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(Research Article)

Development of an organic solar cell using natural dyes for photovoltaic solar panels

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Abstract

This research endeavors to create and produce an organic solar cell employing natural dyes as photoactive materials. The study follows a systematic approach, comprising the identification of suitable dyes, construction, and testing of Grätzel-type cells, and evaluation of the electrical output in relation to the cell's composition. Subsequently, a comparative analysis is conducted to gauge the efficiency of the cell based on the type of natural dye employed. The resulting solar cells demonstrated voltage outputs ranging from 607 mV to 646 mV. The natural dyes are ranked in ascending order of voltage production, with beet juice yielding the lowest and Guinea sorrel yielding the highest output. Notably, the fabricated cells achieve their peak voltages after approximately fifty-two minutes of continuous solar irradiation, following one minute of exposure.

Keywords : Organic Solar Cell; Natural Dye; Grätzel-Type Cell; Solar Irradiation; Voltage

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1. Introduction

Conventional energy sources like coal, oil, peat, and natural gas have played a crucial role in energy production, but their continued use has resulted in environmental pollution and dwindling reserves. Additionally, silicon semiconductor-based technologies used for exploiting these resources have faced numerous challenges, including high production costs, limited applications, and declining profitability.

The growing global energy demand, rising at an approximate rate of 4% per year, presents a significant challenge in meeting future requirements [1]. Furthermore, the continued reliance on conventional energy sources and increasing industrialization contribute to greenhouse gas emissions, posing a severe environmental threat.

In response to these concerns, researchers have shifted their focus to developing a new generation of solar panels that harness photovoltaic (PV) energies. This exploration aims to create sustainable alternatives to replace conventional energy sources.

Driven by these motivations, our study concentrates on designing an organic solar cell using natural dyes sourced from local plants. Specifically, we aim to develop an organic Grätzel-type cell [2], an alternative to traditional semiconductor-based cells.

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In semiconductor materials, the exciton is characterized by an absorption peak at an energy level lower than the material's bandgap energy [3]. This property plays a fundamental role in the operation of our organic solar cell, making it a promising avenue for efficient energy conversion.

2. Materials and methods

For the development and fabrication of the organic solar cell using natural dyes, the following materials were utilized:

- Thin Conductive Oxide (TCO) glass,
- Porous nanocrystalline layer,
- Porous nanocrystalline layer,
- 3D printer,
- 15 cm x 15 cm square glass plate covered with aluminum foil.

In most studies focusing on Dye-Sensitized Solar Cells (DSSCs), the semiconductor is deposited on a glass substrate previously coated with a thin, conductive, and transparent metal oxide layer (TCO, "Thin Conductive Oxide"). In the field of DSSCs, this layer typically consists of fluorine-doped tin oxide (SnO_2: F, FTO), while some studies have also utilized tin-doped indium oxide (In_2O_3:Sn, ITO) [4]. The TCO glass must be highly transparent to allow as much light as possible into the cell, and it must also possess good conductivity to facilitate the transport of electrical current during the cell's operation. Hence, a compromise must be found regarding the thickness of the conductive oxide layer since a thicker layer provides better conductivity but reduces transparency.

2.1. The Porous Nanocrystalline Layer

The porous nanocrystalline layer plays a crucial role in a Dye-Sensitized Solar Cell (DSSC) as it significantly influences its performance through the collection of photons (via the adsorption of the dye on its surface), charges separation (via its electronic configuration), as well as charge transport and recombination. Various semiconductor materials have been tested and used in the field of DSSCs. Only a few oxo-metallic semiconductors, such as tin dioxide (SnO_2), zinc oxide (ZnO), or titanium dioxide (TiO_2), meet these conditions and remain stable when in contact with specific electrolytes, avoiding corrosion and oxidation issues [5].

For our experimentation, we have opted to use titanium dioxide as it is a leading semiconductor. It is cost-effective and exhibits broad absorption capabilities, spanning from ultraviolet to visible and infrared wavelengths. With a bandgap of 3.2 eV, compared to silicon's 1.12 eV, it can efficiently capture electrons from the dye. Although titanium dioxide is challenging to procure in our region, we found an alternative form in certain commercial products that contain nanoparticulate quantities of this material, particularly in items such as sunscreens and toothpaste, where it serves as an anti-UV agent. The exact percentage of this material in such products is unknown to consumers, which prevents any statistical study of its efficiency. Consequently, we utilized "Sensodyne" toothpaste as the semiconductor due to its composition containing a significant proportion of titanium dioxide (TiO_2) [6].

2.2. The Dye

The dye is the photoactive element that absorbs incident light and subsequently generates a pair of free electron-hole charges. The ideal dye should absorb a significant portion of the solar spectrum and enable efficient electron injection into the semiconductor's conduction band (for this purpose, the excited state of the absorbing dye molecule should be positioned above the semiconductor's conduction band edge), while also exhibiting high photochemical stability.

Natural organic dyes originate from plants and can be extracted from leaves, roots, or barks of dye-yielding plants. The corresponding chemical families include flavonoids, indigoids, carotenoids, tannins, betanins, chlorophylls, betacyanins, and anthocyanins.

