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Original Article

Effects of Co-sensitising Chlorophyll and Betanin dyes on Optical Absorption properties and Photovoltaic performance of titanium dioxide-based Dye-Sensitised Solar Cells (DSSSCs)

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DSSCS, FTIR, Natural Dyes, Co-sensitisation, Absorption, UV-Vis Spectrophotometry, PCE

ABSTRACT

To address the increasing energy demands, renewable energy technologies, such as Dye-Sensitised Solar Cells (DSSCs), are considered due to their low fabrication costs and environmental friendliness. However, to date, reduced optical absorption and low carrier collection are the primary reasons for the low Power Conversion Efficiency (PCE) of DSSCs. Previous studies have shown that natural dyes are potential sensitisers and co-sensitisers that enhance the performance of these solar cells. The present work focused on the application of natural dyes, betanin (*Beta vulgaris*) and chlorophyll (*Spinacea oleracea*), in DSSCs synthesised using titanium dioxide (TiO_2) mesoporous films. The pigments were blended in a 1:1 volume ratio. The measurements of optical characteristics were performed using a UV-Vis spectrometer (400-800 nm), while an FT-IR spectrometer was used to determine functional groups. Chlorophyll had a broad absorption peak at 427 and 673 nm, whereas betanin showed a peak at 527 nm. The spectral interactions were confirmed by the shift of chlorophyll peaks to 440 and 671 nm, whereas betanin exhibited a bathochromic shift of 22 nm in the composite dye, respectively. FT-IR analysis revealed the presence of various functional groups, including O-H, C=O, C-H, and C-O, which are essential for light absorption and binding to TiO_2. The co-sensitised DSSCs showed enhanced photovoltaic performance compared to the single-dye cells with a current density (J_{SC}) of 1.22 mA/cm^2, open-circuit voltage (V_{OC}) of 0.63 V, and PCE of 0.56 %. These results demonstrate that natural dye co-sensitisation can be a practical approach for enhancing light trapping and efficiency in DSSCs, offering a sustainable alternative for solar energy applications.

APA CITATION

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INTRODUCTION

The utilisation of renewable energy sources is an unparalleled means to realise the surging demand for electrical energy (Hassan *et al.*, 2024). Solar energy production in one hour exceeds overall energy consumption annually, hence a fitting source of energy to power the world (Dupont *et al.*, 2020). Fossil fuels are getting depleted as a result of surging energy usage (Höök & Tang, 2013). The usage of non-depleting sources of energy, especially photovoltaic (PV), which explores silicon-based technologies in converting optical energy into electrical energy, accounts for over 90% of the market share and boasts of conversion efficiencies exceeding 26% (Sasikumar *et al.*, 2024). However, their high cost of production and complex fabrication procedures counter their full exploitation (Righini & Enrichi, 2020). In other studies, Perovskite Solar Cells (PSC) have been promising alternatives but have not been fully commercialised due to the poor stability of the devices and possibly due to their environmental pollution effects, especially the lead–based PSCs (Wu *et al.*, 2021). The utilisation of Quantum dots has also been hampered by the toxicity of the materials used, such as lead and cadmium (Hu *et al.*, 2021). The dye-sensitised solar cell (DSSC) technology is a cutting-edge innovation of solar cells that displays a near-identical process to photosynthesis (Mahajan *et al.*, 2024) and is extremely promising based on the low-cost materials. Researchers contend that the construction of DSSCs can be done without any advanced process technology and hence their accessibility even in developing countries (Abdullah *et al.*, 2022). Reports show that DSSCs present the advantages of low cost of materials, flexibility, eco-friendliness, and ability to operate in low light compared to traditional crystalline silicon PV cells (Prajapat *et al.*, 2023).

The design of high-performance DSSCs with ruthenium dyes was first done by O'Regan & Gratzel in 1991, and since then, dye sensitisation of solar cells with ruthenium dyes has been an exciting area of research and has merited further studies (Amogne *et al.*, 2020). Ruthenium-based dyes have been known to exhibit superior absorption rates of solar energy and appropriate functional groups for bonding with metal oxide semiconductors (Peter *et al.*, 2021). Nevertheless, these dyes are pricy and unstable at high temperatures; hence, a quest for prospective alternatives to these sensitisers proves to be unavoidable (Wang *et al.*, 2025). Natural plant-based dyes are being considered an alternative to ruthenium-based dyes, as they are simple to extract and synthesise (Ponnambalam *et al.*, 2023). Anthocyanin, betanin, carotenoid, and chlorophyll

