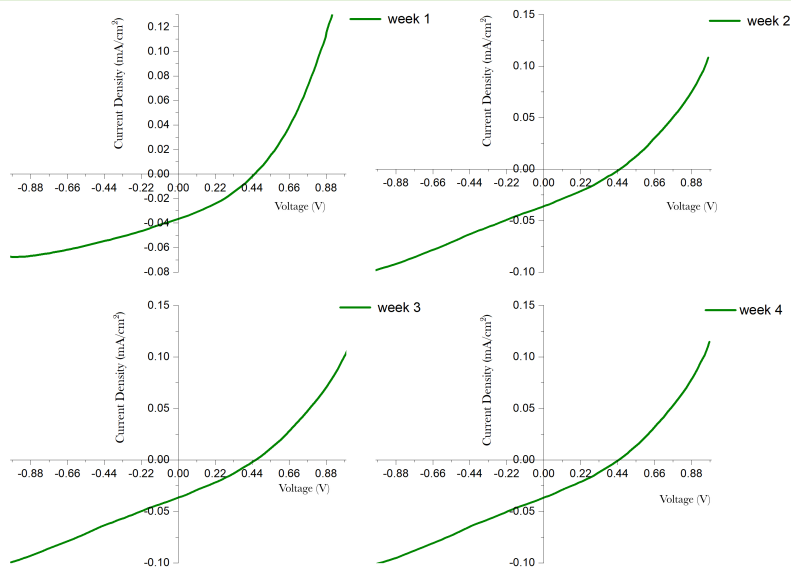


Figure 59

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	37	454	0.18	3.1
7	36.8	453.8	0.18	3
14	36.4	453.7	0.17	2.8
21	36.4	453.5	0.16	2.6

Plant Specie: Coriander Electrode: PP1

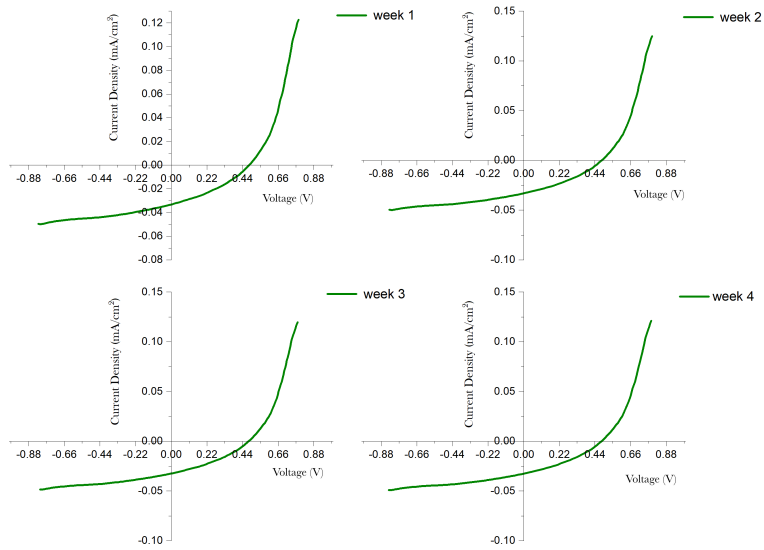


Figure 60

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	33	482	0.20	3.2
7	32.9	481.9	0.20	3.1
14	32.6	481.6	0.19	3
21	32.5	481.4	0.17	2.7

Plant Specie: Coriander Electrode: PP2

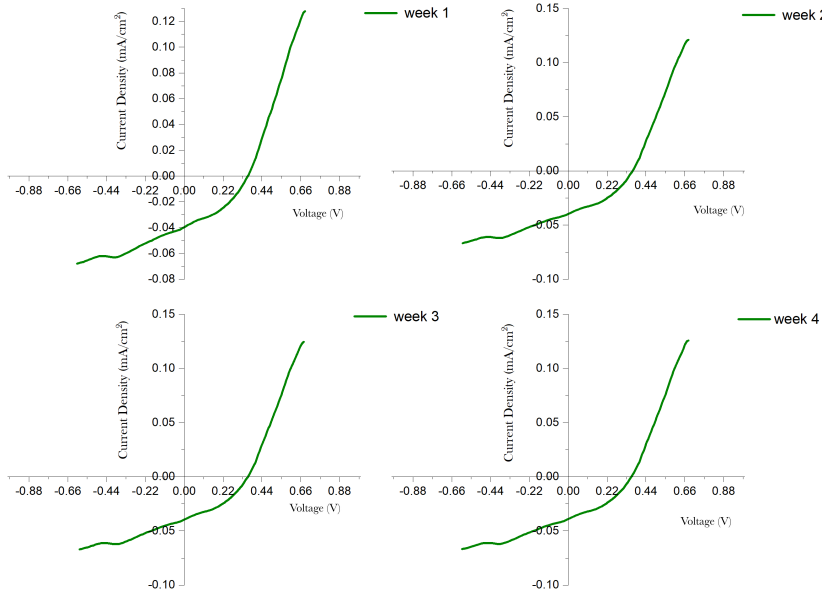


Figure 61

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	40	361	0.23	3.3
7	39.9	360.9	0.22	3.2
14	39.7	360.7	0.22	3.1
21	39.4	360.5	0.21	3

Plant Specie:

Coriander

Electrode:

PA1

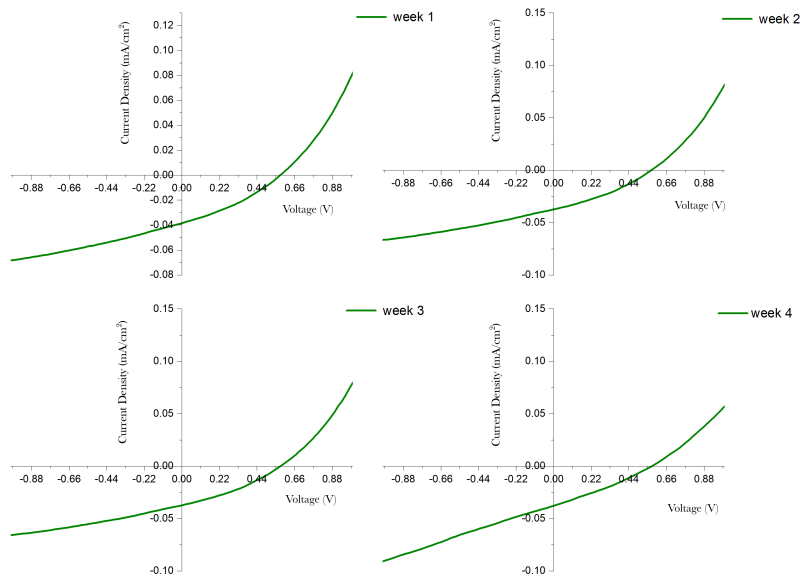


Figure 62

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	38	580	0.13	2.8
7	37.8	579.8	0.12	2.7
14	34.6	579.6	0.12	2.4
21	37.5	579.4	0.11	2.3

Plant Specie:

Coriander

Electrode:

PA2

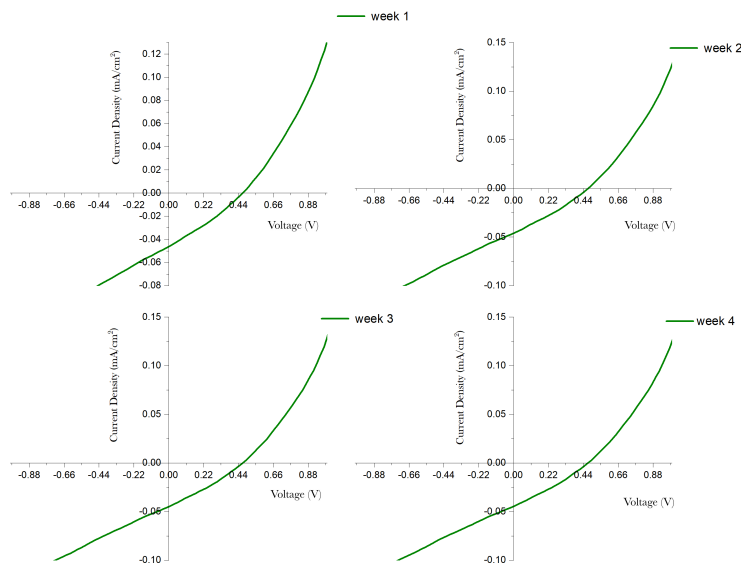


Figure 63

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	46	471	0.12	2.7
7	45.8	470.9	0.12	2.6
14	45.7	470.7	0.12	2.5
21	45.4	470.5	0.11	2.3

Plant Specie: Basil Electrode: PP1

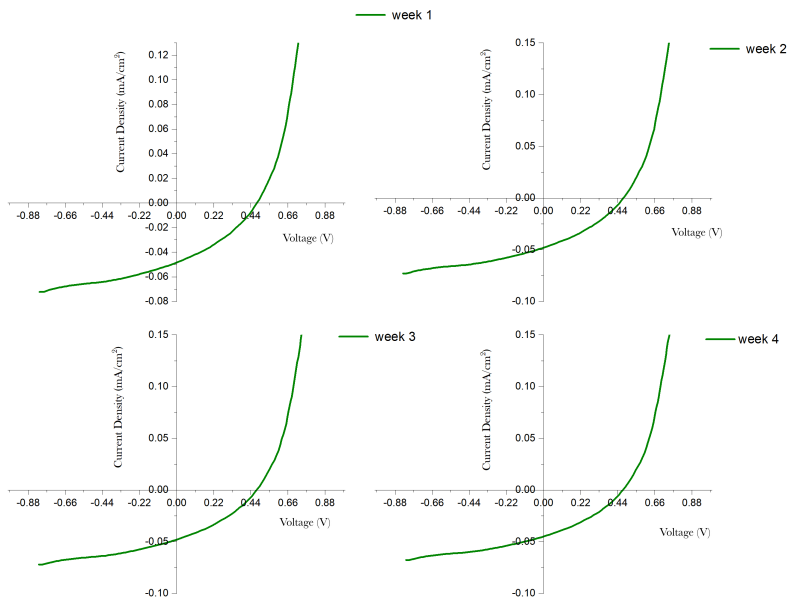


Figure 64

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	48	475	0.30	6.9
7	47.9	474.8	0.30	6.8
14	47.6	474.6	0.29	6.6
21	47.4	474.5	0.28	6.4

Plant Specie: Basil Electrode: PP2

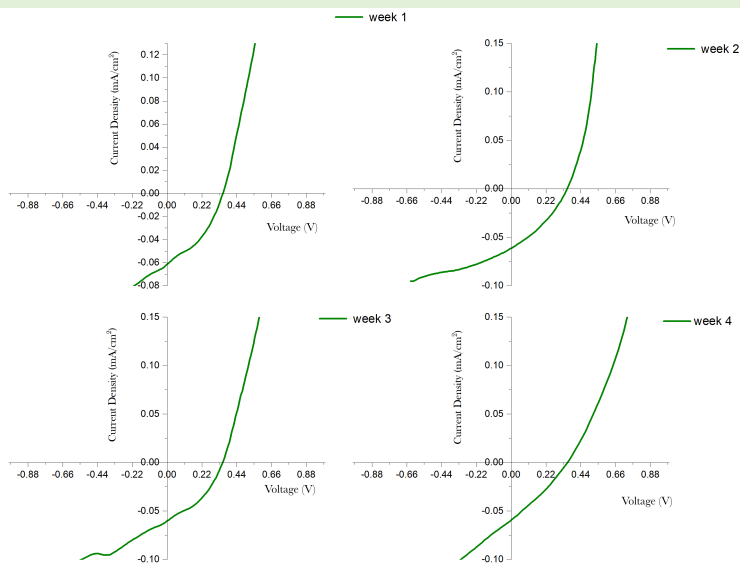


Figure 65

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	61	354	0.33	7.2
7	60.8	353.9	0.33	7.1
14	60.7	353.7	0.33	7
21	60.5	353.4	0.32	6.8

Plant Specie:

Basil

Electrode:

PA1

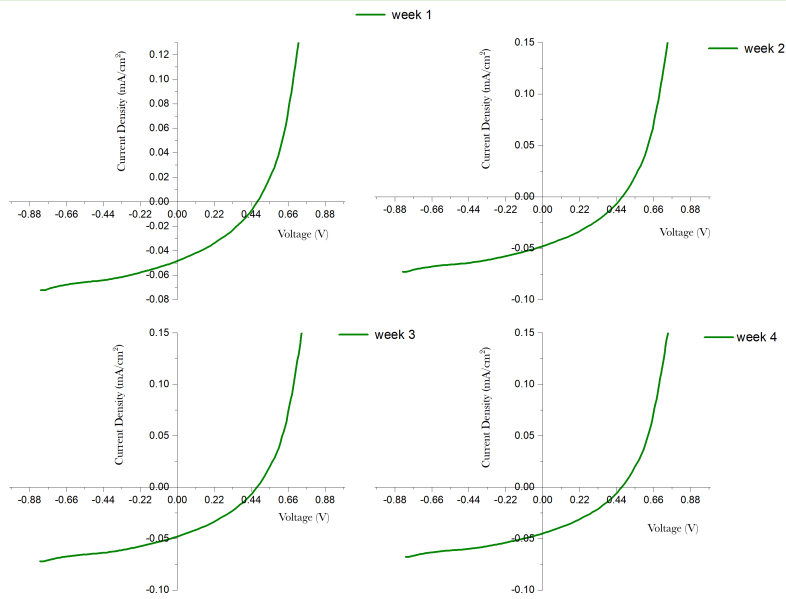


Figure 66

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	40	573	0.25	5.7
7	39.8	572.9	0.25	5.6
14	39.7	572.6	0.24	5.4
21	39.4	572.5	0.23	5.2

Plant Specie:

Basil

Electrode:

PA2

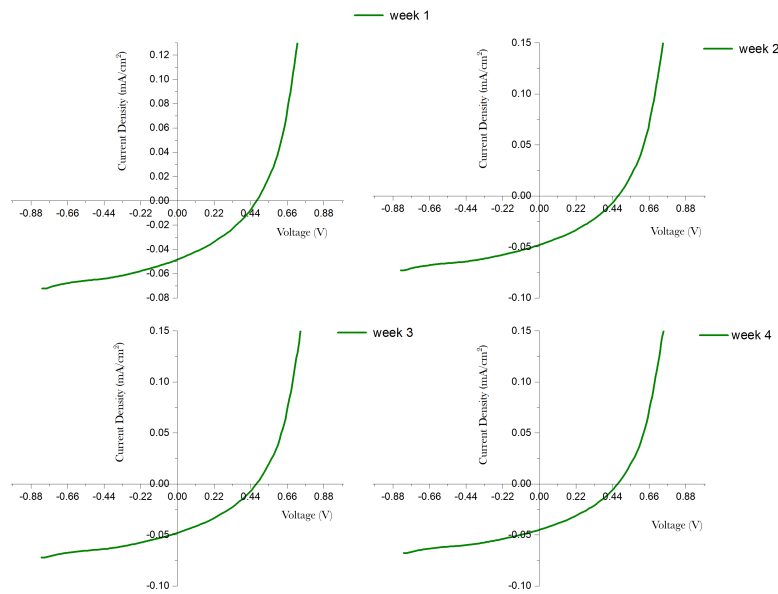


Figure 67

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	42	464	0.31	6.1
7	41.9	463.8	0.31	6
14	41.6	463.7	0.31	5.9
21	41.3	464.4	0.30	5.8

Plant Specie: Stramonium Electrode: PP1

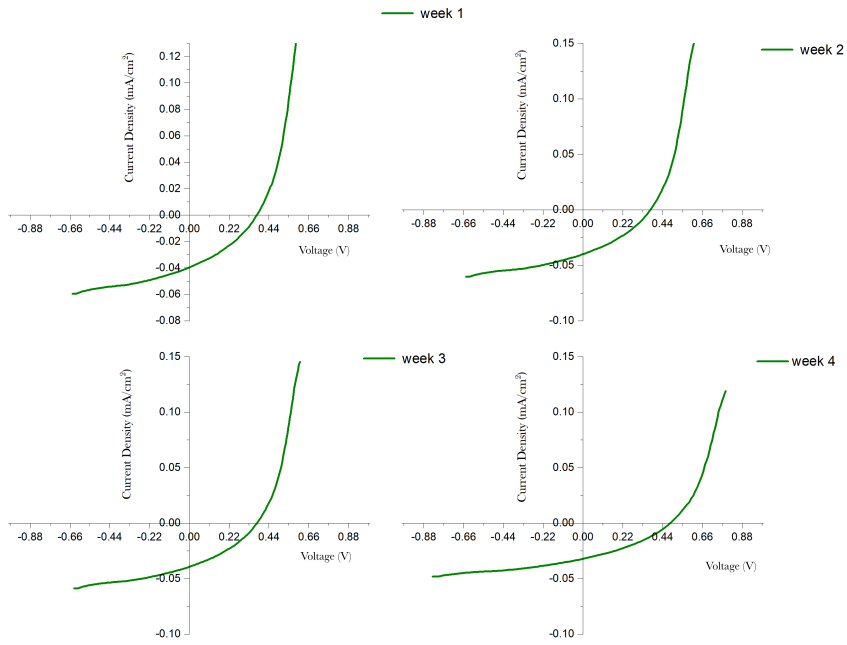


Figure 68

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	40	375	0.37	5.5
7	39.8	374.9	0.36	5.4
14	39.6	374.6	0.35	5.2
21	39.5	374.4	0.34	5

Plant Specie: Stramonium Electrode: PP2

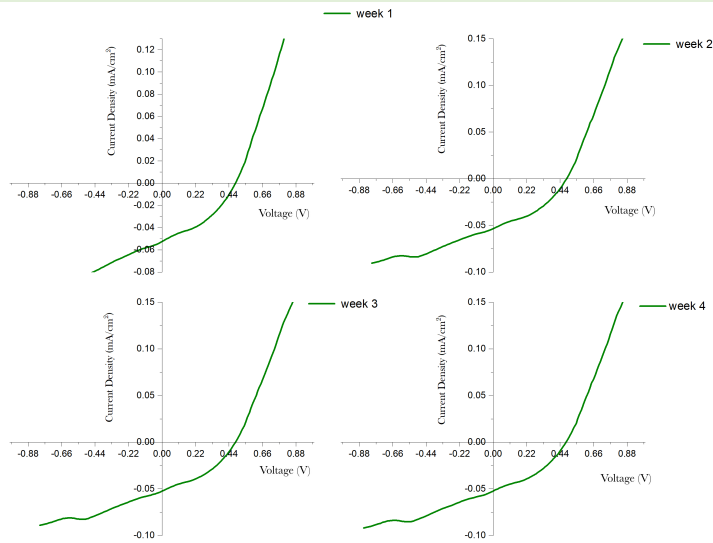


Figure 69

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	53	484	0.25	6.4
7	52.9	483.8	0.24	6.2
14	52.7	483.7	0.24	6.1
21	52.4	483.5	0.23	5.9

Plant Specie: Stramonium Electrode: PA1

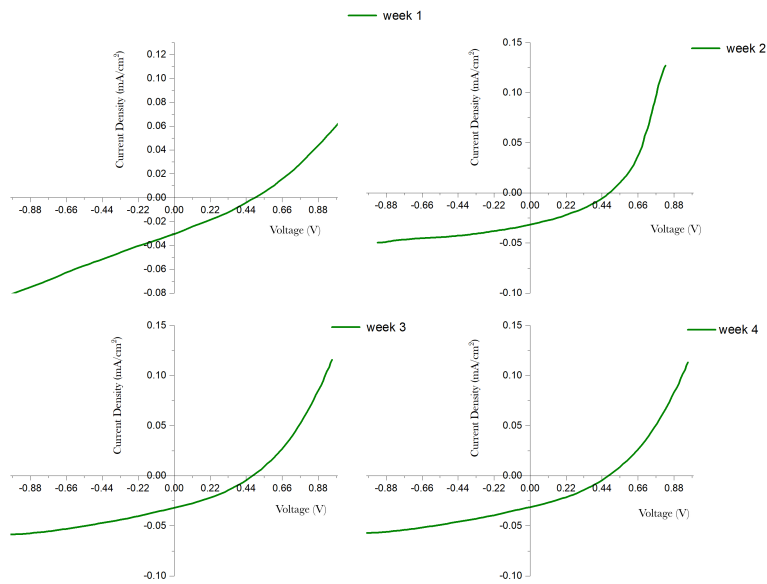


Figure 70

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	32	484	0.34	5.2
7	31.8	483.9	0.32	5
14	31.6	483.6	0.32	4.9
21	31.5	483.4	0.32	4.8

Plant Specie: Stramonium Electrode: PA2

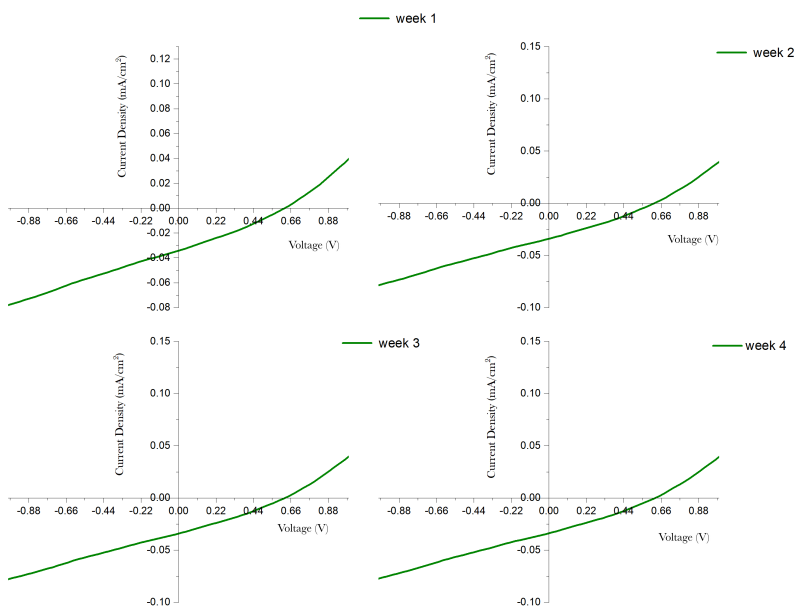


Figure 71

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	34	624	0.15	3.1
7	33.9	623.8	0.14	3
14	33.7	623.7	0.14	2.9
21	33.4	623.5	0.13	2.7

Plant Specie: Green Tea Electrode: PP1

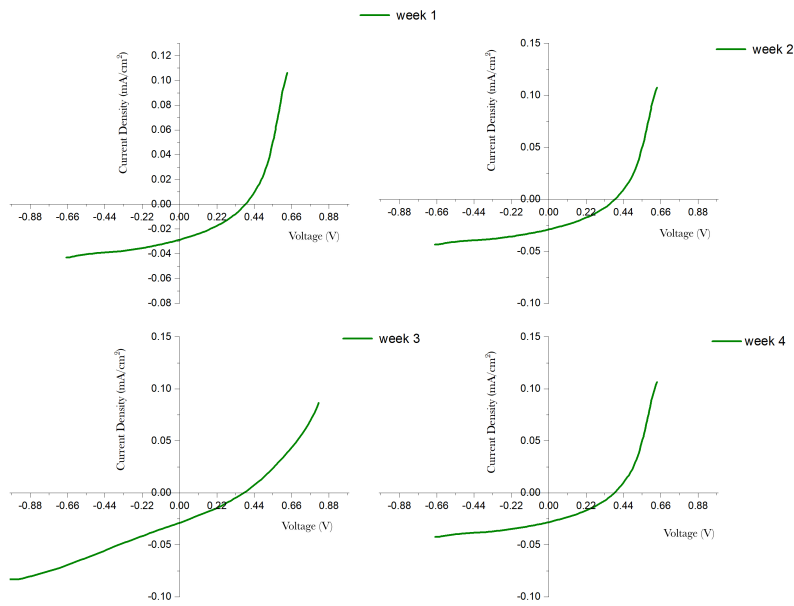


Figure 72

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	29	391	0.28	3.2
7	28.9	390.9	0.27	3.1
14	28.6	390.6	0.27	3
21	28.5	390.4	0.25	2.8

Plant Specie: Green Tea Electrode: PP2

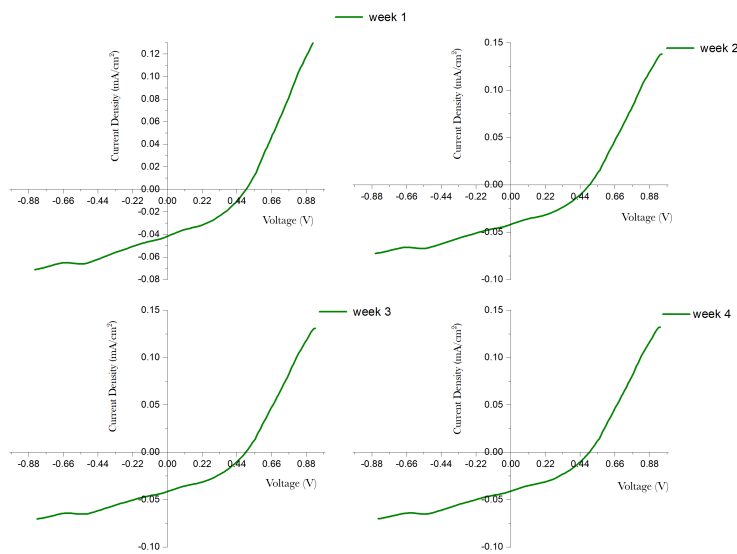


Figure 73

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	42	500	0.15	3.1
7	41.9	499.9	0.14	3
14	41.7	499.7	0.13	2.8
21	41.4	499.5	0.13	2.7

