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Mechanistic correlation between electron injection, recombination, and photovoltage in *Cota tinctoria*, *punica granatum*, and *linaria grandiflora*-based natural dye-sensitized solar cells

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E-mail: yerdogdu@gazi.edu.tr**Keywords:** dye-sensitized solar cells, natural dyes, energy-level alignment, electron injection driving force, recombination resistance, photovoltaic performance

Abstract

Natural dye-sensitized solar cells (*n*-DSSCs) offer a sustainable and low-cost alternative to conventional photovoltaics. Three natural dyes - *Cota tinctoria* (CTT), *Punica granatum* (PG), and *Linaria grandiflora* (LG) - are investigated as a new eco-friendly sensitizer, and their photovoltaic performance is systematically correlated with energetic parameters. Comprehensive FT-IR, UV-vis, cyclic voltammetry (CV), and electrochemical impedance spectroscopy (EIS) analyses were employed to evaluate the relationships between electron injection driving force (ΔG_{inj}), recombination resistance (R_{rec}), and open-circuit voltage (V_{OC}). Among the investigated natural dyes, the CTT-based device obtained the highest short-circuit current density ($J_{SC} = 2.11 \text{ mA cm}^{-2}$), open-circuit voltage ($V_{OC} = 610 \text{ mV}$), and efficiency ($\eta = 0.91\%$). The correlation identified between ΔG_{inj} , R_{rec} , and V_{OC} indicates that injection and recombination energies determine the efficiency of devices. These insights establish a mechanistic framework linking molecular energy alignment with photovoltaic behavior and guide the design of next-generation bio-derived sensitizers. Importantly, the study shows that superior ΔG_{inj} facilitates stronger electron injection into TiO_2 , while higher R_{rec} values suppress interfacial recombination, collectively governing V_{OC} and overall efficiency. Overall, the results demonstrate that interplay between ΔG_{inj} and R_{rec} governs the photovoltaic behavior of natural dye-based DSSCs, establishing *Cota tinctoria* as a particularly promising bio-derived sensitizer for next-generation solar energy applications.

1. Introduction

Solar energy has become one of the most sustainable and environmentally benign energy sources for addressing the growing global energy demand. Among various photovoltaic technologies, dye-sensitized solar cells (DSSCs) have attracted significant attention since the pioneering work of O'Regan and Grätzel, owing to their simple fabrication, low cost, and tunable optoelectronic properties [1, 2]. Over the last three decades, extensive research on sensitizers, photoanodes, and redox electrolytes has led to power conversion efficiencies exceeding 14% in optimized TiO_2 -based systems [3]. Despite this progress, the advancement of *n*-DSSCs has been limited due to the relatively narrow absorption spectra [4], weak anchoring [5], and rapid recombination [6] behavior of natural pigments.

n-DSSCs have garnered increasing attention as a sustainable, low-cost, and eco-friendly alternative to traditional photovoltaic technologies [7, 8]. These devices harness plant-based pigments, especially anthocyanins

and other naturally occurring compounds, as photosensitizers to initiate the electron injection process upon solar illumination [9, 10]. Studies by Yelkovan et al [11] and Sarwar et al [12] highlight natural dyes such as *Hyoscyamus reticulatus*, *Mahonia aquifolium*, *Capsicum annuum*, and *Tamarindus indica* can offer efficiencies ranging from 0.22% to 1.71%, although their performance is typically limited by weak electron injection and dye regeneration forces. Studies by Atli et al [13] and Kocak et al [14] emphasize the significance of chemical functional groups, such as carbonyl, carboxyl, and hydroxyl, in strengthening TiO₂ surface binding and light absorption, and influencing charge transfer efficiency. Notably, the method of dye extraction (e.g., acidic solvents, as shown by Kocak et al) and material pretreatment (e.g., drying time and substrate type in a study [15]) have been shown to significantly influence photovoltaic outcomes. Additionally, Kocak et al [16] demonstrated the potential of carminic acid from insects as organic dye, while Onyemowo et al [17] explored co-sensitization strategies to improve performance using natural dyes. Despite generally lower efficiencies compared to synthetic dyes such as phenothiazine-imidazole-based dyes [18], 1,8-naphthalene imide derivatives [19], azo dyes [20], quinoxaline D- π -A- π -A sensitizers [21] and BODIPY-based dyes [22], innovations in natural dye sourcing, extraction, and device architecture continue to push the boundaries of DSSC performance. These findings collectively suggest that while natural-based DSSCs currently face efficiency limitations, their environmental benefits and adaptability make them promising candidates for sustainable solar energy conversion technologies.

This work introduces *Cota tinctoria* (CTT), *Punica granatum* (PG), and *Linaria grandiflora* (LG) as previously unreported plant-derived dyes and eco-friendly natural sensitizers for DSSCs. This study establishes a direct mechanistic relationship among the electron injection driving force (ΔG_{inj}), recombination resistance (R_{rec}), and open-circuit voltage (V_{OC}) in *n*-DSSCs, offering a thorough understanding of how molecular energy-level alignment and interfacial charge-transfer processes influence photovoltaic performance.

In this study, we investigate three previously unreported plant-based dyes- *Cota tinctoria* (CTT), *Punica granatum* (PG), and *Linaria grandiflora* (LG) as sensitizers in *n*-DSSCs. The morphology of dye-loaded photoanodes was analyzed using field-emission scanning electron microscopy (FE-SEM), while functional groups involved in dye-TiO₂ interactions were identified via Fourier-transform infrared spectroscopy (FT-IR). Optical, electrochemical, and photovoltaic properties were systematically examined using UV-vis spectroscopy, cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and current-voltage (*J*-*V*) measurements. Among the tested dyes, the CTT-based DSSC exhibited the highest power conversion efficiency (0.91%), attributed to a favorable energy offset between the LUMO of the dye and the conduction band of TiO₂, which enhanced electron injection and short-circuit current. This study not only demonstrates the practical potential of lesser-known bio-derived dyes but also clarifies the structure-property-performance relationship underlying device behavior. These findings contribute a framework for the rational selection and design of sustainable sensitizers for next-generation DSSCs.

2. Experimental

2.1. Plant material

2.1.1. *Linaria grandiflora* Desf.

Genus *Linaria* Miller is a member of the *Plantaginaceae* family, generally found in the northern hemisphere except for America. The genus located its diverse center in the Mediterranean area. With around 150 species worldwide, the genus is represented by 21 species in our country, with 9 of them being endemic. *L. grandiflora* is a robust, glaucous perennial plant. It has the potential to reach heights of 30–75 cm [23, 24].

2.1.2. *Cota tinctoria* (L.) J. Gay var. *tinctoria*

The *Cota* J. Gay genus is a member of the *Asteraceae* family and is generally found in Europe (excluding the Northside), northern Africa, the Caucasus, southern Russia, and Anatolia in Afghanistan [24, 25]. Among the 49 species (63 taxa) in the genus, 24 of them are found exclusively in our country, with 10 of them being endemic [26]. *C. tinctoria* (L.) J. Gay, known as 'boyacı papatyası' in Türkiye, is indigenous to Europe, the Mediterranean, and Western Asia. This botanical specimen, exhibiting hues of yellow, buff, and golden orange, has been historically employed for fabric dyeing [27, 28]. *C. tinctoria* is a perennial herb with a greyish-green hairy appearance, reaching a height of 45 cm [29, 30].

2.1.3. *Punica granatum* L.

Probably *P. granatum* originated in the region encompassing Iran, Northern India, and the Himalayas [31]. Grown in various countries with temperate climates, especially in Asia close to the eastern Himalayas and southern Europe [32]. *P. granatum* is a thorny shrub or a small tree without thorns, ranging from 2 to 7 m in height, which sheds its leaves during the winter season.

2.2. Chemical composition of extracted dyes

Strack and colleagues [33] documented the identification of over 8000 phenolic structures frequently present in plants. These are molecules characterized by diverse molecular structures, such as phenolic acids, flavonoids, and coumarins. Natural dye pigments contain significant amounts of phenolic compounds. Phenolic compounds are the primary agents responsible for coloring natural organic colors [34]. The presence of phenolic compounds in plants augments their pigmentation capacity. Hence, substantial quantities of phenolic chemicals are required, as they are directly related to the plant's pigmentation characteristics.

