

# Performance of Dye-Sensitized Solar Cell with Carrot-Based Dyes in Deep Eutectic Solvent and KI/I<sub>2</sub> Electrolytes

Christzon Pagdawan Pasigon

*College of Advanced Education, Ifugao State University, Potia Campus, Ifugao, Philippines*

(Corresponding author's e-mail: [chrp\\_pasigon@ifsu.edu.ph](mailto:chrp_pasigon@ifsu.edu.ph))

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## Abstract

Dye-sensitized solar cells (DSSCs) offer a potential alternative to the conventional silicon-based photovoltaic cells due to their low cost and the wide choice of materials available. Their efficiency and stability, however, greatly depend on the photosensitizer and electrolyte materials. In the study, the possibility of carrot roots and leaves as natural photosensitizers with the combination of Deep Eutectic Solvent (DES) and KI/I<sub>2</sub> electrolytes on DSSC performance was explored.

Among the treatments, Treatment 3 (DES with carrot roots) exhibited the highest performance, with an  $I_{sc}$  of 0.0042 A,  $V_{oc}$  of 1.2 V, and an overall efficiency ( $\eta$ ) of 3.53 %. This performance is attributed to DES's ability to enhance charge transport and minimize recombination losses. Treatment 1 (DES with carrot leaves) also demonstrated favorable results, achieving an efficiency of 2.5 %, attributed to the effectiveness of DES in stabilizing natural dyes. In contrast, Treatment 2 (KI/I<sub>2</sub> with carrot leaves) displayed a reduced efficiency of 1.43 %. Meanwhile, Treatment 4 (KI/I<sub>2</sub> with carrot roots) recorded the lowest efficiency of 0.68 %, suggesting that KI/I<sub>2</sub> electrolyte limits charge transfer in natural dye-based DSSCs.

Conductivity measurements supported these findings, with Treatment 3 exhibiting the highest conductivity ( $3.50 \times 10^{-4} \Omega^{-1} \cdot m^{-1}$ ) and the lowest resistance (285.71  $\Omega$ ), followed by Treatment 1. Conversely, Treatments 2 and 4 exhibited higher resistance values, correlating with their lower photovoltaic performance. Additionally, dark current analysis demonstrated that DES-based treatments exhibited lower current leakage over time, reinforcing their potential for long-term stability.

Conclusively, these results have demonstrated the potential of DES-based electrolytes in improving natural photosensitizer efficiencies in DSSCs and provide evidence for designing a more effective and stable solar cell. Moreover, it contributes to the development of renewable energy in which natural materials of low cost are combined with DES to develop green solar technologies as an alternative to fossil fuels.

**Keywords:** Carrots, Photovoltaics, Renewable, Solar, Sustainable, Technology

## Introduction

The increasing demand for global energy, fueled by population and industrial growth, has increased the demand for renewable and sustainable power resources. Conventional energy generation depends on fossil resources, which are not renewable and are major contributors to environmental deterioration. To address increasing demands, 85 - 90 % of power resources are still non-renewable and cause sustainability problems in developing nations, affecting services and the economy

efficiency [1,2]. The UN Sustainable Development Goals (SDGs) highlight Goal 7: Affordable and Clean Energy, with a vision to have access to reliable and sustainable power by 2030 [3,4]. Renewable power options, including wind, geothermal, and solar energy, can help achieve this goal [5,6].

Grätzel's dye-sensitized solar cells (DSSCs) utilize a photosensitizer for the absorption of light and generation of charge carriers at the dye-semiconductor

interface. DSSCs, unlike the photovoltaic cells based on silicon, are flexible, light, low-cost, and available in colors, transparent, and used in a wide variety of environments [7-9]. Their commercialization is, however, constrained by low efficiency, instability, and short lifespan [10,11]. Although the conventional redox electrolytes of the iodide/iodine ( $I^-/I_3^-$ ) increase efficiency, the electrolytes being corrosive restrict the light-harvesting capacity of the DSSC [12]. Also, the thermal stability of the electrolyte limits the commercialization of the DSSC [13]. Moreover, there is also a potential leakage due to the  $I/I_3$  electrolytes [14].

While synthetic dyes, such as ruthenium-based dyes, are efficient and long-lasting but are expensive and even toxic [15], plant-derived natural dyes are low-cost and non-toxic but are limited with drawbacks such as photo instability, narrow band absorbance, and degradation due to the photocatalytic properties of the  $TiO_2$  electrodes [16,17]. In addition,  $TiO_2$  interactions are responsible for desorption and lower power conversion efficiency and ultimately damage the performance of DSSCs in general [18]. Natural dyes such as anthocyanin, carotenoid, flavonoid, and chlorophyll are highly absorbent but are not yet efficient in comparison with their synthetic counterparts. Strategies intended to boost the performance of DSSCs based on natural dyes are working on developing new redox pairs, photosensitizer design, and biomimetics. But even with these technologies, power conversion efficiency in the case of eco-friendly DSSCs is still lower than 1 % [19], implying a need for further research and process refinement.

Deep eutectic solvents (DESs) and room-temperature ionic liquids (RTILs) are being identified as green and effective alternatives for the redox electrolytes traditionally used for electrochemical energy storage devices. These next-generation electrolytes exhibit high thermal stability, low cost, and excellent electrode compatibility. DESs, particularly, represent a new generation of ionic liquids with low melting and lattice energies, and hence, proven effective and environmentally friendly compared with traditional electrolytes. They also exhibit low vapor pressure, wide liquid ranges, and non-flammability, allowing for rapid dissociation of ions at low temperatures. DES-based electrolytes also exhibit increased differential capacitance with rising temperature, which enhances the

charge transport and efficiency of DSSC [20]. High thermal stability, low cost, and electrode compatibility make them an eco-friendly and efficient alternative to traditional redox electrolytes [21,22].