Plant Specie: Green Tea Electrode: PA1

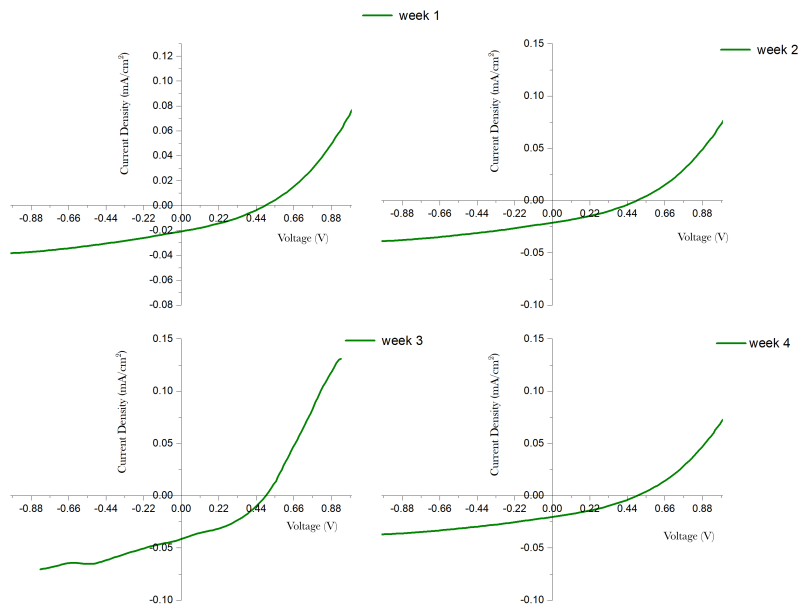


Figure 74

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	21	500	0.15	1.6
7	20.9	499.9	0.13	1.4
14	20.6	499.6	0.13	1.3
21	20.5	499.4	0.12	1.2

Plant Specie: Green Tea Electrode: PA2

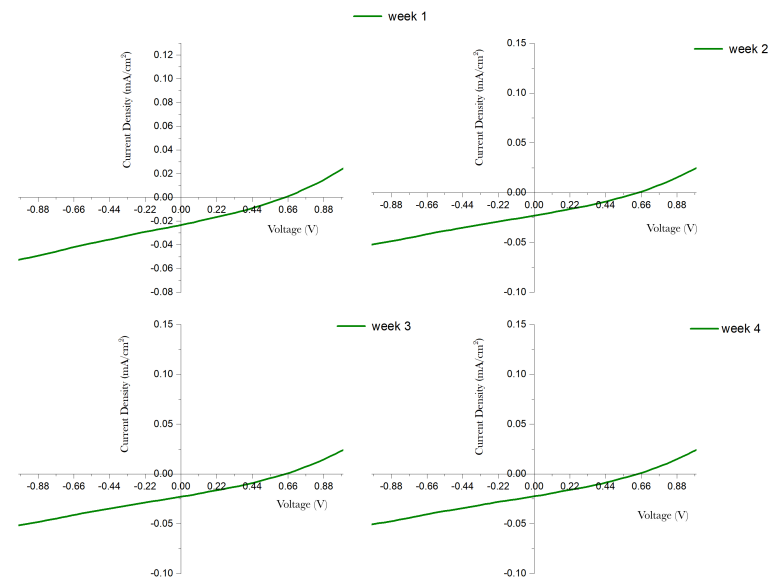


Figure 75

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	23	640	0.10	1.4
7	22.9	639.9	0.08	1.2
14	22.7	639.7	0.07	1
21	22.4	639.5	0.05	0.7

Plant Specie: Neem Electrode: PP1

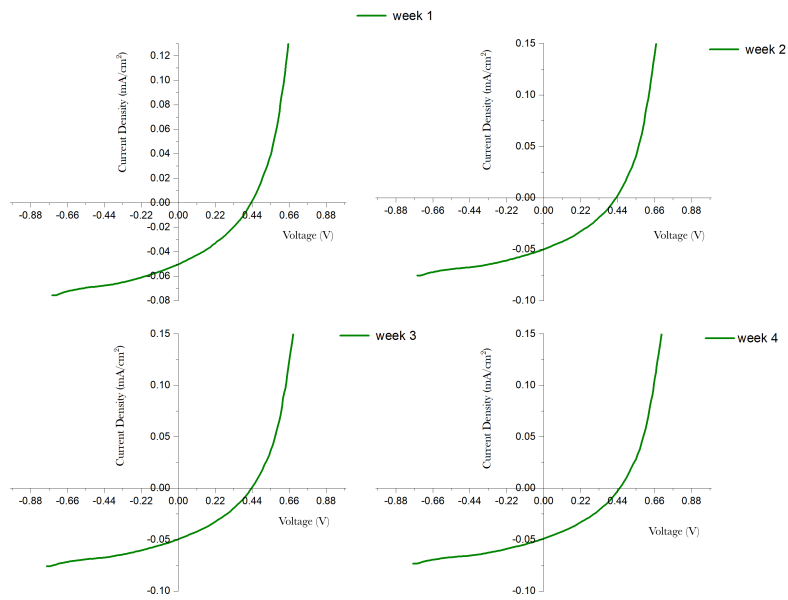


Figure 76

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	50	436	0.16	3.4
7	49.9	432.8	0.15	3.3
14	49.7	435.6	0.14	3.1
21	49.5	435.4	0.13	2.9

Plant Specie: Neem Electrode: PP2

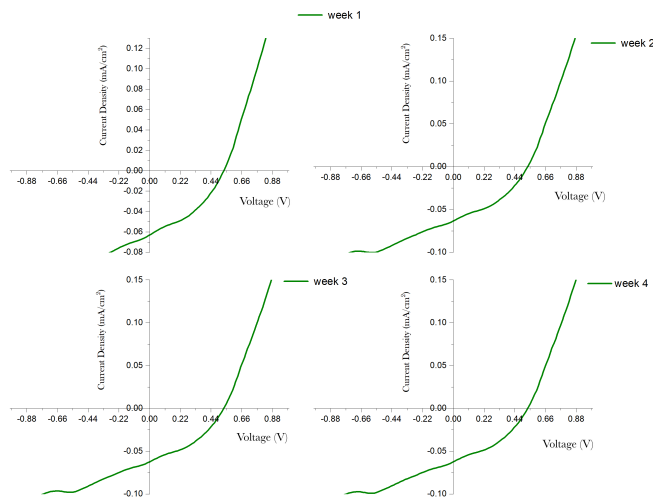


Figure 77

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	63	535	0.18	6.1
7	62.9	534.8	0.18	6
14	62.6	534.9	0.17	5.8
21	62.4	534.5	0.17	5.7

Plant Specie: Neem Electrode: PA1

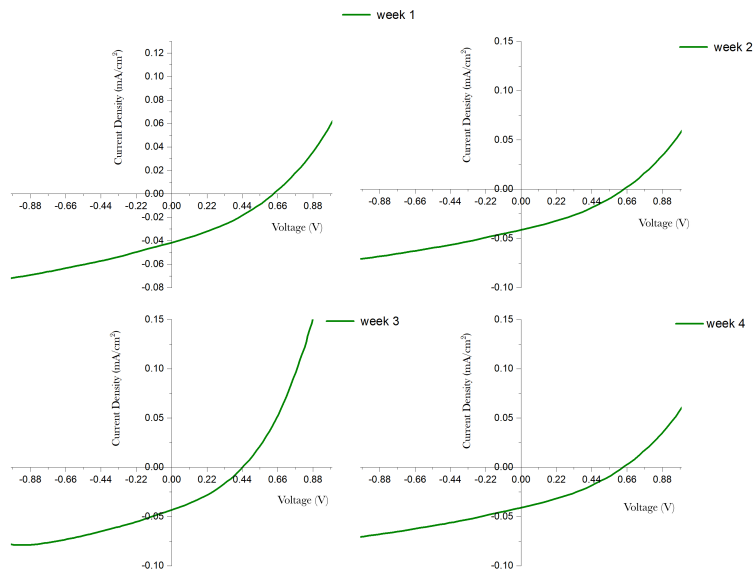


Figure 78

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	42	643	0.22	5.9
7	41.8	642.9	0.22	5.8
14	41.7	642.6	0.21	5.6
21	41.5	642.4	0.20	5.3

Plant Specie: Neem Electrode: PA2

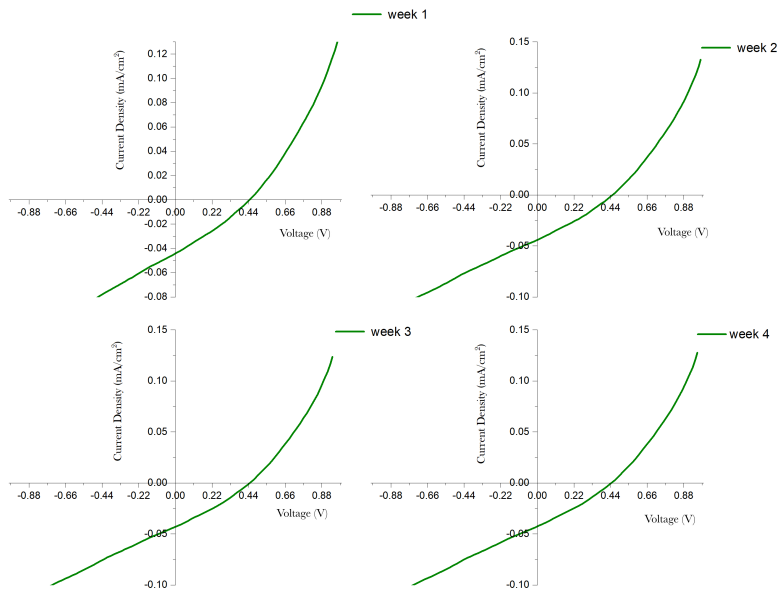


Figure 79

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	44	449	0.21	4.2
7	43.8	448.9	0.21	4.1
14	43.6	448.7	0.20	4
21	43.4	448.5	0.19	3.7

Plant Specie: Radish Electrode: PP1

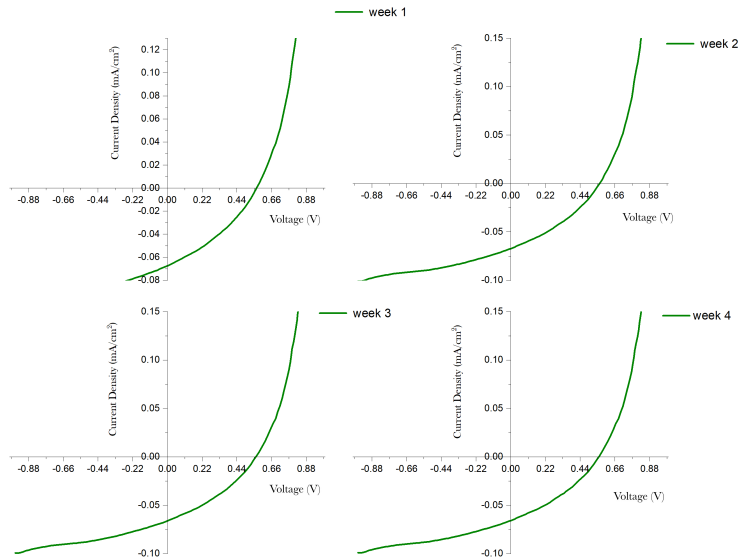


Figure 80

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	67	564	0.16	6.1
7	66.9	563.9	0.16	6
14	66.6	563.6	0.16	5.9
21	66.4	563.5	0.15	5.7

Plant Specie: Radish Electrode: PP2

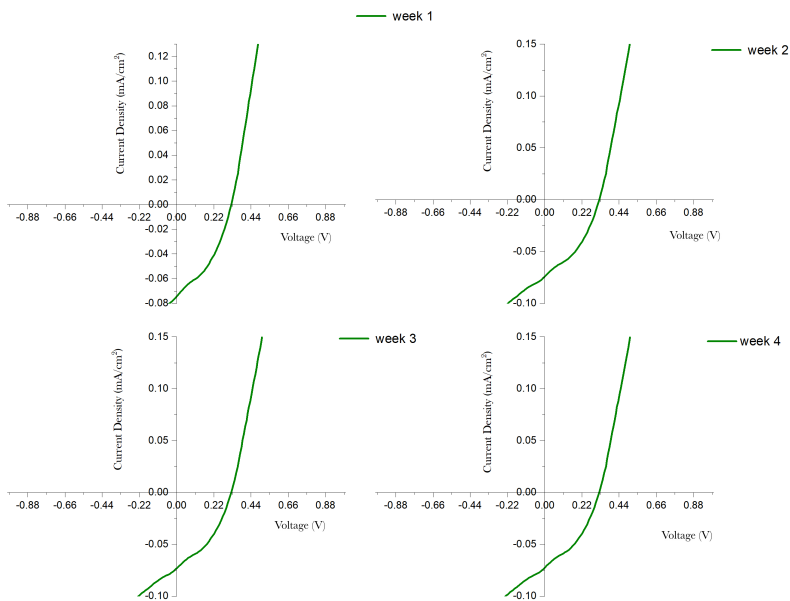


Figure 81

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	74	324	0.29	6.9
7	73.9	323.9	0.28	6.8
14	73.7	323.7	0.28	6.7
21	73.5	323.4	0.27	6.5

Plant Specie: Radish Electrode: PA1

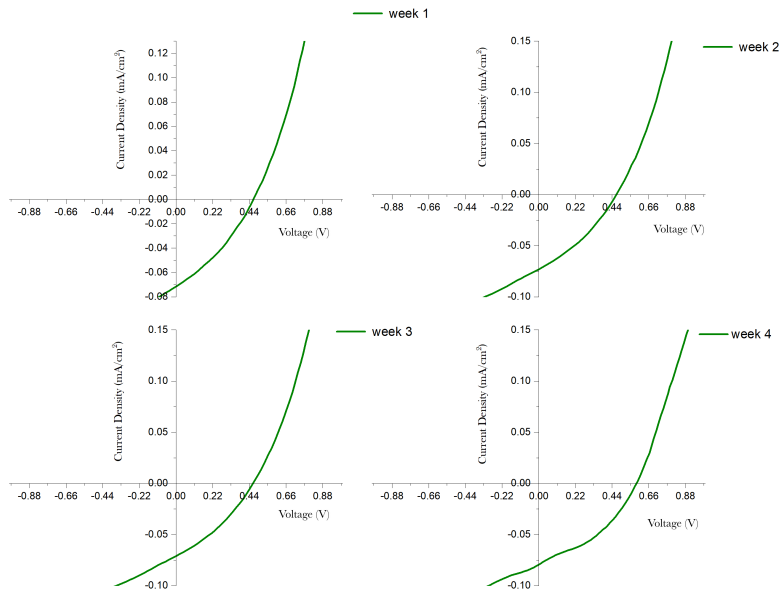


Figure 82

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	72	467	0.12	4.2
7	71.9	466.9	0.12	4.1
14	71.6	466.6	0.12	4
21	71.4	466.3	0.11	3.8

Plant Specie: Radish Electrode: PA2

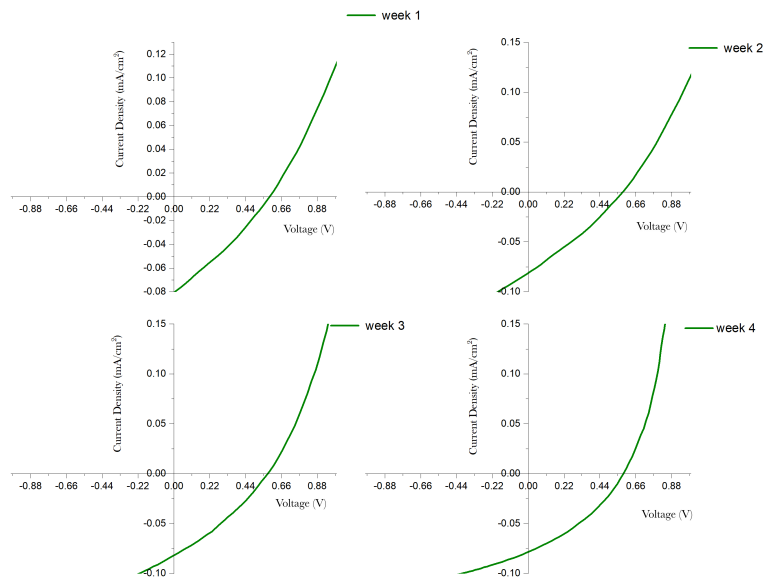


Figure 83

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	80	589	0.09	4.1
7	79.9	588.9	0.09	4
14	79.7	588.7	0.08	3.8
21	79.5	588.4	0.08	3.7

Plant Specie: Amaranthus Electrode: PP1

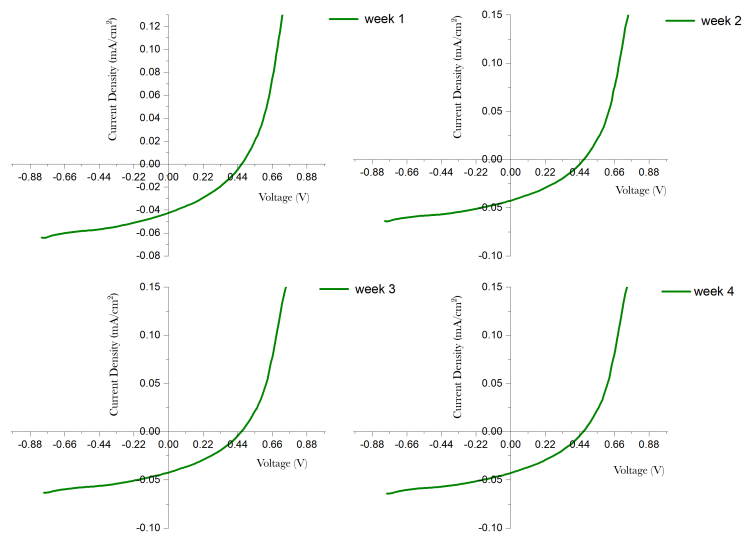


Figure 84

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	45	479	0.34	7.3
7	44.8	478.9	0.34	7.2
14	44.6	478.7	0.33	7
21	44.3	478.3	0.32	6.8

Plant Specie: Amaranthus Electrode: PP2

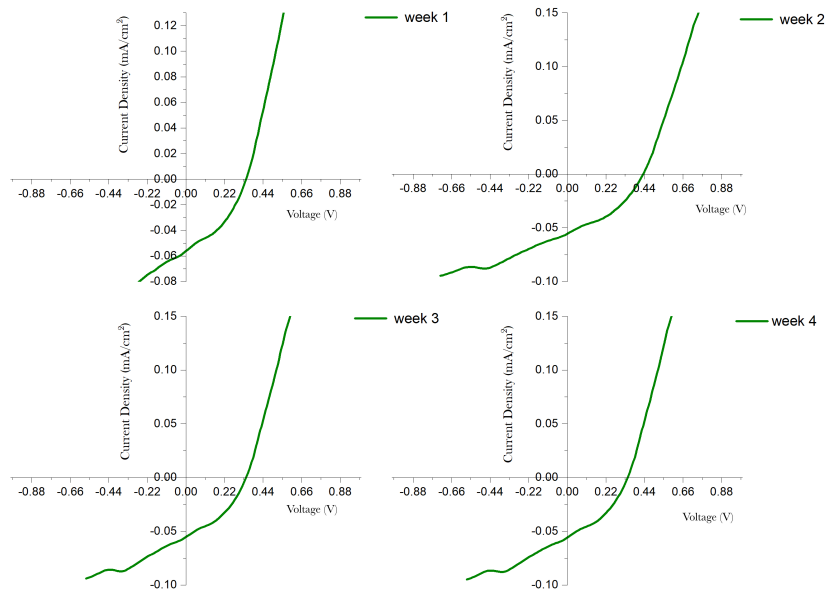


Figure 85

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	52	352	0.38	6.9
7	51.9	357.8	0.37	6.8
14	57.7	357.6	0.32	6.7
21	51.4	357.4	0.35	6.5

Plant Specie: Amaranthus Electrode: PA1

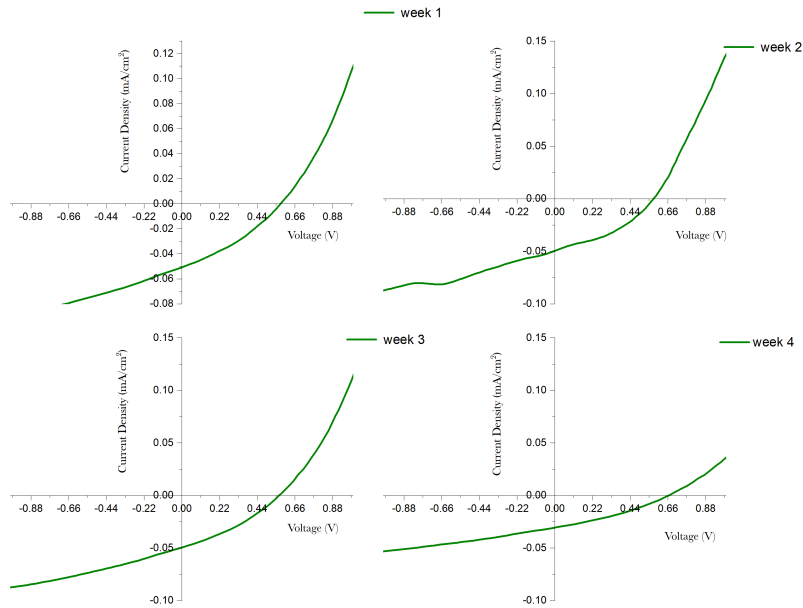


Figure 86

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	50	577	0.15	4.2
7	49.9	576.8	0.14	4.1
14	49.6	576.7	0.14	4
21	49.5	576.5	0.13	3.8

Plant Specie: Amaranthus Electrode: PA2

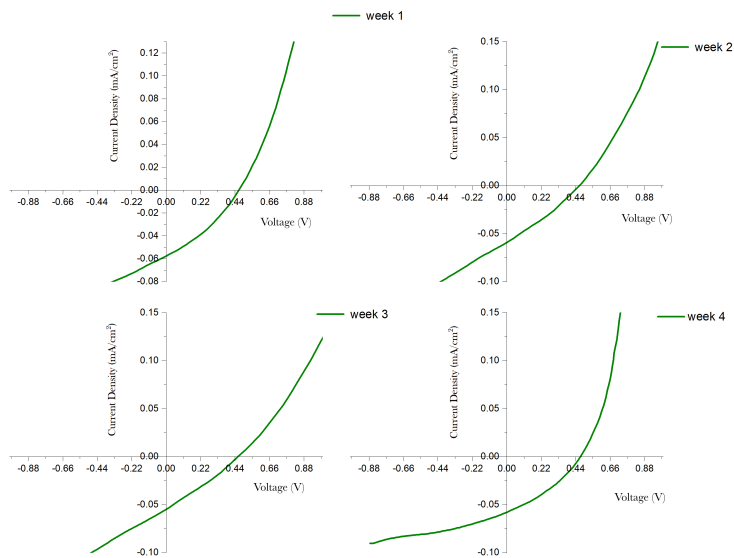


Figure 87

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	58	468	0.15	4.1
7	57.8	467.9	0.14	3.8
14	57.7	467.6	0.14	3.7
21	57.3	467.3	0.13	3.5

Plant Specie: Giant calotrope Electrode: PP1

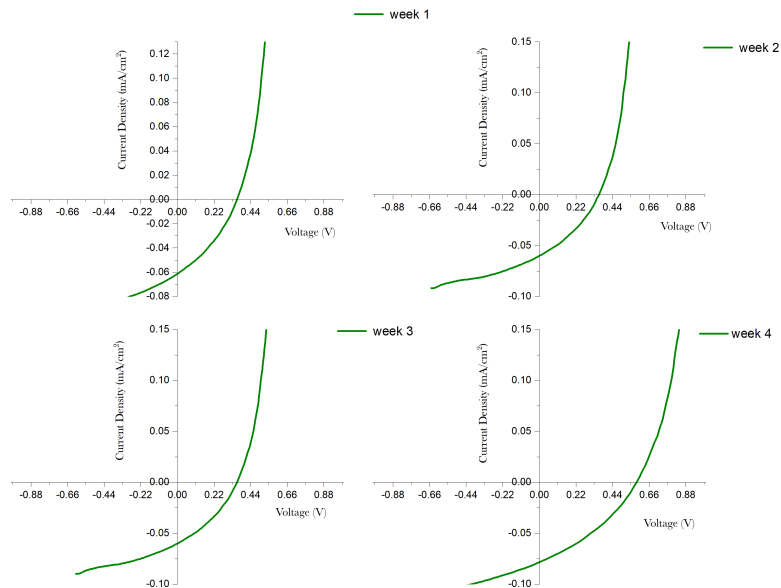


Figure 88

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	61	359	0.24	5.3
7	60.9	358.8	0.24	5.2
14	60.6	358.6	0.23	5.1
21	60.3	358.3	0.23	4.9

Plant Specie: Gaint calotrope Electrode: PP2

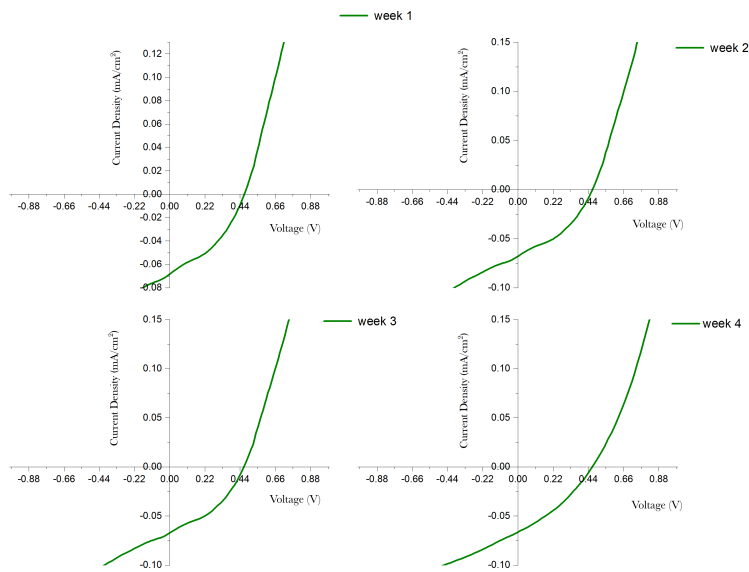


Figure 89

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	68	468	0.22	6.9
7	67.8	467.9	0.21	6.8
14	67.7	467.7	0.21	6.7
21	67.4	467.5	0.21	6.5