Eser *et al* reported that the phenolic compounds found in the dried 100 g flowers of the *Cota tinctoria* (L.) J. Gay var. *tinctoria* capitulum plant was chlorogenic acid (71.0 mg), caffeic acid (0.08 mg), apigenin 7-glycoside (61.96 mg), rosmarinic acid (0.05 mg), and quercetin (1.02 mg). According to Eser *et al* the main phenolic compounds in *Cota tinctoria* (L.) J. Gay var. *tinctoria* capitulum is chlorogenic acid and apigenin 7-glycoside [35]. Bekir *et al* performed a chemical constituent study of *Punica granatum* L. flowers and identified phenolic acids, flavonoids, tannins, and anthocyanins [36]. The report identified gallic acid as the most abundant phenolic acid. Phenolic acids, flavonoids (quercetin), tannins (catechin), and anthocyanins (cyanidin-3-glucoside) were identified in ethanolic extracts. Cheriet *et al* [37] conducted an extensive analysis of the chemical components and biological characteristics of the genus *Linaria*. Cheriet *et al* extensively evaluated 95 papers about the genus *Linaria*, which encompasses over 200 species primarily found in Europe. Phytochemical investigations of the genus *Linaria* identified 191 substances, including phenolic acids, iridoids, flavone O-glycosides, flavonoids, triterpenoids, and alkaloids [37].

2.3. Preparation of natural dye sensitizers

This study utilized extracts from the petals of *Punica granatum*, *Linaria grandiflora*, and *Cota tinctoria* var. *tinctoria* capitulum as a natural dye to serve as a photosensitizer in the synthesis of DSSCs. Samples of the botanical species, specifically the petals of *P. granatum*, *Cota tinctoria* var. *tinctoria* capitulum, and *L. grandiflora*, were gathered in Kirsehir, Turkey (figure 1). All botanical specimens obtained for natural dye purposes were stored in the herbarium of Kirsehir Ahi Evran University. The petals were dried for approximately 24 h at a temperature of 50 °C. Subsequently, the dehydrated materials were ground into a fine powder. In the extraction process, 2 g of petals were combined with 50 ml of 96% ethanol.

Building upon our previous findings [14], we performed preliminary solvent screening for the dyes used in the current study and found that ethanol at 40 °C for 24 h provided the most consistent and efficient extraction for *Cota tinctoria*, *Punica granatum*, and *Linaria grandiflora*. Other tested solvents and conditions either led to pigment degradation or lower photovoltaic response, likely due to dye instability or insufficient anchoring functional groups. Therefore, the extraction parameters reported here were selected based on prior optimization efforts and are specific to the plant materials used in this study. Each sample underwent a separate extraction procedure using a mixer for a full day. During extraction, the heating was applied at 40 °C. The extract was filtered the following day. Until the analysis was conducted, the samples were shielded from light exposure and maintained at a temperature of +4 °C [7, 8].

2.4. Preparation and characterization of n-DSSC

Firstly, fluorine-doped oxide (FTO, surface resistance $\sim 7 \Omega \text{ sq}^{-1}$, optical transmittance ranged 80% $\sim$ 82%, Sigma Aldrich) were washed and treated with UV/O₃ for 15 min to remove organic contaminants.

TiO₂ paste was prepared by using P25 (Degussa P25, Aeroxide TiO₂ P 25, Evonik), terpeneol (95%), ethyl cellulose (48%) and ethanol (99%) with final ratio of 13.2:46.8:4.0:36.0 wt% respectively. The TiO₂ paste was spin coated on surface of the FTO glass as a dynamic coating technique (4000 rpm, for 90 s). The photoanode was kept at 500 °C for 15 min. Ultimately, the photoanodes were submerged in a 100 mM TiCl₄ solution and subjected to treatment at 450 °C for a duration of 30 min [7, 8]. After all processes, the final thickness of mesoporous TiO₂ was observed to be 10 μm (figure 2). The counter electrode consisted of a FTO that had been thermally platinized. The photoanodes were immersed in a 2 g sample of natural dye extract and then diluted in 50 ml of ethyl alcohol. The electrode was sensitized by exposing it to this chemical process for 18 h at room temperature in the dark condition.

This study utilizes a redox electrolyte made from a blend of volatile solvents. It contains 0.5 M tert-butylpyridine, 0.1 M lithium iodide, 0.05 M iodine, 0.05 M guanidinium thiocyanate, and 0.6 M 1-butyl-3-methylimidazolium iodide (BMII). The solvent mixture has an acetonitrile-to-valeronitrile ratio of 15:85 v/v [7, 8]. To create DSSC structure, electrolyte droplets were introduced between the photoanode and the counter electrode. The photoanodes have an active surface area measuring 0.27 cm². Every characterization performed on the cells and TiO₂ photoanodes was reported elsewhere [7, 8].



Figure 1. (a) *Linaria grandiflora* Desf. (b) *Cota tinctoria* (L.) J.Gay, (c) *Punica granatum* L.

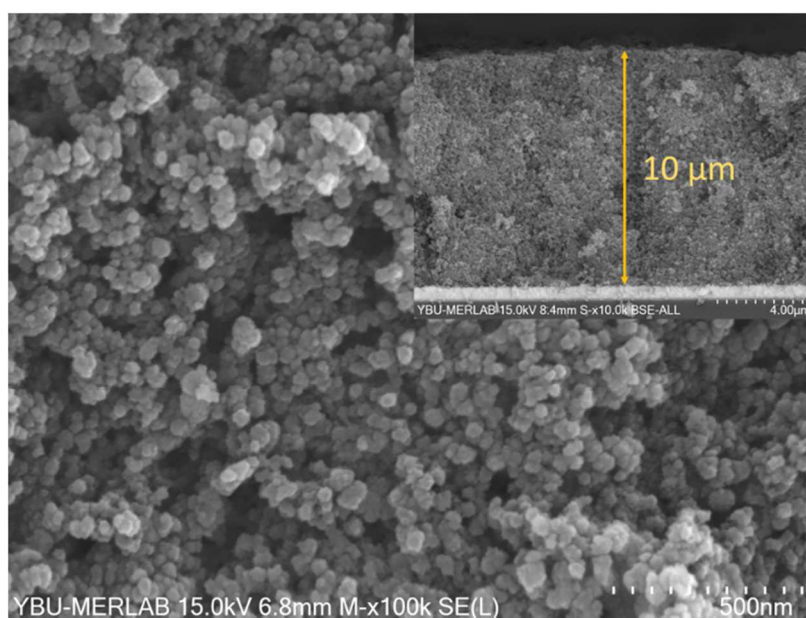


Figure 2. FE-SEM images depicting the surface and cross-sectional morphology of the TiO_2 mesoporous layer (see inset image).