DES also showed promising results in various energy storage and conversion devices. In supercapacitors, choline chloride-based DES with non-conducting materials exhibited super dielectric behavior, enhancing specific capacitance by up to 14-fold [23]. In battery-supercapacitor hybrid devices, a urea-based DES with magnesium and lithium ions exhibited high performance with good reversibility and stability of the anode [24]. In DSSCs, choline chloride-based DES with urea or ethylene glycol exhibited comparable efficiency with ionic liquids, with possibilities for an inexpensive and eco-friendly alternative [25]. However, despite their potential, the study of DES in DSSC applications is still limited, thus necessitating further investigation in terms of its long-term stability, charge transfer mechanisms, and interactions with natural dyes.

Carrot dyes are potential photosensitizer agents in DSSCs. Within the UV range of 200 to 800 nm, the maximum absorbency is in carrot root crops at 461 nm wavelength [26]. The total chlorophyll content in carrot leaves is 1.42 mg/g, and the roots contain total carotenoids (54.62  $\mu\text{g/g}$ ) and beta-carotene (24.97  $\mu\text{g/g}$ ) [27]. As these have high concentrations of chlorophyll and carotene pigments, the leaves and roots of carrots are prospective photosensitizer sources in dye-sensitized solar cells. The primary function in photosynthesis in carrot leaves is the conversion of sunlight into chemical energy, where the absorbed light is a photocatalyst in stimulating the electrons and oxidation and reduction reactions [28]. The accessory pigment beta-carotene assists in absorbing a range of lights. While the primary absorbency is in red and blue lights in the presence of chlorophyll, beta-carotene is in green and blue lights and scatters orange and red lights [29].

There has been a greater demand for clean and sustainable energy sources worldwide, and thus, there has been extensive research on alternative photovoltaic technology. Among these, dye-sensitized solar cells (DSSCs) have been a promising solution as they possess low fabrication costs, are eco-friendly, and have tunable optical characteristics. DSSCs utilize natural or

synthetic dyes as a sensitizer for absorbing the sun's rays and converting them into electricity. The efficiency and stability of these cells, however, are influenced by factors such as dye choice, electrolyte constitution, and electrode materials.

This work investigates the efficiency of dye-sensitized solar cells (DSSCs) with natural dyes from carrots as photosensitizers combined with deep eutectic solvent (DES) and KI/I<sub>2</sub> electrolytes. As conventional DSSCs are characterized by low efficiency, instability, and environmental degradation due to the employment of synthetic dyes and aggressive electrolytes, this work explores the use of carrot-derived pigments and DES-based electrolytes as a low-cost, sustainable, and environmentally friendly alternative. By determining the efficiency of the materials as DSSCs, this work will contribute to the development of renewable energy technologies and the emergence of more viable DSSCs.

## Materials and methods

### Preparation of materials

The indium tin oxide (ITO) glass substrate was cleaned with 70 % ethanol and distilled water and then dried at room temperature. Meanwhile, the resistance was measured with a multimeter to check which side of the ITO was conductive. The edges of the ITO were taped to make a consistent working area in the following processes.

Meanwhile, the Carrot roots and leaves were collected from the same species and site in Tinoc, Ifugao. Collected 250 g of carrot roots and 250 g of leaves and washed with distilled water. Without peeling, the carrot roots were crushed using a mortar and pestle. The finely ground roots were combined with 125 mL

solvent in a 1:5 ratio and stirred at 300 rpm with a magnetic stirrer at 60 °C for 1 h. After that, the solution was kept in the dark for 24 h and filtered through the Whatman No. 2 filter paper.

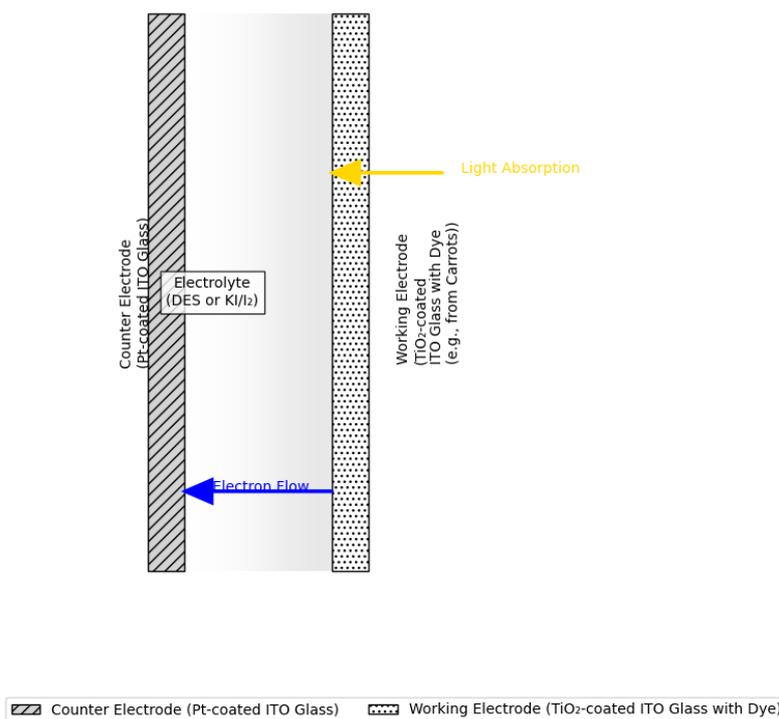
The carrot leaves were cleaned and cut into small pieces. Mechanical extraction was done under controlled conditions to obtain chlorophyll for stability. These extracts were kept in amber bottles to minimize their exposure to light.