Plant Specie: Giant calotrope Electrode: PA1

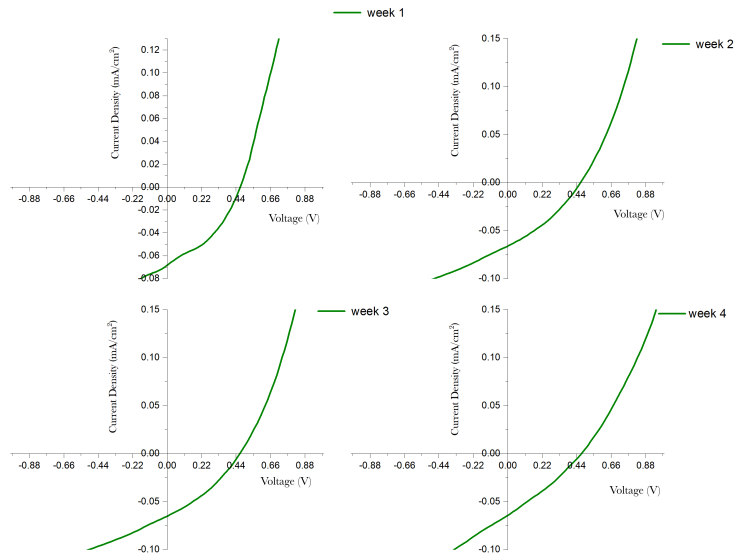


Figure 90

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	66	468	0.16	4.8
7	45.9	467.8	0.22	4.7
14	65.6	467.6	0.15	4.5
21	65.5	467.3	0.14	4.3

Plant Specie: Giant calotrope Electrode: PA2

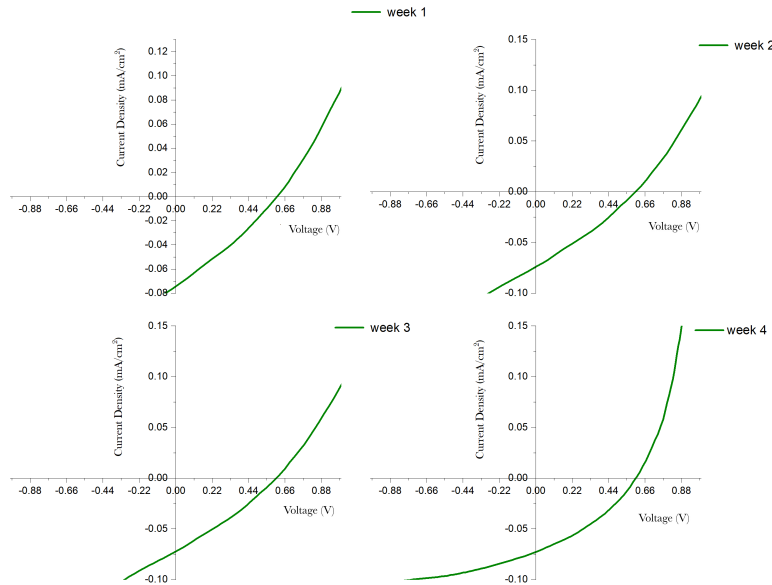


Figure 91

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	74	608	0.11	5.1
7	73.8	607.9	0.11	4.9
14	73.7	607.7	0.10	4.6
21	73.3	607.5	0.09	4.2

Plant Specie: *Murraya koenigii* Electrode: PP1

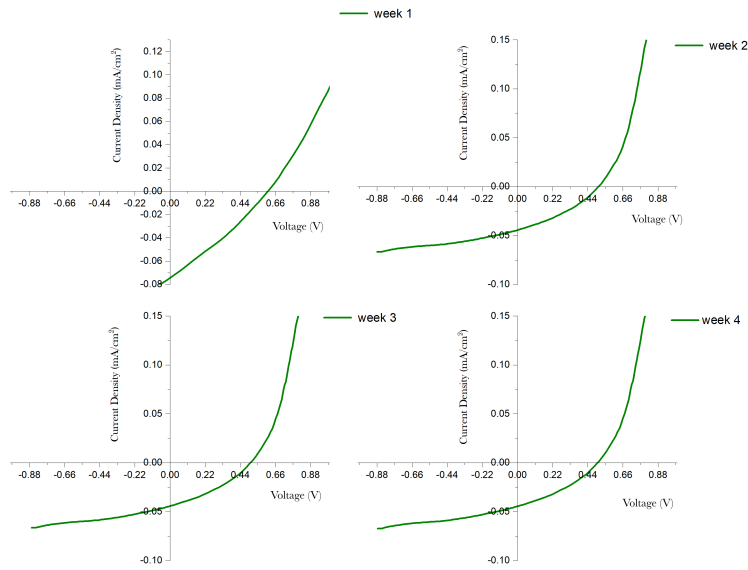


Figure 92

Day	J _{sc} (mA/cm ²)	V _{oc} (mV)	FF	Efficiency(%)
0	45	507	0.27	6.1
7	44.8	506.9	0.26	6
14	44.6	506.6	0.26	5.9
21	44.4	506.4	0.25	5.6

Plant Specie: *Murraya koenigii* Electrode: PP2

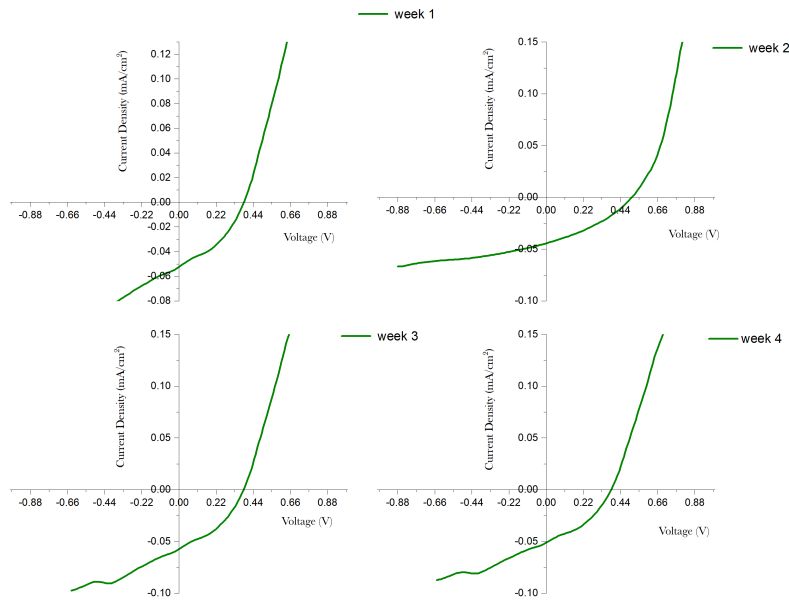


Figure 93

Day	J _{sc} (mA/cm ²)	V _{oc} (mV)	FF	Efficiency(%)
0	52	386	0.34	6.8
7	51.8	385.9	0.34	6.7
14	57.7	385.7	0.29	6.5
21	51.5	385.5	0.32	6.4

Plant Specie: *Murraya koenigii* Electrode: PA1

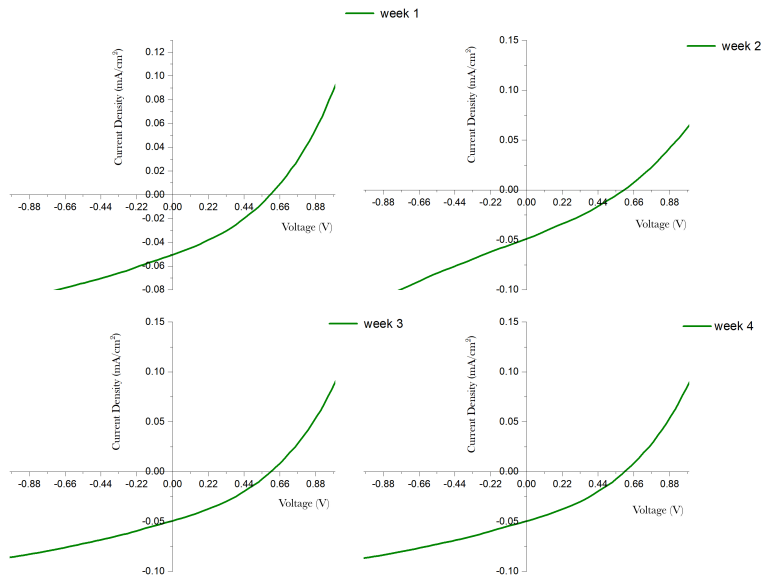


Figure 94

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	50	605	0.16	4.8
7	49.9	604.8	0.16	4.7
14	49.6	604.6	0.15	4.5
21	49.3	604.4	0.15	4.4

Plant Specie: *Murraya koenigii* Electrode: PA2

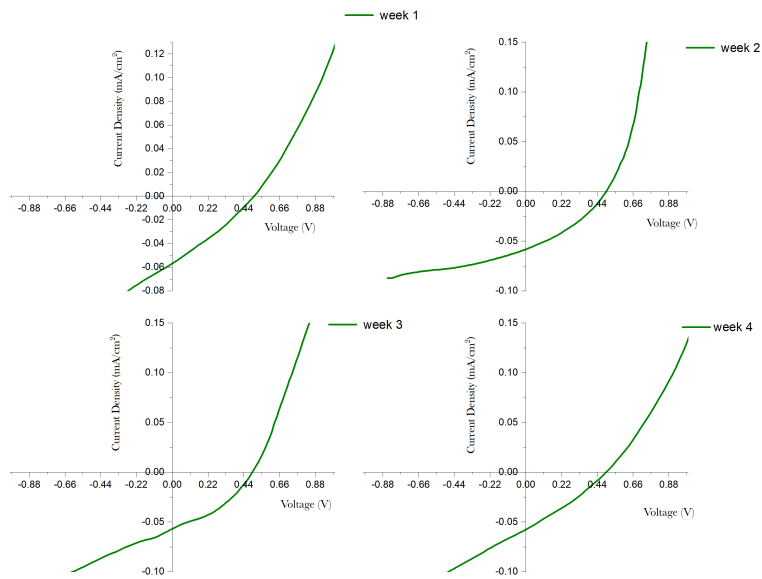


Figure 95

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	58	496	0.18	5.1
7	57.9	495.8	0.17	5
14	57.7	495.7	0.17	4.9
21	57.3	495.4	0.17	4.7

Plant Specie:

Durento

Electrode:

PP1

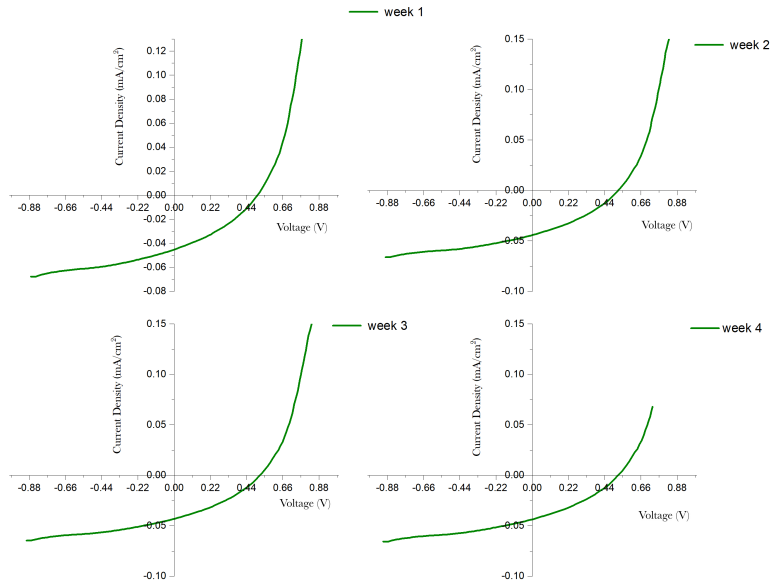


Figure 96

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	44	523	0.13	3.1
7	43.9	523.8	0.13	2.9
14	43.6	522.6	0.12	2.8
21	43.4	522.4	0.11	2.5

Plant Specie:

Durento

Electrode:

PP2

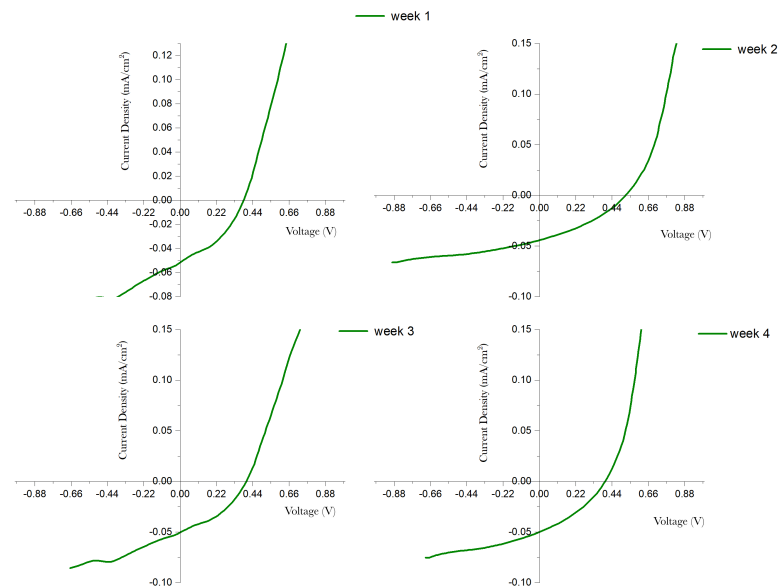


Figure 97

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	51	402	0.13	2.6
7	50.8	401.9	0.12	2.5
14	50.7	401.7	0.12	2.4
21	50.5	401.3	0.11	2.3

Plant Specie: Durento Electrode: PA1

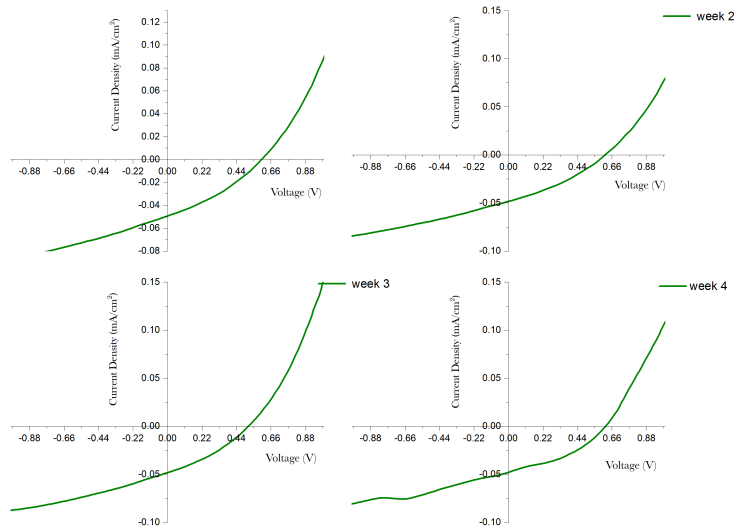


Figure 98

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	49	621	0.11	3.4
7	48.9	602.8	0.11	3.3
14	48.6	620.6	0.11	3.2
21	48.3	620.5	0.10	3.1

Plant Specie: Durento Electrode: PA2

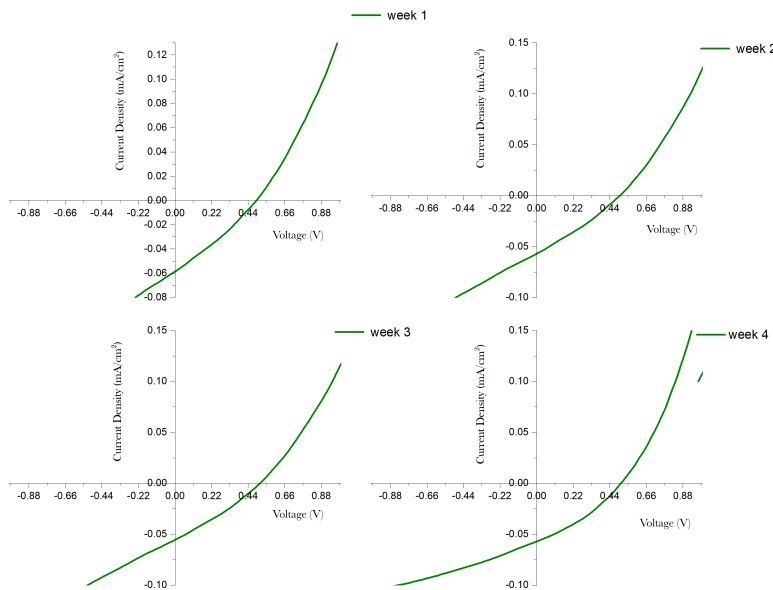


Figure 99

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	57	542	0.09	2.7
7	56.8	511.9	0.09	2.6
14	56.7	511.7	0.08	2.4
21	56.4	511.5	0.08	2.2

Plant Specie: Fenugreek Electrode: PP1

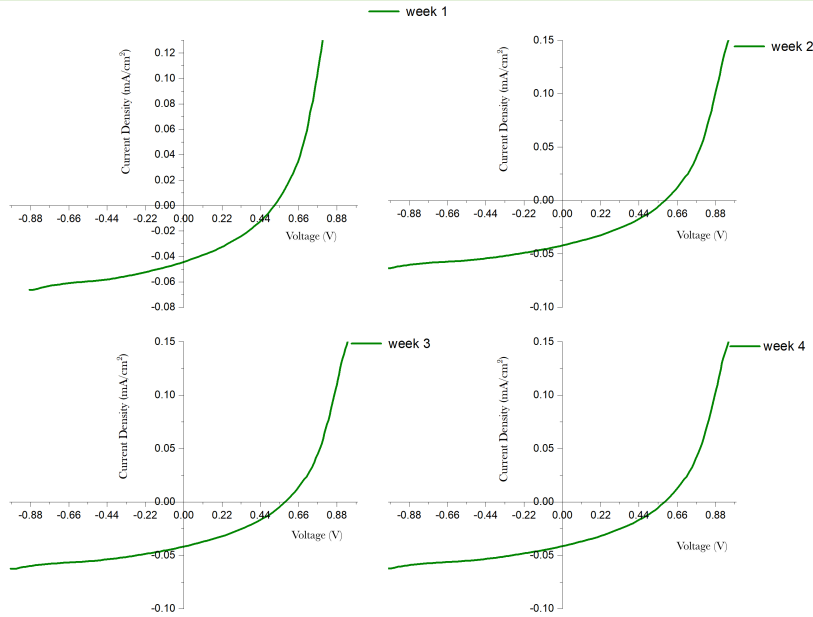


Figure 100

Day	J _{sc} (mA/cm ²)	V _{oc} (mV)	FF	Efficiency(%)
0	47	688	0.18	5.8
7	46.8	687.8	0.17	5.6
14	46.7	687.5	0.17	5.4
21	46.5	687.4	0.17	5.3

Plant Specie: Fenugreek Electrode: PP2

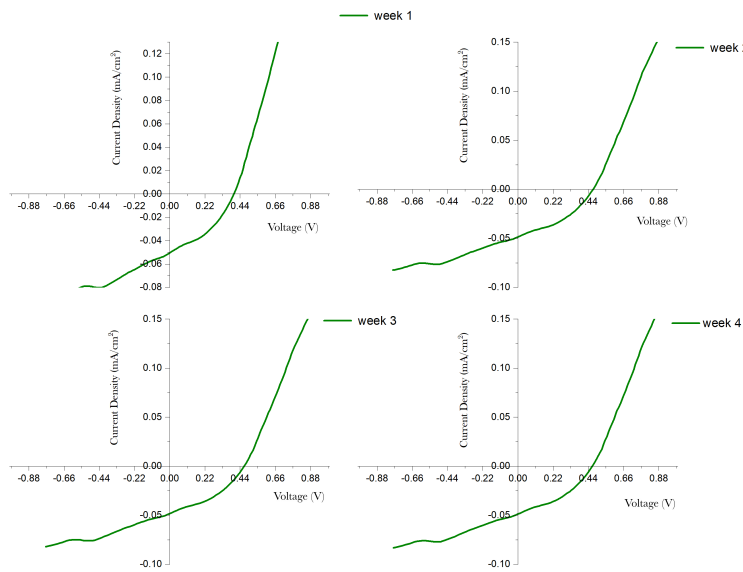


Figure 101

Day	J _{sc} (mA/cm ²)	V _{oc} (mV)	FF	Efficiency(%)
0	49	469	0.22	5
7	48.9	468.9	0.21	4.9
14	48.6	468.6	0.21	4.8
21	48.4	468.5	0.21	4.7

Plant Specie: Fenugreek Electrode: PA1

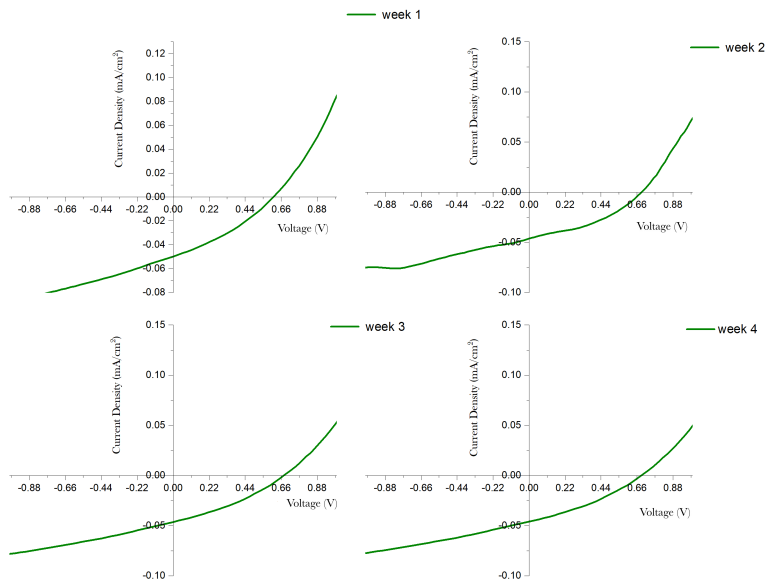


Figure 102

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	47	688	0.18	5.8
7	46.8	687.8	0.17	5.6
14	46.7	687.5	0.17	5.4
21	46.5	687.4	0.17	5.3

Plant Specie: Fenugreek Electrode: PA2

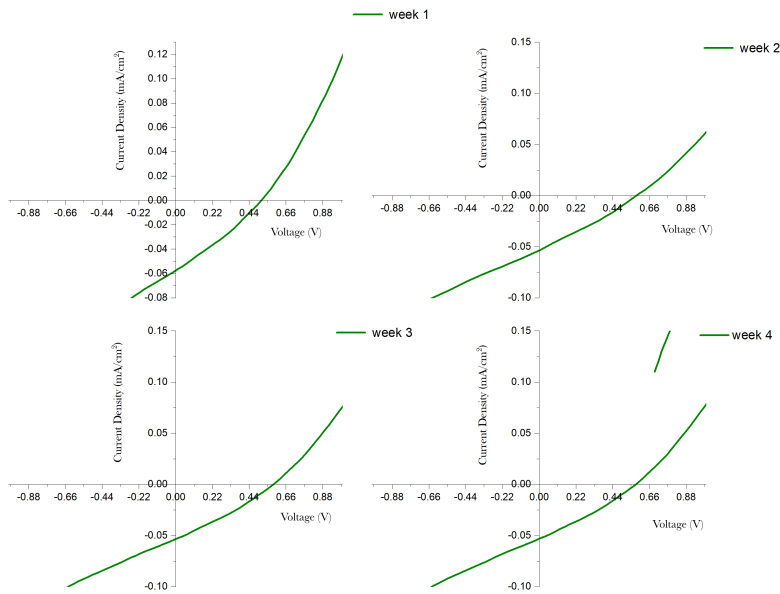


Figure 103

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	55	579	0.15	4.9
7	54.8	578.9	0.15	4.7
14	54.6	578.5	0.15	4.6
21	54.3	578.5	0.14	4.4

Plant Specie: Ficus religiosa **Electrode:** PP1

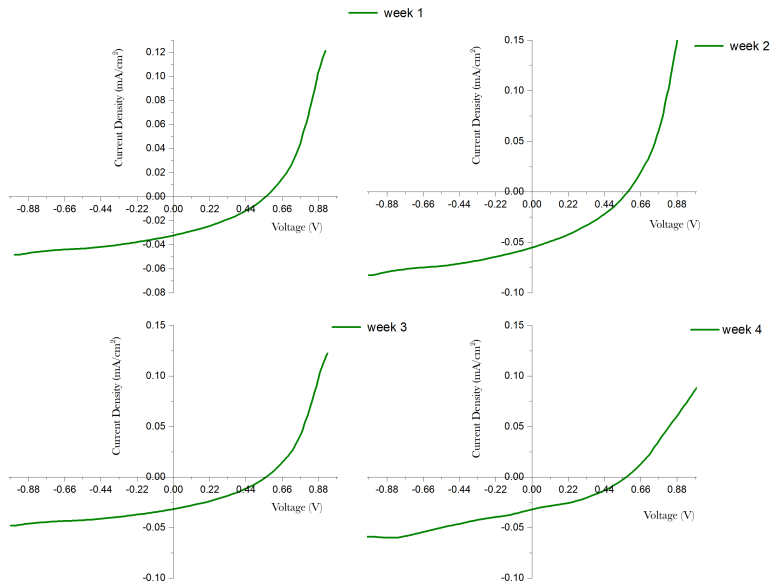


Figure 104

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	32	566.6 Voltage (V)	0.31	5.6
7	31.9	565.8	0.30	5.5
14	31.6	565.6	0.30	5.4
21	31.5	565.4	0.29	5.2