- For our experimentation, we utilized three dyes:
- The red dye from beetroot juice,
- Beetroot red (Beta vulgaris subsp. Vulgaris) is a red pigment belonging to the betacyanin family, and it is the predominant dye in beetroot juice, known by its industrial designation E162.
- The red dye from "Bissap" guinea sorrel juice,

- Bissap juice is obtained after infusing the calyxes of Hibiscus sabdariffa flowers, which is a herbaceous plant of the Malvaceae family. Its red coloration is attributed to the presence of anthocyanin at 58.60 mg/g of dried leaves [7]. Its classification as a dye is E163.
- The red dye from "Jatropha Rouge" juice,
- It is extracted from Jatropha, which belongs to the dicotyledonous plant genus of the Euphorbiaceae family.
- The obtained dye juices are nearly identical and are presented as indicated in the figure below.

Figure 1 Natural dye juice obtained

2.3. The Electrolyte

The electrolyte plays a crucial role in the cell's operation as it facilitates the regeneration of the dye. It must meet several conditions to ensure the stability of the cells. Specifically, it should not be toxic, possess a low vapor pressure, have a boiling point above 70°C, and be minimally reactive, stable, and cost-effective. Aqueous systems fulfill these criteria, with the most commonly employed and efficient mediator being the iodine/iodide couple (I^{3-}/I).

For our experimentation, we will be using a saltwater electrolyte. It was prepared by dissolving iodized salt in water until saturation.

2.4. The Counter-Electrode

The counter-electrode serves to complete the Dye-Sensitized Solar Cell (DSSC) circuit compared to the works of H. Alesa & al. [8]. Its role is to recover the electron that has been injected by the dye and to regenerate the reduced form of the redox pair from the oxidized form, thus closing the DSSC's electrical circuit. The counter-electrode in our cell is fabricated using a 15 cm x 15 cm square translucent glass. As the glass is not electrically doped, we added aluminum strips to enhance conductivity.

A comprehensive list of the materials used is provided in the table below :

Table 1 List of Materials Used

Materials	**Roles**
Two glass plates of size 15 cm x 15 cm	electrodes
Titanium dioxide TiO2 (From Sensodyne toothpaste)	Semi-conductor
Beetroot (Beta vulgaris subsp. Vulgaris, dye E162) [36] Guinea Sorrel (Hibiscus sabdariffa) (dye E163) [36] Red Jatropha (Jatropha gossypifolia)	Dye
Saltwater	Electrolyte
Aluminum foil	Improve conductivity

Electrical multimeter	Measure the voltage
Moulinex	Grind the beetroot
Sieve	Filter the obtained solutions
3D printer	Printing of the Cell Supports
A cup/glass	Collect the solutions

Below, we present the image of the 3D p rinter (Figure 2) that enabled us to obtain cell support using recycled plastic material filaments.

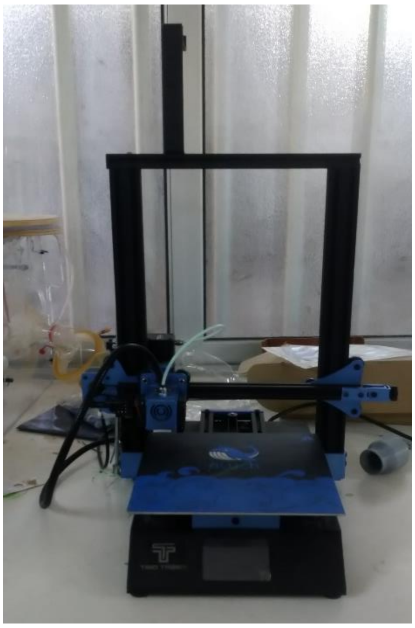


Figure 2 3D Printer

3. Method

In order to harness maximum solar energy, the development of new materials as raw materials and production systems allows for the advancement of more efficient photovoltaic solar panels. This new generation of modules encompasses, based on their constructive arrangements : bifacial photovoltaic solar panels, and based on the nature of photovoltaic cells:

- Modules with perovskite cells,
- Modules with multi-layer cells,
- Modules with organic cells.

Our study focused on photovoltaic solar panels composed of organic cells. The innovation introduced lies in the use of locally-sourced natural dyes in cell construction to enhance the efficiency of solar cells. We relied on the model of Grätzel solar cells [9].

The realization of this organic photovoltaic solar cell with natural dyes involved several steps summarized below:

- Extraction of natural dyes,
- Formation of the monocrystalline layer,
- Construction of the electrodes,
- Addition of the electrolyte and assembly of the cell.

3.1. Extraction of Coloring Pigment

There are several techniques for extracting pigments, including infusion, filtration, pressing, decoction, enfleurage, maceration, and hydrodistillation. Considering the morphology of the plants and the available equipment, we used pressing for the extraction of beetroot juice and infusion for the extraction of guinea sorrel and red jatropha juice. The three extractions of the red pigment, responsible for solar light absorption, were performed as follows:

Extraction of red pigment from beetroot is carried out as follows:

- Wash the beetroots and remove the leaves and roots,
- Peel the beetroots and cut them into small pieces,
- Grind the beetroots in a blender,
- Collect the sieved juice of crushed beetroots (filtration) in a beaker.

Extraction of red pigment from guinea sorrel: the extraction of the dye is done by infusing dried calyxes of guinea sorrel in hot water. To obtain a good concentration, half a liter of water is required for 25g of calyx. The extraction is performed by boiling, mixing, and filtering to obtain a solution without aggregates.