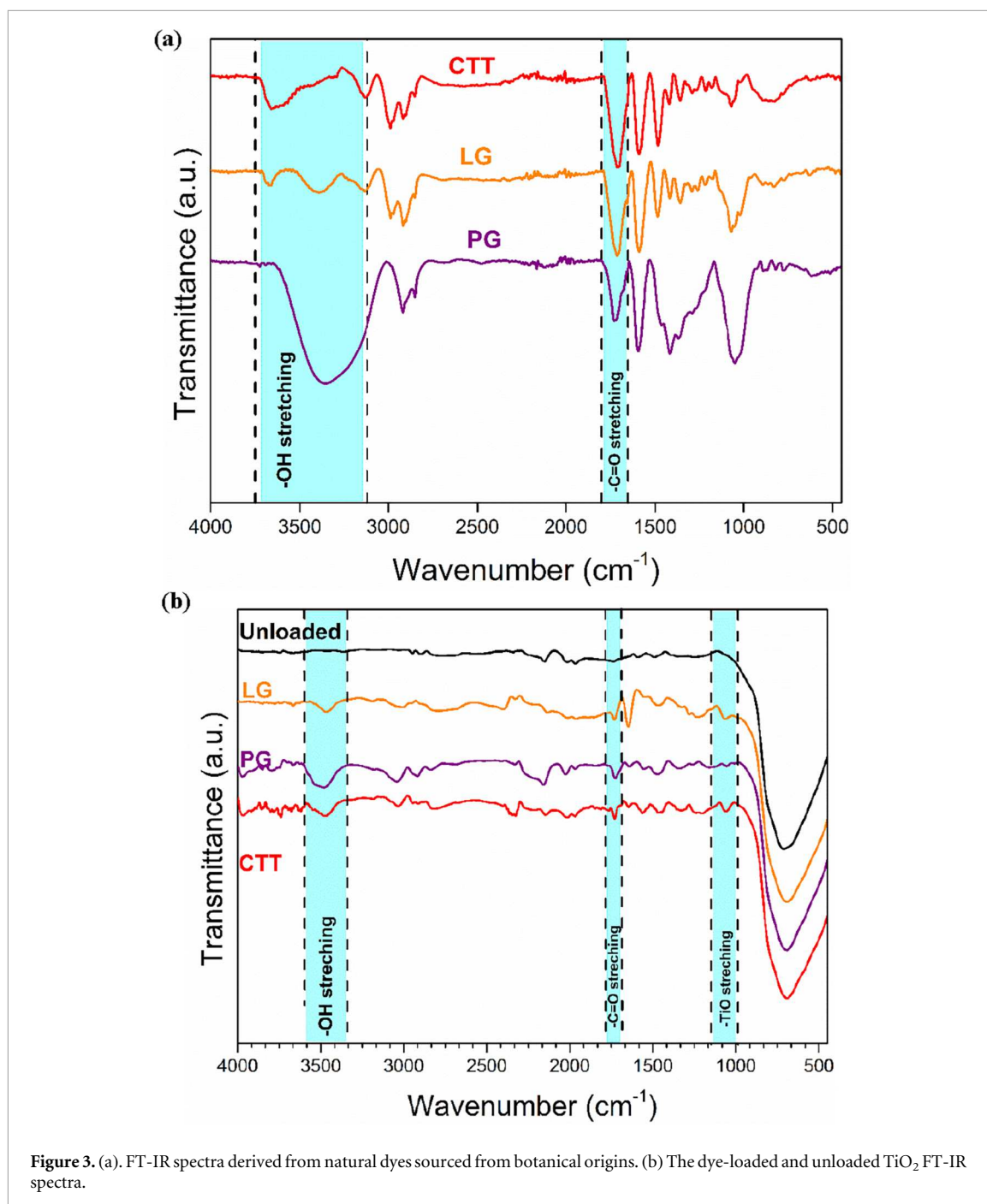
3. Results and discussion

3.1. Fourier transform infrared spectroscopy

Figure 3(a) illustrates the transmittance curve of natural dyes, as ascertained by FT-IR. The O-H stretching vibration in non-intermolecular bonding occurs within the frequency range of $3500\text{--}3700\text{ cm}^{-1}$. Intermolecular hydrogen bonding, however, diminishes the wave number of the O-H stretching, yielding a range of $3550\text{--}3200\text{ cm}^{-1}$. The peak observed in the range of $1780\text{--}1700\text{ cm}^{-1}$ is associated with the C=O stretching vibration mode [38, 39].

The FT-IR spectra obtained from natural dyes sourced from LG dye exhibited peaks at 3401 , and 3671 cm^{-1} , identified as O-H vibrations. The dye derived from LG dye exhibits a C=O vibration at 1714 cm^{-1} . The FT-IR spectra of the dye derived from PG dye displayed peaks at 3723 and 3372 cm^{-1} , indicative of O-H stretching vibrations, and at 1729 cm^{-1} , indicative of C=O stretching vibrations. The OH stretching vibration of CTT dye was assessed using FT-IR spectra at of 3662 cm^{-1} . The maxima at 1712 cm^{-1} in the FT-IR spectra of the natural dye obtained from the CTT dye is attributed to the C=O vibration. These peaks indicate the presence of C=O and O-H functional groups. The existence of C=O and O-H groups in the dyes signifies chemical interactions with TiO_2 , promoting the transfer of electrons from the dyes to TiO_2 .

Figure 3(b) depicts the dye-loaded and unloaded TiO_2 FT-IR spectra. The findings suggest that the photoanode, without any load, shows a peak of modest intensity at 3335 cm^{-1} . These vibrations are identified as O-H

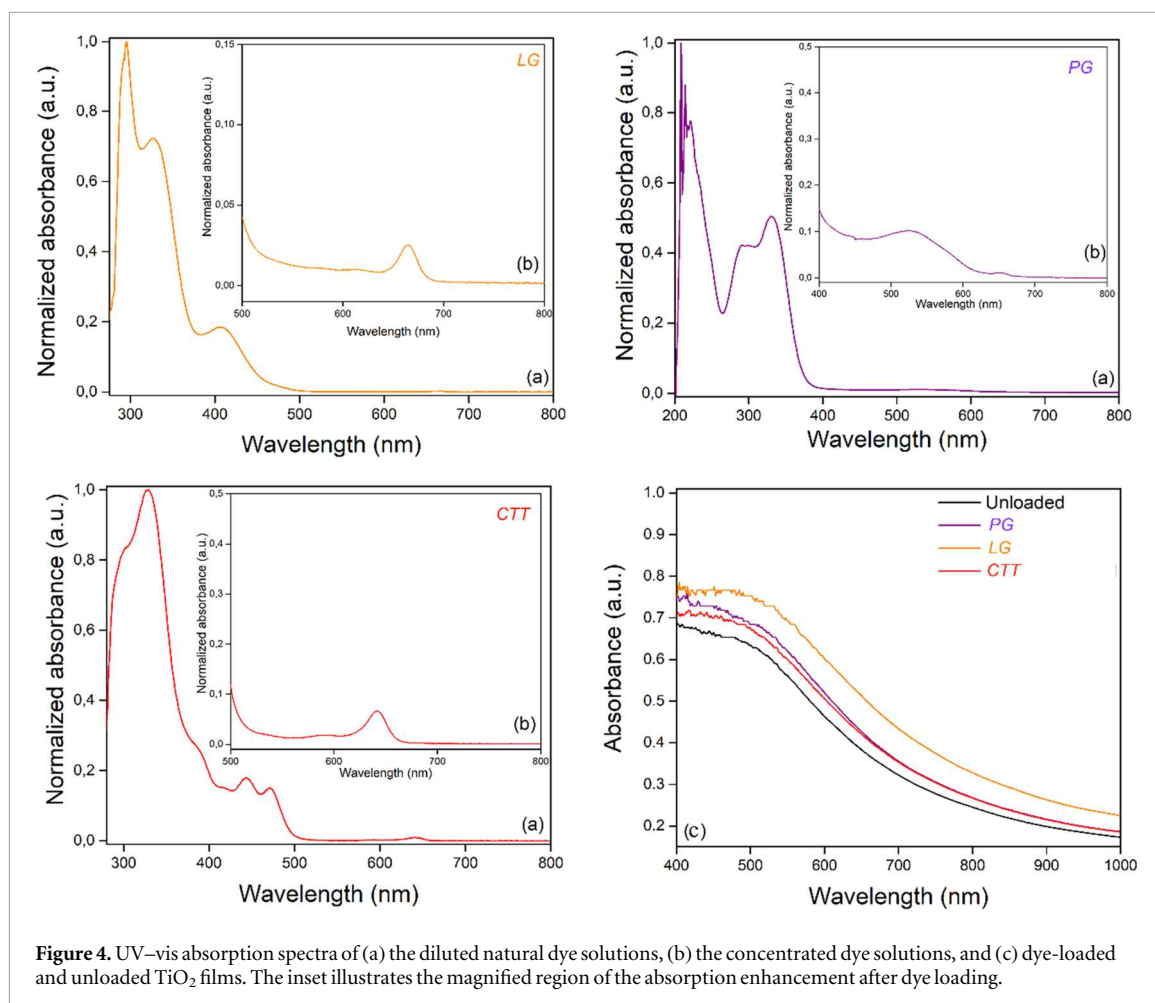


stretching modes. As expected, the photoanode with the dyes exhibited a shift towards shorter wavelengths in the peak, specifically at 3400 cm^{-1} [40, 41].

However, the broadened peaks detected about 1060 cm^{-1} can be attributed to the intense stretching vibrations resulting from the interactions between titanium and oxygen. The results indicate that the dye molecules have effectively adhered to the surface of TiO₂. As reported in previous study articles [42–44], the peaks seen at 1053 cm^{-1} for PG dye, 1061 cm^{-1} for LG dye, and 1056 cm^{-1} for CTT dye are most likely attributed to the stretching vibration mode between titanium and oxygen. The presence of the peak at 1730 cm^{-1} for PG-CTT and the peak at 1726 cm^{-1} for LG dye, attributed to the C=O stretching vibration mode, optimizes the electron transfer mechanism from the dye to TiO₂. Consequently, this enhances the efficiency of DSSCs [41].

3.2. Absorption spectroscopy

The UV–vis absorption spectra provide crucial information about the absorption characteristics of the solar spectrum in the photoanode, as well as the transitions occurring between the ground and excited states of the dye molecule. Dyes derived from biological sources contain C=O and O-H functional groups, enabling them to interact effectively with the TiO₂ layer, thereby improving power conversion efficiency. The experiments



were conducted over a wavelength range extending from 200 to 800 nm. In UV-vis spectra, chlorophyll absorption maxima are typically found in the 630–700 nm wavelength range [45]. Researchers identified chlorophyll peaks at wavelengths of 663 nm that corresponded to *CTT* dye. Belay *et al* identified a peak of chlorogenic acid (CGA) in the UV-vis spectra of coffee beans, falling within 300–350 nm [46]. Analysis of the UV-vis spectrum for *CTT* identified a prominent peak at 327 nm, which was identified as the peak generated by CGA.