Plant Specie: Ficus religiosa **Electrode:** PP2

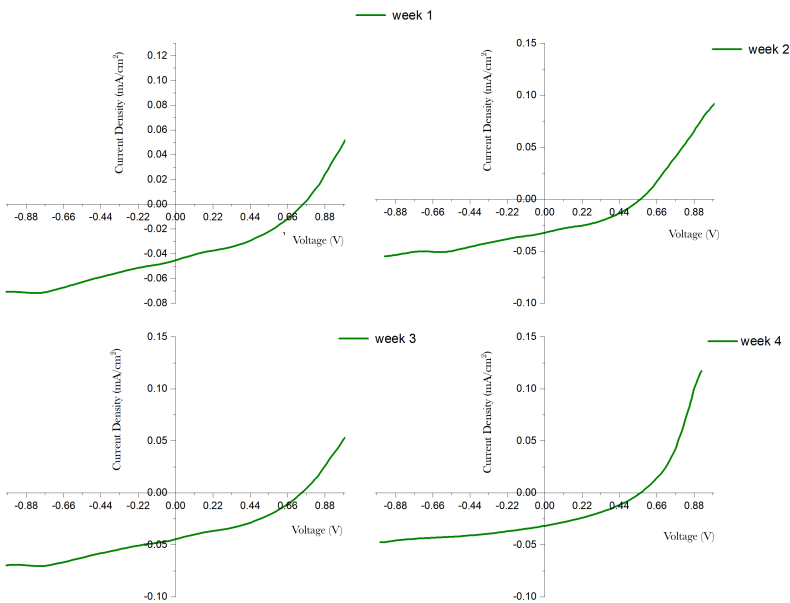


Figure 105

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	45	754	0.19	6.6
7	44.8	753.9	0.19	6.5
14	44.7	753.7	0.19	6.4
21	44.4	753.5	0.19	6.3

Plant Specie: Ficus religiosa **Electrode:** PA1

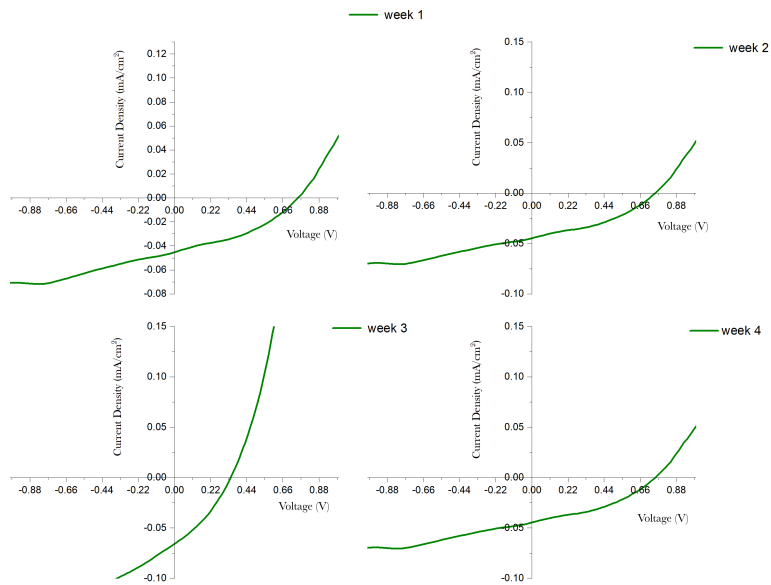


Figure 106

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	67	345	0.23	5.4
7	66.8	344.9	0.23	5.3
14	66.6	344.5	0.23	5.2
21	66.3	344.3	0.22	5.1

Plant Specie: Ficus religiosa **Electrode:** PA2

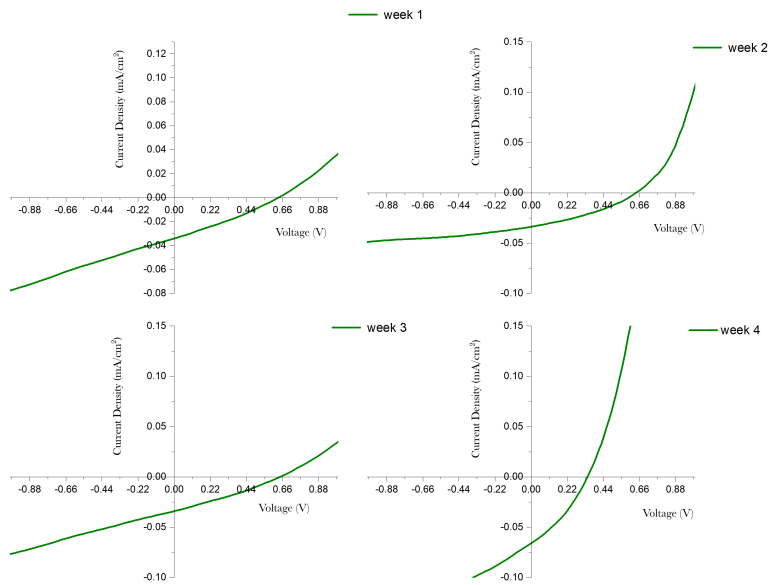


Figure 107

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	34	645	0.27	5.9
7	33.9	644.8	0.26	5.7
14	33.7	644.5	0.26	5.6
21	33.4	644.5	0.26	5.5

Plant Specie: **Mint** Electrode: **PP1**

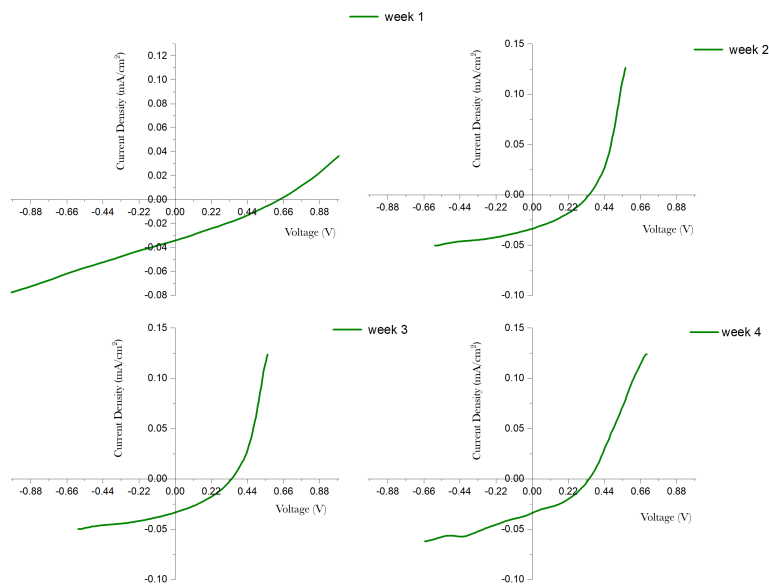


Figure 108

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	34	347	0.57	6.7
7	33.8	346.9	0.56	6.6
14	33.7	346.6	0.56	6.5
21	33.5	346.5	0.54	6.3

Plant Specie: **Mint** Electrode: **PP2**

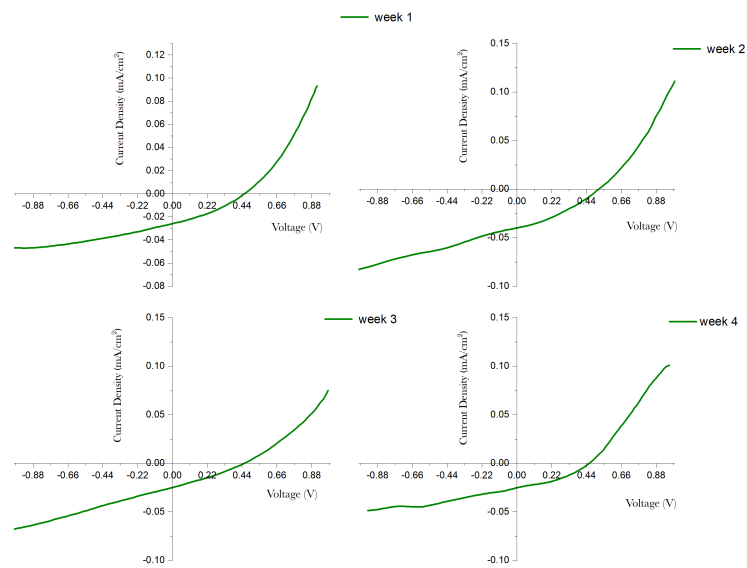


Figure 109

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	56	453	0.29	7.4
7	55.9	452.8	0.29	7.3
14	55.7	452.7	0.29	7.2
21	55.4	452.4	0.28	7.1

Plant Specie:

Mint

Electrode:

PA1

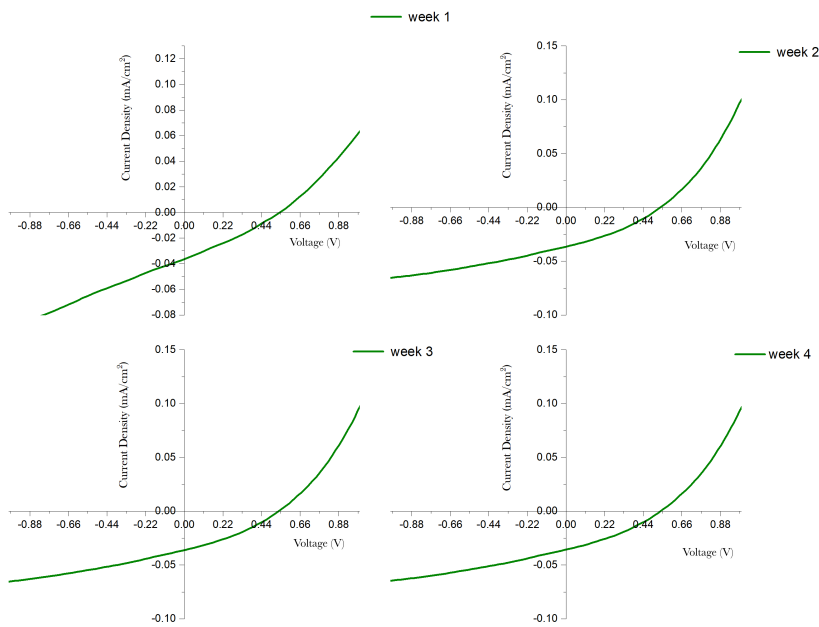


Figure 110

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	36	543	0.31	6.1
7	35.9	542.8	0.31	6
14	35.6	542.5	0.30	5.8
21	35.3	542.3	0.30	5.7

Plant Specie:

Mint

Electrode:

PA2

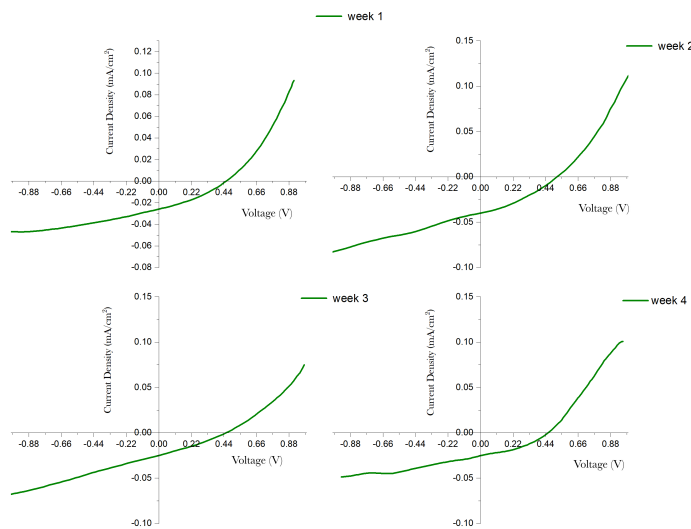


Figure 111

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	26	456	0.47	5.6
7	25.8	455.9	0.46	5.4
14	25.5	455.5	0.45	5.2
21	25.4	455.4	0.43	5

Plant Specie: Holy basil Electrode: PP1

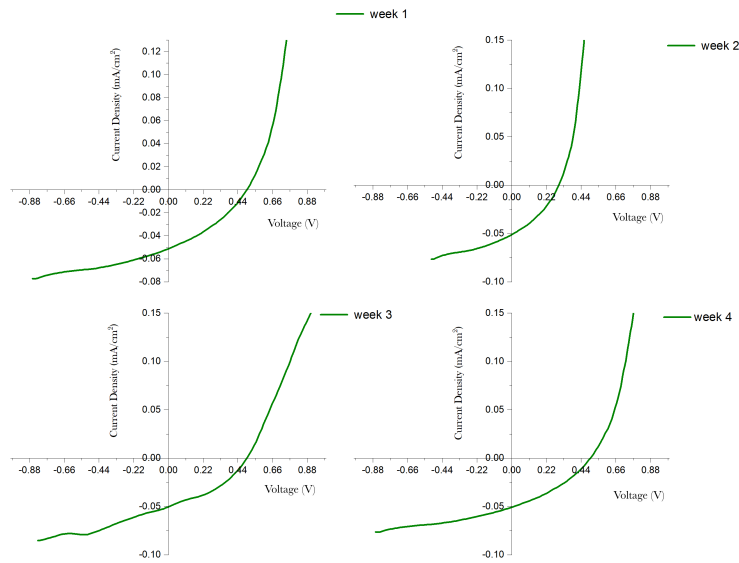


Figure 112

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	51	499	0.27	6.9
7	50.8	498.9	0.26	6.7
14	50.6	498.6	0.26	6.6
21	50.5	498.4	0.25	6.4

Plant Specie: Holy basil Electrode: PP2

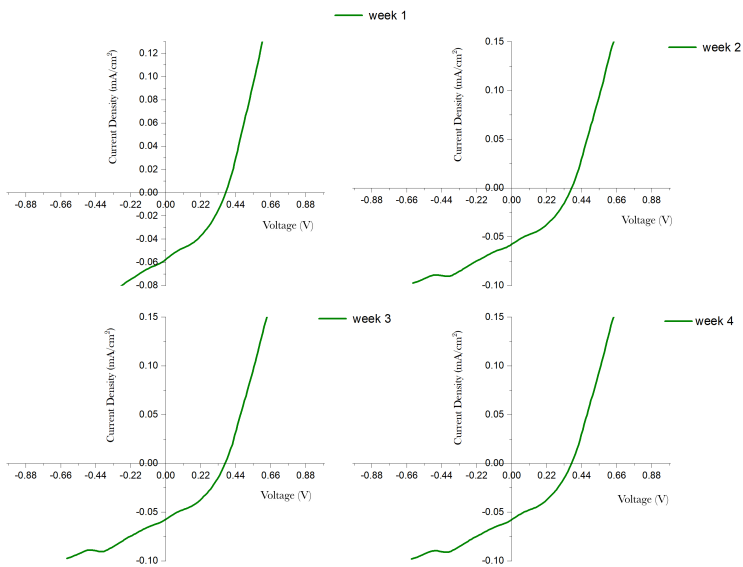


Figure 113

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	58	378	0.35	7.7
7	57.8	377.9	0.35	7.6
14	57.7	377.6	0.34	7.5
21	57.4	377.5	0.34	7.4

Plant Specie: Holy basil Electrode: PA1

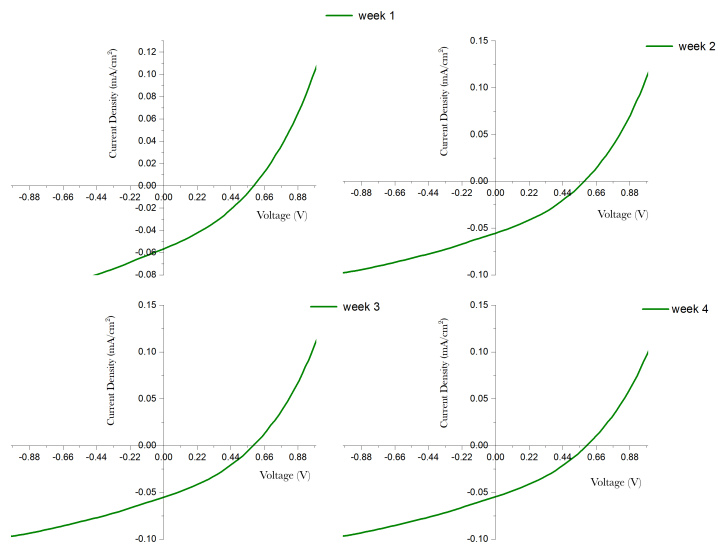


Figure 114

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	56	597	0.18	6.1
7	55.9	596.8	0.18	6
14	55.6	596.7	0.17	5.8
21	55.3	596.3	0.17	5.7

Plant Specie: Holy basil Electrode: PA2

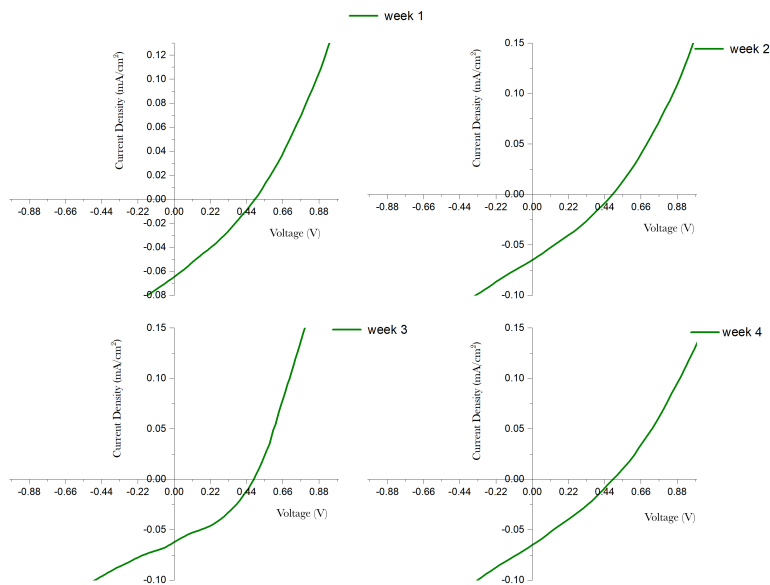


Figure 115

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	64	488	0.18	5.7
7	63.9	487.8	0.18	5.5
14	63.7	487.7	0.17	5.4
21	63.4	487.4	0.17	5.3

Plant Specie: Banyan Electrode: PP1

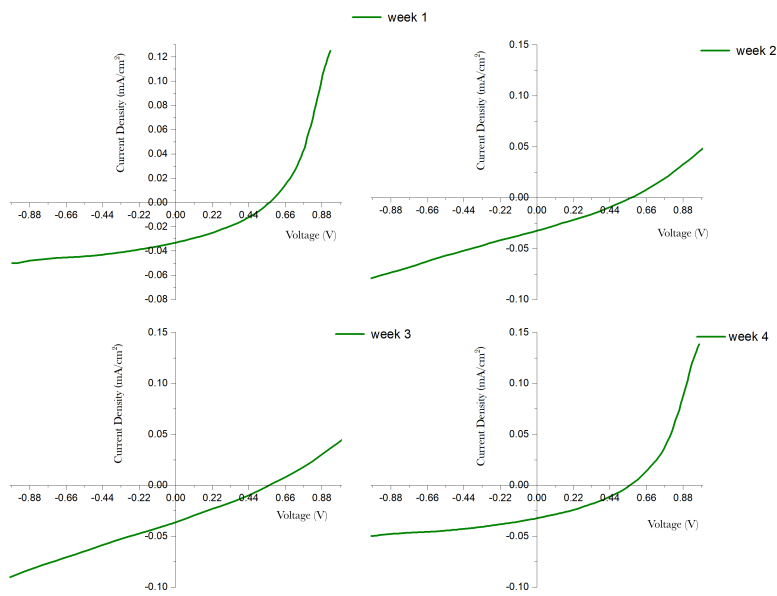


Figure 116

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	33	564	0.31	5.8
7	32.9	563.8	0.31	5.7
14	32.5	563.7	0.30	5.5
21	32.4	563.4	0.29	5.3

Plant Specie: Banyan Electrode: PP2

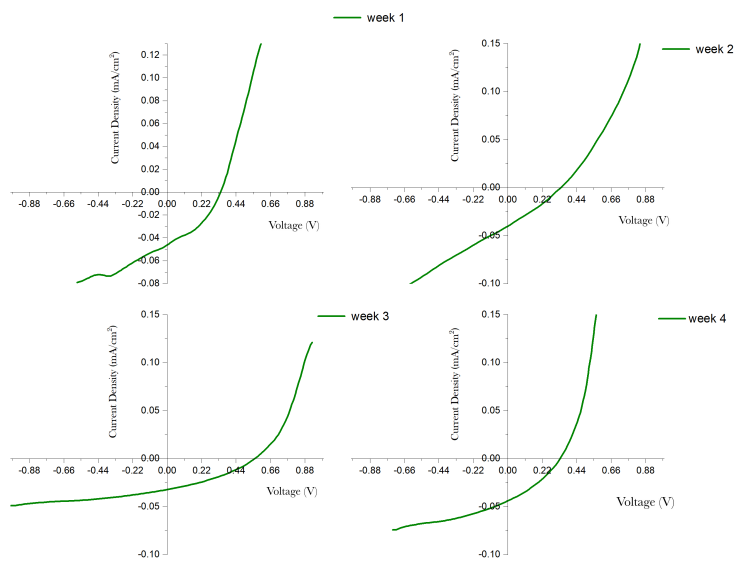


Figure 117

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	46	342	0.39	6.1
7	45.8	341.9	0.38	6
14	45.5	341.5	0.38	5.9
21	45.5	341.5	0.37	5.8

Plant Specie: Banyan Electrode: PA1

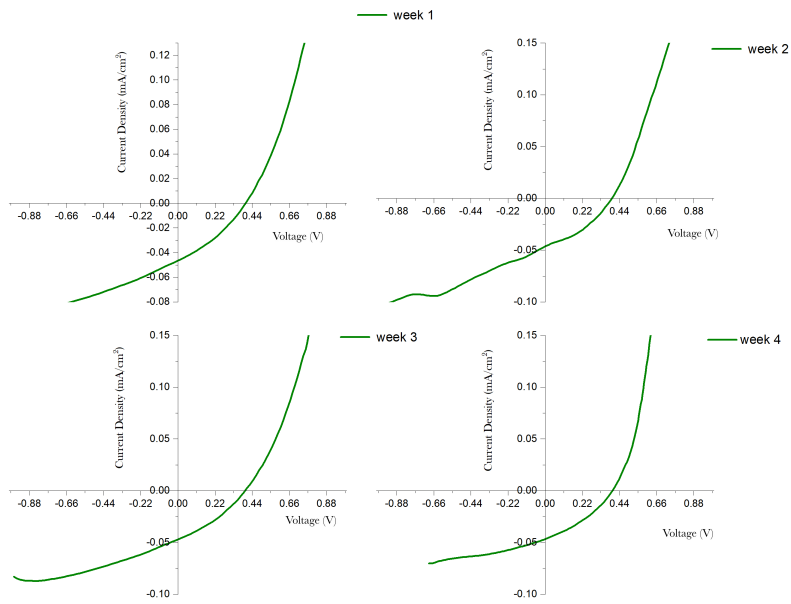


Figure 118

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	47	398	0.27	5.1
7	46.9	397.8	0.27	5
14	46.6	397.5	0.26	4.9
21	46.4	397.3	0.25	4.7

Plant Specie: Banyan Electrode: PA2

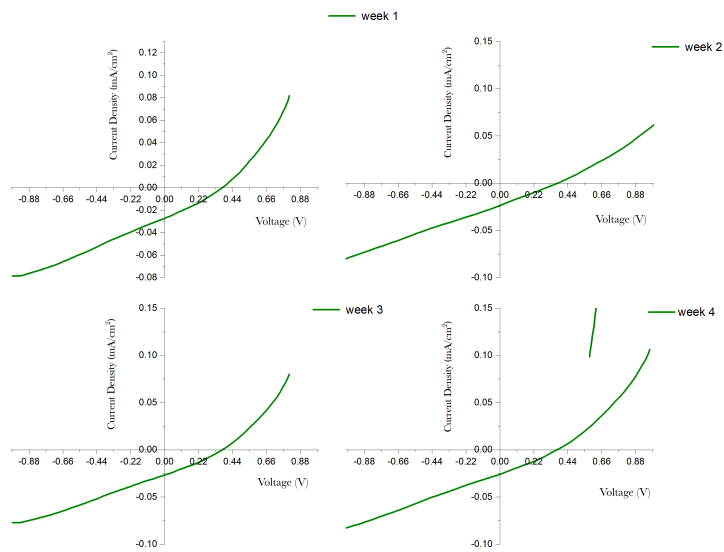


Figure 119

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	27	375	0.53	5.4
7	26.8	374.9	0.53	5.3
14	26.5	374.6	0.52	5.2
21	26.3	374.4	0.52	5.1

Plant Specie: **Arbi** Electrode: **PP1**

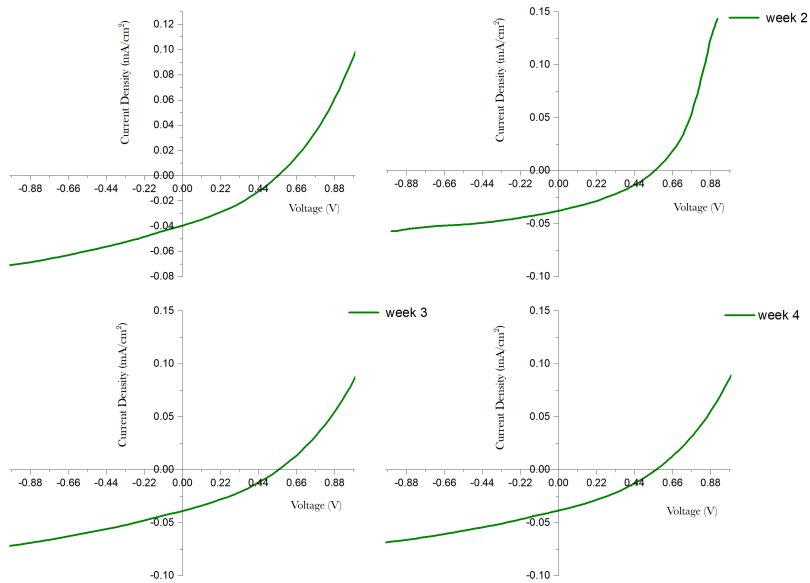


Figure 120

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	39	561	0.21	4.6
7	38.9	560.9	0.20	4.4
14	38.6	560.6	0.19	4.2
21	38.3	560.4	0.19	4.1