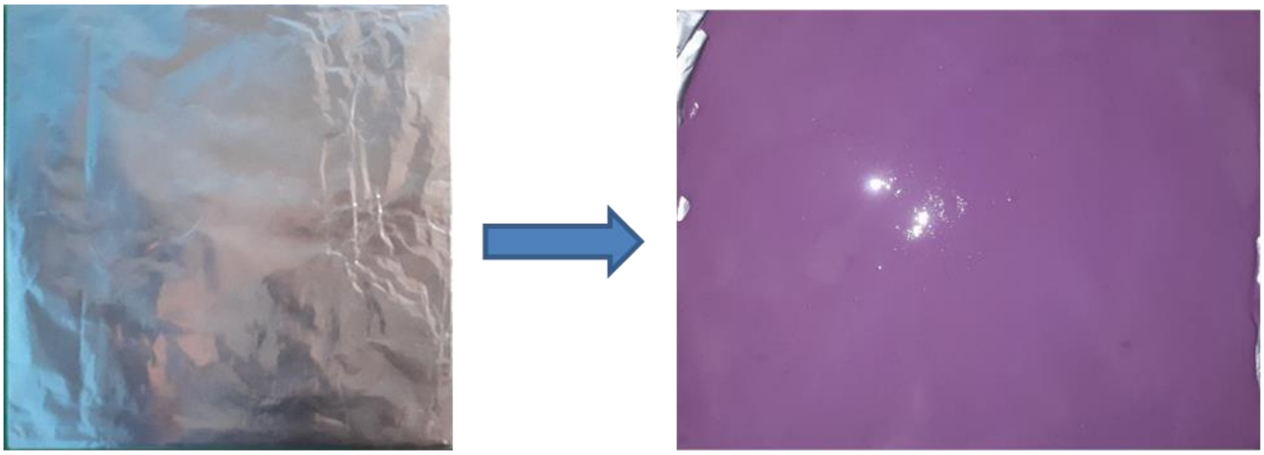
Extraction of red jatropha juice: the extraction of the dye is done by infusing Jatropha leaves in hot water. To obtain a good concentration, half a liter of water is required for 25g of Jatropha. The extraction is carried out as previously mentioned by boiling, mixing, and filtering to obtain a solution without aggregates.

3.2. Formation of the Monocrystalline Layer

This step involves mixing the dye with titanium dioxide (TiO_2). It must be done in a way to obtain a final pasty texture. The result of this operation constitutes the desired monocrystalline layer.

3.3. Construction of the Electrodes

This involves depositing the monocrystalline layer obtained with titanium dioxide on a translucent glass covered with aluminum foil to form the cathode. To obtain the anode, aluminum foil is simply attached to the ends of the other glass. The aluminum foil on the edges of the glass plates ensures the conductivity and maneuverability of the cell.



(a) Electrodes covered with Aluminum Foil

(b) Electrode covered with the toothpaste-colorant mixture.

Figure 3 Electrode fabrication

3.4. Addition of Electrolyte and Assembly of the Cell

Saltwater is added to the anode, and the cathode is then placed above the anode, allowing the saltwater and aluminum to come into contact with the mixture (the semiconductor dye, which is titanium dioxide (TiO_2)). Our Grätzel cell consists of a cathode and an anode, both made of glass, which we rendered conductive by covering their edges with a thin layer of aluminum foil. The semiconductor layer is composed of titanium dioxide (TiO_2), with a sensitizer or dye adsorbed on its surface. Between the two glass plates lies an aqueous solution: the electrolyte.

This configuration constitutes the organic cell, as shown in the figures below.

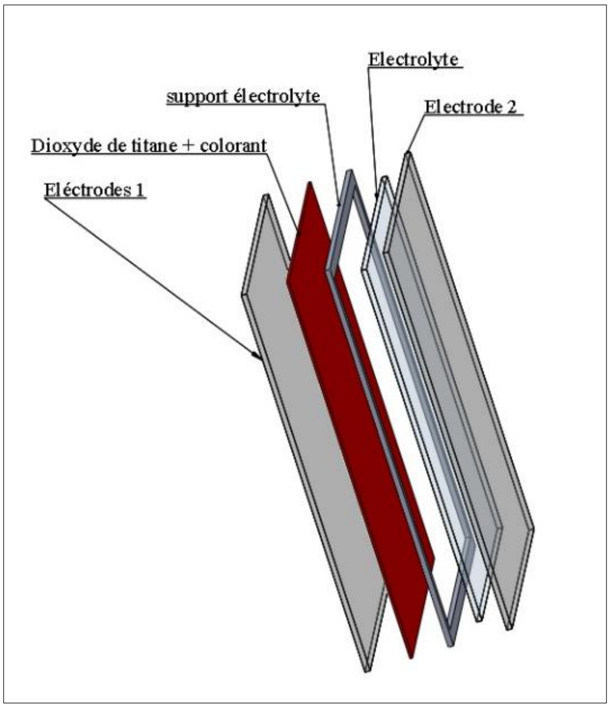


Figure 4 Exploded View of the Composition of the Elaborated Organic Cell [11]