For the Deep Eutectic Solvent, a small beaker was charged with ZnCl<sub>2</sub> and urea at a 3:1 molar ratio [30]. The mixture was heated to 125 °C with continuous stirring until the mixture was fully liquefied. After cooling to room temperature, the DES obtained was mixed directly with the prepared carrot extract to form a stable dye solution.

The TiO<sub>2</sub> nanopowder was dissolved in 70 % ethanol. The mixture was homogenized in a vortex stirrer until it had a paste-like consistency. Finally, the paste was stored in a container covered by aluminum foil to avoid direct sunlight and the influence of evaporation processes. The standardized thickness of the paste was 0.020 mm and was measured using a calibrated applicator.

### DSSC assembly

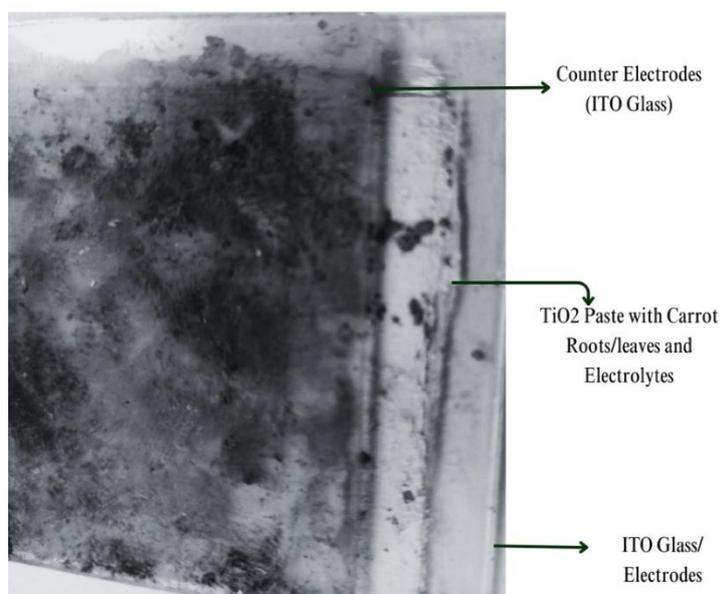
The DSSC was assembled following the schematic diagram in **Figure 1**. The conductive side of the ITO glass was coated with the prepared TiO<sub>2</sub> paste and spread evenly to a thickness of 0.020 mm. The coated ITO glass was annealed on a hot plate at 500 °C for 1 h and cooled to room temperature. The annealed plate was immersed in carrot extract (roots or leaves) for 24 h to enable dye adsorption.



**Figure 1** Schematic diagram of the DSSC.

Two drops of the electrolyte (DES or KI/I<sub>2</sub>) were applied to the dye-coated TiO<sub>2</sub> electrode. The dye-coated electrode acted as the working electrode. A platinum-coated ITO glass plate conductive side was used as the counter electrode. The working and counter

electrodes were clamped together to assemble the DSSC. A gasket was utilized to seal the DSSC to ensure electrical contact, as shown in **Figure 2**. The DSSCs were tested using a calibrated digital multimeter under 100 W halogen light.



**Figure 2** The assembled DSSC follows a sandwich-type structure.

**Table 1** shows the different treatments to be conducted in the study. Four treatments were performed to

investigate the performance of various dyes and electrolyte combinations.

**Table 1** The various treatments of the DSSC.

Treatment	Electrolyte	Organic dye
T1	Deep eutectic solvent	Carrot leaves
T2	KI/I <sub>2</sub>	Carrot leaves
T3	Deep eutectic solvent	Carrot roots
T4	KI/I <sub>2</sub>	Carrot roots

### Data measurement

The different parameters of the solar cell were measured by using a 100 W halogen light to simulate the visible spectrum emitted from the sun [45]. Voltage and current parameters, such as  $V_{oc}$ ,  $I_{sc}$ ,  $V_m$ , and  $I_m$ , were measured by a digital multimeter using a Fluke 87 V. Next, the solar cell was connected to a multimeter and set to an appropriate range of voltage and current for measurement at standard conditions of illumination.

For the Dark Current Variation test, all the solar cells from each different treatment were placed inside a dark box, only leaving one lead protruding to be connected to the Voltage-Ohm-Ampere multimeter. Then, the halogen light of intensity 100 W exposed the cells for 12 h. Measurements were recorded at certain intervals, such as 0, 20 min, 4, 12, 24, and 48 h, while  $V_{oc}$  was measured at each. The current and voltage values were measured upon exposure. Meanwhile, the formula for conductivity from [31,32] was applied:

$$\sigma = \frac{1}{RA} \quad (1)$$

$\sigma$  = is conductivity ( $\Omega^{-1} \cdot m^{-1}$ );  $R$  = is for resistance ( $\Omega$ );  $l$  = distance of 2 electrodes (m);  $A$  = cross-sectional surface area of the electrode ( $m^2$ )

The DSSCs were treated to continue studying how each performed thermally. Each cell was placed on a hot plate and heated for 10 min. The temperature was continuously monitored with an Omega HH309A

Thermocouple Handheld Thermometer with Data Logging for accurate and precise temperature readings. The temperature was recorded automatically every 45 s to track continuous variations in temperature during the experiment. A Fluke 87 V was used for measuring key solar parameters like  $V_{oc}$ ,  $I_{sc}$ ,  $V_m$ , and  $I_m$ , respectively. The same Voltage-Ohm-Ampere digital multimeter was utilized in determining the dark energy variation, material conductivity, and temperature variation. The fill factor was calculated using the formula [33]:

$$FF = \frac{P_m}{I_{sc} \cdot V_{oc}} \quad (2)$$

The  $P_m$  (maximum power) was calculated from the  $V_m$  (maximum voltage) and  $I_m$  (maximum current). Furthermore, the efficiency of the solar cells was computed using the formula:

$$\eta = \frac{P_{out}}{P_{in}} = I_{sc} \cdot V_{oc} \frac{FF}{P_{in}} \quad (3)$$

where  $P_{in}$  is the power input from the light source of the solar cell and  $P_{out}$  is the power output [34].