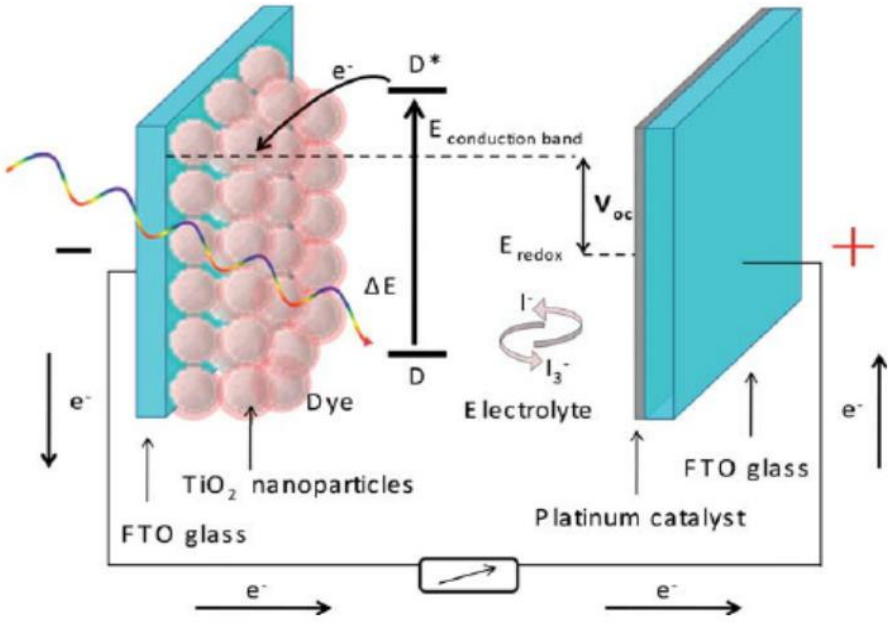
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extracted from various plant parts have been employed as photosensitizers in DSSCs (Castillo-Robles *et al.*, 2021). Their application targets sustainability and reliability, and supports an eco-friendly environment (Dhorkule *et al.*, 2024).

Natural dyes, however, are constrained by their slim absorption window, which limits the PCE of DSSCs sensitised with such dyes (Cole *et al.*, 2019). Co-sensitisation of dyes is an exceptionally trending topic in DSSC development, presently receiving significant attention from researchers (Krishna *et al.*, 2017). In this case, semiconductor thin films are usually coated with multiple dyes with complementary absorption spectra (Barraza-Jiménez *et al.*, 2023). Many attempts at co-sensitised DSSCs have been conducted to broaden the absorption spectra of the cells (Akhtaruzzaman *et al.*, 2021). For example, a broader absorption spectrum and PCE of 1.14% are reported for DSSC made by combining anthocyanin and chlorophyll dyes (Ezike *et al.*, 2021). In another study, an improved efficiency of 3.73% was demonstrated by solar cells using a blend of three natural photosensitizers obtained from *H. sabdarifa, B. vulgaris,* and *S. oleracea* (Patni *et al.*, 2020). An efficiency of 0.601% was reported for DSSC realised by combining natural dyes extracted from red beetroot and spinach in an optimised ratio (Sreeja & Pesala, 2018). Similarly, an efficiency of 0.20% was obtained by combining *O. dillenii* and *T. indica* dyes, which is higher than the individual *T. indica* sensitised DSSC (0.14%) (Ramamoorthy *et al.*, 2016). Overall, co-sensitisation has been shown to enhance the PCE of a DSSC by overcoming the limitation imposed by the narrow spectral range of individual sensitisers. This enhancement can be attributed to the synergistic effect of improved PCE and short circuit current density *(Akhtaruzzaman et al*., 2021). A typical DSSC is assembled from dye adsorbed on a metal oxide semiconductor (photo-anode), a counter electrode, and an electrolyte solution with a dissolved iodine/tri-iodide (I^-/I_3^-) redox couple (Francis & Ikenna, 2021). Figure 1 shows the design and functioning of a DSSC (Calogero *et al.*, 2012).

Figure 1: Schematic Design and Operational Principles of a DSSC



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Initially, a photon is absorbed by a dye sensitiser, elevating an electron into the excited state of the dye from the ground state. These electrons are introduced into the conduction band of the TiO_2 semiconductor. TiO_2 draws in a modest portion of solar energy from the visible region, therefore initiating the oxidation of the dye (Qurratulain *et al.*, 2025). These photogenerated electrons are subsequently transported through the TiO_2 semiconductor to the substrate, initiating the electrical current in the solar cell. An electrolyte between the electrodes acts as a redox couple; it accommodates the electron from the counter electrode and passes it back to the dye to regenerate its ground state, thus completing the electrical circuit as shown in Figure 1. The redox process is catalysed by platinum, deposited as a thin film onto the counter electrode (Qamar & Ela, 2024).

This study stresses the potential of betanin and chlorophyll dyes from *Beta vulgaris* roots and *Spinacea oleracea* leaves, respectively, as co-sensitisers for TiO_2 DSSCs. These findings provide valuable insights into the future development of more efficient and sustainable DSSCs.

EXPERIMENTAL DETAILS

Materials

All the chemicals and solvents used were reagent grade. Fluorine-doped tin oxide (FTO) glasses, Degussa P25 titanium dioxide (TiO_2) nanopowder, titanium (IV) tetraisopropoxide, 0.5 M potassium iodide, methanol, deionised water, iodine (I_2) crystals, sodium thiosulphate, platinum (IV) chloride, and hydrochloric acid solution were purchased from Sigma-Aldrich (analytical grade, 99.9 % purity). *Beta vulgaris* roots and *Spinacea oleracea* leaves for extracting betanin and chlorophyll dyes, respectively, in this study were collected from Nakuru City, Kenya.