Plant Specie: **Arbi** Electrode: **PP2**

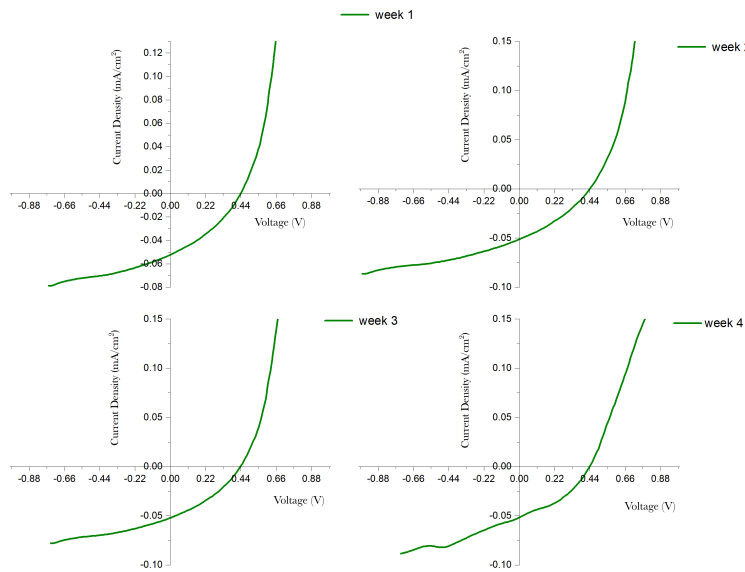


Figure 121

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	52	440	0.27	6.2
7	51.9	439.9	0.27	6.1
14	57.7	439.7	0.20	5
21	51.4	439.5	0.26	5.9

Plant Specie:

Arbi

Electrode:

PA1

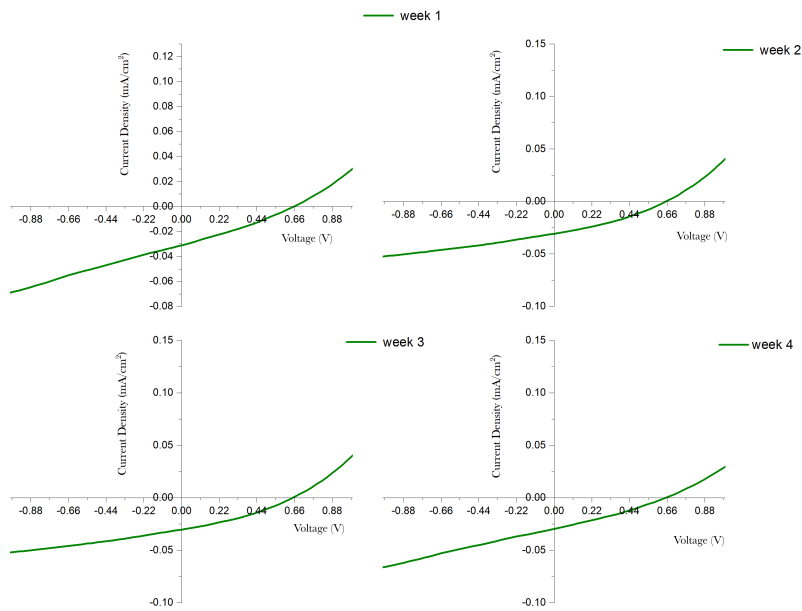


Figure 122

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	31	659	0.15	3.1
7	30.9	658.9	0.15	3
14	30.6	658.6	0.14	2.8
21	30.5	658.4	0.13	2.7

Plant Specie:

Arbi

Electrode:

PA2

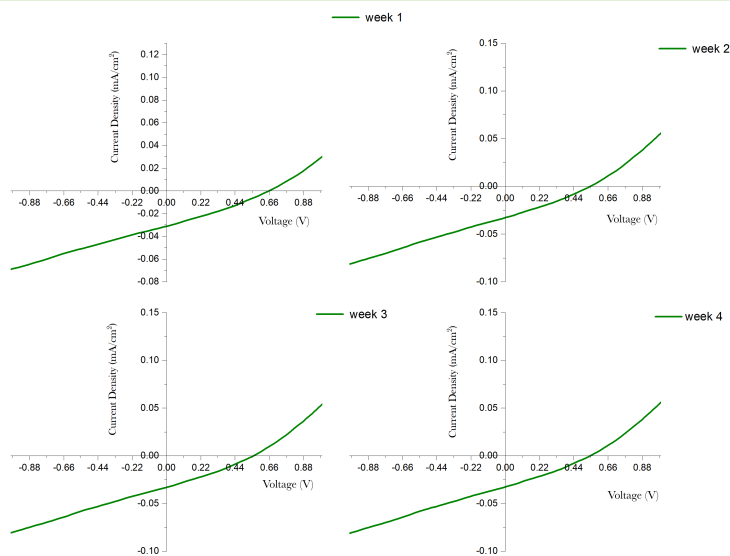


Figure 123

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	33	550	0.16	2.9
7	32.9	549.9	0.15	2.8
14	32.7	549.7	0.14	2.6
21	32.3	549.3	0.14	2.4

Plant Specie: Longofolia Electrode: PP1

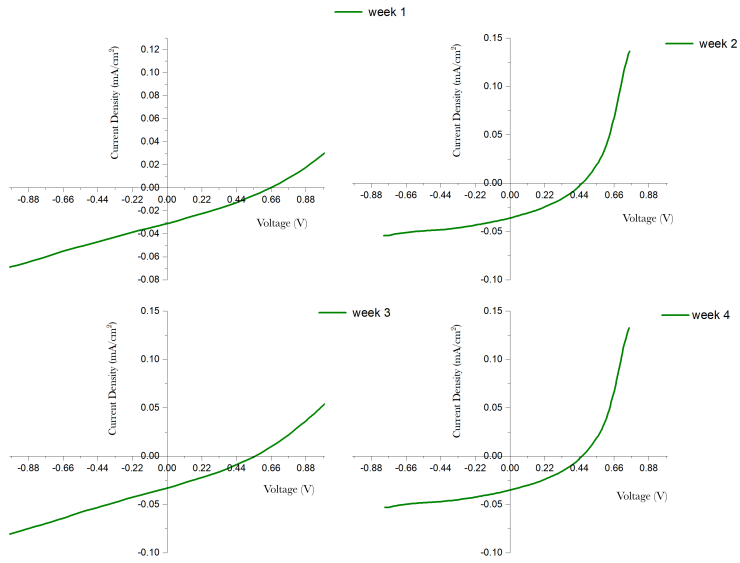


Figure 124

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	36	459	0.19	3.1
7	35.9	458.8	0.18	3
14	35.7	458.7	0.18	2.9
21	35.5	458.4	0.17	2.7

Plant Specie: Longofolia Electrode: PP2

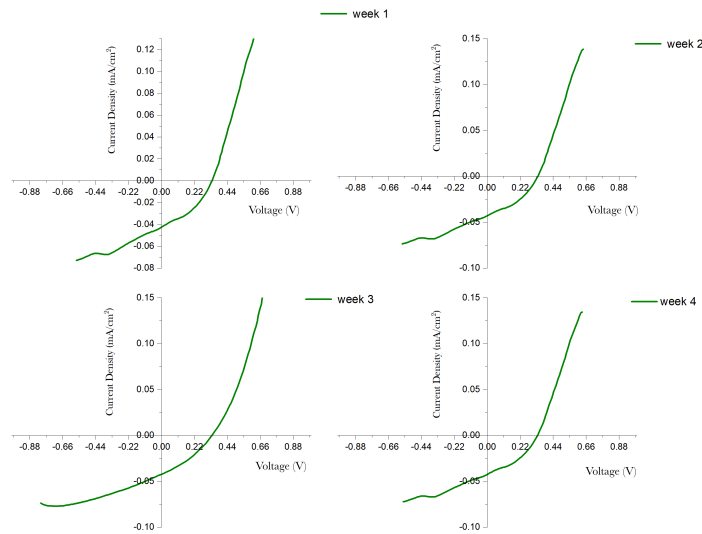


Figure 125

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	43	338	0.25	3.6
7	42.8	337.9	0.24	3.5
14	42.6	337.6	0.24	3.4
21	42.3	337.5	0.22	3.2

Plant Specie:

Longofolia

Electrode:

PA1

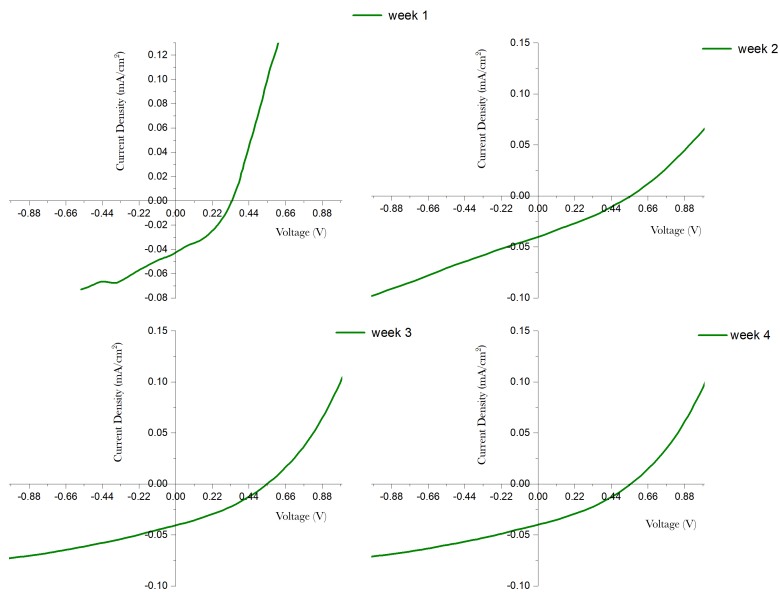


Figure 126

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	44	557	0.12	2.9
7	40.9	556.8	0.12	2.8
14	40.7	556.7	0.12	2.7
21	40.4	556.4	0.11	2.5

Plant Specie:

Longofolia

Electrode:

PA2

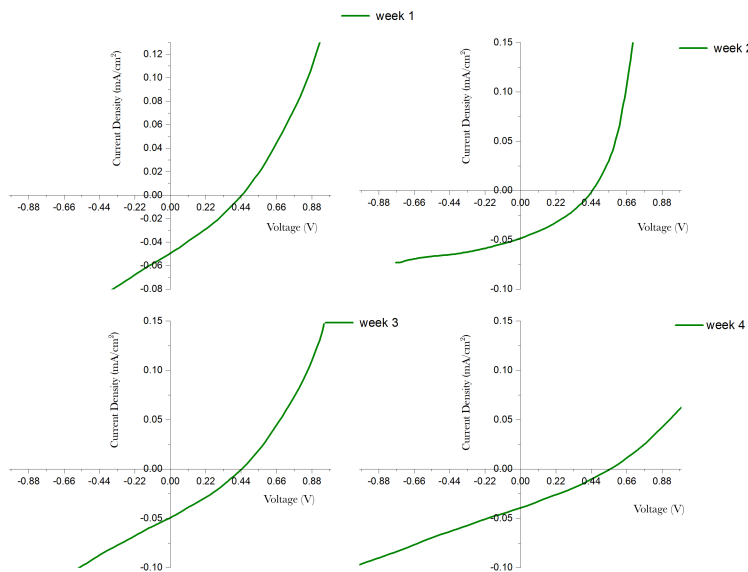


Figure 127

Day	Jsc (mA/cm ²)	Voc (mV)	FF	Efficiency(%)
0	49	448	0.10	2.1
7	48.8	447.9	0.09	2
14	48.6	447.6	0.08	1.8
21	48.5	447.3	0.07	1.5

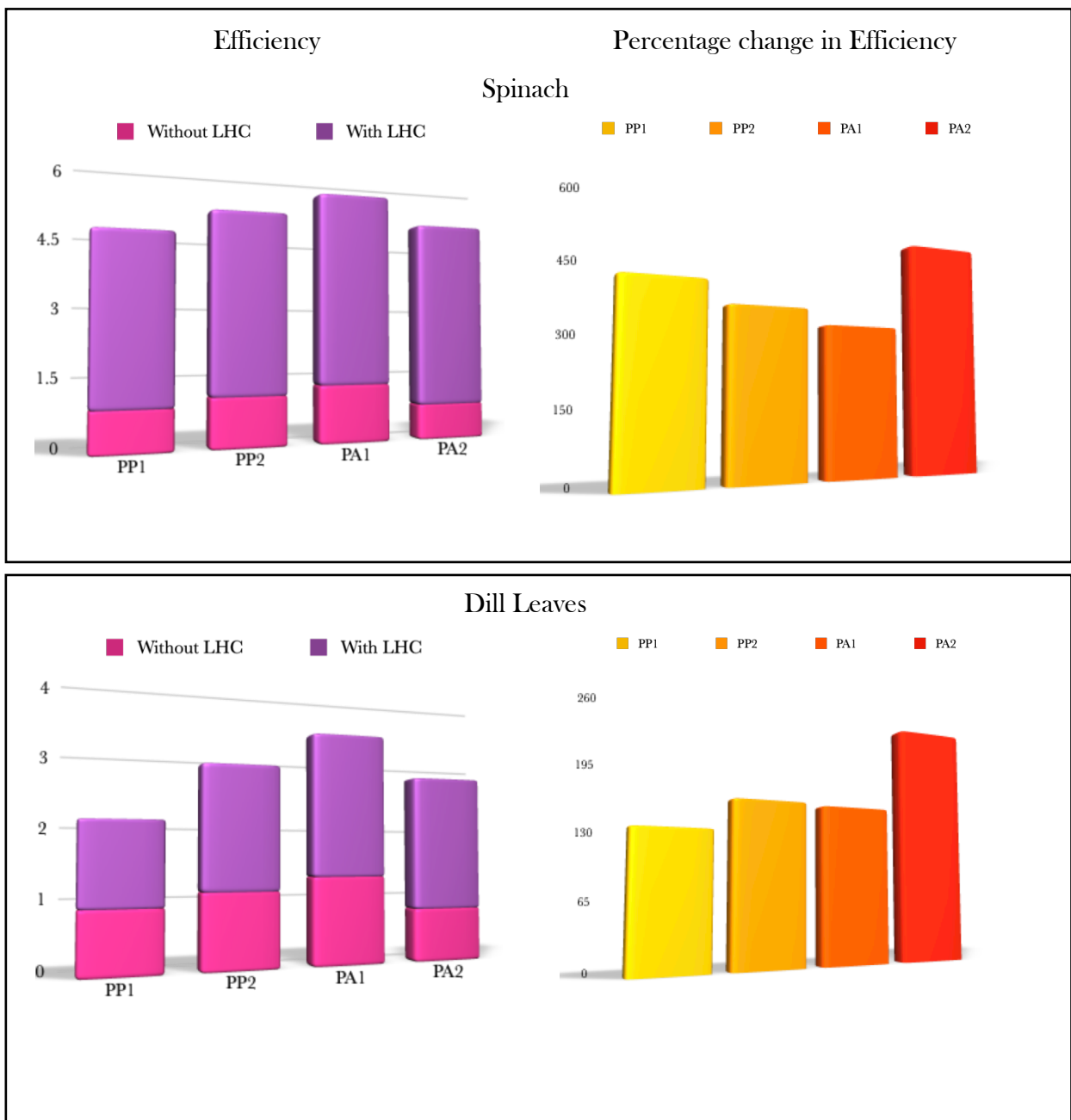
LIGHT HARVESTING COMPLEXES AS DYES

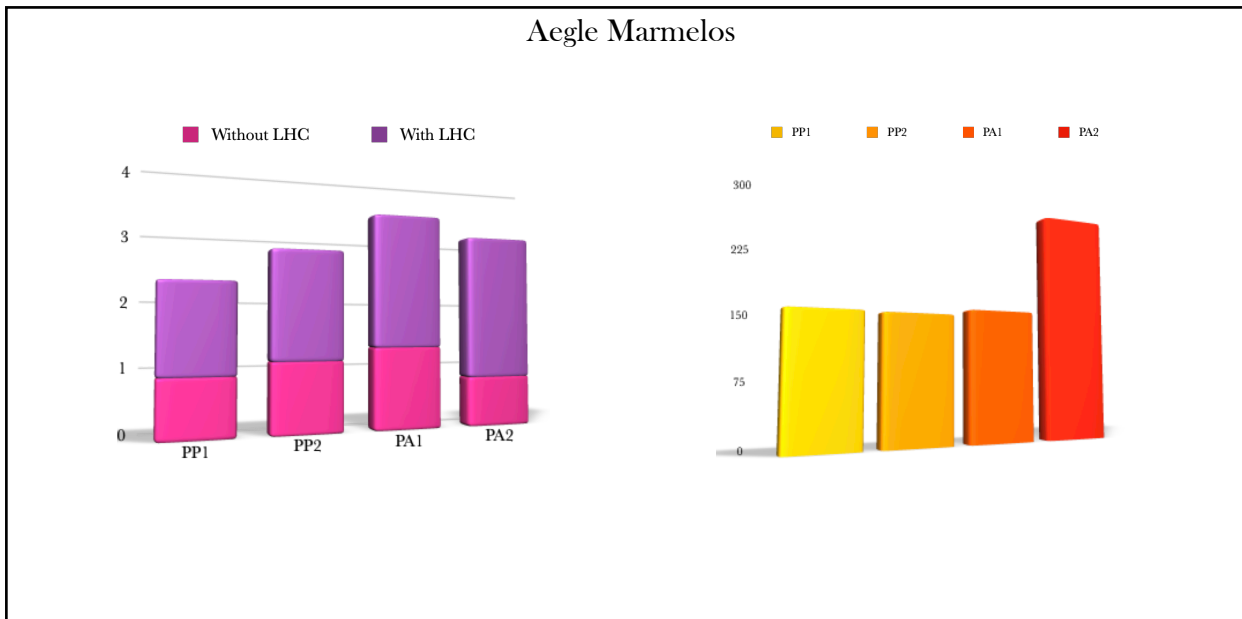
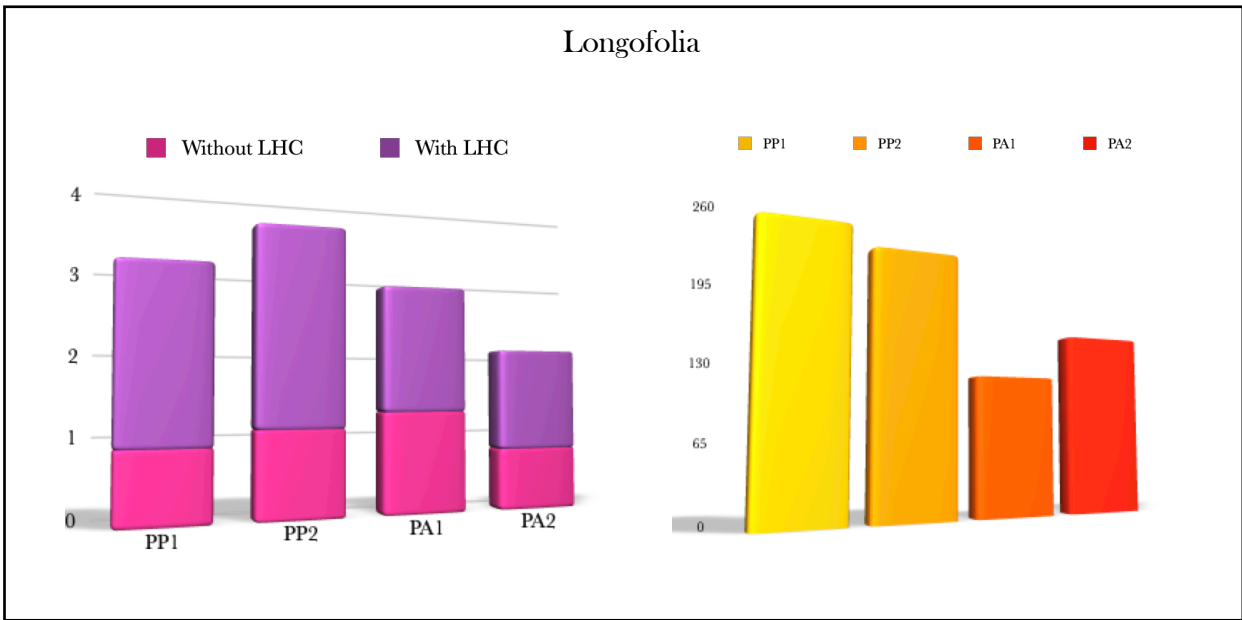
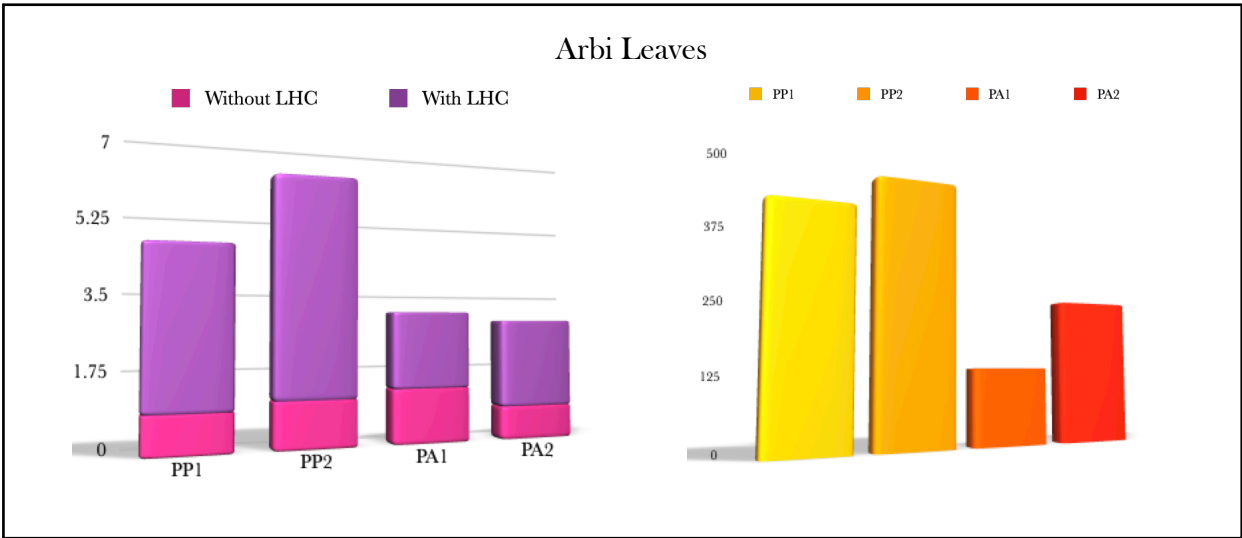
COMPARISON OF EFFICIENCIES WITH AND WITHOUT LHCS

A big difference in efficiency has been observed between cells fabricated without using LHCS and those with LHCS. This is on expected lines, as the dye or LHC in this case is meant to absorb more light and thereby enhance the efficiency.

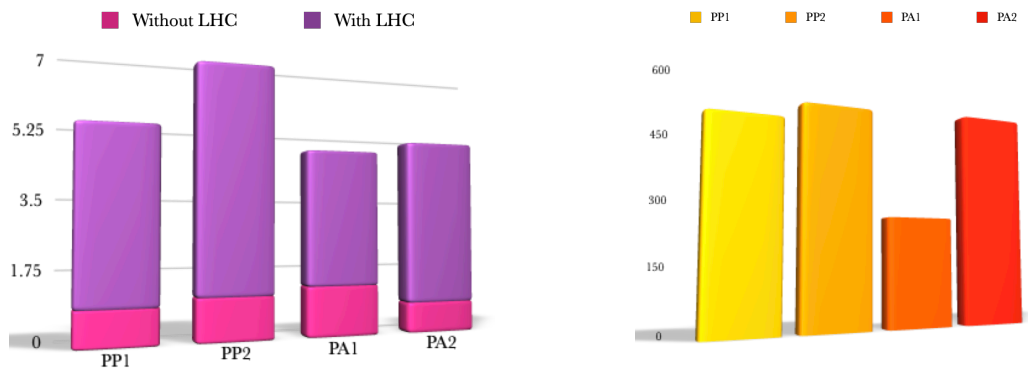
The results are given in the form of bars, with efficiencies in the left side and percentage change in efficiency on the right. The pink section at the bottom shows the efficiency of the cell without LHC having a particular polymer as the counter electrode. The violet section shows the rise in efficiency with LHC from particular plant species. The bars on the right give the percentage increase in efficiencies of the same cells.

Results make it amply clear that LHCS can serve effectively in dye-based solar cells.