## Results and discussion

### The $V_{oc}$ , $I_{sc}$ , and efficiency performance of the DSSC

**Table 2** shows the performance of different treatments, such as T1, T2, T3, and T4, acting as Dye-Sensitized Solar cells. The dependent variables are  $I_{max}$ ,  $V_{max}$ ,  $I_{sc}$ ,  $V_{oc}$ , fill factor (FF), and efficiency ( $\eta$ ).

**Table 2** Performance of the DSSC under different treatments.

Treatment	$I_{sc}$ (A)	$V_{oc}$ (V)	FF	Efficiency (%)	$I_{max}$ (A)	$V_{max}$ (V)
T1	0.0035	1.1	0.65	2.5	0.00284	0.88
T2	0.0025	0.95	0.6	1.43	0.00188	0.76
T3	0.0042	1.2	0.7	3.53	0.00368	0.96
T4	0.0018	0.75	0.5	0.68	0.00113	0.6

The results of the 4 treatments (T3, T1, T2 and T4) reveal differences in the solar cell's performance. Treatment 3 (T3) performs the highest short-circuit current ( $I_{sc} = 0.0042$  A), open-circuit voltage ( $V_{oc} = 1.2$  V), fill factor (FF = 0.7), and efficiency ( $\eta = 3.53$  %), indicating the optimal charge generation, low recombination, and optimal charge transport. Moreover, T1 has the second-best performance, with  $I_{sc} = 0.0035$  A,  $V_{oc} = 1.1$  V, FF = 0.65, and  $\eta = 2.5$  %, reflecting the occurrence of some recombination loss and the presence of room for enhancement. However, T2 has a decrease in terms of performance, with  $I_{sc} = 0.0025$  A,  $V_{oc} = 0.95$  V, FF = 0.6,  $\eta = 1.43$  %, demonstrating higher series resistance and more prominent recombination. Lastly, T4 is the lowest performing with the lowest value in all parameters ( $I_{sc} = 0.0018$  A,  $V_{oc} = 0.75$  V, FF = 0.5,  $\eta = 0.68$  %), signifying low charge transport and excessive loss.

The results suggest that while KI/I<sub>2</sub> is a conventional electrolyte, it may not be as effective when paired with carrot leaves as Deep Eutectic Solvent (DES), as indicated by Treatments 1 and 2. Furthermore, Deep Eutectic Solvent (DES) combined with carrot roots significantly enhances cell performance as proven by treatment 3. Generally, DES is more effective as an electrolyte, particularly when paired with carrot roots, yielding higher efficiency among the DSSCs. Combining KI/I<sub>2</sub> with either carrot roots or leaves yields lower performance, indicating that alternative electrolytes like DES could be more beneficial for DSSC output. The Deep Eutectic Solvent (DES) functions as an electrolyte by forming a strong hydrogen bond network with the polymer matrix, leading to good ionic conductivity and suitability for supercapacitors. Due to its high viscosity and electrical conductivity, the

DES is an effective electrolyte solvent in DSSC devices, enhancing device performance by improving conductivity and reducing freezing point [35,36].

The J-V curve results, as shown in **Figure 3** alongside the values in **Table 2**, reveal an alignment between the plotted data and the tabulated values. The plotted current-versus-potential (J-V) curve demonstrates the photovoltaic behavior of the DSSC cells. It begins with the short-circuit current ( $I_{sc}$ ) at 0 V, and as the potential increases, the current decreases, reaching 0 near the open-circuit voltage ( $V_{oc}$ ).

The JV graph provides the total visualization of the performances of the treatments of the solar cells (T3, T1, T2 and T4) as a voltage-current density relationship. For the case of T3, the curve is the highest  $V_{oc} = 1.2$  V with  $I_{sc} = 0.0042$  A, indicating optimal charge generation with minimal loss of recombination. As shown in the figure, it has the "squarest" curve, indicating minimal series resistance with optimal charge transport with the optimal FF = 0.7. Next, T1 with  $V_{oc} = 1.1$  V with  $I_{sc} = 0.0035$  A, with a less square curve, indicating moderate loss with higher series resistance. For the case of T2, there is a higher loss in the performance with  $V_{oc} = 0.95$  V with  $I_{sc} = 0.0025$  A, with the less optimal appearance of the curve, indicating higher loss with resistance. Moreover, there is the lowest  $V_{oc} = 0.75$  V with  $I_{sc} = 0.0018$  A, with the least appearance of the square curve, indicating low charge transport with the highest loss for T4. Overall, the JV curves effectively demonstrate the higher performances of the case of T3, then T1, followed by T2, then T4, respectively, with the appearance and the position of each curve indicating the charge generation, transport, and collection efficiency and the quality in each case.