Anthocyanins exhibit two well-defined absorption bands. The first absorption peak is detected in the 270 to 280 nm wavelength range and is followed by the next peak occurring between 465 to 550 nm. The UV-vis spectra of the *CTT* dye exhibit distinct peaks at 443 and 471 nm, which may indicate that the peaks belong to anthocyanin compounds.

The UV-vis spectrum of aromatic hydrocarbons, like gallic acid, a phenolic molecule, shows that benzene rings have three absorbance peaks connected to the π -system. Researchers observe specific absorbance peaks associated with the aromatic ring chromophore at wavelengths of 184, 204, and 256 nm [47]. In the present work, researchers identified the peak belonging to gallic acid at a wavelength of 208 nm, which corresponds to the *PG* dye. Experimental data at approximately 370 nm has been utilized to ascertain the transition energy from π to π^* in the UV-vis spectra of the quercetin molecule [48]. The peak detected at 330 nm for *PG* dye was determined to be the peak generated by quercetin. The *PG* dye extract has absorption properties within the wavelength range of 465–550 nm, with the absorption peaks detected at 536 nm. Chlorophyll peaks appear in UV-vis spectra typically within the wavelength range of 630–700 nm [45]. Our analysis revealed chlorophyll maxima at wavelengths of 641 nm that corresponded to *LG* dye. The observed peaks at wavelengths of 296 nm, 327 nm, and 405 nm in the *LG* dye are ascribed to the presence of phenol, flavones, anthocyanin, and other chemical compounds.

Flavonoid compounds, including flavones, flavonols, flavonones, and anthocyanins can absorb energy that falls within 400–700 nm [49]. Therefore, it can be concluded that the absorption is attributed to the flavonoid molecules found in the natural dye solvent extracts obtained [50]. Figure 4 displays the spectra of photoanodes that have been treated with dye compared to those that have not been treated. The performance of the photoanode showed enhancement across the entire spectrum following dye application, with the most notable improvement observed in the 450–600 nm range. While FT-IR and UV-vis analyses provide sufficient

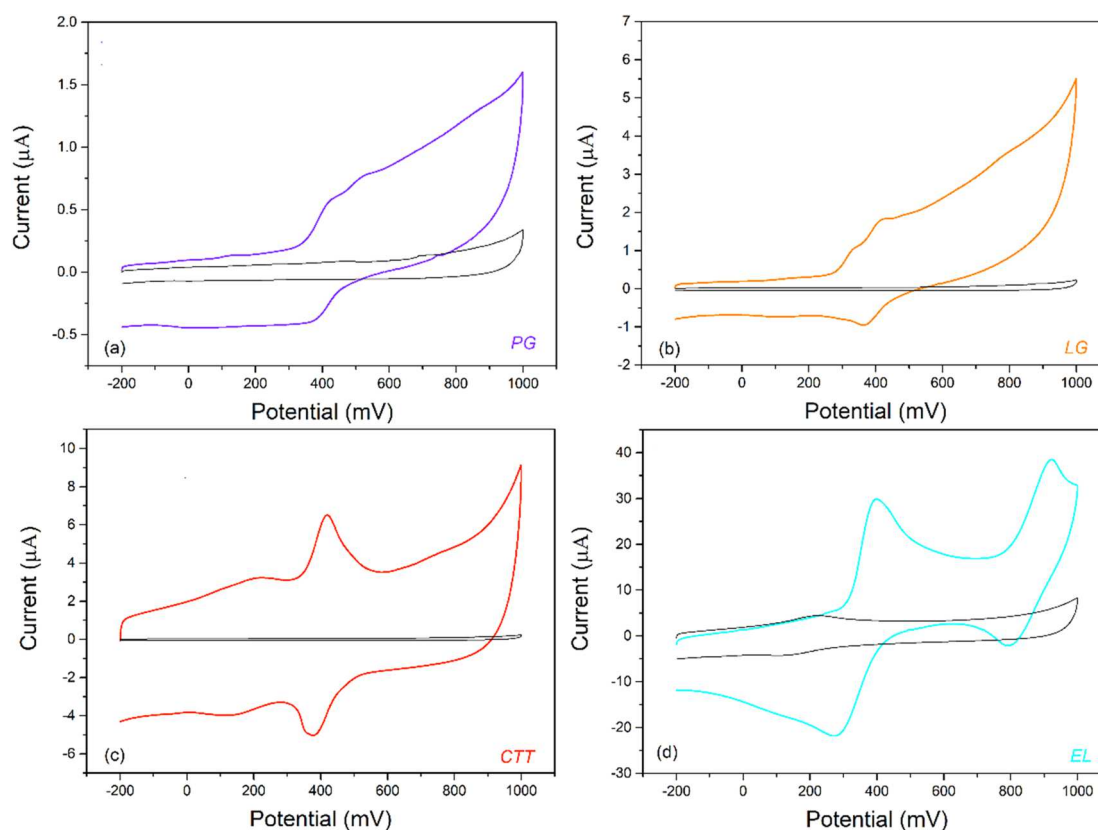


Figure 5. Cyclic voltammetry (CV) plots recorded at a scan rate of 20 mV s^{-1} for the PG dye (a), LG dye (b), and CTT dye (c), along with the EL electrolyte (d).

Table 1. Photophysical and electrochemical information regarding PG, LG, and CTT dyes.

	λ_{max} (nm) ^a	$E_{\text{OX}}/E_{\text{HOMO}}$ (V) ^b	E_{0-0} (eV) ^c	$E_{\text{OX}}^*/E_{\text{LUMO}}$ (V) ^d	ΔG_{inj} (V) ^e
PG dye	536	0.405	1.797	−1.392	−0.892
LG dye	663	0.416	1.786	−1.370	−0.870
CTT dye	641	0.476	1.878	−1.402	−0.902

^a Experimental maximum absorbance value.

^b Oxidation potential obtained from CV measurements.

^c The optical bandwidth is derived from the experimental ultraviolet spectrum. The value is derived by dividing the location where the tangent drawn from the greatest absorbance intersects the x-axis by 1240.

^d $E_{\text{OX}}^* = E_{\text{OX}} - E_{0-0}$.

^e $\Delta G_{\text{inj}} = (E_{\text{LUMO}} - \text{CB}_{\text{TIO}_2})$.

information on the functional groups and general pigment classes (anthocyanins, flavonoids, chlorophyll derivatives), the precise molecular composition of each extract remains unresolved.

3.3. Cyclic voltammetry

The CV evaluated the electrochemical characteristics of the dye pigments and the electrolyte. An Ag/AgCl (3 M KCl) electrode was used as the reference electrode, while a Pt wire performed as the auxiliary electrode. In this experiment, a disposable pencil graphite electrode, possessing a surface area of 0.095 cm^2 , was utilized as the working electrode [51–53].

Figure 5 displays the Cyclic voltammograms (CV) plots of the PG, LG, and CTT dyes alongside the electrolyte. CV were used to get ground oxidation potentials (E_{OX}) of the PG, LG, and CTT dyes, that correspond to their HOMO levels and evaluated to be 0.405, 0.416 and 0.476 V in comparison to the normal hydrogen electrode (versus NHE), respectively. The optical band gaps (E_{0-0}) of the dyes PG, LG, and CTT were determined from their absorption onset and calculated to be 1.797, 1.786, and 1.878 eV, respectively. The oxidation potentials in the excited state (E_{OX}^*) associated with the LUMO levels (derived from $E_{\text{OX}} - E_{0-0}$) are measured at −1.392, −1.370, and −1.402 V versus NHE, respectively. The energy levels of both the HOMO and LUMO of the dye pigments under investigation have been quantified and are compiled in table 1, as illustrated in figure 6.