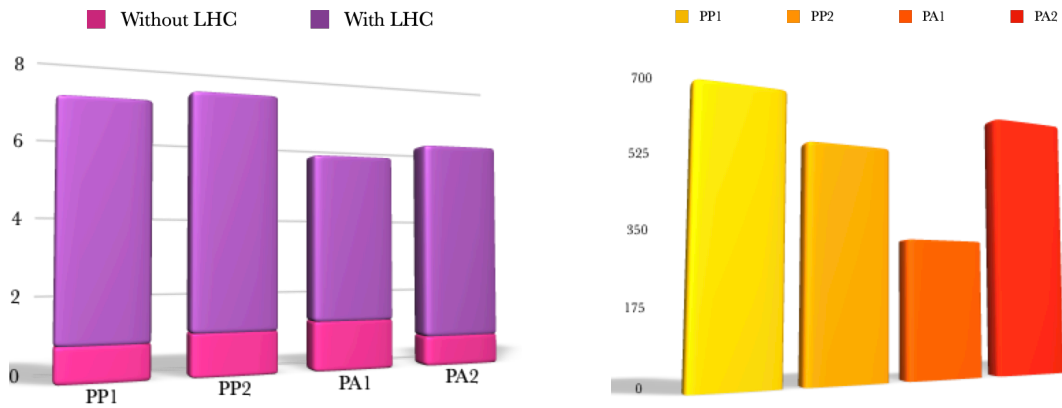




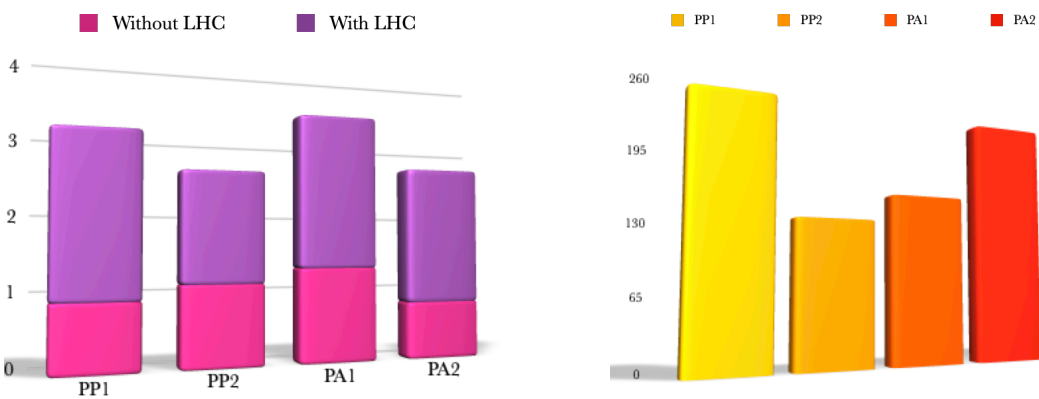
Giant Calotrope



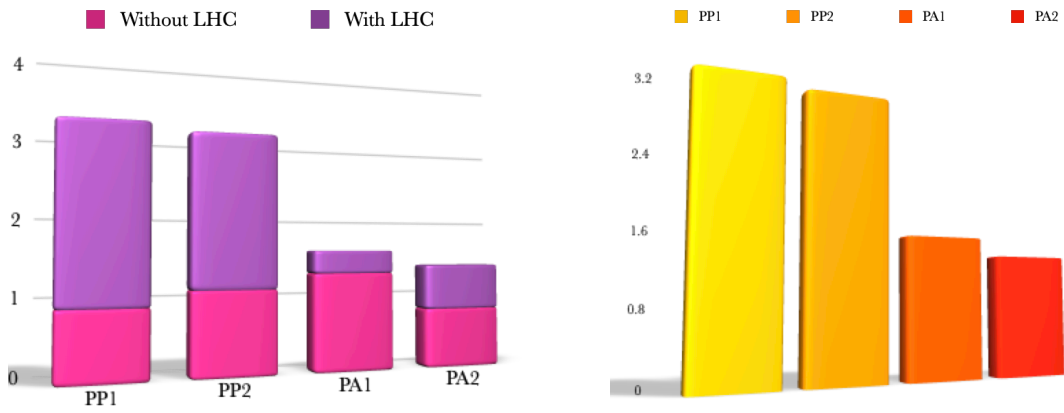
Basil



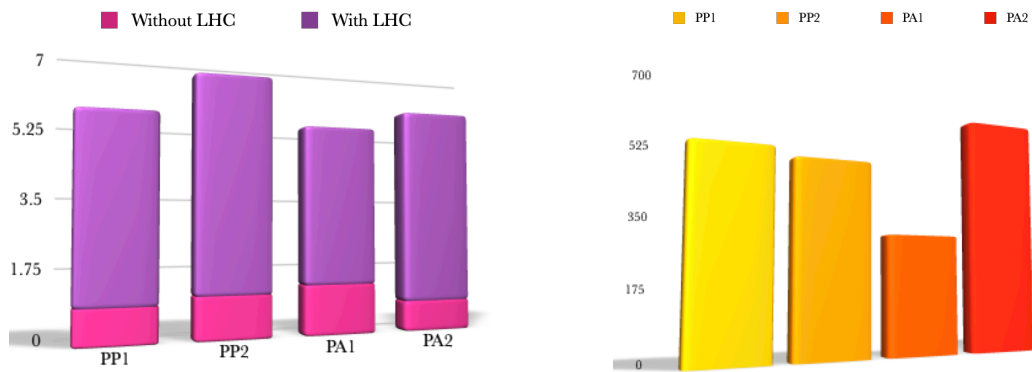
Durento



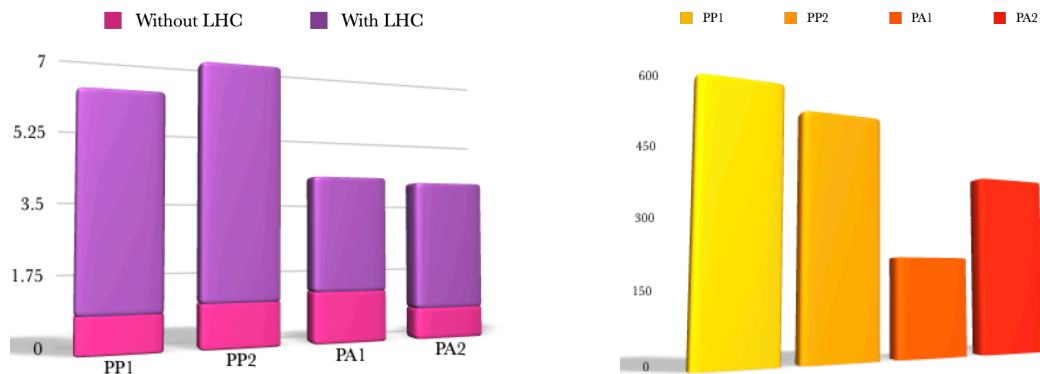
Green Tea



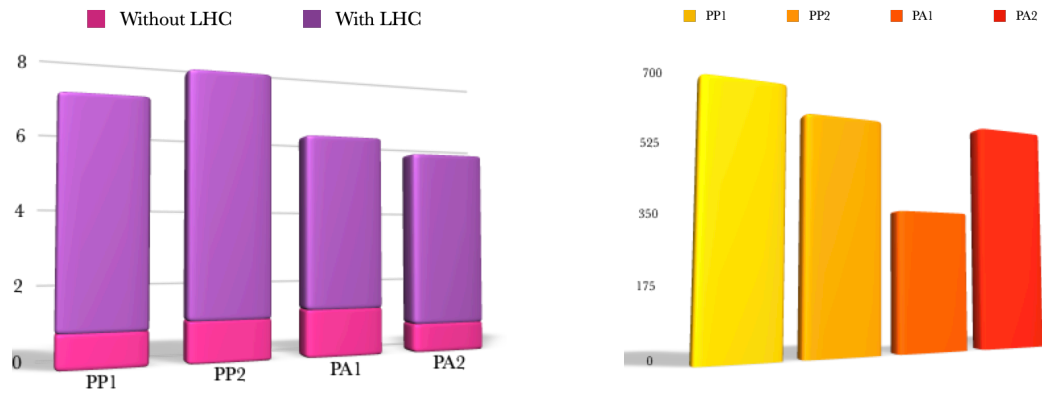
Ficus religiosa



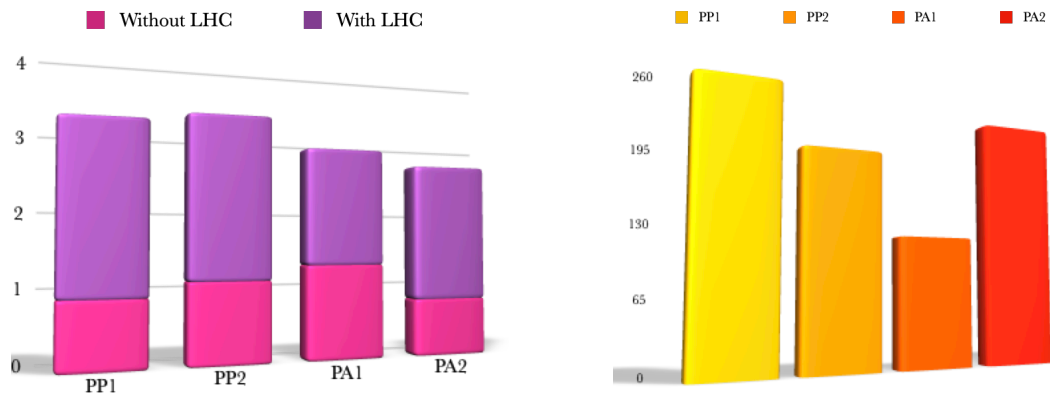
Radish



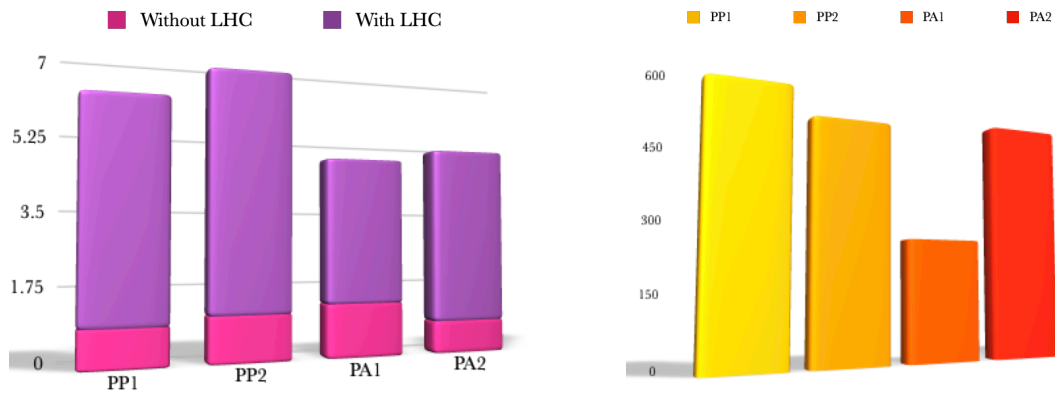
Holy Basil



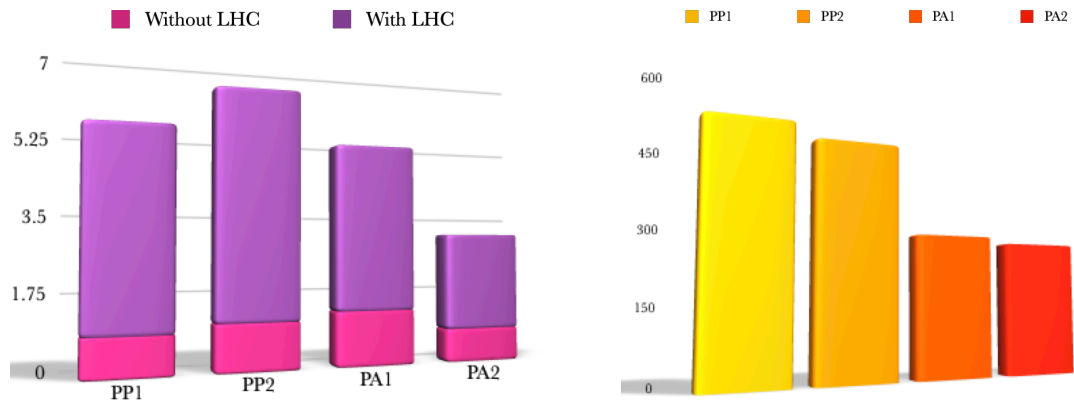
Corriander



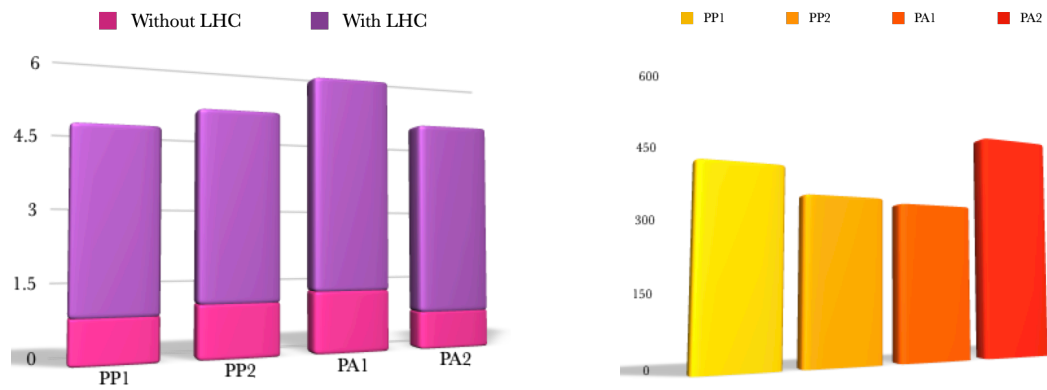
Murrayakoenigii



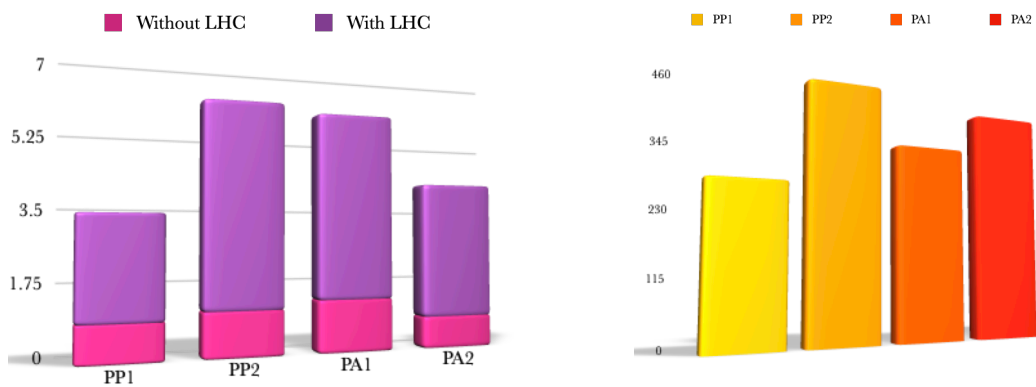
Stramonium



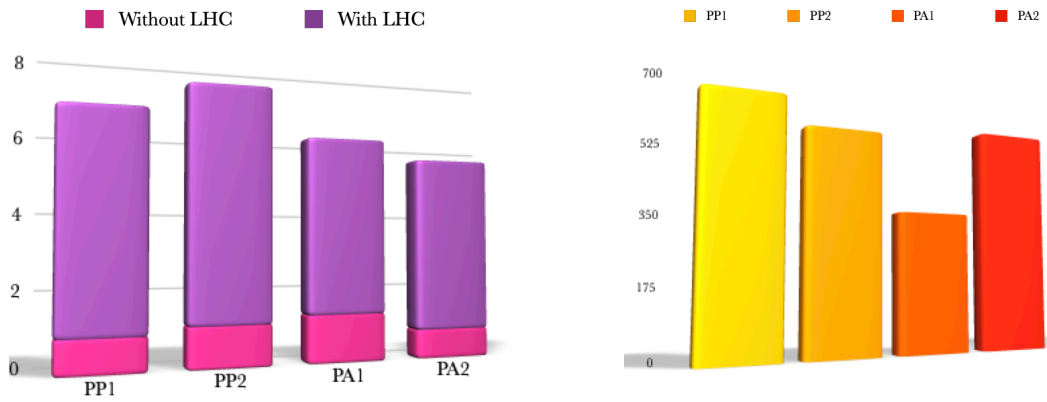
Fenugreek



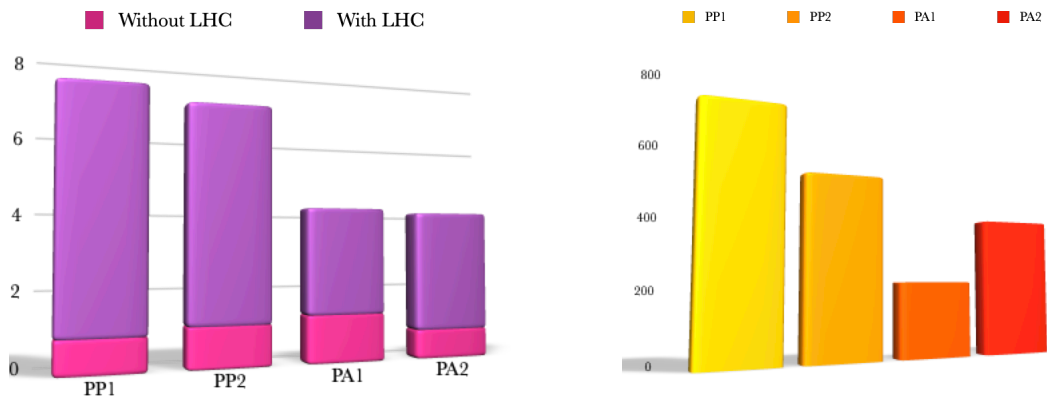
Neem



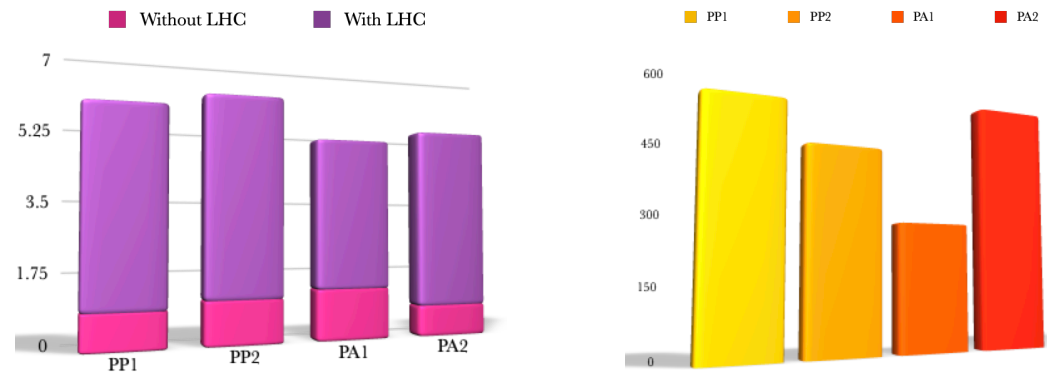
Mint



Amaranthus



Banyan



COMPARISON OF EFFICIENCIES OF SOLAR CELLS MADE USING DIFFERENT LHCs WITH PP1 AS COUNTER ELECTRODE

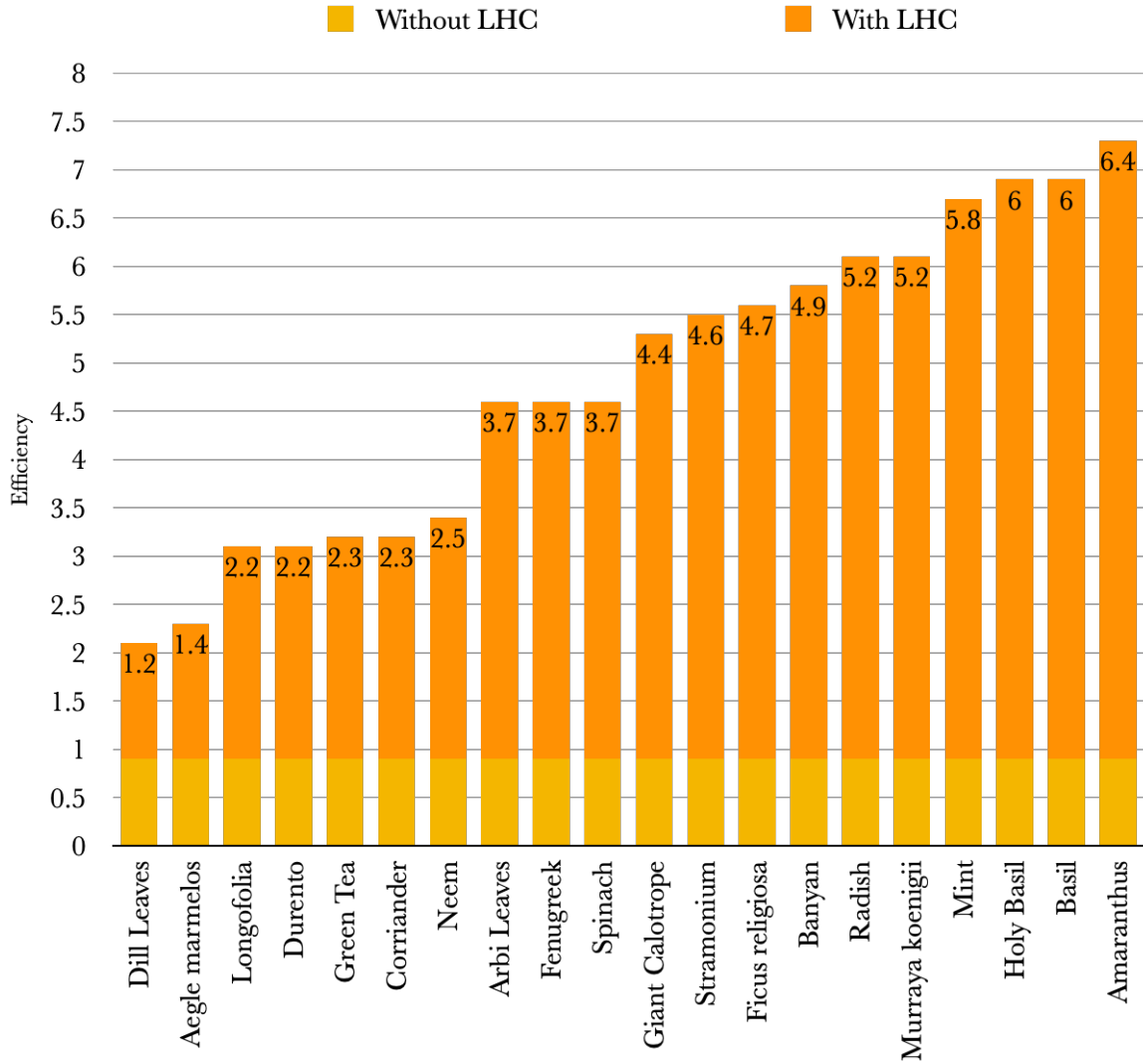


Figure 128

COMPARISON OF EFFICIENCIES OF SOLAR CELLS MADE USING DIFFERENT LHCs WITH PP2 AS COUNTER ELECTRODE

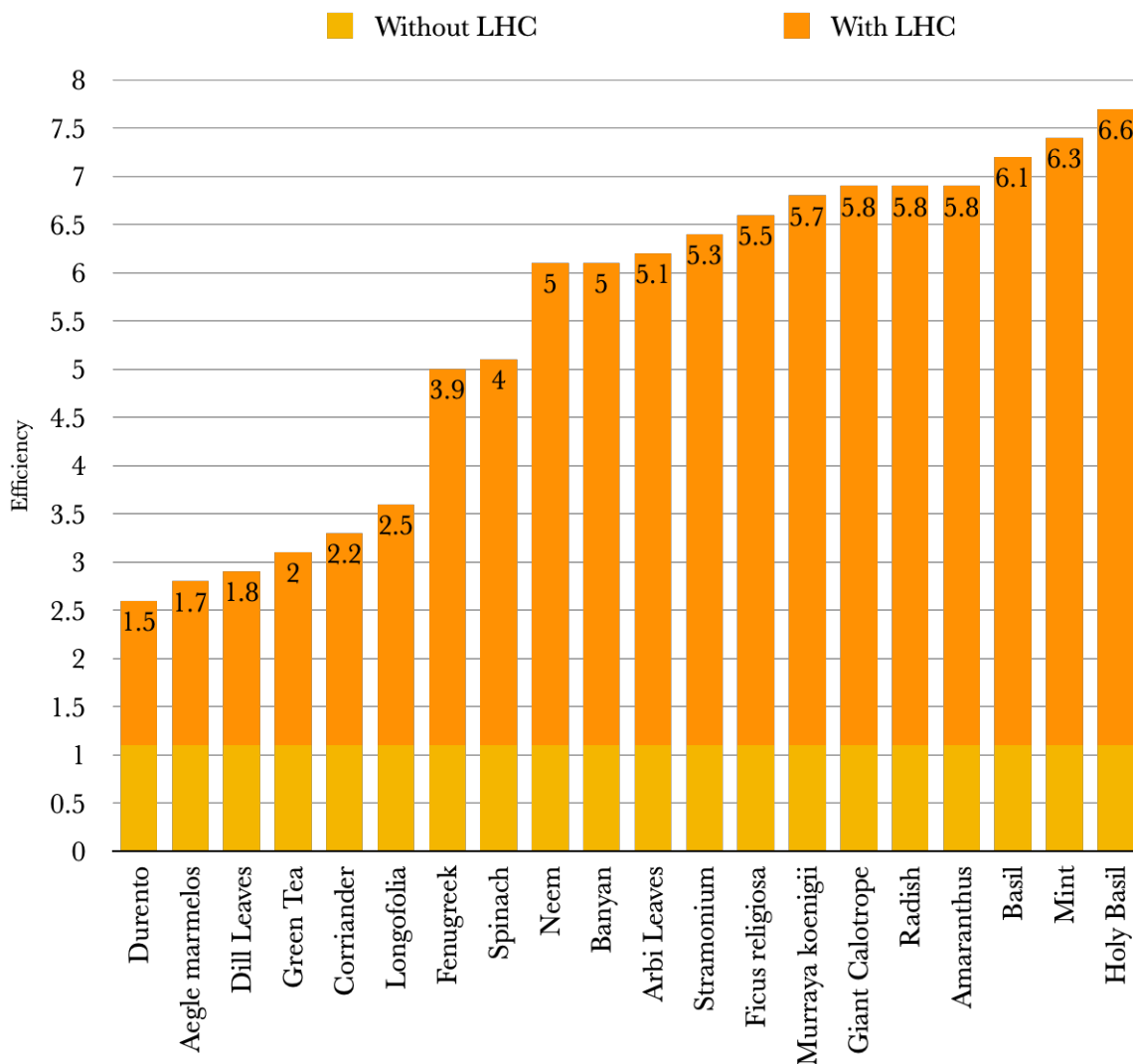


Figure 129

In the cells with combination of different LHCs with Polypyrrole (PP1), the highest efficiency was obtained with Amaranthus with the value of 7.3% followed by Basil and Holy Basil at 6.9% and Mint at 6.7%.