Sample Preparation

Dye Extraction

Fresh leaves taken from *Spinacea oleracea* were washed in distilled water. Thereafter, 100 g of chopped leaves were kept separately in a blender and ground for 2 minutes. Subsequently, the extracts were poured into separate glass bottles, followed by the addition of methanol to a volume of 200 ml. On the other hand, distilled water was used to clean fresh tubers of *Beta vulgaris* before being cut into small pieces. 100 g of sliced fruits were kept separately in a blender and ground for 2 minutes. The blended extracts were poured into a glass bottle, and then methanol was added to a volume of 200 ml. The bottles were kept under 40 °C extracting temperature conditions and later covered with aluminium foil overnight for sedimentation. All extracts were filtered and then concentrated using a rotary evaporator and kept in a refrigerator at 4.0 ℃, ready for use in the subsequent experimental steps.

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Figure 2: Extracts of (a) *Spinacea oleracea* (green), (b) *Beta vulgaris* (vibrant red)



Fabrication of DSSCs

The TiO_2 film was prepared through a mixture comprising 3.5 g of commercial TiO_2 nano-powder and 15.0 ml of ethanol, and later sonicated for 30 minutes. Subsequently, 0.5 ml of titanium (IV) tetraisopropoxide was added to the suspension and magnetically stirred for homogeneity. Using transparent tape, FTO glass was taped down with its conductive side facing up, and then TiO_2 paste was applied on the conducting side employing the doctor blade technique. The TiO_2-coated FTO substrates then underwent preheating at 150.0 °C for 30 minutes, followed by cooling, and were finally annealed at 450°C over a hot plate for 1 hour.

To prepare CE, the electrolyte solution was synthesised by dissolving platinum (IV) chloride ($PtCl_4$) powder in hydrochloric acid solution (HCl, 0.00156 M) and then stirring at 350 rpm for half an hour. This was spread on the FTO substrate through the doctor blading method. The platinum-coated FTO substrate underwent sintering at 500°C for 1 hour. The FTO/TiO_2 surface was later preheated to 80°C and immersed in prepared dyes for adsorption for 2 hours in the dark. Afterwards, the samples were left to dry at 25°C for further use.

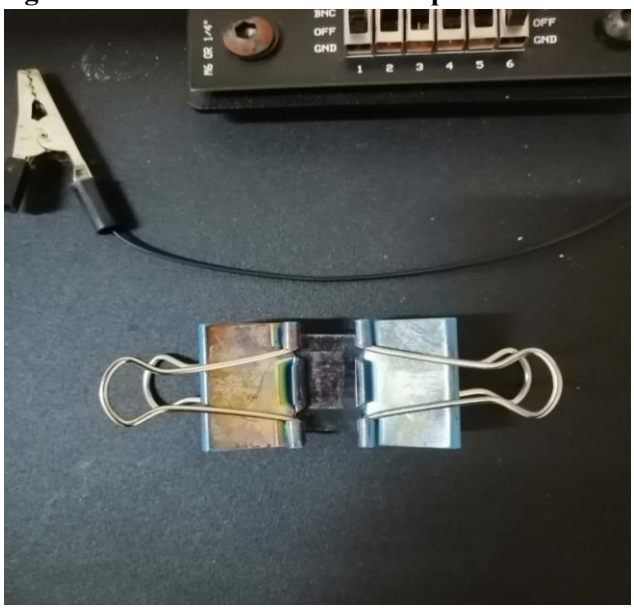
To prepare a 0.5 M iodine solution, 200 g of potassium iodide was first dissolved in about 350 ml of deionised water. Later, 127 g of iodine (I_2) was added and mixed until all the iodine crystals dissolved. Next, the solution was transferred into a 1000 ml volumetric flask and filled to the mark with deionised water. The solution was finally standardised using sodium thiosulfate. The resulting electrolyte solution was stored in an opaque container away from light exposure.

DSSC was finally assembled by placing a platinum-coated counter electrode onto the dye-sensitised photo-anode, and the two were secured together using clips to avoid the movement of the glasses. Finally, the electrolyte solution was introduced between the photo-anode and counter electrode. A finished DSSC is shown in Figure 3.

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Figure 3: A Fabricated DSSC Sample



Characterisation and Measurements

Fourier-transform infrared (FTIR) spectroscopy was adopted to characterise anchoring groups within *Beta vulgaris* and *Spinacea oleracea* dye extracts. The absorption of light by these dye extracts and their mixture was studied by employing an ultraviolet-visible (UV-Vis K 9000) spectrophotometer across a wavelength range of 400–800 nm with a sampling interval of 0.5 nm. The performance of fabricated DSSCs was analysed from current density–voltage (J–V) curves employing a solar simulator under 100 mW/cm² illumination. The fill factor (FF) was estimated from the J–V curves by using Equation (1), while the power conversion efficiency (PCE) of the DSSC was determined by Equation (2) (Halidun *et al.*, 2025).

$$FF = \frac{J_{max} \times V_{max}}{J_{SC} \times V_{OC}} \quad (1)$$

$$PCE = \frac{FF \times J_{SC} \times V_{OC}}{P_{light}} x\ 100 \quad (2)$$

Where J_{sc} indicates the short-circuit current density and V_{oc} the open-circuit voltage, while J_{max} and V_{max} represent the maximum current density output and maximum voltage output, respectively.