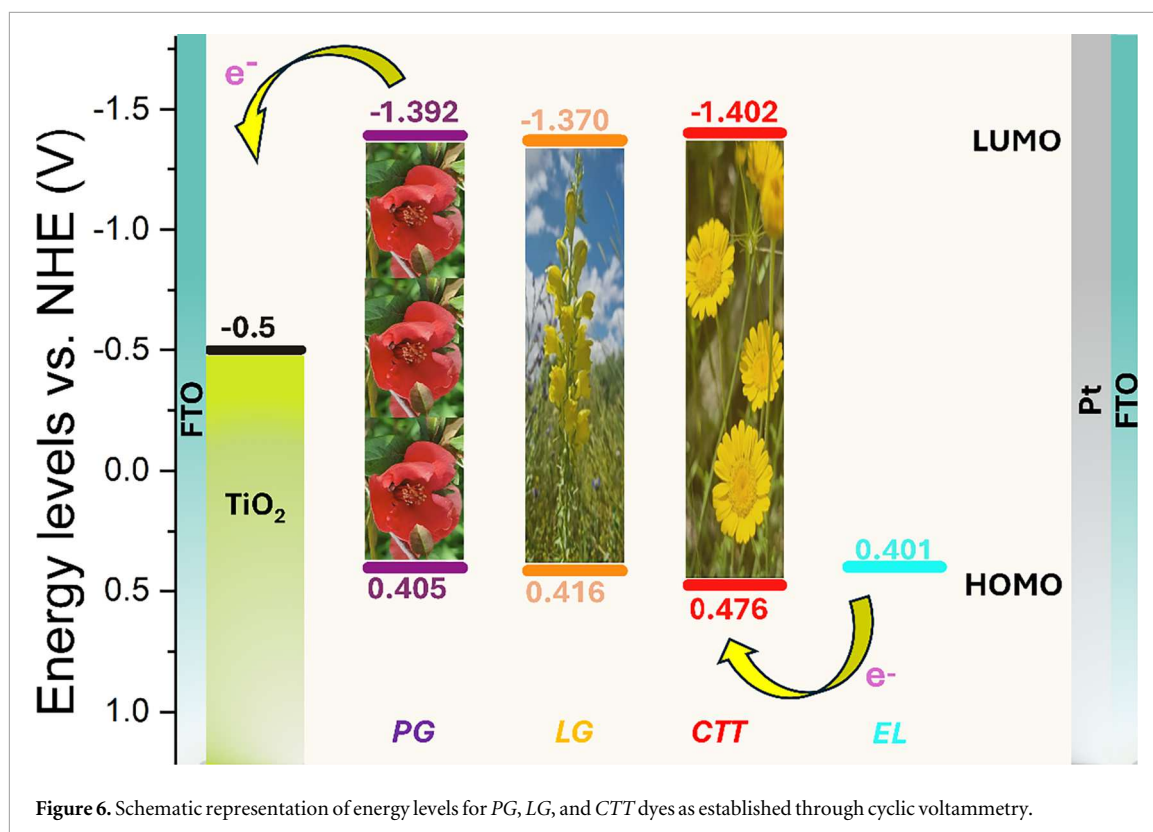


Figure 6. Schematic representation of energy levels for PG, LG, and CTT dyes as established through cyclic voltammetry.

Table 2. Distinctive photovoltaic characteristics of the cells.

Dye	J_{SC} (mA cm ⁻²)	V_{OC} (V)	FF	η (%)
PG dye	0.97 ± 0.04	0.59 ± 0.00	0.85 ± 0.03	0.49 ± 0.01
LG dye	0.70 ± 0.00	0.52 ± 0.00	0.67 ± 0.03	0.24 ± 0.01
CTT dye	2.11 ± 0.03	0.57 ± 0.00	0.76 ± 0.00	0.91 ± 0.00

*Values are averaged over five repeated J - V measurements of a single device per dye.

Consequently, the HOMO levels of PG, LG, and CTT are significantly more positive compared to the EL (0.401 V versus NHE) energy level, thereby ensuring that the oxidized dye can be effectively regenerated by the electrolyte. Additionally, the LUMO levels of all dyes are considerably more negative than the conduction band (CB) of TiO₂ (−0.5 V versus NHE), thus creating a substantial driving force for electron injection from the LUMO level into the CB of TiO₂ [54, 55].

3.4. Photovoltaic performance

Under 1 Sun illumination, the performance of the photovoltaic devices is evaluated. The parameters of the cells, which encompass fill factor (FF), photovoltaic efficiency (η), short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), and the photocurrent density–voltage (J - V) curve, are presented in figure 7 and table 2. The findings indicate that the efficiency of the devices vary between 0.24% and 0.91%, and the increase in efficiency can primarily be ascribed to an enhancement in J_{SC} . The device sensitized by the CTT dye exhibited a higher photovoltaic efficiency ($\eta = 0.91\%$) compared to other devices, with $J_{SC} = 2.11$ mA cm⁻². The devices sensitized by PG and LG perform 0.49%–0.24% PCE and 0.97 mA cm⁻²–0.70 mA cm⁻² J_{SC} , respectively. Numerous parameters, including the structure of dye, absorbance, and electron injection capacity, influence the J_{SC} value, which is reliant upon the way in which the sensitizer and TiO₂ interact [56–58].

The LUMO energy level of the sensitizer should be greater than the conduction band (CB) level of TiO₂ to ensure efficient electron injection. When the gap widens between the LUMO and the CB, the driving force triggering the electron injection will become greater [54]. This resulted in a higher J_{SC} value. For all dyes, the value of driving force facilitating the electron injection listed at table 1. However, CTT sensitizer-based device exhibits the greatest LUMO level, revealing that the driving force of electron injection is the highest, which may lead to highest J_{SC} value for CTT dye based DSSCs. The prevailing trend in the driving mechanism of electron

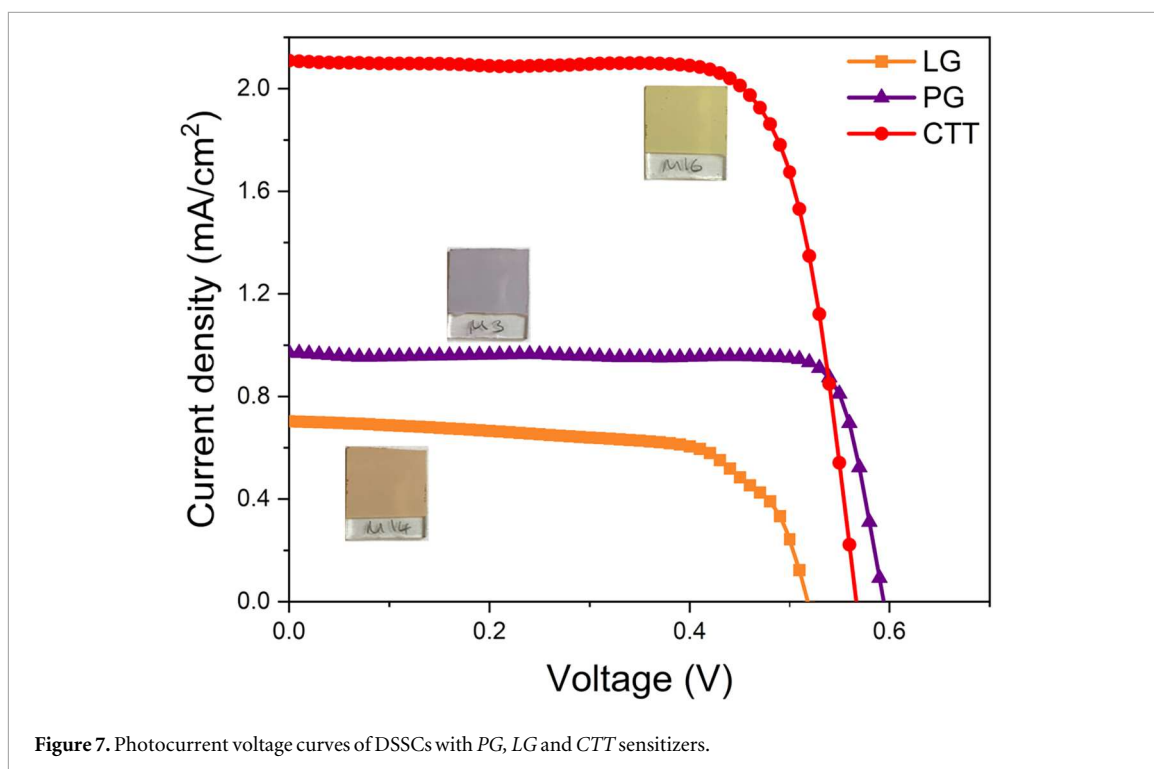


Figure 7. Photocurrent voltage curves of DSSCs with PG, LG and CTT sensitizers.