For Polypyrrole (PP2) the highest efficiency was found for Holy Basil at 7.7%, followed by Mint at 7.4%. Basil at 7.2% and Amaranthus at 6.9%.

LHCs from Dill leaves, Aegle Marmelos, Longofolia, Durento, Green Tea and Corriander gave the lowest efficiencies in either of the polymer samples (PP1 and PP2).

COMPARISON OF EFFICIENCIES OF SOLAR CELLS MADE USING DIFFERENT LHCs WITH PA1 AS COUNTER ELECTRODE

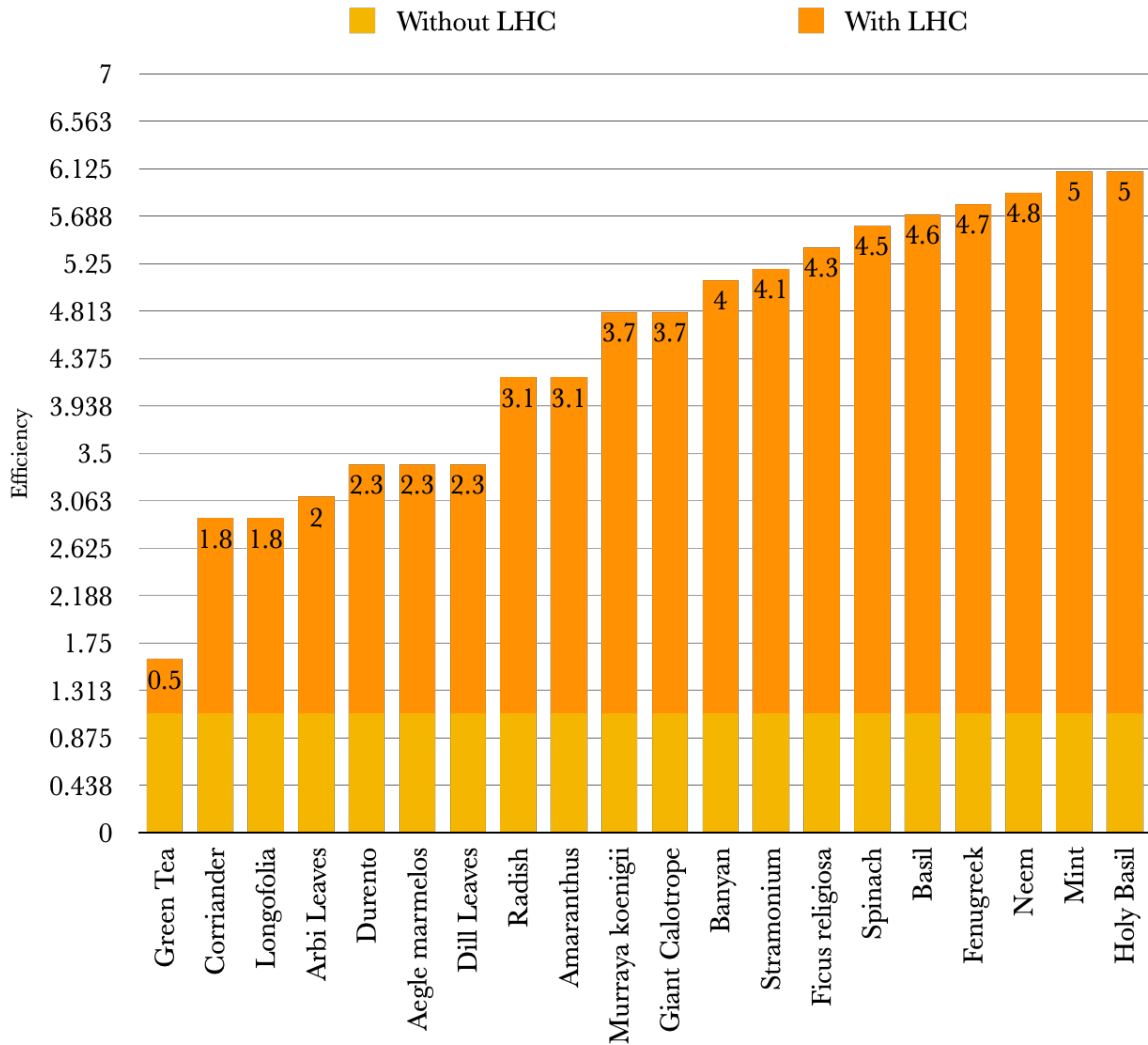


Figure 130

COMPARISON OF EFFICIENCIES OF SOLAR CELLS MADE USING DIFFERENT LHCs WITH PA2 AS COUNTER ELECTRODE

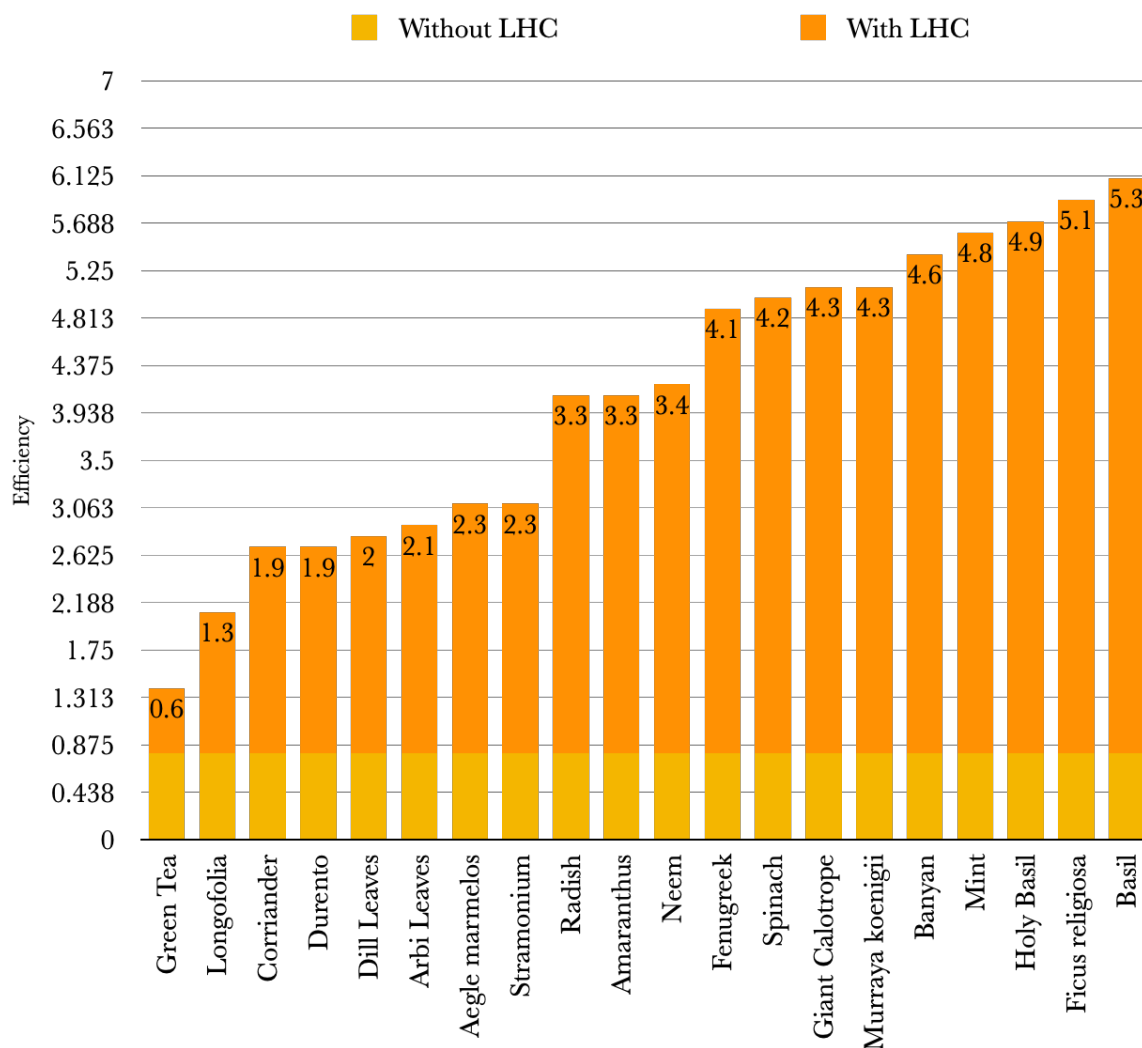


Figure 131

In the cells with combination of different LHCs with Polyaniline (PA1), the highest efficiency was obtained with Holy Basil and Mint at 6.1% followed by Neem at 5.9%, Fenugreek at 5.8% and Basil at 5.7 %.

For Polyaniline (PA2) highest efficiency was found for Basil at 6.1%, followed by Ficus Religiosa at 5.9%, Holy Basil at 5.7% and Mint at 5.6%.

LHCs from Dill leaves, Aegle Marmelos, Longofolia, Durento, Green Tea and Corriander gave the lowest efficiencies in either of the polymer samples (PA1 and PA2) in this case also.

Some of the general observation from the results is as under.

- The highest efficiency of 7.7 % was obtained for the cell with LHC from Holy Basil and counter electrode of Polypyrrole sample 2 (PP2)
- The cell with same LHC (Holy Basil) and counter electrode of Polypyrrole sample 1 (PP1) gave an efficiency of 6.9 %.
- Efficiency of cells with Holy Basil LHC and Polyaniline electrodes PA1 and PA2 was found to be 6.1% and 5.7%, respectively.
- Interestingly, the efficiency of cells with Basil LHC and Polyaniline electrodes PA1 and PA2 was found to be 5.7% and 6.1 %, respectively.
- The maximum average efficiency for all the cells with counter electrode of one polymer sample having different LHCs was found to be 5.49% for Polypyrrole - sample 2 (PP2), followed by 5.31% for Polyaniline - sample 2 (PA2), 4.66% for Polypyrrole - sample 1 (PP1) and 4.48% for Polyaniline - sample 1 (PA1).

EFFICIENCIES OF SOLAR CELLS FOR DIFFERENT LHCS (FOR ALL FOUR POLYMER SAMPLES)

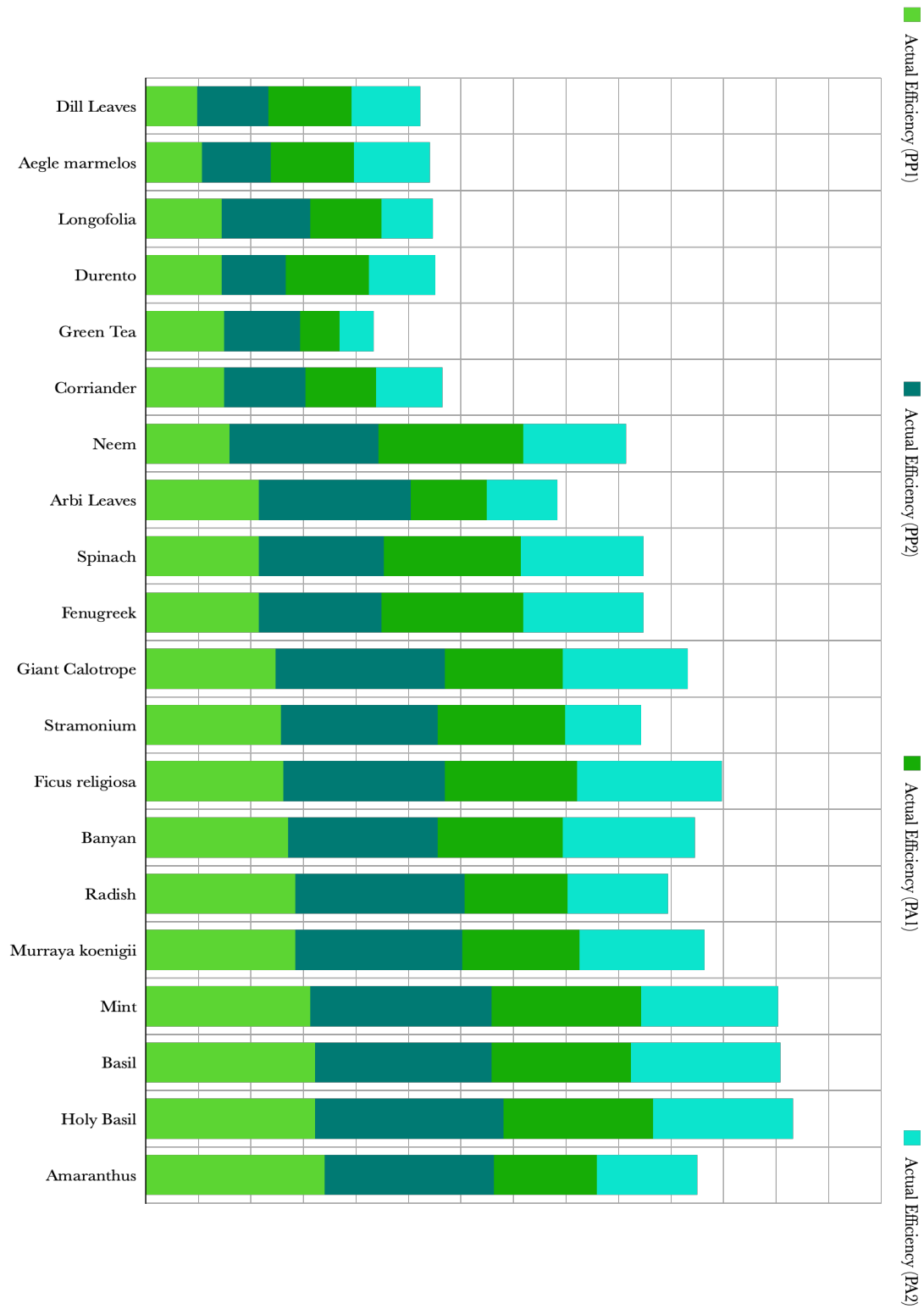


Figure 132

- The rise in efficiency of the cells with different LHCs varied from about 1.5 to 8 times in comparison to those without LHCs.
- The maximum gain in efficiency of a cell with LHC, in comparison with the same cell without LHC is about eight times for Amaranthus - PP1 combination
- For PPy 1 (Polypyrrole prepared using method 1) the combination with LHCs derived from Amaranthus gave a maximum efficiency of 7.4 %.
- For PPy 2 (Polypyrrole prepared using method 2) and LHC derived from Holy Basil, the maximum efficiency achieved was 7.6%.
- For PANI 1 (Polyaniline prepared using method 1) the combination with Holy Basil LHCs gave the maximum efficiency of 6%. PANI 1 with mint LHCs also gave the same efficiency.
- For PANI 2 (Polyaniline prepared using method 2) and Basil LHCs, the maximum efficiency achieved was 6.3%.
- The best results were found for the members of the plant family “lamiaciae” namely, Holy Basil (Tulsidhar), Basil (Tulsi) and Mint (Pudhina).
- Ficus religiosa (Peepal) and Banyan, which belong to the same family, also gave similar results.
- Spinach and Fenugreek (Methi) also yielded similar results.
- Giant Calotrope (Aakado) and Murraya Koenigii (Curry leaves) gave similar results.
- Some of the plant extracts like Coriander, Green Tea, Durrento, Longofolia, Aegle Marmelos and Dill leaves gave consistently poor results.

Thus, it can be observed that the variation in efficiencies happen for different polymer samples and are more pronounced from plant to plant. The combination of polymer-LHC also yields different efficiencies. Hence, the variation in frequency can be attributed to

- Polymer of the counter electrode
- Light Harvesting Complexes
- Polymer - LHC combination

This brings the role of polymer - LHC interaction and its impact on the efficiency of devices into focus.

The efficiency of dye-based solar cells in general depends on several factors like.

Absorption of light

The dye molecule is used to absorb light and generate electron-hole pairs, which are then separated at the semiconductor-electrolyte interface. The absorption efficiency of the dye molecule depends on its absorption spectrum. A narrow absorption spectrum means that a significant part of the solar spectrum is not utilized by the device.

The dye being the Light Harvesting Complex (LHC) in this case, its absorption was studied using UV-Vis spectroscopy. The results show multiple absorption peaks, covering a significant portion of the visible range and beyond, towards the long wavelength side. Thus, the LHCs have good absorption properties over an extended range of wavelength.

Charge recombination

The electron-hole pairs are transported to the electrodes. Charge recombination can occur at various points in the device, such as at the dye-semiconductor interface, the semiconductor-electrolyte interface, or within the bulk of the semiconductor.

The absorption energy levels in the LHCs are provided by the numerous protein molecule units present in them. These energy levels provide intermediate energy levels between the conduction band and valence band of the semiconductor i. e. TiO_2 in this case. It can thus serve as an alternate path for the charge carriers to reach the counter electrode, preventing the direct transition of the electrons from conduction to valence band.

Both the above factors highlight the role of Light Harvesting Complexes in enhancing the efficiency of the solar cells.

Electron transport

The rate of electron transport through the semiconductor depends on the mobility of the electrons, the density of states and the presence of defects or impurities in the semiconductor. The property of the electrolyte, particularly viscosity of the electrolyte also affects the transport rate of the charges while the chemical stability of the electrolyte can affect the lifetime.

The semiconductor in all the cells is the same i. e. TiO_2 , while the electrolyte is also common i.e. Iodine. They being common for all the cells are expected to impact the performance uniformly.

The polymer also plays an important role in charge transport. The dielectric properties of organic polymers are influenced by the polar groups, which are responsible for charge-transport capability including ionic conduction in the polymers.

Polypyrrole and Polyaniline are conducting polymers with high electrical conductivity. Their fibrous network promotes rapid ionic transport within the bulk matrix. There is interaction between the polymer matrix and tie chain polymers. The length of conjugation-break spacer (CBS) in matrix polymers influences the charge transport properties.

Polymer –dye interactions

As reflected by the variation in efficiencies of the cells, the interaction between dyes and polymers is a significantly factor.

The dye molecules have “Moieties”, a specific group of atoms within a molecule that is responsible for characteristic chemical reactions of that molecule. They are basically functional groups but bigger in size. The polymers also have their functional groups or atoms.

In the context of present study, the dye is in the form of **Light Harvesting Complexes**. The ion-coordinating moieties in LHCs are in the chlorophylls and xanthophylls. They form coordination bonds with metal ions, amino acid side chain ligands and other coordinating groups. These coordination bonds play the significant role of capturing light energy and subsequently transfer the excitation energy to reaction centres.

When combined with polymers, the ion-coordinating moieties in LHCs lead to the formation of hybrid systems. In combination, the ion-coordinating moieties from LHCs with polymers form antenna complexes that exhibit cooperative plasmonic effects, allowing for the enhancement of light harvesting and energy transfer processes.

The role of coordination bonds need to be emphasized. The lone pair of electrons in the nitrogen of polymers gets co-ordinately bonded to the central metal ions of the LHCs. This lone pair carries the charge and energy through the chain.

It is suggested that the resulting energy states due to the coordinating moieties also provide an alternate path for the electrons in the conduction band of the active semiconductor material i.e. TiO_2 to transit to these states and subsequently be collected at the counter electrode, instead of dropping directly to the valence band of TiO_2 , thus preventing recombination.

Some studies which support the above are as under.

- Polypyrrole and polyaniline are known for their high electrical conductivity and charge transport properties. When incorporated with LHCs, these conducting polymers can facilitate efficient charge transport, leading to improved electron mobility and reduced charge recombination, ultimately enhancing the overall efficiency. (Biswas & Drzal (2010))
- The incorporation of polypyrrole and polyaniline with LHCs can lead to enhanced light harvesting due to the ability of these polymers to provide direct conduction pathways and increased surface area for higher dye loading. This can result in improved light absorption and energy conversion efficiency. (Babel & Jenekhe 2003)
- Polypyrrole and polyaniline, when integrated with LHCs, can contribute to increased photocurrent and energy conversion efficiency. The combination of these polymers with LHCs can lead to improved light harvesting and charge separation, resulting in higher power conversion efficiency. (Gumma et al. 2021)
- The incorporation of polypyrrole and polyaniline with LHCs can lead to plasmonic enhancement, which can improve the light harvesting and energy conversion efficiency. This enhancement can be achieved through the synergistic effects of plasmonic nanocomposites and conducting polymers, leading to increased efficiency in light absorption and charge separation. (Sivaraman et al. 2006)
- Polypyrrole and polyaniline can be used as efficient counter electrodes in DSSCs, contributing to improved charge transfer and reduced recombination. The use of these polymers as counter electrodes can lead to enhanced electron conductivity and catalytic activities, ultimately increasing the efficiency. (Zahid et al. 2021)
- Researchers have demonstrated that charge recombination is reduced by the presence of "ion-coordinating" moieties on the dye. The reduction in recombination due to the moieties leads to longer electron lifetimes and higher solar cell efficiency. (Cui et al. 2001)
- The stronger coordination bonds between the Mg atom in chlorophylls and amino acid side chain ligands enhance the import of chlorophylls into the chloroplast and the assembly of light-harvesting complexes (Bhowmik et al. 2016)
- The coordination bonds between the ion-coordinating moieties and the polymer matrix facilitate the efficient transfer of excitation energy, leading to charge separation and the generation of relatively long-lived charge carriers. This process is essential for the overall efficiency of light harvesting and energy transfer in the hybrid systems (Kim et al. 2021)

- The coordination of ion-coordinating moieties with polymers in the antennae complexes enables the control of strong plasmon-exciton coupling, which contributes to the efficient capture and transfer of light energy (Singh et al. 2009)
- The interaction between dyes and polymers is evident in the use of polymer electrolytes and hole transport materials. Singh et al. (2022) and Kumari et al. (2021) highlighted the use of polymer electrolytes and composite materials in dye-based solar cells, emphasizing the role of polymers in facilitating ion conduction and charge transport.
- Polymers such as polypyrrole and polyaniline play a crucial role in facilitating ion conduction and charge transport in various applications. They are conducting polymers with high electrical conductivity and have been used in various applications, including super capacitor electrodes. (Rahimipour & Yazdani 2010).
- The nanostructured network of polypyrrole demonstrates rapid ionic transport within the bulk matrix, highlighting its role in facilitating ion conduction (Wang et al. 2012).
- The matrix – polymer interaction plays a significant role in charge transport properties, emphasizing the importance of the polymer matrix in facilitating charge transport (Jiang et al. 2018).
- In the case of polyaniline, the charge-carrier transport in ion-implanted polyaniline films near the metal-insulator transition is influenced by electron-electron Coulomb interactions, indicating the role of polyaniline in charge-carrier transport (Aleshin et al., 1996). The conductive properties of polypyrrole prepared via bio-catalysis have been compared to those of other conductive materials, demonstrating the role of polypyrrole in charge transport. The comparison highlights the charge transport properties of polypyrrole prepared via bio-catalysis, both with and without ABTS as the counter anion, indicating the influence of the polymer matrix on charge transport properties (Song & Palmore, 2005).
- The role charge transport and ion conduction in polymers is significant, particularly in the context of energy-storable materials (Stempień et al. 2015).
- The interaction between dyes and polymers involves the loading and segregation of dye molecules within the polymer matrix. It is also found that most dye molecules are segregated at the donor/acceptor interface due to the crystallinity of matrix polymers and fullerenes in polymer/fullerene solar cells. This selective dye loading at the heterojunction is crucial for efficient charge separation and transport. The segregation of dye molecules in a polymer matrix is influenced by various factors and the mechanism

of segregation involves complex interactions between the dye molecules and the polymer matrix. Several references provide insights into the principles and mechanisms underlying the segregation of dye molecules in polymer matrices.

- Jin et al. (2013) demonstrated that strong non-covalent interactions between a host polymer and guest dye molecules drastically suppress the tendency of dye aggregation, thereby allowing high doping levels. It suggests that the mechanism of segregation involves the formation of non-covalent interactions that prevent the aggregation of dye molecules within the polymer matrix.
- Chen et al. (2002) highlighted the importance of factors that affect the dispersion of a dye within a polymer matrix or its tendency to form aggregates to optimize the optical performance of polymer/dye blends. The mechanism of segregation involves the regulation of dye dispersion and aggregation within the polymer matrix to achieve the desired optical properties.
- Bergman & Hanks (2000) discussed the interfacial segregation of carbon nanotubes in a polymer matrix, which prevents molecular diffusion between the polymer matrix pellets. It suggests that the mechanism of segregation involves the formation of segregated networks within the polymer matrix, affecting the interfacial interaction between the carbon nanotubes and the polymer matrix.
- Saini et al. (2011) investigated the orientation and spectral properties of Stilbazolium Merocyanine dyes in stretched and unstretched polyvinyl alcohol films. The results indicated that the mechanism of segregation involves the molecular motion of the dye molecules within the polymer matrix, leading to the formation of excimers and changes in spectral properties.

Thus the overall performance of the device is the result of interplay between dyes, polymers and other components of the device. This is supported by the study conducted by Zhang et al. (2014) dealing with interfacial engineering for DSSCs, which involves optimizing the interaction between dyes, polymers and other components to enhance the overall performance of the solar cell. This includes the design of materials to improve charge transfer and light harvesting properties.

Fabrication defects

The dye-based devices fabricated for the study have been made using low-cost materials and simple processes. Hence, there is a possibility of the devices of being non-uniform in terms of the active layer, electrode layer, dye coverage and infiltration of the electrolyte. They can lead to additional recombination pathways or reduce the effective area of the device, thus compromising the performance.

However, such non uniformity is ruled out on a large scale for the following reasons.

- The efficiencies have not been found to be varying randomly.
- The efficiencies follow a pattern.
- The efficiency values indicate their dependence on the type (material) of electrode layer i.e. the polymer, giving consistently higher or lower values for cells having a combination of one particular polymer sample with different LHCs
- The efficiency values indicate their dependence on the type (material) of dye i.e. the LHCs, giving consistently higher or lower values of cells with a particular plant species or a family of plants.