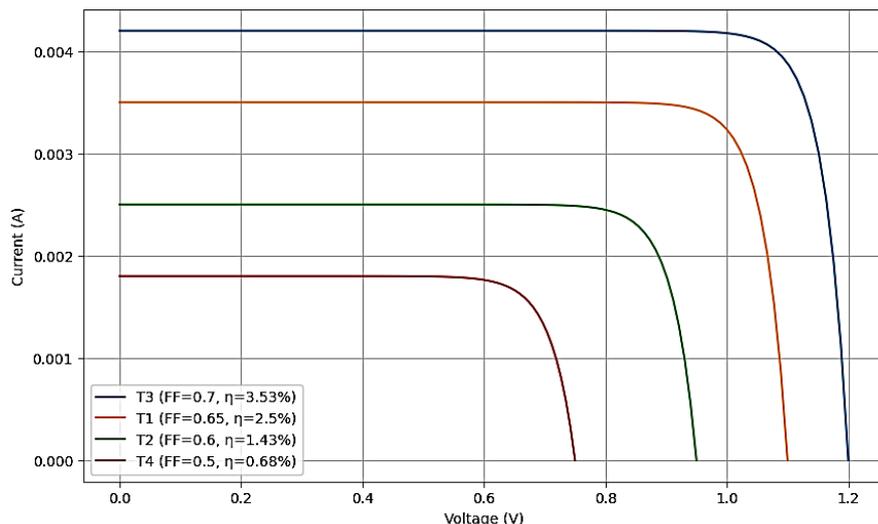


Figure 3 J-V graph of the different treatments.

Figure 4 shows individual J-V characteristics for different treatments, with better efficiency for T3 (DES + Carrot Roots) with a maximum Voc (1.2 V) and Isc (0.0042 A), which indicates better charge transport and minimum recombination losses. It is followed by moderate efficiency for T1 (DES + Carrot Leaves), and low efficiency for T2 (KI/I<sub>2</sub> + Carrot Leaves) and T4

(KI/I<sub>2</sub> + Carrot Roots) due to increased recombination and resistance. The results authenticate that DES enhances DSSC efficiency and stability, especially with beta-carotene-abundant carrot roots, and thereby emerge as a probable alternative electrolyte for sustainable solar technology.

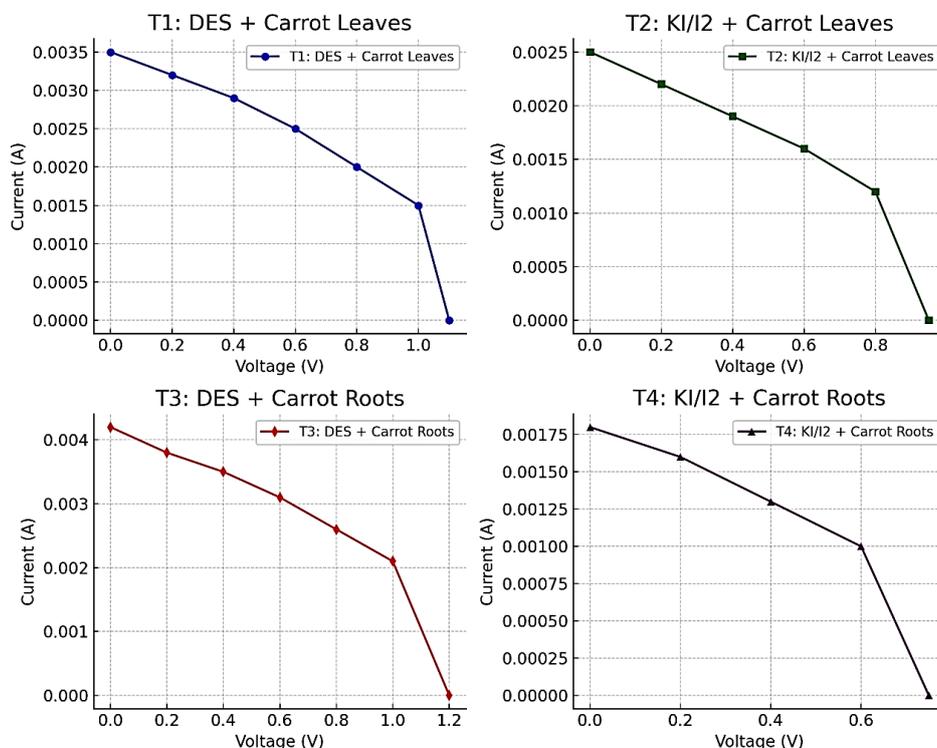


Figure 4 Individual J-V graph of the various treatments.

Conclusively, the efficiency of treatments 1 and 3 is higher as compared to other efficiencies based on

chlorophyll. Hassan [18], for instance, was able to realize efficiency with a quasi-solid PVA-based

electrolyte with double iodide salts and additives of 2.62 %. An efficiency of 1.97 % was achieved when a PAN-based electrolyte was used. Moreover, an efficiency of 1.50 % was attained using chlorophyll extracted from *Sargassum* sp. [37,38]. An indication of the strength of impact that dye solution concentration may pose on DSSC performance is depicted by the optimum value of the concentration at 90 mM obtained from the chlorophyll extracted from the leaves of papaya. Although fill factors, in general, with the dyes were lying in the range 0.432 - 0.73 [39].