RESULTS AND DISCUSSION

The optical absorbance and Fourier Transform Infrared (FTIR) spectroscopy analysis for *Beta vulgaris* and *Spinacea oleracea* dye extracts were conducted to find out the absorbance and the characteristic chemical bonds for these dyes. The photovoltaic performance of the fabricated DSSCs was also carried out, and the observed results are summarised and discussed in the subsections.

Optical Properties

Dye Optical Absorption Analysis

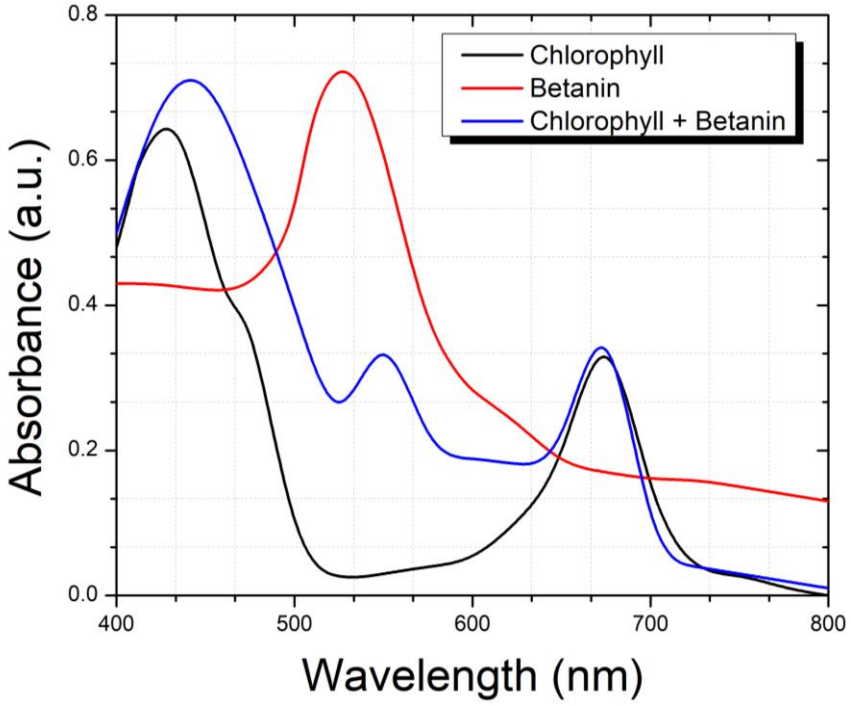
This particular section investigated the optical properties of synthesised dye extracts from *Beta vulgaris* roots, *Spinacea oleracea* leaves for their application as novel sensitiser materials in dye-sensitised solar cells (DSSCs). Betanin dye was synthesised from *Beta vulgaris*, while chlorophyll was obtained from *Spinacea oleracea*. The effect of co-sensitisation as a method in enhancing absorption was investigated by monitoring the combined effect of the composite of betanin and chlorophyll dyes on the light trapping of the DSSCs. The optical properties in each case were characterised using a double-beam UV-Vis spectrophotometer.

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Figure 4 shows the wavelength scan measurements of the absorption spectra of dye extracts, chlorophyll, betanin, and their composite. The absorption signature for chlorophyll in its free form (in ethanol/methanol solvent) is shown in black, whereas those of betanin and the composite/mixture are shown in red and blue, respectively. Chlorophyll dye exhibited two intense, strong, and broad absorption bands with maxima at 427 and 673 nm within the visible region. The peak at 427 nm could be attributed to ligand-to-metal charge transfer transitions of the porphyrin and Mg-metal ion present in the chlorophyll, while the peak that lies at 673 nm is due to spin-allowed *d-d* transitions of the Mg-metal ion present in the chlorophylls. Previous studies have shown that chlorophyll pigments exhibit absorption bands with peak maxima within these wavelength ranges (Hussin, 2021). It can be seen that betanin dye exhibits a strong, broad, and intense singular absorption band with a peak maximum at 527 nm, which has been reported in literature (Dumbravă *et al.*, 2012).

Figure 4: Absorption Spectra of Dye Extracts



An overlay of the spectrum of the composite solution onto the individual spectra of the dyes showed somewhat spectral "fingerprints" of chlorophyll and betanin compounds (i.e., high light absorption in the 400–500 and 600–700 nm ("chlorophyll" region) and a characteristic peak maximum between 500 and 600 nm in the "betanin" region). A cursory check on the spectrum of the composite (chlorophyll and betanin) shows that the absorption peak related to betanin in the mixture was observed at 549 nm. It is therefore evident that this peak was bathochromically shifted by about 22 nm. A comparison of the peaks related to chlorophyll in the composite and that of chlorophyll in its free/pure form revealed that there was a red shift for the peak at 427 nm in its free form to about 440 nm in the composite, while that at 673 nm was hypsochromically shifted to about 671 nm. These shifts could be attributed to metal-ligand chelation when in the composite.