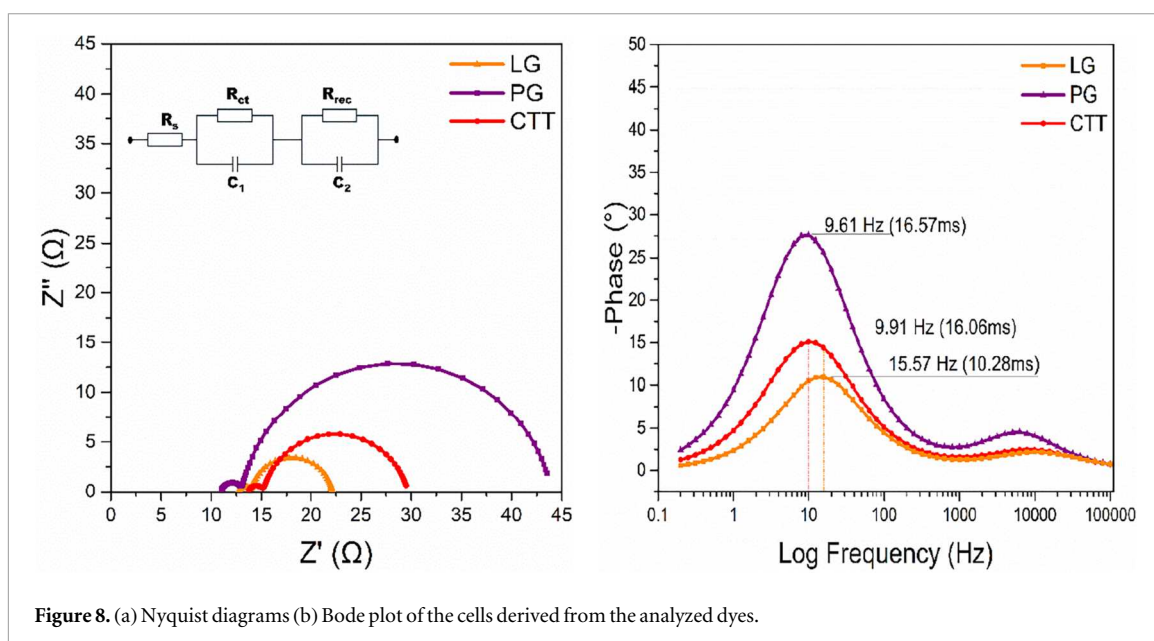


Figure 8. (a) Nyquist diagrams (b) Bode plot of the cells derived from the analyzed dyes.

injection is in the sequence of $\Delta G_{inj-CTT}(-0.902 \text{ V}) > \Delta G_{inj-PG}(-0.892 \text{ V}) > \Delta G_{inj-LG}(-0.870 \text{ V})$ which is correctly consistent with the J_{SC} sequence of the dyes. While the V_{OC} values were close to each other, the PG dye exhibit the highest V_{OC} value (0.59 V). Given that the V_{OC} value in DSSCs is associated through the processes of recombination, photogeneration, and the alignment of energy bands within the solar cell, this may lead to a significant level of recombination resistance [59, 60].

3.5. Electrochemical impedance spectroscopy

To conduct a more in-depth analysis of the recombination process and the behaviors of interfacial resistance in DSSCs utilizing these natural dyes, investigations were carried out under dark conditions and applied at bias voltages close to their open-circuit voltage (V_{OC}) values through electrochemical impedance spectroscopy (EIS). Figure 8 illustrates the Nyquist plots (a) and the Bode plots (b) for the DSSCs that are based on natural dyes. The EIS parameters have been fitted using a suitable equivalent circuit model for DSSCs. The equivalent circuit model employed is depicted in the inset of figure 8(a), and the fitted results are presented in table 3. The

Table 3. Parameters fitted from EIS measurements of the PG, LG, and CTT natural dye-based DSSCs.

Dye	$R_s (\Omega)$	$R_{ct} (\Omega)$	$R_{rec} (\Omega)$	τ (ms)
PG	11.1	2	31.1	16.57
LG	12.69	1.25	8.23	10.28
CTT	13.67	1.52	14.57	16.06

charge transfer resistance (R_{ct}) at the platinum/electrolyte interface is represented by the first semi-circle of the Nyquist plot, whereas the recombination resistance (R_{rec}) at the TiO_2 /dye/electrolyte interface is indicated by the second semi-circle [54]. A higher R_{rec} signifies a reduced charge recombination of electrons, thereby leading to an increase in the V_{OC} values of the DSSCs [54]. PG dye sensitized DSSC exhibit the highest R_{rec} values of 31.1 Ω , followed by CTT and LG with 14.57 Ω and 8.23 Ω , respectively. The trend in the R_{rec} in the order of $PG > CTT > LG$ which is correctly consistent with the V_{OC} sequence of the dyes.

As demonstrated previously, even when ΔG_{inj} is favorable, the actual injection efficiency may be limited by factors such as molecular orbital overlap [54], dye aggregation [55], and interfacial dynamics [56]. Similarly, it was emphasized that high ΔG_{inj} must be balanced with recombination resistance (R_{rec}) and spectral absorption to achieve meaningful performance gains [57, 58]. In our case, although the CTT dye exhibited the highest ΔG_{inj} (−0.902 V), its V_{OC} was slightly lower than PG, due to its lower recombination resistance. This underscores that ΔG_{inj} should be interpreted in conjunction with other parameters, particularly R_{rec} and dye absorption characteristics. A large ΔG_{inj} can promote injection, but if recombination pathways are not simultaneously suppressed (i.e., via higher R_{rec} or improved dye- TiO_2 binding), gains in J_{SC} may not translate to increased V_{OC} or overall efficiency.

Furthermore, whereas the PG dye exhibits the highest FF of 85%, the CTT and PG sensitized samples show smaller FF values of 76% and 67%, respectively. Their considerably decreased recombination resistance in comparison to the PG-sensitized sample is consistent with these observations. As shown in table 3 and figure 8(a) of the manuscript, the PG-sensitized device exhibited the highest R_{rec} (31.1 Ω), followed by CTT (14.57 Ω) and LG (8.23 Ω), consistent with their respective open-circuit voltages (V_{OC}). Higher R_{rec} indicates reduced charge recombination at the TiO_2 /dye/electrolyte interface, thereby extending the electron lifetime, as confirmed by the Bode analysis. Structurally, PG and CTT dyes contain abundant phenolic and carbonyl functional groups (as revealed by FT-IR), which enhance dye- TiO_2 binding and help suppress back-electron transfer, leading to higher R_{rec} and longer τ values. Regarding the CV curve not forming a full cycle, this is due to the irreversible nature of the redox reactions of the natural dyes under the applied potential range and scan rate (20 mV s^{-1}), which is a common feature in CV profiles of natural pigments.

The Bode phase diagram (figure 8(b)) illustrates that the charge transfer occurring at the counter electrode corresponds to the minor peak observed at a higher frequency, whereas the charge recombination rate is indicated by peaks at a lower frequency. The electron lifetime (τ) is inversely related to the charge recombination rate. The electron lifetime can be determined using the formula $\tau = 1/(2\pi f_{\max})$, where $f_{\max}$ denotes the location of the frequency peak within the lower frequency range of the Bode plots. Relatively longer electron lifetimes are generally associated with lower dark current, higher resistance to charge recombination, and better V_{OC} [54]. Defect states in TiO_2 leading to immobile electrons should be suppressed for enhanced electron transport, leading to a degradation in V_{OC} [61, 62].

PG sensitizer device exhibits longest electron lifetime with 16.57 ms (inset figure 8(b)), like performed highest V_{OC} and R_{rec} parameters. The trend observed in electron lifetime follows the order of $PG > CTT > LG$, which aligns accurately with the V_{OC} and R_{rec} of the devices [63, 64]. The PG-based device demonstrated the longest lifetime (16.57 ms), followed closely by CTT (16.06 ms) and then LG (10.28 ms). This trend mirrors the order of R_{rec} and V_{OC} , indicating a strong correlation between recombination suppression and prolonged carrier lifetime. The longer τ in PG- and CTT-based DSSCs is attributed to their richer content of anchoring functional groups (e.g., OH and C=O), which provide better dye adhesion and interfacial stability, limiting electron back-transfer. These results reinforce the mechanistic insight that effective recombination suppression is a key determinant of improved photovoltaic behavior in *n*-DSSCs.

Table 4 presents a comparison between the documented DSSCs that use natural dyes and the DSSCs that were examined in the present study. The new natural sensitizer demonstrates enhanced properties when compared with alternative natural dyes. This comparison indicates that our devices outperform the other naturally DSSCs in terms of J_{SC} and FF values. However, we obtained that the efficiencies (~0.91%) achieved in this study are lower than those of synthetic dyes and some optimized bio-dye systems. This performance limitation primarily arises from the inherent molecular characteristics of natural dyes, which typically lack the donor- π -acceptor structures that facilitate broad spectral absorption and efficient charge transfer in synthetic dyes

Table 4. An analysis of the photovoltaic performance of different natural dye-based DSSCs in comparison to existing literature.