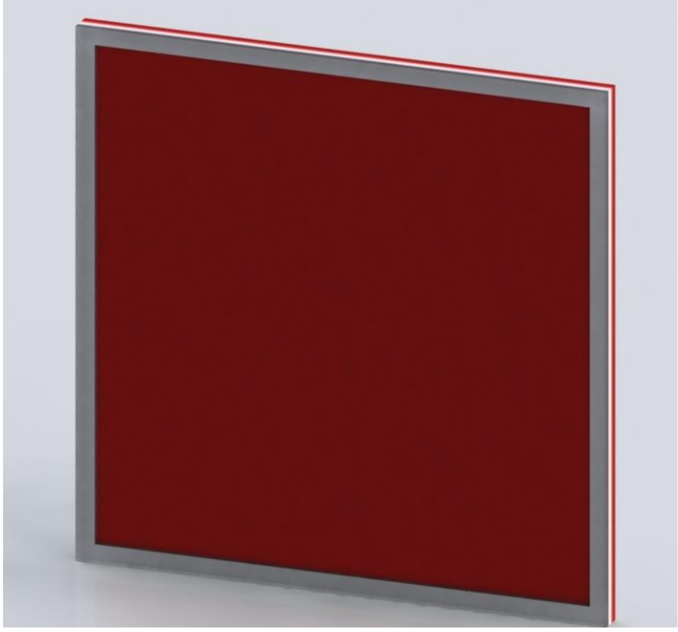


Figure 5 Organic Solar Cell with Natural Dye Obtained [12]

The operation of a Grätzel cell follows a regenerative cycle, wherein an incident photon traverses the glass and the semiconductor layer until it reaches the dye, where it is absorbed. The dye loses an electron and becomes an S+ ion. This electron is then injected into the conduction band of the semiconductor layer, which is only possible if the energy of the electron produced by the dye is high enough and corresponds to that of the semiconductor's conduction band. The injected electron then passes through the semiconductor layer to reach the anode and flows through the external circuit to the cathode. At the cathode, this electron, which has lost energy during its journey, recombines with the electrolyte's oxidizing agent, the triiodide ion, to form the iodide ion I^-, which reacts with the oxidized dye and provides it with an electron. This completes the cycle, returning the system to its initial state, and forms a loop that allows for an electric circuit. The positioning of energies in the system determines the voltage between the electrodes.

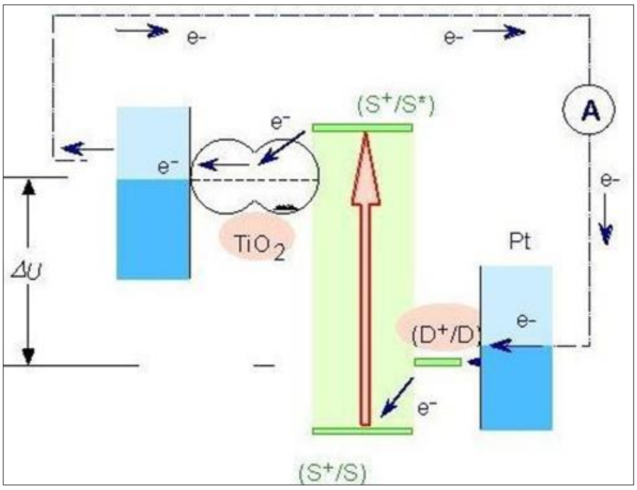


Figure 6 Operating Principle of the Grätzel Cell [8], [9]

The closed cycle described above is governed by the following chemical equations:

$$\begin{cases} S + h\nu \rightarrow S* & (1) \\ S* \rightarrow S^+ + e^- & (2) \\ I_3^- + 2e^- \rightarrow 3I^- & (3) \end{cases}$$

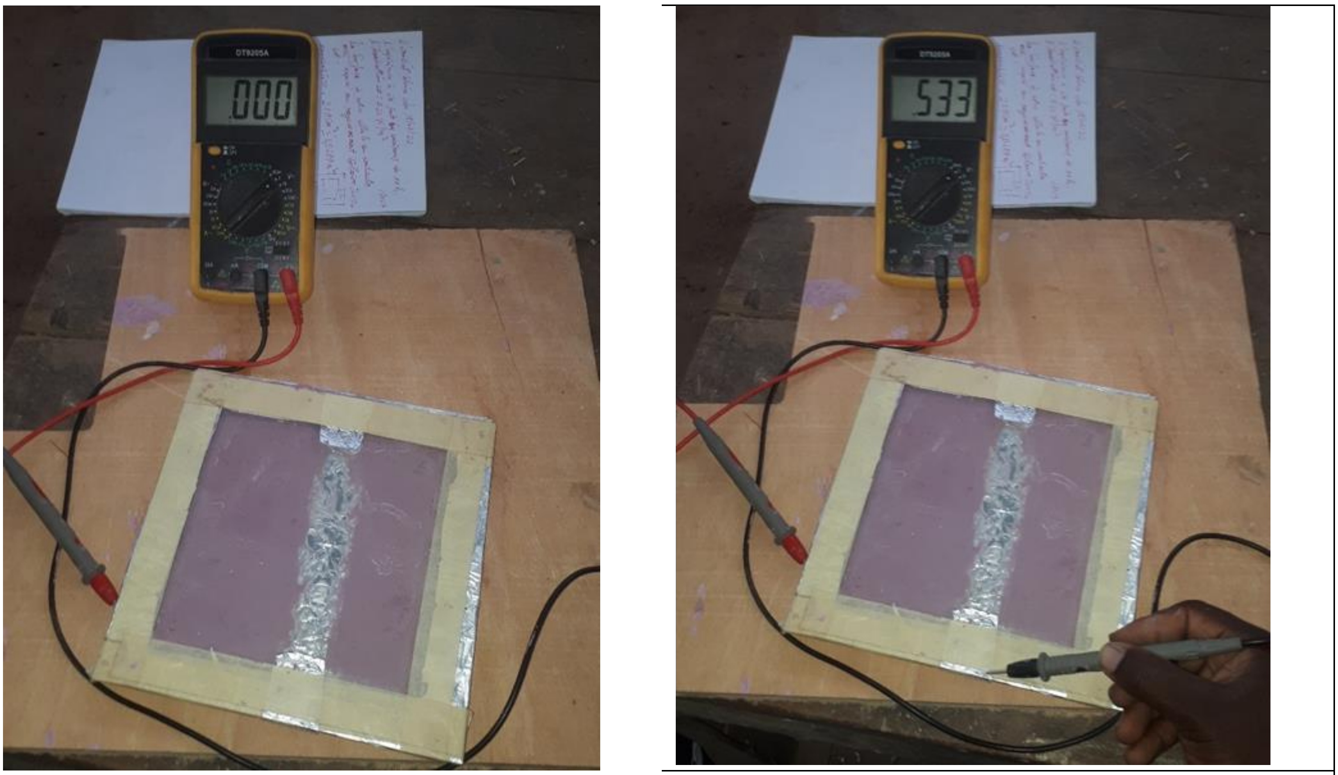
$$2S^+ + 3I^- \rightarrow 2S + I_3^- \quad (4)$$