With such uniformity in the efficiency values, the non uniformity in the physical and structural aspects comes into play. These deformities would obviously impact the resistance of the cells and their conduction properties. Hence they are reflected by the measure of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the fabricated devices. The open circuit voltage (V_{oc}), which is the maximum voltage that can be generated by a solar cell when no external load is connected. The V_{oc} provides valuable insight into the cell's ability to produce current (I), and can be used to compare the performance of different electrodes. The V_{oc} is the primary factor as the current drawn from the cell depends on it.

An analysis is presented below.

CHANGES IN VOC AND ISC WITH RESPECT TO AVERAGE VALUES IN CELLS WITH PP1 ELECTRODE

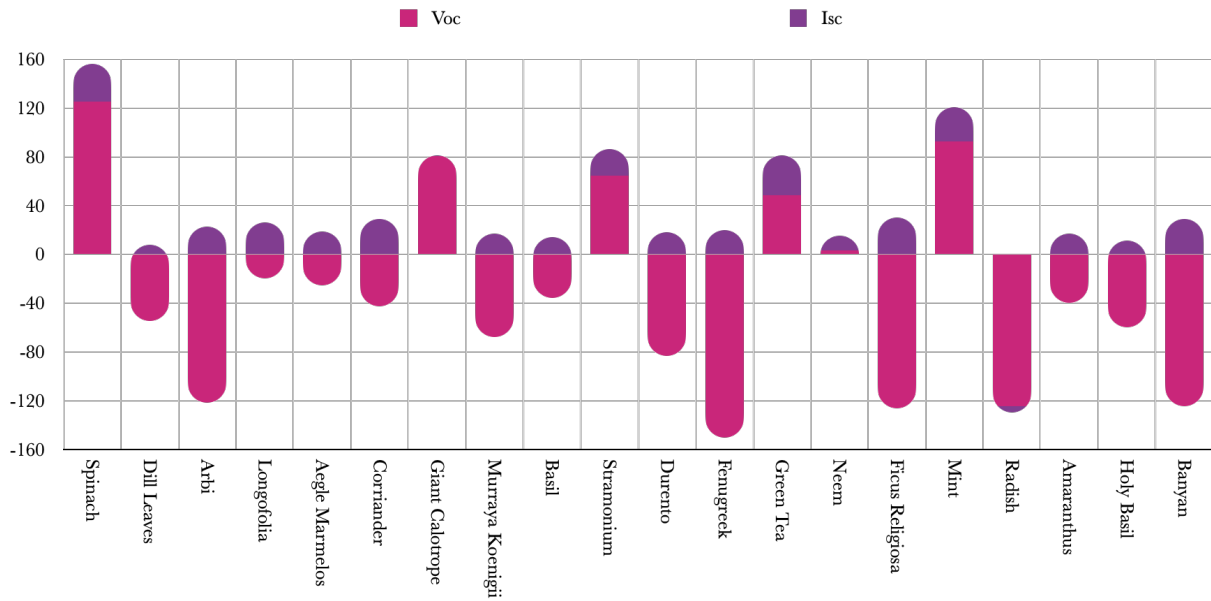


Figure 133

CHANGES IN VOC AND ISC WITH RESPECT TO AVERAGE VALUES IN CELLS WITH PP2 ELECTRODE

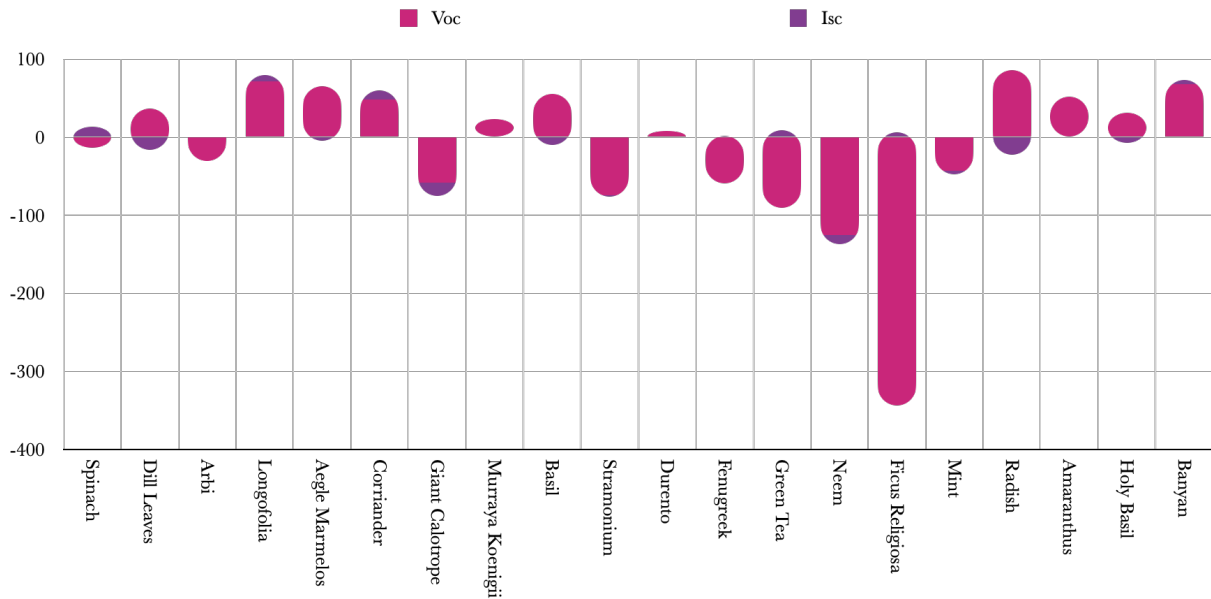


Figure 134

CHANGES IN VOC AND ISC WITH RESPECT TO AVERAGE VALUES IN CELLS WITH PA1 ELECTRODE

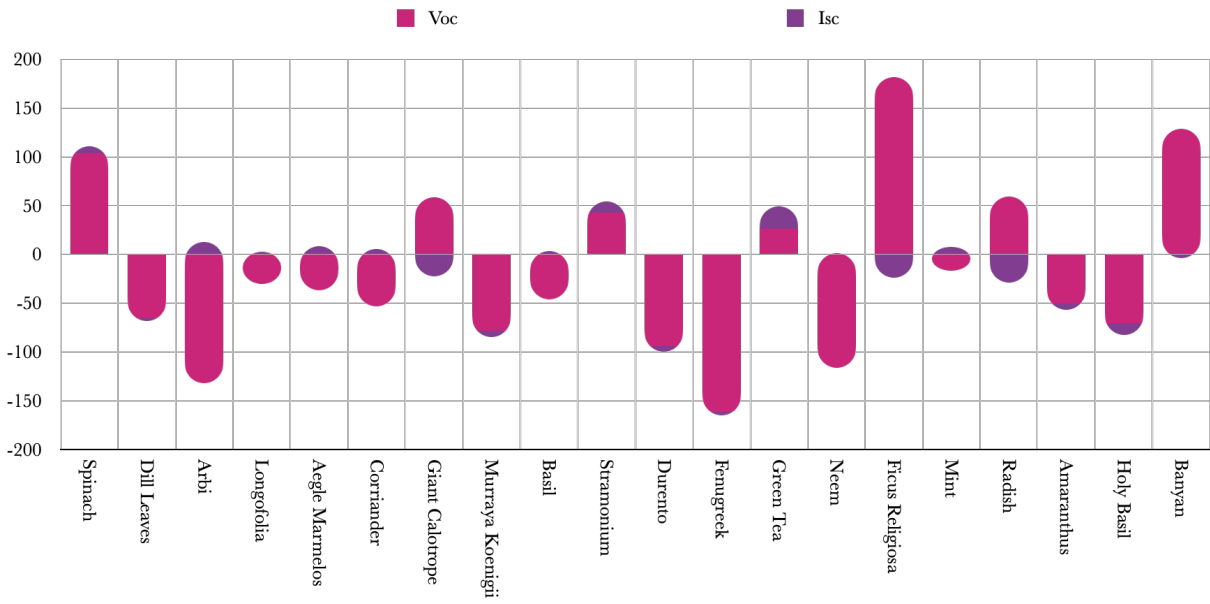


Figure 135

CHANGES IN VOC AND ISC WITH RESPECT TO AVERAGE VALUES IN CELLS WITH PA2 ELECTRODE

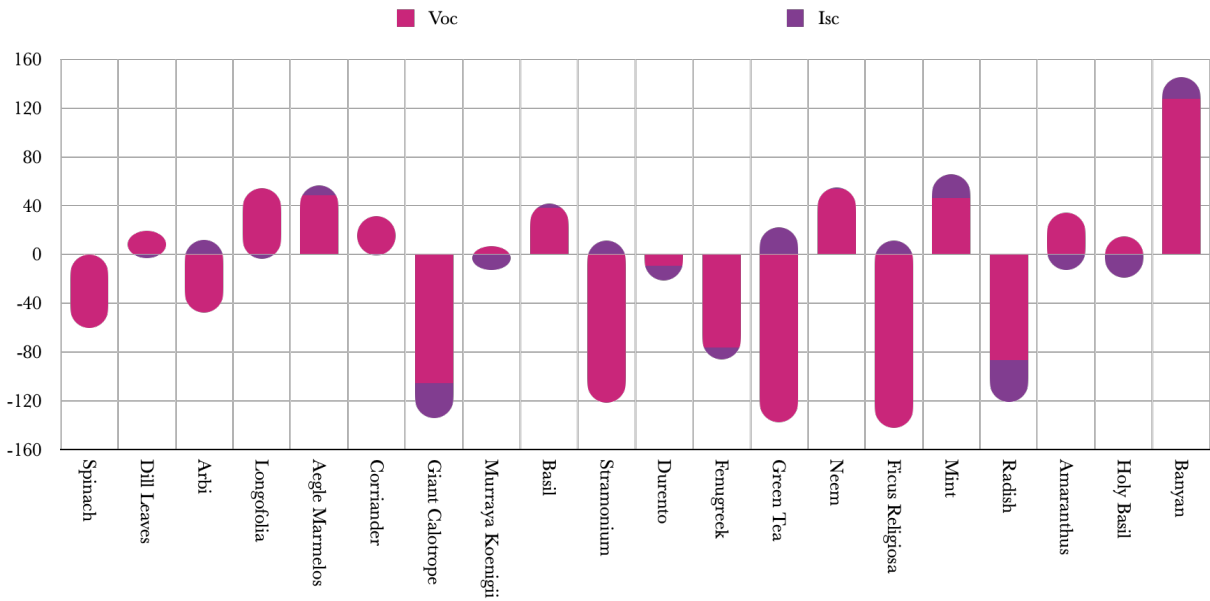


Figure 136

To gain a better understanding of the Voc values obtained for different solar cell electrodes, it is helpful to examine the difference between the Voc value of a cell and the average Voc value obtained for all the cells using that particular electrode. This difference is represented in the graphs given above and provides an indication of the cells that have the potential for optimal performance. By analyzing these graphs, the electrodes which are best suited for a particular light harvesting complex (LHC) can be identified.

It can be observed that there are few cells with Voc less than the average and a few more than the average.

- Voc values more than the average and Isc values more than the average.

PP1: Spinach, Giant Calotrope, Stramonium and Mint.

PP2: Dill Leaves, Longofolia, Aegle Marmelos, Corriander, Murraya Koeinigii, Basil, Neem, Mint and Banyan.

PA1: Spinach, Stramonium, Banyan

PA2: Aegle Marmelos, Basil, Neem and Banyan.

Since the above cells give positive deviation values of voltage and current, the probability of internal deformities is less. However, in these cases, a higher value of voltage is needed to draw the current. In this category, the low efficiencies of cells can be attributed to the effectiveness of the LHCs.

- Voc values more than the average and Isc values less than the average.

PP1: None

PP2: Dill Leaves, Aegle Marmelos, Basil, Radish, Holy Basil

PA1: Giant Calatropé, Ficus Religiosia, Radish, Banyan

PA2: Longofolia, Murraya Koeinigii, Amaranthus, Holy Basil

These combinations have given mixed results. The bar of Banyan leaves derived LHCs with Polyaniline electrodes illustrates that. Both have positive deviation of Voc but with PA1, Isc deviation is negative where as with PA2, it is positive. So even with a good potential, PA1 assisted cell could not generate higher current but PA2 could generate better value of current. This is also reflected in their efficiency and efficiency gain values. With PA1 and PA2 the efficiency values are almost similar at is 5.1 and 5.4 respectively but efficiency gains are approximately 3 times with PA1 and 6 times with PA2, in comparison to the cells without LHC.

Even with higher values of voltage, the current obtained is on the lesser side. This indicates a poor performance. However, the reason cannot be entirely attributed to internal deformities.

There is a scope for improvement. Hence the cells e. g. combination of Banyan – PA2 has better chance of improvement.

- Voc values less than the average and Isc values more than the average.

PP1: Dill Leaves, Arbi, Longofolia, Aegle Marmelos, Corriander, MurrayaKoenigii, Basil, Durento, Fenugreek, Ficus Religiosa, Amaranthus, Holy Basil, Banyan

PA1: Arbi, Aegle Marmelos, Corriander,

PA2: Arbi, Stramonium, Green tea, Ficus religiosa

In these cells, a higher current is obtained for relatively less voltage. These are supposed to be the better performing cells in terms of the structural deformities. These cells have the potential to generate better efficiencies with further improvement.

- Voc values less than the average and Isc values less than the average.

Almost one third of the cells fall in this category. Therefore, all the parameters including internal deformities can be said to be responsible for the performance.

Based on the analysis of the PP1 and PP2 electrodes, it has been observed that the PP2 assisted device exhibits relatively less variation in both open circuit voltage (Voc) and short circuit current (Isc) compared to the average value. However, when it comes to the PP1 and both the polyaniline electrodes, the observable deviations in both Voc and Isc are relatively high.

The overall results suggest that the light harvesting complexes (LHCs) having performed quite consistently, the minor variations can be attributed to the errors that could occur during the fabrication process of the cell, which is quite obvious, given that the layers of materials are spin-coated.

ROLE OF LIGHT HARVESTING COMPLEX (ENHANCEMENT OF EFFICIENCY)

One of the major reasons that we have understood from past studies and literature review for the fall of efficiency is the recombination effect. Recombination is an effect where the excited electron of the photoelectric material in its conduction band, instead of getting collected to ITO or FTO plate, it shifts to its own valance band.

The light harvesting complexes contains a series of sub protein molecules each processing a different valance and conduction bands. The presence of LHCs results into a number of energy levels within the cell matrix. These levels have been ascertained by the UV-Vis analysis in this study. Due to the presence of various bands of LHC, the excited electrons, instead of recombining to valance band of TiO_2 go to the intermediate levels. This provides a path way to the electrons to reach the counter electrode, thereby decreasing the probability of recombination. This is explained in the diagrams given below.

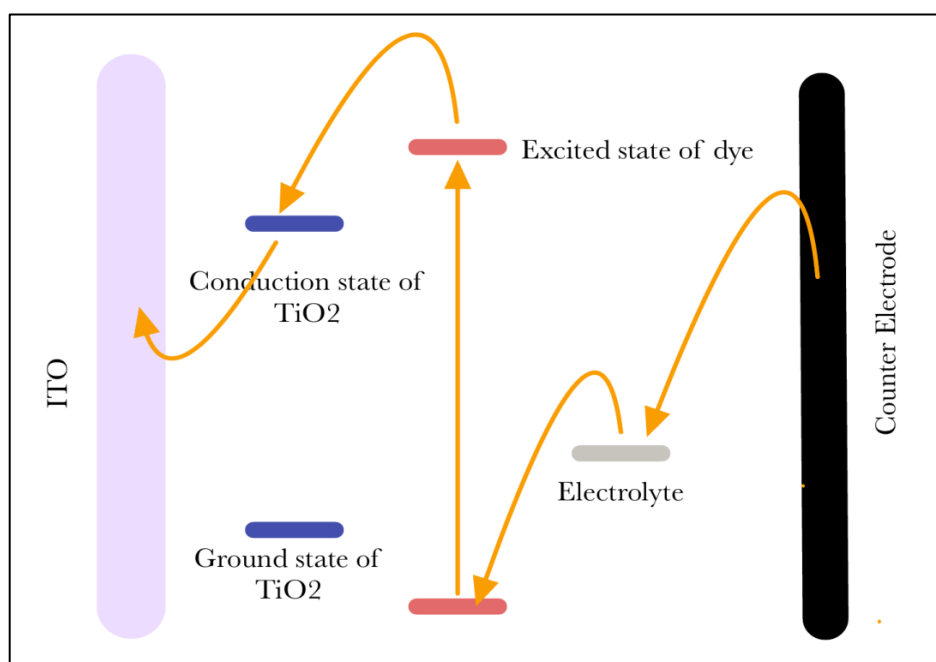


Figure 138: Ideal working mechanism of Cell

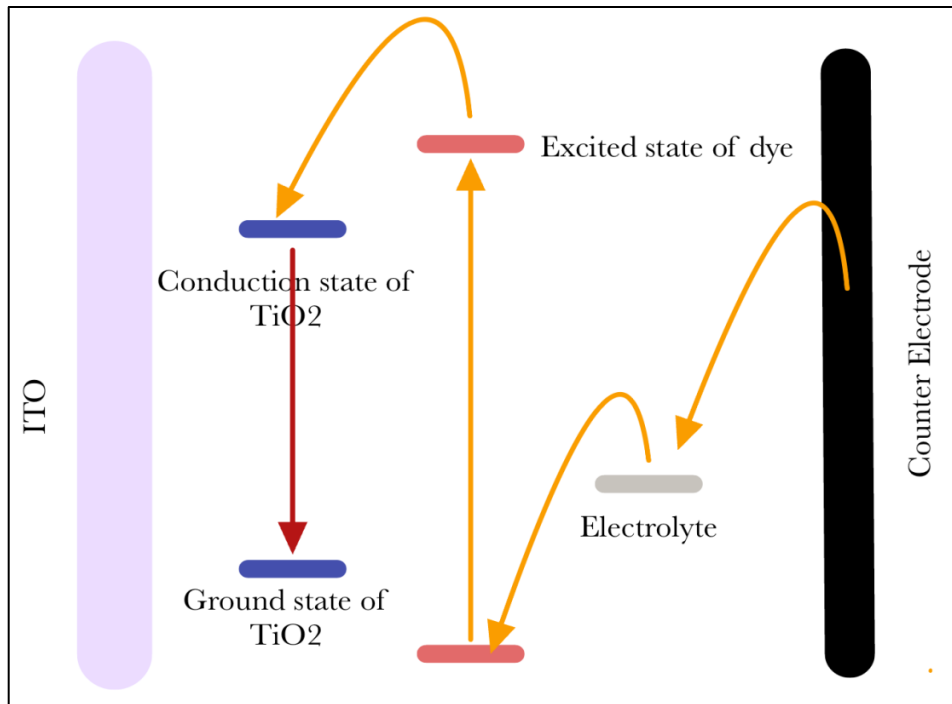


Figure 139: Recombination route

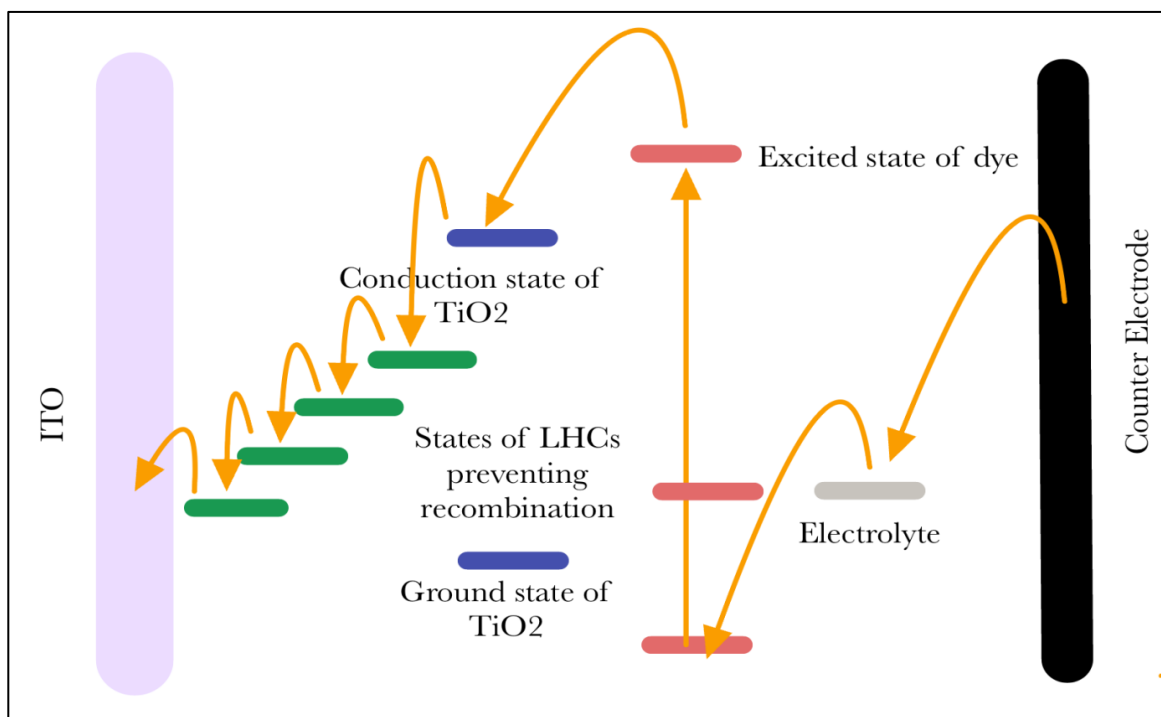


Figure 140: Incorporation of intermediate energy levels and limiting of recombination process

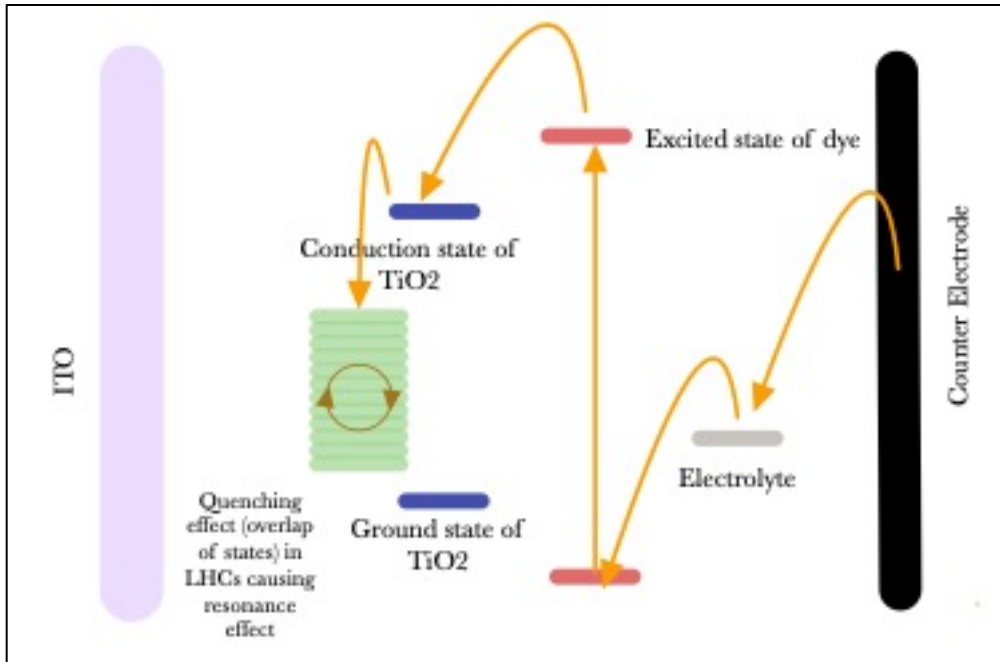


Figure 137: Overlap of energy levels leading to quenching

FUTURE SCOPE

It has been observed that the cells with PP1 electrode and LHCs extracted from Basil and Holy Basil has achieved efficiency of 6.9% which is amongst the highest values. These are the cells which give higher value of current for lower value of Voc. Hence, these cells have bright scope of improvement.

In the cells with combination of different LHCs with Polypyrrole (PP1), the highest efficiency was obtained with Amaranthus with the value of 7.3%.

For Polypyrrole (PP2) the highest efficiency was found for Holy Basil at 7.7%, followed by Mint at 7.4%. Basil at 7.2% and Amaranthus at 6.9%.

In the cells with combination of different LHCs with Polyaniline (PA1), the highest efficiency was obtained with Holy Basil and Mint at 6.1% followed by Neem at 5.9%, Fenugreek at 5.8% and Basil at 5.7 %.

For Polyaniline (PA2) highest efficiency was found for Basil at 6.1%, followed by Ficus Religiosa at 5.9%, Holy Basil at 5.7% and Mint at 5.6%.

They also provide good scope of improvement.

Areas that can worked upon in future:

In this work, the TiO₂ and polymer layers in the cells have been applied using spin coating technique which is not one of the best techniques of growing a uniform layer. If a technique which can give uniform layer is used, it can result in decrease in deformities and can reduce the resistance of the device.

Before using TiO₂ for spin coating, it was calcined at high temperature so that it becomes mesoporous. But the formulation of ink in terpeneol may cause aggregation which might not allow the LHCs to be absorbed well. So an alternate material like ZnO, which is mesoporous at lower temperature might allow the LHCs to be absorbed better than TiO₂, which is a matter of investigation.

Generally TiO₂ is calcined after deposition on the cellulose substrate so that it can retain its microporosity. But in this case the substrate which is the cellulose sheet is found to be thermally stable up to 110°C whereas the TiO₂ has to be calcined around 400° C in order to gain its microporosity.

This will require certain additives like the cross linking polymers to be added to cellulose gel before casting it into sheets, to improve the thermal stability of the substrates.

One of the future scope of working lies in fabrication of multi-layer cells. The LHCs that have given highest efficiencies can be deposited layer by layer on a particular electrode complimenting the energy levels and thereby limiting the recombination. But this is a matter of investigation as our research findings have suggested that more energy levels can lead to quenching. Multiple polymer layers with a proper optimization of layer thickness might also give rise to higher efficiency.

If the above parameters are worked upon, cells with higher efficiencies in this work might achieve still higher values.