### Dark current variation

The dark current in Table 3 with time for the 4 treatments (T1, T2, T3 and T4) presents the degradation

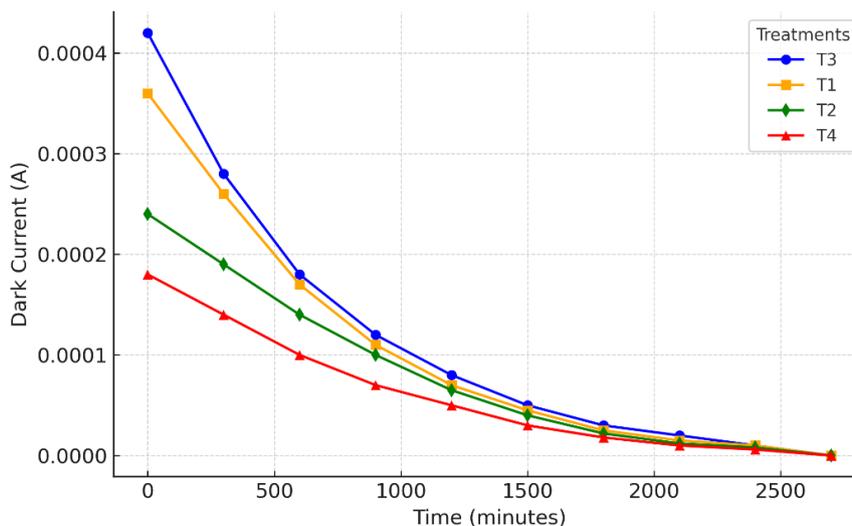
and recombination characteristics of the solar cells under dark conditions. The performance and stability of DSSCs were evaluated based on dark current ( $I_{\text{dark}}$ ) over time. Treatment 1, with DES as the electrolyte and carrot leaves as the photosensitizer, showed moderate stability with slow degradation in  $I_{\text{dark}}$ . Carotenoids in carrot leaves were responsible for light absorption and electron transfer, whereas chlorophylls were less efficient. Meanwhile, Treatment 2, with KI/I<sub>2</sub> electrolyte and carrot leaves, showed drastic degradation in performance because of the instability of the electrolyte, which resulted in greater recombination losses and lower efficiency.

**Table 3** Dark current variation of the DSSC cells.

Time (mins)	T1 Dark current (A)	T2 Dark current (A)	T3 Dark current (A)	T4 Dark current (A)
0	0.00035	0.00025	0.00042	0.00018
20	0.000336	0.00024	0.000403	0.000173
240	0.000229	0.000164	0.000275	0.000118
720	0.000098	0.00007	0.000118	0.00005
1,440	0.000035	0.000025	0.000042	0.000018
2,880	0.000005	0.000003	0.000006	0.000002

Treatment 4, which utilized DES with carrot roots, showed the greatest stability, with the longest degradation in the dark current (0.00042 to 0.000002 A within 2,880 min). The stability is due to beta-carotene's intense light absorption and efficient electron donation that well matches the TiO<sub>2</sub> conduction band, minimizing recombination losses. Treatment 4, involving KI/I<sub>2</sub> with

carrot roots, exhibited the quickest degradation, with dark current falling from 0.00018 to 0.000002 A, reflecting poor electrolyte stability and weak material interactions. The results highlight the importance of electrolyte choice to guarantee DSSC efficiency and durability, as shown in Figure 5, the DES-based electrolyte shows a minimal current loss.



**Figure 5** Dark current variation of the DSSCs.

Carotenoids, especially  $\beta$ -carotene, naturally present in carrot roots, have been explored for their electron injection into nanoparticles of  $\text{TiO}_2$  upon photoexcitation, and the electron transfer was found to be very rapid on a timescale of femtoseconds, as evidenced by experiments by Pan *et al.* [40]; Meng *et al.* [41]. Their efficiency of electron injections is highly dependent on the conjugation length of carotenoids, with maximum efficiency at the average length of the conjugation segment. Because of the involvement in charge transfer processes, the efficiency of electron injections plays an important role in all the performances of the DSSC. Because the energy level of the carrot root carotenoids is compatible with the conduction band of the  $\text{TiO}_2$ , effective electron transfer was obtained and thus avoided recombination. It could be evidenced by Treatment 3, with the addition of DES and carrot roots, that the high concentration of  $\beta$ -carotene was one reason for good stability over time; even after 48 h,  $V_{oc}$  remains quite high. This also justifies that the efficient electron donation property of  $\beta$ -carotene supports effective energy conversion in the DSSC.

On the other hand, Carrot leaves contain both carotenoids and chlorophylls, the latter being less efficient at electron transfer to  $\text{TiO}_2$ . Although carotenoids can donate electrons, the presence of chlorophylls probably causes increased recombination losses [42] and higher dark current because the electron transfer process is less efficient [43,44]. Such a non-efficient electron transfer process may be the

explanation, besides the instability of  $\text{KI/I}_2$  as an electrolyte with higher reactivity and more electron-electrolyte recombination for this increase of dark current upon Treatment 2. These results agree well with the fast degradation in both  $V_{oc}$  and  $I_{dark}$  under Treatment 2, suggesting some deterioration of the electron transfer, making the whole cell stability low.

The DES used as an electrolyte in Treatments 1 and 3 has some advantages. DESs generally have high ionic conductivity with low viscosity [45,46], facilitating higher mobility of ions with reduced recombination rates under process conditions. DES forms strong hydrogen bonds, especially in the case of choline chloride combined with carboxylic acids [47], which contributes to better ion transport, improving its stability in the electrolyte. This reduces the possibility of energy dissipation and loss, thus maximizing open-circuit voltages  $V_{oc}$ , while there is a limited growth rate of dark currents over time with Treatment 1 and Treatment 3. Hydrogen bonding in the case of DES facilitates stability in the electrolytes themselves, preventing the generation of local reactions resulting in higher dark current.