- Excitation of the dye at the anode.
- Injection of the electron into titanium dioxide (TiO_2) at the anode.
- Transport of the electron through reduction of iodide ion towards the cathode.
- Regeneration of the dye at the anode.
- To obtain the experimental values such as the irradiation duration and the voltage delivered by the cell, we set up a measurement assembly as shown in the photos (a) and (b).

An organic solar cell is primarily composed of an organic semiconductor, and it is essential to recall the principle of its functioning to obtain the desired physical quantity.

When a material absorbs a photon, the energy of that photon is transferred to an electron in the material. The electrons most likely to receive this energy are those in the outermost atomic layer, i.e., the valence electrons. These electrons participate in the cohesion of atoms and cannot spontaneously engage in electron conduction. When the electron receives energy from the photon, it is promoted to a higher energy level if the transition is allowed. This possibility is an intrinsic parameter of the material. Therefore, the final energy state of the electron must be free and allow this phenomenon to occur. If this is the case, the electron joins the so-called conduction band. The electrons in this band are entirely delocalized and facilitate electron conduction from one atom to another. The valence and conduction bands are separated by the "band gap." This gap defines forbidden electronic transitions, corresponding to wavelengths of photons whose energies do not allow the promotion of an electron to a higher energy level.

Semiconductors have a band gap ranging from 0.1 eV to 3 eV. As a result, the material can absorb solar photons and promote electrons into the conduction band without being rapidly de-excited in the form of heat. These absorption and conduction properties make them excellent candidates for solar cell applications [10].



a) Open Circuit Voltage Measurement

(b) Voltage Measurement Across the Cell

Figure 7 Measurement of Voltage Obtained by the Natural Dye Cell

4. Results and discussions

After exposure to timed irradiation, we recorded voltage values over time, at 2-minute intervals for approximately sixty (60) minutes. This allowed us to collect data for each natural dye. The obtained voltage values are recorded in the following Table 2:

Table 2 Voltage values obtained as a function of irradiation time, Day 1

Irradiation Time (minutes)	**Voltage (mV)**	**Irradiation Time (minutes)**	**Voltage (mV)**
0	570	30	607
2	571	32	607
4	573	34	608
6	575	36	610
8	578	38	614
10	579	40	618
12	815	42	622
14	585	44	625
16	587	46	626
18	587	48	628
20	589	50	628.1
22	591	52	628.2

24	592	54	628.3
26	595	56	628.3
28	601	60	628.3

4.1. Data Processing

The voltage across the obtained cell increases with irradiation time (Figure 8). It reaches its maximum after 52 minutes of irradiation at a voltage of 0.628 V. The arithmetic mean of the voltages over the sixty-minute irradiation period is 0.6 V. The difference between the maximum and minimum voltages is approximately 0.0583 V.