Source	J_{SC} (mA cm ⁻²)	V_{OC} (V)	FF	η (%)	Reference
<i>Beetroot</i>	0.36	0.42	0.51	0.078	[62]
<i>Alpinia purpurata</i>	0.49	0.53	0.40	0.65	[65]
<i>Red lantana</i>	0.73	0.265	0.48	1.02	[66]
<i>Mediterranean olive</i>	0.66	0.64	0.31	0.31	[67]
<i>Azadirachia indica</i>	4.1	0.75	0.40	0.84	[68]
PG	0.97	0.59	0.85	0.49	Our Study
LG	0.70	0.52	0.67	0.24	Our Study
CTT	2.11	0.57	0.76	0.91	Our Study

[21, 58]. Additionally, the natural dyes used in this study may possess fewer anchoring groups, leading to less stable adsorption on the TiO₂ surface and reduced electron injection efficiency [18, 59]. Although we optimized the extraction conditions to preserve functional groups and maximize dye performance, the dyes still exhibit limited light absorption in the red-NIR region and may be susceptible to aggregation or photodegradation. On the device side, conventional TiO₂ photoanodes and standard electrolyte compositions were used without advanced enhancements such as co-sensitization, scattering layers, or optimized redox mediators, which are known to improve photovoltaic performance. Moving forward, strategies such as molecular modification of natural dyes, co-sensitization, and tailored device architecture could help overcome these limitations and improve both efficiency and stability.

4. Conclusions

In summary, we succeeded in fabricating DSSCs based on natural dyes extracted from *Punica granatum* L. petal (PG), *Cota tinctoria* (L.) J.Gay var. *tinctoria* capitulum (CTT), and *Linaria grandiflora* Desf. petal (LG). From the analysis, we find that the fabricated devices perform well over the solar spectrum, playing a major role in absorbing of the light. The DSSCs loaded with dye extracted from CTT perform better than those loaded with other derived dyes, with an overall conversion efficiency of 0.91%. This is explained by the fact that the DSSC loaded with dye derived from CTT had a larger differential between LUMO and CB of TiO₂, which primarily increases the short-circuit current. This thorough examination of the dyes under investigation is unquestionably a step in the right direction toward affordable natural DSSCs.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

- [1] Ghann W, Kang H, Sheikh T, Yadav S, Chavez-Gil T, Nesbitt F and Uddin J 2017 Fabrication, optimization and characterization of natural dye-sensitized solar cell *Sci. Rep.* **7** 41470
- [2] O'Regan B and Grätzel M 1991 A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films *Nature* **353** 737–40
- [3] Ren Y, Zhang D, Suo J, Cao Y, Eickemeyer F T, Vlachopoulos N, Zakeeruddin S M, Hagfeldt A and Grätzel M 2022 Hydroxamic acid pre-adsorption raises the efficiency of cosensitized solar cells *Nature* **613** 60–5
- [4] Pesala B S 2019 Performance enhancement of betanin solar cells co-sensitized with indigo and lawsone: a comparative study *ACS Omega* **4** 18023–34
- [5] Teja A S, Srivastava A, Satrugna J A K, Tiwari M K, Kanwade A, Yadav S C and Shirage P M 2022 Optimal processing methodology for futuristic natural dye-sensitized solar cells and novel applications *Dyes Pigm.* **210** 110997
- [6] Patni N, Pillai S G and Sharma P 2020 Effect of using betalain, anthocyanin and chlorophyll dyes together as a sensitizer on enhancing the efficiency of dye-sensitized solar cell *Int. J. Energy Res.* **44** 10846–59
- [7] Erdoğan M, Atilgan A, Erdogan Y and Yildiz A 2023 Natural dyes extracted from *Ligustrum vulgare*, *Juniperus sabina*, and *Papaver rhoeas* for novel DSSC applications *Mater. Lett.* **358** 135811
- [8] Erdogan M, Atilgan A, Erdogan Y and Yildiz A 2023 Flavonoid from *Hedera helix* fruits: a promising new natural sensitizer for DSSCs *J. Photochem. Photobiol., A* **448** 115288
- [9] Golshan M, Osfour S, Azin R, Jalali T and Moheimani N R 2021 Co-sensitization of natural and low-cost dyes for efficient panchromatic light-harvesting using dye-sensitized solar cells *J. Photochem. Photobiol., A* **417** 113345
- [10] Obi K, Frolova L and Fuierer P 2020 Preparation and performance of prickly pear (*Opuntia phaeacantha*) and mulberry (*Morus rubra*) dye-sensitized solar cells *Sol. Energy* **208** 312–20
- [11] Yelkovan M E et al 2025 Driving forces of injection and regeneration in natural dye-sensitized solar cells: insights into photovoltaic performance *Sol. Energy* **295** 113523
- [12] Sarwar N et al 2024 Synergistic photovoltaic performance of DSSCs based on ZnO charge transport layers, counter electrodes and C annuum and T indica as natural dyes *Materials Science and Engineering: B* **307** 117543
- [13] Atli A et al 2019 St. Lucie cherry, yellow jasmine, and madder berries as novel natural sensitizers for dye-sensitized solar cells *Int. J. Energy Res.* **43** 3914–22
- [14] Kocak et al 2019 Extraction method dependent performance of bio-based dye-sensitized solar cells (DSSCs) *Mater. Res. Express* **6** 095512
- [15] Iman R N et al 2024 Fabrication of efficient natural dye-sensitized solar cells using Mediterranean olive leaves as natural dye sensitizer *J. Photochem. Photobiol., A* **450** 115477
- [16] Kocak Y and Yildiz A 2021 Carminic acid extracted from cochineal insect as photosensitizer for dye-sensitized solar cells *Int. J. Energy Res.* **45** 16901–7
- [17] Onyemowo M, Unpaprom Y and Ramaraj R 2024 Exploring the potential of natural dyes in DSSCs: innovations for efficient light harvesting and charge separation through co-sensitization *Opt. Mater.* **148** 114860
- [18] Bifari E N et al 2026 Phenothiazine–imidazole-based dye containing furan π -linker for dye-sensitized solar cells *J. Mater. Sci.* **61** 905–917
- [19] Yurdakul E B et al 2025 Cutting-edge dyes for p-type dye-sensitized solar cells: a theoretical study of 1, 8-naphthalene imide derivatives *J. Comput. Electron.* **24** 181
- [20] Ozel K et al 2025 An assessment of the photovoltaic characteristics of some azo dyes for dye-sensitized solar cells: insights from experimental and theoretical studies *Opt. Quantum Electron.* **57** 432
- [21] Al-Marhabi A R et al 2025 The impact of aryl amine donors on the performance of dye-sensitized solar cells based on quinoxaline D- π -A- π -A sensitizers *J. Mol. Struct.* **1333** 141746
- [22] Singh S P and Gayathri T 2014 Evolution of BODIPY dyes as potential sensitizers for dye-sensitized solar cells *Eur. J. Org. Chem.* **2014** 4689–707
- [23] Sutton D A 1988 *A Revision of the Tribe Antirrhineae* (Oxford University Press)
- [24] Davis P H and Hedge I C 1975 The flora of Turkey; past, present and future *Candollea* **30** 331–51
- [25] Oberprieler C H, Vogt R and Watson L E 2007 Tribe anthemideae cass *The Families and Genera of Vascular Plants, Vol. VIII: Flowering Plants, Eudicots, Asterales* ed K Kubitzki (Springer) pp 342–74
- [26] Özbeke M U 2012 *Cota Türkiye Bitkileri Listesi (Damarlı Bitkiler)* ed A Güner et al (Nezahat Gökyiğit Botanik Bahçesi ve Flora Araştırmaları Derneği) pp 146–8
- [27] IBU Flora 2024 <https://ibuflora.ibu.edu.tr/tur/cota-tinctoria> Cota tinctoria (accessed 25 April 2024)
- [28] Bizim B 2024 <https://bizimbitkiler.org.tr/> Türkiye Florası (accessed 25 April 2024)
- [29] Davis P H 1965 *Flora of Turkey and the East Aegean Islands* vol 5 (Edinburgh University Press)
- [30] Davis P H 1975 *Flora of Turkey and the East Aegean Islands* vol 6 (Edinburgh University Press) 654–72
- [31] Levin G M 2006 *Pomegranate* (Third Millennium Publishing) 3–23
- [32] Kochhar S L 1998 *Economic Botany in the Tropics* (Man Millan India Limited) 604
- [33] Strack D 1997 Phenolic metabolism ed P M Dey and J B Harborne *Plant Biochemistry* (Academic) 387–416
- [34] Oreopoulou V and Russ W 2006 *Utilization of By-Products and Treatment of Waste in the Food Industry* (Springer Science & Business Media)
- [35] Eser F, Yaglioglu A S, Dolarslan M, Aktas E and Onal A 2016 Dyeing, fastness, cytotoxic properties and phenolic constituents of *Anthemis tinctoria* var. *tinctoria* (Asteraceae) *J. Textile Inst.* **108** 1489–95