FTIR Analysis

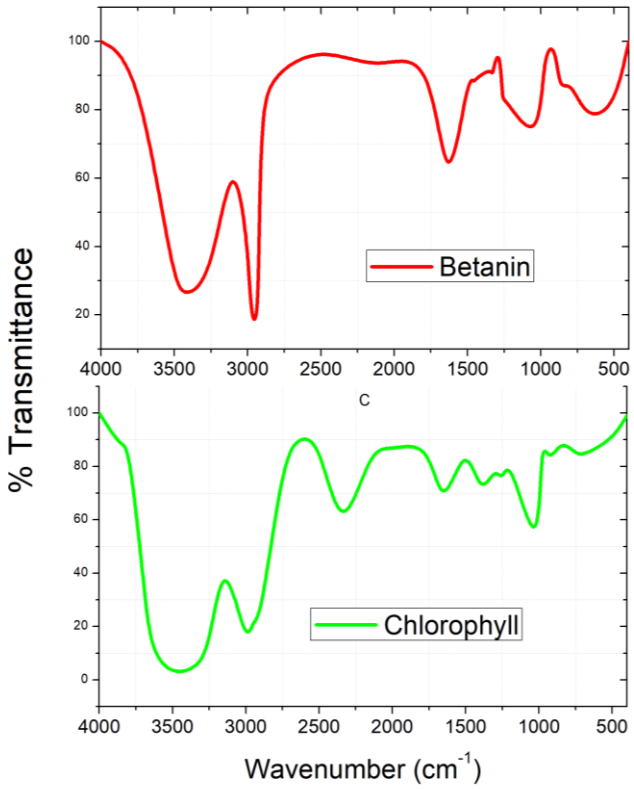
The purpose of this part was to examine the vibration frequencies characteristic of betanin and

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chlorophyll functional groups. The assignment of functional groups and vibration modes was accomplished according to the literature. Figure 5 displays the FTIR spectra of a betanin sample in the area of 4000–400 cm^{-1}. Different absorption bands indicative of functional groups of betanin and chlorophyll were detected. From Figure 5 (orange), the band at 3310 cm^{-1} was attributed to the stretching vibration of the –OH bond (Kumar *et al*. 2017); on the other hand, the band located at 2907 cm^{-1} was attributed to the stretching vibration of the C-H bond (Aztatzi-Rugerio *et al.*, 2019).

Figure 5: FTIR Spectrum of Dye Extracts



The C=O stretching vibration bond was identified with a band at 1736 cm^{-1}, whereas the aromatic rings' C=N bond stretching vibration was identified at 1609 cm^{-1}. The stretching vibration of the C-H bond was identified as the source of another band at 1370 cm^{-1}. While the 989 cm^{-1} peak corresponds to C-H bond deformation, the band at 1257/1030 cm^{-1} suggests the presence of the C-O bond of the carboxylic acid stretching vibration (Shafqat *et al.*, 2023). The presence of these functional groups confirmed that the extracted pigment from *Beta vulgaris* belongs to betanin pigments.

Spinacea oleracea FTIR spectrum illustrates the bulk of chemical structure attributes of chlorophyll. Intermolecular bonded O-H stretching vibration was noted at a broad peak of 3650-3450 cm^{-1} (Sravan Kumar *et al.*, 2015), whereas peak 1730 cm^{-1} showed C=O of porphyrin groups. The CH_3 stretching vibration of the porphyrin structure matched the peak at 1420 cm^{-1} (Chang *et al.*, 2013). In addition, the peak at 1408 cm^{-1} is designated to C-H bending vibration, whereas the peaks at 1308 cm^{-1}, 1244 cm^{-1}, and 1041 cm^{-1} are assigned to the C-O group of chlorophyll dyes, as shown in Figure 5 (green).