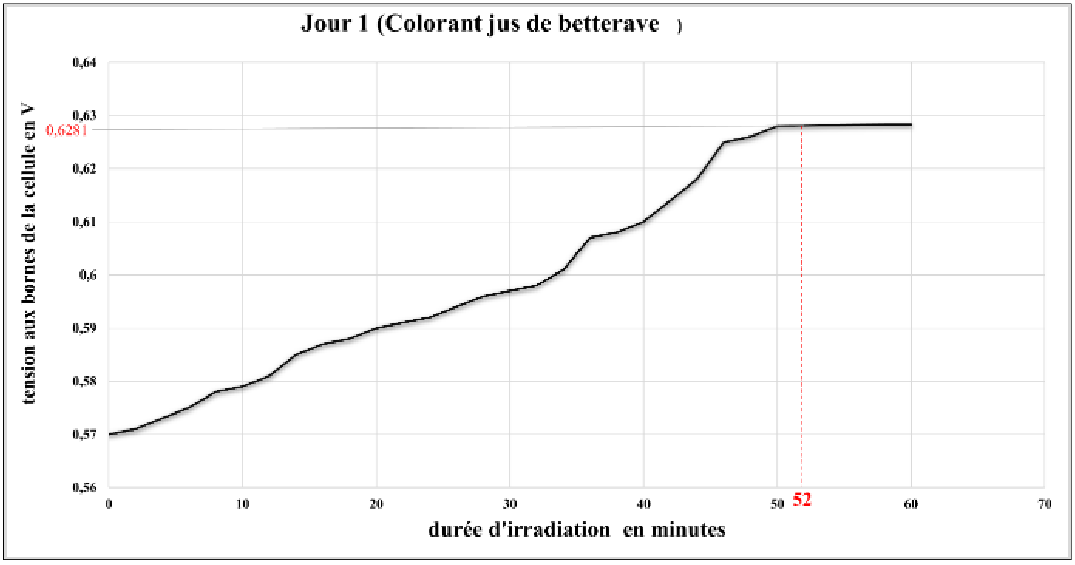


Figure 8 Graphical representation of Day 1 Data

4.2. Experimentation 2: Red Jatropha Juice Dye

The dye used is the juice extracted from the leaves of the jatropha plant.

Experimental protocol: following the implementation plan.

4.3. Experimental Data

The voltage produced by our cell is measured using a multimeter, with one terminal immersed in the mixture of jatropha juice and toothpaste constituting the cathode, and the other terminal connected to the anode. The voltage is recorded at 2-minutes period from 12:00 PM to 1:00 PM (irradiance of 232 W/m^2) [36]. The data is documented in Table 3 below:

Table 3 Voltage values obtained as a function of irradiation time, Day 2

Irradiation Time (minutes)	**Voltage (mV)**	**Irradiation Time (minutes)**	**Voltage (mV)**
0	560	30	583
2	563	32	586
4	564	34	588
6	564	36	589
8	566	38	591
10	567	40	593

12	568	42	596
14	572	44	599
16	573	46	600
18	575	48	604
20	576	50	606
22	576	52	607
24	579	54	607.1
26	582	56	607.1
28	582	60	607.1

4.4. Treatment of Experimental Data

The voltage across our cell increases with irradiation time (Figure 9). It reaches its maximum value after 52 minutes of irradiation, at a voltage of 0.607 V. The arithmetic mean of the voltages over one hour of irradiation is 0.585 V. The difference between the maximum and minimum voltage is approximately equal to 0.0471 V.

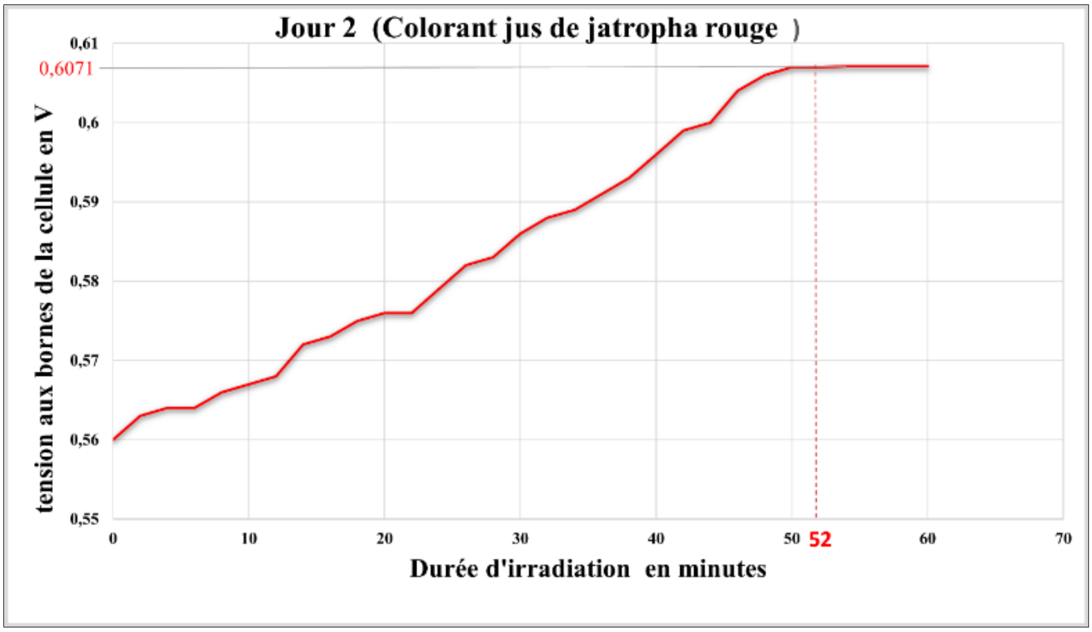


Figure 9 Graphical representation of Day 2 data

4.5. Experiment 3: Guinea Sorrel Juice Dye

The dye used is Guinea sorrel juice.

The experimental protocol adopted follows the plan of implementation.