In contrast, Treatment 2 and Treatment 4 used  $\text{KI/I}_2$  electrolytes, which produced higher recombination of electrons with the electrolyte, hence yielding lower  $V_{oc}$  and  $I_{dark}$  values.  $\text{I}_2$  and  $\text{I}_3^-$  in the electrolyte elevate the chances of recombination, especially upon illumination, where the current density of the recombination could be enhanced 2 - 3 times from the dark condition [45]. The higher recombination rate

within the KI/I<sub>2</sub>-based systems contributes to the observed instability in Treatments 2 and 4, where both V<sub>oc</sub> and I<sub>dark</sub> rapidly decreased.

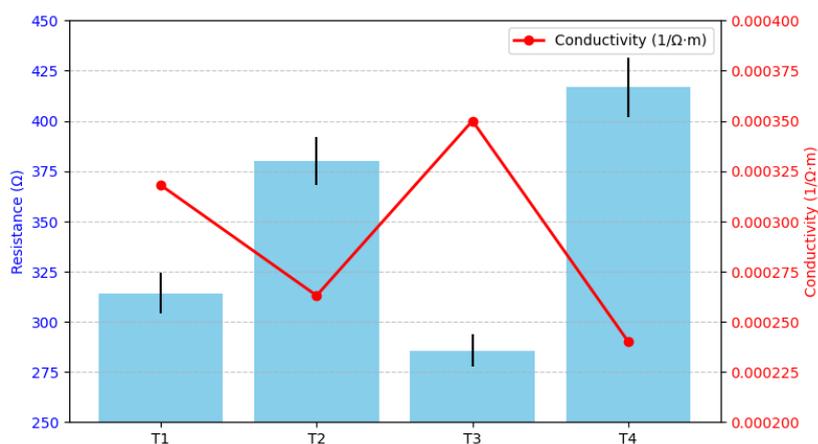
### Conductivity of the DSSC

Table 4, alongside Figure 6, presents the conductivity of the DSSCs (T1, T2, T3, and T4). The conductivity levels of the DSSC treatments measure the charge transport effectiveness of the materials. Of the

treatments, the conductivity is the greatest for T3 at  $3.50 \times 10^{-4}$  S/m<sup>2</sup>, also with the highest I<sub>sc</sub> value at 0.0042 A and the V<sub>oc</sub> value at 1.2 V. Its low resistance value at R = 285.71 Ω confirms the higher electron transport in the system as the most effective treatment. In close second is the conductivity at  $3.18 \times 10^{-4}$  S/m<sup>2</sup> for T1 with I<sub>sc</sub> and V<sub>oc</sub> at somewhat lower levels, indicating a moderately effective charge transport process.

**Table 4** Conductivity of the various DSSC treatments.

Treatment	I <sub>sc</sub> (A)	V <sub>oc</sub> (V)	Resistance (R,Ω)	Conductivity (σ, 1 Ω <sup>-1</sup> ·m <sup>-1</sup> )
T1	0.0035	1.1	314.29	$3.18 \times 10^{-4}$
T2	0.0025	0.95	380	$2.63 \times 10^{-4}$
T3	0.0042	1.2	285.71	$3.50 \times 10^{-4}$
T4	0.0018	0.75	416.67	$2.40 \times 10^{-4}$



**Figure 6** Graphical presentation of the resistance and conductivity of the treatments.

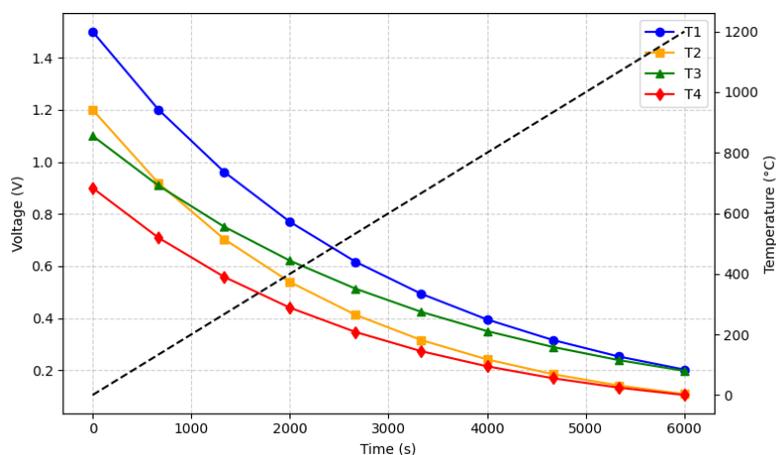
Conversely, T2 and T4 exhibit considerably lower conductivities ( $2.63 \times 10^{-4}$  and  $2.40 \times 10^{-4}$  S/m, respectively), indicating higher resistance to charge flow. Increased resistance from 380 Ω in T2 to 416.67 Ω in T4 corroborates the conductivity reduction trend. This result shows that the electrolyte-dye combination in these treatments results in a higher recombination rate or ineffective charge transmission, consequently lowering the overall DSSC performance. The conductivity value trend is supported by the efficiency results, with the DSSC performance being higher in the case of T3 compared with other treatments, justifying the optimization of the electrolyte composition and the electrode material for improved DSSC performance.

### Temperature dependence of the DSSC

Figure 7 shows the temperature dependence of the open-circuit voltage of Dye-Sensitized Solar Cells with time. It was found that V<sub>oc</sub> decreases with the increase in temperature. All 4 treatments exhibit the same tendency. The performance remains almost the same below about 100 °C, but decreases apparently beyond this temperature. It is from the stability observed within the first 450 s that the cells can work effectively under lower-temperature conditions. Above 100 °C, all the cells present degradation performance. T2 is the most affected and with a faster decline in V<sub>oc</sub>. The fast V<sub>oc</sub> drop for T2 is attributed to the thermal instability of the KI/I<sub>2</sub> electrolyte, which is known to be thermally degraded at such high temperatures [48]. Thus,

corresponding to a temperature at about 200 °C and a period of about 5,000 s, almost complete destruction of

the cell is experienced by T2, which is the critical temperature for the failure of the redox couple.