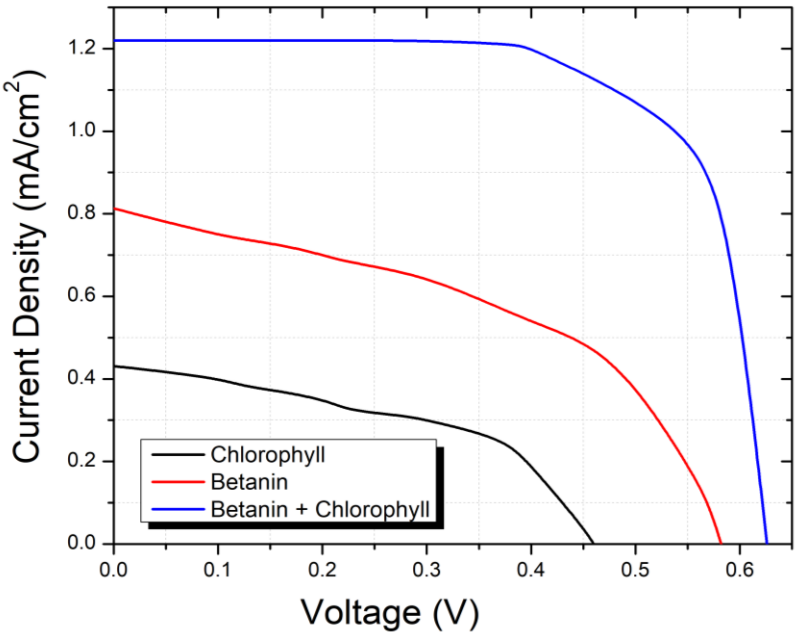
Photovoltaic Performance of DSSCs

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The photovoltaic properties of DSSCs hinge on efficient absorption of light and transfer of electrons from dyes to the TiO_2 mesoporous layer. In this study, dye-sensitised solar cells (DSSCs) of the following configurations were fabricated: betanin-based DSSC, chlorophyll-based DSSC, and betanin–chlorophyll-based DSSC. To guarantee the replicability of the data collected, three unique DSSCs were fabricated for each configuration, and the mean values were reported. Current density-voltage (J-V) characteristics for the fabricated DSSCs were evaluated from a source meter fitted with a solar simulator under a standard AM1.5G illumination condition of 100 mW/cm$^{2.}$

Figure 6: J-V Curve for Fabricated DSSCs Sensitised with Dye Extracts.



The J–V characteristic curves for the fabricated DSSCs are presented in Figure 6. Additionally, the average values of open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}), fill factor (FF), and power conversion efficiency (PCE) are presented in Table 1. An optimal interaction between the dye and the semiconductor film is crucial for improving the charge transfer and PCE of fabricated DSSCs.

Table 1: Photovoltaic Parameters of Fabricated DSSC

Dye sensitizer	**Photovoltaic Parameters**			
	J_{SC} (mA/cm²)	V_{OC} (V)	Fill Factor (FF) (%)	PCE (%)
Chlorophyll	0.43	0.46	47.66	0.10
Betanin	0.81	0.58	81.69	0.39
Betanin + Chlorophyll	1.22	0.63	73.46	0.56

Betanin-based DSSCs gave a better PCE of 0.39 %, while chlorophyll-based DSSCs achieved 0.1%; this is attributed to their different anchoring functional groups. Betanin structure has several

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carboxylic functional groups, promising good dipole interactions with TiO_2 and enhancing a strong anchoring system (Sandquist & McHale, 2011). On the other hand, chlorophyll molecules have poor anchorage to the surface of TiO_2 molecules (Fuziki *et al.*, 2023). In contrast, when betanin and chlorophyll extracts were co-sensitised, the performance of DSSCs improved. This is due to an increased current density, which can be attributed to its increased absorption spectrum by the complementary absorbing regions of these two dyes, effectively harvesting more light energy from the solar spectrum. Betanin-chlorophyll-based DSSCs had J_{SC} of 1.22 mA/cm² and V_{OC} of 0.63 V with an FF of 73.46% and a maximum PCE of 0.56 %. As depicted in Table 1, there was an average increase in PCE for betanin-chlorophyll-based DSSCs of 0.17 % and 0.46 %, compared to betanin- and chlorophyll-based DSSCs, respectively. From the results, it can be concluded that combining two or more appropriate dyes enhances the PCE of DSSCs.

CONCLUSION

In the study, the fabrication of DSSCs utilising TiO_2 mesoporous thin films (photoanode) sensitised with betanin and chlorophyll separately and co-sensitised with their composite (mixture of betanin and chlorophyll) natural dyes was successfully performed. The optical properties of the cells were characterised using UV-Vis wavelength scan measurements, whereas the FT-IR spectra were used to give insights into the fundamental functional groups responsible for absorption. The intensity and characteristic absorption bands/peaks were applied in the assignment of the optical properties. The photovoltaic parameters were also successfully evaluated and compared with the literature.

The results of the optical property analysis showed that co-sensitisation greatly improved the light trapping properties of the DSSCs, as evident in the intensity of the absorption bands of the composite (betanin and chlorophyll). The analysis of the FT-IR spectra showed that the fundamental functional groups responsible for the light absorption properties of the dyes were O-H, C-H, and C=O stretching vibrations. The DSSCs fabricated using co-sensitisation of betanin and chlorophyll dyes showed an improved PCE compared to individual betanin- and chlorophyll-dye-based DSSCs. It was manifested that the increased PCE was due to broader photo-absorption in the visible region. The co-sensitisers employed in this study effectively compensate for the absorption deficiencies of single dyes, leading to an enhanced photo-response in DSSCs. Although the efficiencies of natural dye-sensitised solar cells are still quite far from the requirements for practical applications, the results hold promising potential to offer a feasible and alternative solution for future energy production by harnessing natural dyes as photosensitizers in DSSCs.

This study faced certain limitations, for example, the widely used metal complex dyes are expensive, limited, and toxic. Even though eco-friendly, the dye synthesis process is complicated, and the dye aggregation on the semiconductor surface is quite sensitive and may result in DSSCs that are less efficient and unreliable.