4.6. Experimental Data

The voltage produced by our cell is measured using a multimeter, with one terminal immersed in the mixture of bissap juice and toothpaste constituting the cathode, and the other terminal connected to the anode. The voltage is recorded at 2-minutes period from 12:00 PM to 1:00 PM (irradiance of 232 W/m^2) [11]. The data is documented in the following table:

Table 4 Data table for Day 3

Irradiation Time (minutes)	**Voltage (mV)**	**Irradiation Time (minutes)**	**Voltage (mV)**
0	565	30	620
2	568	32	625
4	570	34	633
6	575	36	638
8	580	38	640
10	585	40	642
12	586	42	643
14	589	44	643
16	591	46	643
18	595	48	644
20	599	50	645
22	601	52	646
24	605	54	646
26	610	56	646
28	615	60	646

4.7. Data Analysis of the day3 results

The voltage across our cell increases over the irradiation time (Figure 10). It reaches its maximum after 52 minutes of irradiation, with a voltage of 0.646 V. The arithmetic mean of the voltages over the sixty minutes of irradiation is 0.614 V. The difference between the maximum and minimum voltage is approximately 0.081 V.

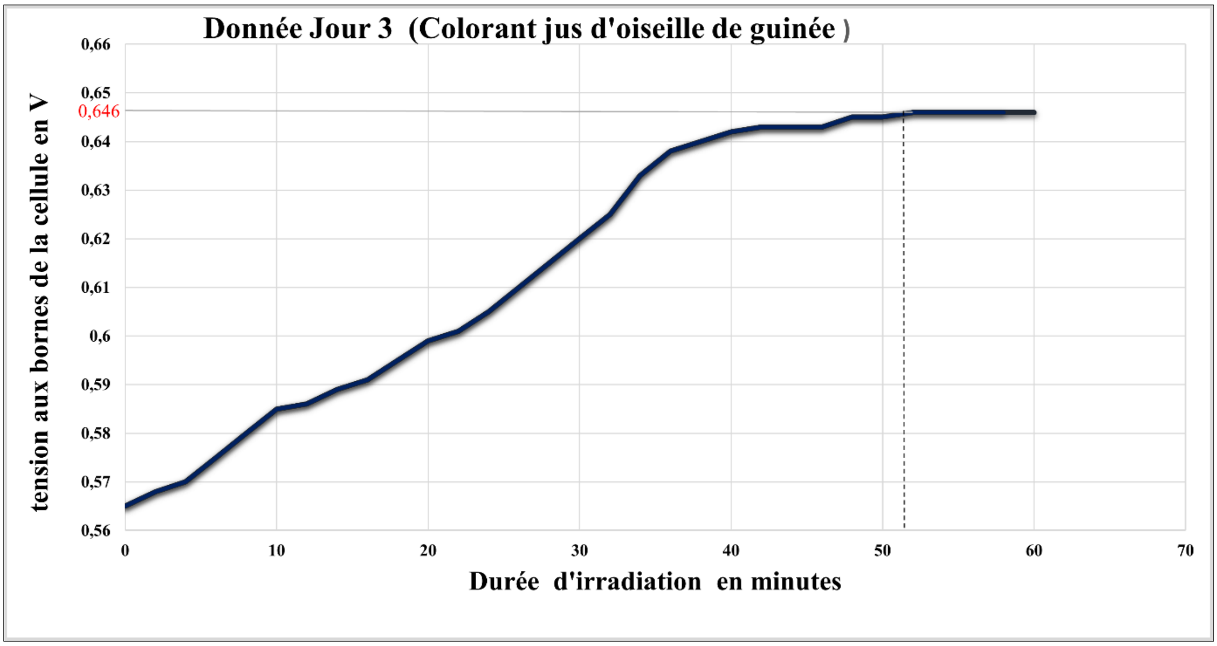


Figure 10 Graphical Representation of Day 3 Data

To compare these results and make choice of the most interesting natural dye, we ploted together the three graphical representations (figure 11) obtained from our experimentation.