**Figure 7** Temperature dependence of the DSSCs.

The performance of DSSCs is also temperature-dependent since temperature controls charge transport processes, electrolyte stability, and the recombination rate. Fluctuation in DSSC efficiency with treatments is indicated in the results from **Figure 7**, which can be correlated with the heat characteristics of the electrolyte and the photosensitizer. In most of the treatments, temperature enhancement is expected to enhance ionic conductivity in the electrolyte, consequently improving charge transfer internal resistance. This is depicted in the case of Treatments 1 (T1) with 3 (T3), which included DES-based electrolytes with higher efficiencies of 1.80 and 2.10 %, respectively. Increased temperature is anticipated at higher performances due to low viscosity and the high heat resistance of DES, enhancing ion mobility and the transmission of electrons at the electrolyte-semiconductor interface.

In contrast, treatments 2 (T2) and 4 (T4) with KI/I<sub>2</sub> electrolytes have efficiencies of 1.05 and 0.85 %, respectively, as a reflection of their heat susceptibility. KI/I<sub>2</sub> electrolyte is also seen to experience more recombination loss at higher temperatures as the redox pair is degraded, accounting for low charge separation and overall cell efficiency. Also, the low fill factors of 0.58 for T2 and 0.50 for T4 point toward the decrease in charge collection efficiency, substantiating the perception that the use of traditional iodide-based electrolytes is challenged under temperature conditions.

Also, the influence of temperature on  $V_{oc}$  is also observed as DSSCs with DES electrolytes (T1 and T3)

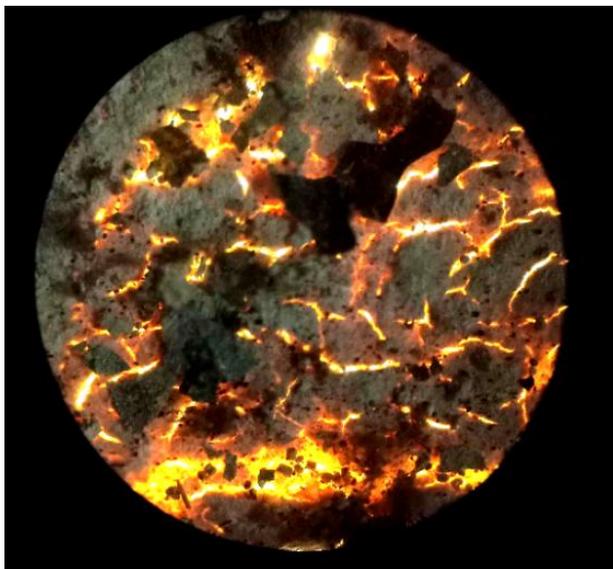
exhibited very stable  $V_{oc}$  values of 1.10 and 1.20 V, respectively, while DSSCs with KI/I<sub>2</sub> electrolytes (T2 and T4) exhibited low  $V_{oc}$  values of 0.91 and 0.75 V, respectively. This supports the fact that DES can minimize the thermal recombination phenomena, retaining voltage stability under temperature variations.

Various studies have shown that increasing temperature negatively impacts DSSC efficiency [50,51]. With increasing temperature, open circuit voltage and short circuit current decrease, leading to low overall efficiency [52]. The T1 and T4, however, showed a slow decrease in  $V_{oc}$ . On this point, T4 now shows greater thermal stability, most probably due to the carrot root dye maintaining photoactive properties at relatively high temperatures. This agrees with observations that carotenes derived from carrots demonstrate better thermal stability than colorants sourced from other materials, such as grapes or even those from synthetic origins [49]. T3, using carrot root dye, exhibited the best thermal performance, since it provides a high initial  $V_{oc}$  that degraded gradually after the critical temperature. This suggests that the carrot root dye provides good thermal robustness to the DSSC to maintain performance at higher temperatures.

The general trend was that the DES-based electrolytes in both T1 and T3 showed better thermal stability than KI/I<sub>2</sub> electrolytes containing T2 and T4. These results showed that DES possesses a maintained solvent property, suggesting that the resulting electrolyte performances, even at low- and moderately

applied temperatures, will enhance charge transport inside cells and subsequently efficiency and thermal robustness. It is, however, that DSSC efficiency compromises higher temperatures, especially with the degradation of the electrolyte and the cell itself, as

shown in **Figure 8**. In this regard, long-term efficiencies under practical applications need further improvement, especially in an elevated-temperature environment, which calls for the use of stable electrolytes and photoactive dyes.



**Figure 8** Sample of degradation of the dssc cell due to temperature.

### Conclusions

The choice of electrolyte and sensitizing material strongly influences the performance and stability of DSSCs. In terms of electrolytes, DES-based electrolytes show the highest efficiency and stability as an attractive alternative to conventional KI/I<sub>2</sub> electrolytes. Carrot roots, being rich in beta-carotene, improve the electron injection and overall performance of cells when working with DES, as proved by treatment 3. Treatments using KI/I<sub>2</sub> demonstrate low performance and a faster degradation rate, especially upon combination in carrot leaves, as shown by treatments 2 and 4.

All these findings suggest that deeper studies on the application of DES-based electrolytes, together with natural dyes, for instance, carrot roots, may lead to more efficient and stable DSSCs, which could support further steps toward the development of cost-effective and sustainable solar energy technologies. Some other future research directions that might allow for even better performance in DSSCs concern the optimization of the concentration and composition of DES electrolytes and studies of other natural dyes.

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