This study recommends that, going forward, studies can explore co-sensitisation using a combination of organic dyes and porphyrin-based metal complex dyes. Organic dyes offer high molar extinction coefficients, while porphyrin-based metal complexes, despite their lower molar extinction coefficients, contribute to broader spectral absorption and improved photovoltaic performance. The incorporation of graphene-based materials and their composites as cost-effective alternatives to platinum, due to their excellent electrocatalytic activity and electrical conductivity. Finally, molar dye ratios during co-sensitisation can be considered as an alternative route to enhance the performance of the fabricated cell. This is because dye concentration plays a crucial role in the attainment

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of optimal dye loading, spectral coverage, and charge transfer dynamics.

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Author Contributions: Z. Moronge Conceptualisation, fabrication, and characterisation; formal analysis; manuscript formulation & interpretation. Dr Duke Oeba Conceptualisation, Formal analysis, Funding acquisition, Methodology, Supervision, Writing - review & editing. Dr Charles Muga Conceptualisation, Formal analysis, Methodology, Supervision, Writing - review & editing. All authors worked together to proofread the manuscript. All authors have read and agreed to the published version of the manuscript.

REFERENCES

Abdullah, M., Adilah, M. S., Noorsal, E., Azurahanim, C., Mamat, M., Ahmad, M.,…Rusop, M. (2022). Synergistic effect of complementary organic dye co-sensitizers for potential panchromatic light-harvesting of dye-sensitized solar cells. *Optical Materials*, *133*, 113016.

Akhtaruzzaman, M., Shahiduzzaman, M., Selvanathan, V., Sopian, K., Hossain, M. I., Amin, N., & Hasan, A. M. (2021). Enhancing spectral response towards high-performance dye-sensitised solar cells by multiple dye approach: A comprehensive review. *Applied Materials Today*, *25*, 101204.

Amogne, N. Y., Ayele, D. W., & Tsigie, Y. A. (2020). Recent advances in anthocyanin dyes extracted from plants for dye-sensitized solar cells. *Materials for Renewable and Sustainable Energy*, *9*(4), 23.

Aztatzi-Rugerio, L., Granados-Balbuena, S. Y., Zainos-Cuapio, Y., Ocaranza-Sánchez, E., & Rojas-López, M. (2019). Analysis of the degradation of betanin obtained from beetroot using Fourier transform infrared spectroscopy. *Journal of food science and technology*, *56*(8), 3677-3686.

Barraza-Jiménez, D., Mancinas, D. M. L., Flores-Hidalgo, H. I., Corral, R. A. O., Torres-Herrera, S. I., & Flores-Hidalgo, M. A. (2023). Perspectives of Organic Dyes Cosensitization and Its Utilization in TiO 2 Nanoclusters for Photocatalysis Applications.

Calogero, G., Yum, J.-H., Sinopoli, A., Di Marco, G., Grätzel, M., & Nazeeruddin, M. K. (2012). Anthocyanins and betalains as light-harvesting pigments for dye-sensitized solar cells. *Solar energy*, *86*(5), 1563-1575.

Castillo-Robles, J. A., Rocha-Rangel, E., Ramírez-de-León, J. A., Caballero-Rico, F. C., & Armendáriz-Mireles, E. N. (2021). Advances on dye-sensitized solar cells (DSSCs) nanostructures and natural colorants: A review. *Journal of Composites Science*, *5*(11), 288.

Chang, H., Kao, M.-J., Chen, T.-L., Chen, C.-H., Cho, K.-C., & Lai, X.-R. (2013). Characterization of natural dye extracted from wormwood and purple cabbage for dye-sensitized solar cells. *International Journal of Photoenergy*, *2013*(1), 159502.

Cole, J. M., Pepe, G., Al Bahri, O. K., & Cooper, C. B. (2019). Cosensitization in dye-sensitized solar cells. *Chemical reviews*, *119*(12), 7279-7327.

Dhorkule, M., Lamrood, P., Ralegankar, S., Patole, S. P., Wagh, S. S., & Pathan, H. M. (2024). Unveiling the efficiency of dye-sensitized solar

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cells: a journey from synthetic to natural dyes. *ES Food & Agroforestry*, *16*(2), 1086.

Dumbravă, A., Enache, I., Oprea, C., Georgescu, A., & Gîrţu, M. (2012). Toward a more efficient utilisation of betanins as pigments for dye-sensitised solar cells. *Digest Journal of Nanomaterials & Biostructures (DJNB)*, *7*(1).

Dupont, E., Koppelaar, R., & Jeanmart, H. (2020). Global available solar energy under physical and energy return on investment constraints. *Applied Energy*, *257*, 113968.

Ezike, S. C., Hyelnasinyi, C. N., Salawu, M. A., Wansah, J. F., Ossai, A. N., & Agu, N. N. (2021). Synergistic effect of chlorophyll and anthocyanin Co-sensitizers in TiO2-based dye-sensitized solar cells. *Surfaces and Interfaces*, *22*, 100882.

Francis, O. I., & Ikenna, A. (2021). Review of dye-sensitized solar cell (DSSCs) development. *Natural Science*, *13*(12), 496-509.

Fuziki, M. E., Tusset, A. M., dos Santos, O. A., & Lenzi, G. G. (2023). Chlorophyll Sensitization of TiO2: A Mini-Review. *Reactions*, *4*(4), 766-778.