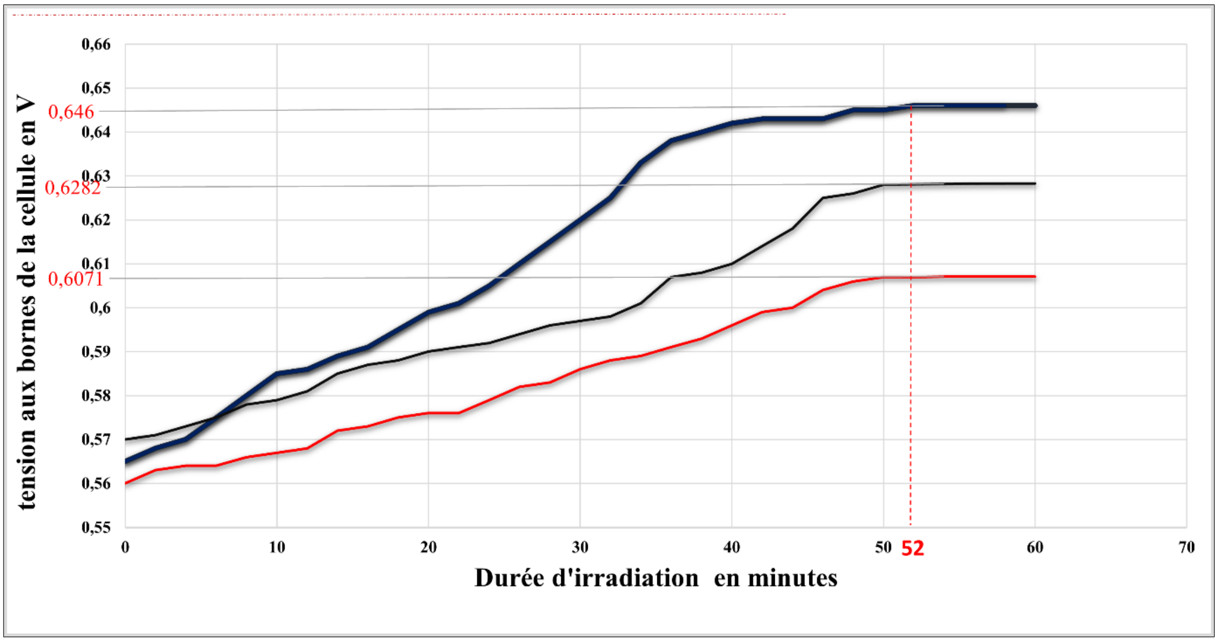


Figure 11 Summary of curves showing voltage evolution as a function of irradiation for one hour (60 minutes) for the three natural dyes.

Table 5 Maximum and average Voltage values obtained for 52 minutes of irradiation as a function of the used dyes.

Dyes	**Maximum Voltage**	**Average Voltage**
Beetroot Juice	628 mV	600 mV
Red Jatropha Juice	607 mV	585 mV
Hibiscus Juice	646 mV	mV

Considering both table 5 and figure 11 of the graphical representation It is clear that the hibiscus juice has the best results of the three dyes.

5. Conclusion

This work aims to develop an organic photovoltaic cell with natural dyes extracted from local plants. This led to experimentation on the use of natural dyes as photosensitizing pigments for an organic solar cell of the Grätzel type. We have identified materials such as organic matter, perovskite, and their multi-junctions with or without silicon as the fundamental elements of new-generation solar cells. The physicochemical, optical, and thermal properties of these materials make new-generation solar panels promising for the future of photovoltaic energy. Additionally, we explored methods for optimizing maintenance related to environmental factors, including vegetation, glass breakage, and cracks, as well as dust and sand soiling. Several maintenance and cleaning optimization methods for solar panels were proposed, including photocatalytic cleaning and electrostatic field cleaning, to increase the profitability of solar panels.

The final part of the study focused on investigating a Grätzel-type organic solar cell with three natural dyes extracted from three plants: beetroot (Beta vulgaris subsp), guinea sorrel petals (hibiscus sabdariffa), and red jatropha leaves (jatropha gossypifolia). These three dyes were used in the fabrication of organic Grätzel-type solar cells. Despite the lack of adequate equipment for fabrication and measurements, the results obtained after exposure to solar irradiation were analyzed and discussed, allowing us to deduce the following:

- it is possible to produce photovoltaic electricity using natural dyes extracted from these three plants,
- we were able to classify these dyes based on their spectrum of solar radiation absorption,

- the concentration of the pigment responsible for coloration in flowers and leaves influences their ability to absorb solar radiation.

Thus, the ranking of solar spectrum absorption capacity in descending order is as follows: guinea sorrel dye (anthocyanin pigment 58.60 mg/g), beetroot dye (betacyanin pigment), and red jatropha juice dye (anthocyanin pigment 40.85 mg/g).

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] BOUGHNIM Nahed, TRIPOUL David, AUDIBERT Jonathan « Cellule photovoltaïque de Graetzel : quels sont les facteurs majeurs influant sur le rendement ? » Compte rendu final SITE de physique, Université de Nice Sophia-Antipolis, France

[2] M. GHEBBACHE, « stratégies de commande d'un système photovoltaïque connecté au réseau électrique dans le but d'optimiser la qualité de l'énergie », thèse de doctorat, l'Université du Québec à Trois-Rivières, juillet 2019.

[3] «https://www.nouvelr-energie.com/pv/nouveau-panneau-solaire,» consulté le 05/04/2022

[4] M. T. Ibrahim « Modélisation et simulation des cellules solaires à base des matériaux organiques Application à la structure P3HT : PCBM ». Mémoire, master, Algérie, 2017.

[5] H.Dehdouh, « Propriétés physico-chimiques des couches minces del’oxyde de titane Effet de la concentration»,Mémoire Magister,Univ. Mentouri –, Constantine, Mémoire Magister,Univ. Mentouri – (2009).

[6] Ab. Benyoucef & al., Structural and morphological study of TiO2 magnetron sputtering thin film for a photovoltaic application, Revue des Energies Renouvelables ICRESD-07 pp. 61 – 65, Tlemcen (2007)

[7] A. d. S. e. H. B. Tom Nahon, «Mémoire Olympiades de Physique,» chez Ein Zell et Grätzel,une relation électrique, Rennes, 2018 - 2019.

[8] M. Grätzel, C. R. Chimie, Vol. 9, p. 578 - 583, 2006.

[9] Natural Pigment –Poly Vinyl Alcohol Nano composites Thin Films for Solar Cell, Baghdad Science Journal, september 2020

[10] CHENNI Rachid « Étude technico-économique d'un système de pompage photovoltaïque dans un village ». Mémoire de Master, Université Mantouri de Constantine, 2007.

[11] E. K. M. E. Amine . « Étude des propriétés optiques et piézoélectriques du Pérovskite CaTiO3 », Mémoire de Master, Université Abdelhamid Ben Badis, 2018.

[12] Gérald Bastard, *Wave mechanics applied to semiconductor heterostructures*, Les éditions de physique, coll. « Monographies de physique », 1988, p. 357