- [36] Bekir J, Mars M, Vicendo P, Fterrich A and Bouajila J 2013 Chemical composition and antioxidant, anti-inflammatory, and antiproliferation activities of pomegranate (*Punica granatum*) flowers *J. Med. Food* **16** 544–50
- [37] Cheriet T, Mancini I, Seghiri R, Benayache F and Benayache S 2015 Chemical constituents and biological activities of the genus *Linaria* (Scrophulariaceae) *Nat. Prod. Res.* **29** 1589–613
- [38] Erdogdu Y, Baskose U C, Saglam S, Erdogdu M, Ogutcu H and Özçelik S 2020 Structural, thermal, spectroscopic, electronic and biological activity properties of coumarin-153 dyes for DSSCs: a DFT benchmark study *J. Mol. Struct.* **1221** 128873
- [39] Erdogdu Y 2012 Investigations of FT-IR, FT-Raman, FT-NMR spectra and quantum chemical computations of Esculetin molecule *Spectrochim. Acta Part A* **106** 25–33
- [40] Ferreira B C, Sampaio D M, Babu R S and De Barros A L F 2018 Influence of nanostructured TiO₂ film thickness in dye-sensitized solar cells using naturally extracted dye from *Thunbergia erecta* flowers as a photosensitizer *Opt. Mater.* **86** 239–46
- [41] Ferreira F C, Babu R S, De Barros A L F, Raja S, Da Conceição L R B and Mattoso L H C 2020 Photoelectric performance evaluation of DSSCs using the dye extracted from different color petals of *Leucanthemum vulgare* flowers as novel sensitizers *Spectrochim. Acta Part A* **233** 118198
- [42] Santos F M M D, Leite A M B, Da Conceição L R B, Sasikumar Y, Atchudan R, Pinto M F, Babu R S and De Barros A L F 2022 Effect of bandgap energies by various color petals of *Gerbera jamesonii* flower dyes as a photosensitizer on enhancing the efficiency of dye-sensitized solar cells *J. Mater. Sci., Mater. Electron.* **33** 20338–52
- [43] Da Conceicao L R B, De Barros A L F, Haddad D B and Babu R S 2020 *Passiflora edulis* and *Cocos nucifera* extracts as light-harvesters for efficient dye-sensitized solar cells *IEEE Andescon* **1–5**
- [44] Jeyaram S and Geethakrishnan T 2020 Vibrational spectroscopic, linear and nonlinear optical characteristics of anthocyanin extracted from blueberry *Results in Optics* **1** 100010
- [45] Sakshi N, Singh P K and Shukla V K 2021 Widening spectral range of absorption using natural dyes: applications in dye-sensitized solar cell *Mater. Today Proc.* **49** 3235–8
- [46] Belay A and Gholap A V 2009 Characterization and determination of chlorogenic acids (CGA) in coffee beans by UV–vis spectroscopy *African Journal of Pure and Applied Chemistry* **3** 234–40
- [47] Baek N-W, Fan X-R, Yuan J-G, Xu J and Wang Q 2021 Polymerization and dyeing properties of gallic acid on silk fabric catalyzed by horseradish peroxidase *Fibers Polym.* **22** 2145–55
- [48] Andrade-Filho T, Ribeiro T C S and Del Nero J 2009 The UV–vis absorption spectrum of the flavonol quercetin in methanolic solution: a theoretical investigation *The European Physical Journal E* **29** 253–9
- [49] Bechtold T and Mussak R 2009 *Handbook of Natural Colorants* (Wiley) **10.1002/9780470744970**
- [50] Deveoğlu O and Karadağ R 2019 Doğal boya kaynağı—flavonoidler üzerine derleme *International Journal of Advances in Engineering and Pure Sciences* **31** 188–200
- [51] Donmez S, Arslan F and Arslan H 2015 A nucleic acid biosensor for detection of hepatitis C virus genotype 1a using poly(L-glutamic acid)-modified electrode *Appl. Biochem. Biotechnol.* **176** 1431–44
- [52] Donmez S, Çağdaş L, Arslan H and Arslan F 2019 Electrochemical nucleic acid hybridization biosensor based on poly(L-aspartic acid)-modified electrode for the detection of short oligonucleotide sequences related to hepatitis C virus 1a *Preparative Biochemistry & Biotechnology* **49** 900–7
- [53] Kumara N T R N, Ekanayake P, Lim A, Iskandar M and Ming L C 2013 Study of the enhancement of cell performance of dye-sensitized solar cells sensitized with *Nephelium lappaceum* (F: Sapindaceae) *J. Sol. Energy Eng.* **135** 011001
- [54] Ying W, Guo F, Li J, Zhang Q, Wu W, Tian H and Hua J 2012 Series of new D–A– π –A organic broadly absorbing sensitizers containing isoindigo unit for highly efficient dye-sensitized solar cells *ACS Appl. Mater. Interfaces* **4** 4215–24
- [55] Ni J-S, Chiu T-Y, Kao W-S, Chou H-J, Su C-C and Lin J T 2016 Organic photosensitizers incorporating rigidified dithieno[3,2-f:2',3'-h]quinoxaline segment tethered with thiophene substitutes for dye-sensitized solar cells *ACS Appl. Mater. Interfaces* **8** 23066–73
- [56] She Z, Cheng Y, Zhang L, Li X, Wu D, Guo Q, Lan J, Wang R and You J 2015 Novel ruthenium sensitizers with a phenothiazine conjugated bipyridyl ligand for high-efficiency dye-sensitized solar cells *ACS Appl. Mater. Interfaces* **7** 27831–7
- [57] Orona-Navar A, Aguilar-Hernández I, López-Luke T, Zarazúa I, Romero-Arellano V, Guerrero J P and Ornelas-Soto N 2019 Photoconversion efficiency of titania solar cells co-sensitized with natural pigments from cochineal, papaya peel and microalga *Scenedesmus obliquus* *J. Photochem. Photobiol. A* **388** 112216
- [58] Zhu H, Li W, Wu Y, Liu B, Zhu S, Li X, Ågren H and Zhu W 2014 Insight into benzothiadiazole acceptor in D–A– π –A configuration on photovoltaic performances of dye-sensitized solar cells *ACS Sustainable Chemistry & Engineering* **2** 1026–34
- [59] Akdogan N, Ortatepe B, Atli A, Disli A, Erdogdu Y and Yildiz A 2023 A joint theoretical and experimental study on a tetrazole-anchored BODIPY-based dye at the surface of TiO₂ for dye-sensitized solar cell applications *Physica Status Solidi (A)* **221** 2300513
- [60] Qian X, Zhu Y-Z, Chang W-Y, Song J, Pan B, Lu L, Gao H-H and Zheng J-Y 2015 Benzo[a]carbazole-based donor– π –acceptor type organic dyes for highly efficient dye-sensitized solar cells *ACS Appl. Mater. Interfaces* **7** 9015–22
- [61] Yu L, Fan K, Duan T, Chen X, Li R and Peng T 2014 Efficient panchromatic light harvesting with co-sensitization of zinc phthalocyanine and bithiophene-based organic dye for dye-sensitized solar cells *ACS Sustainable Chemistry & Engineering* **2** 718–25
- [62] Shah W, Faraz S M and Awan Z H 2023 Photovoltaic properties and impedance spectroscopy of dye-sensitized solar cells co-sensitized by natural dyes *Physica B* **654** 414716
- [63] Salimi K et al 2019 Plasmonic mesoporous core–shell Ag–Au@TiO₂ photoanodes for efficient light harvesting in dye-sensitized solar cells *Sol. Energy* **193** 820–7
- [64] Altinkaya C et al 2020 Facile fabrication of low-cost low-temperature carbon-based counter electrode with an outstanding fill factor of 73% for dye-sensitized solar cells *Int. J. Energy Res.* **44** 3160–70
- [65] Da Conceição L R B, Da Cunha H O, Leite A M B, Babu R S, Raja S, Ribeiro C and De Barros A L F 2023 Evaluation of solar conversion efficiency in dye-sensitized solar cells using natural dyes extracted from *Alpinia purpurata* and *Alstroemeria* flower petals as novel photosensitizers *Colorants* **2** 618–31
- [66] Yadav S C, Tiwari M K, Kanwade A, Lee H, Ogura A and Shirage P M 2022 *Butea monosperma*, crown of thorns, red lantana camara and royal poinciana flower extracts as natural dyes for dye-sensitized solar cells with improved efficiency *Electrochim. Acta* **441** 141793
- [67] Iman R N, Harrabi K, Younas M and Mekki A 2024 Fabrication of efficient natural dye-sensitized solar cells using Mediterranean olive leaves as natural dye sensitizer *J. Photochem. Photobiol., A* **450** 115477
- [68] Prabhu T G V, Chandrasekaran J, Balasubramani V, Vivek P, Yogeshwaran A, Manigandan M, Al-Mohaimed A M and Al-Onazi W A 2024 Natural dye-sensitized solar cells fabricated using TiO₂/1 wt% SrTiO₃ as photoanodes *Opt. Mater.* **148** 114973