Halidun, W. O. N. S., Erniwati, E., & Saleh, I. (2025). The effect of solvent extraction of natural dye on band gap energy for DSSC application. AIP Conference Proceedings,

Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M.,…Jaszczur, M. (2024). The renewable energy in the global energy Transformations. *Renewable Energy Focus*, *48*, 100545.

Höök, M., & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change—A review. *Energy policy*, *52*, 797-809.

Hu, L., Zhong, H., & He, Z. (2021). Toxicity evaluation of cadmium-containing quantum dots: A review of optimizing physicochemical properties to diminish toxicity. *Colloids and Surfaces B: Biointerfaces*, *200*, 111609.

Hussin, S. H. A.-S. (2021). Properties of organic green spinach dye as a substitute for the harmful chemical green dye. Journal of Physics: Conference Series,

Krishna, N. V., Krishna, J. V. S., Mrinalini, M., Prasanthkumar, S., & Giribabu, L. (2017). Role of co-sensitizers in dye-sensitized solar cells. *ChemSusChem*, *10*(23), 4668-4689.

Mahajan, U., Prajapat, K., Dhonde, M., Sahu, K., & Shirage, P. M. (2024). Natural dyes for dye-sensitized solar cells (DSSCs): An overview of extraction, characterization, and performance. *Nano-Structures & Nano-Objects*, *37*, 101111.

Patni, N., G. Pillai, S., & Sharma, P. (2020). Effect of using betalain, anthocyanin, and chlorophyll dyes together as a sensitizer on enhancing the efficiency of the dye-sensitized solar cell. *International Journal of Energy Research*, *44*(13), 10846-10859.

Peter, I. J., Vijaya, S., Anandan, S., Ramachandran, K., & Nithiananthi, P. (2021). Alternative low-cost photon sensitizer for dye-sensitized solar cells using less explored natural fabric dyes. *International Journal of Energy Research*, *45*(5), 7764-7782.

Ponnambalam, S., Junluthin, P., Ramaraj, R., & Unpaprom, Y. (2023). A comprehensive review of the evolution of dye-sensitized solar cells from ruthenium dyes to organic pigments with the influence of graphene nanoribbons. *Maejo International Journal of Energy and Environmental Communication*, *5*(2), 1-13.

Prajapat, K., Dhonde, M., Sahu, K., Bhojane, P., Murty, V., & Shirage, P. M. (2023). The evolution of organic materials for efficient dye-sensitized solar cells. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, *55*, 100586.

 This work is licensed under a Creative Commons Attribution 4.0 International License

Article DOI: https://doi.org/10.37284/eaje.8.2.3819

Qamar, S., & Ela, S. E. (2024). Dye-sensitized solar cells (DSSC): Principles, materials and working mechanism. *Current Opinion in Colloid & Interface Science*, 101871.

Qurratulain, Kazmi, S. A., Hameed, S., Pachauri, R. K., Khan, B., & Ali, A. (2025). Study on dye-sensitized solar cell efficiency improvement using methyl orange dye. *Materials for Renewable and Sustainable Energy*, *14*(1), 24.

Ramamoorthy, R., Radha, N., Maheswari, G., Anandan, S., Manoharan, S., & Victor Williams, R. (2016). Betalain and anthocyanin dye-sensitized solar cells. *Journal of Applied Electrochemistry*, *46*, 929-941.

Righini, G. C., & Enrichi, F. (2020). Solar cells' evolution and perspectives: a short review. *Solar Cells and Light Management*, 1-32.

Sandquist, C., & McHale, J. L. (2011). Improved efficiency of betanin-based dye-sensitized solar cells. *Journal of Photochemistry and Photobiology A: Chemistry*, *221*(1), 90-97.

Sasikumar, R., Thirumalaisamy, S., Kim, B., & Hwang, B. (2024). Dye-sensitized solar cells: Insights and research divergence towards alternatives. *Renewable and Sustainable Energy Reviews*, *199*, 114549.

Shafqat, O., Rehman, Z., Shah, M. M., Ali, S. H. B., Jabeen, Z., & Rehman, S. (2023). Synthesis, structural characterization, and in vitro pharmacological properties of betanin-encapsulated chitosan nanoparticles. *Chemico-Biological Interactions*, *370*, 110291.

Sravan Kumar, S., Manoj, P., & Giridhar, P. (2015). Fourier transform infrared spectroscopy (FTIR) analysis, chlorophyll content, and antioxidant properties of native and defatted foliage of green leafy vegetables. *Journal of food science and technology*, *52*, 8131-8139.

Sreeja, S., & Pesala, B. (2018). Co-sensitization aided efficiency enhancement in betanin–chlorophyll solar cell. *Materials for Renewable and Sustainable Energy*, *7*(4), 25.

Wang, X.-L., Huang, J.-F., Liu, J.-M., & Tsiakaras, P. (2025). Recent advances in metal-free photosensitizers for dye-sensitized photoelectrochemical cells. *Coordination Chemistry Reviews*, *522*, 216143.

Wu, T., Qin, Z., Wang, Y., Wu, Y., Chen, W., Zhang, S.,…Liu, J. (2021). The main progress of perovskite solar cells in 2020–2021. *Nano-Micro Letters*, *13*, 1-18.

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