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Research Article

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Optical, Spectroscopic and Band-Gap Characterisation of Natural Dyes Extracted from *Delonix regia* Flower, *Curcuma longa* (Turmeric) and Their 1:1 Mixture as Photosensitisers for Dye-Sensitised Solar Cells

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Abstract

Natural dyes are inexpensive, abundant and environmentally benign photosensitisers for third-generation dye-sensitised solar cells (DSSCs), but their light-harvesting behaviour is governed by pigment chemistry, extraction solvent and the mode of anchoring on the semiconductor surface. In this study, natural dyes were extracted from Delonix regia (royal poinciana) flower and Curcuma longa (turmeric), together with a 1:1 (v/v) mixture of the two extracts, using a 50:50 distilled water-methanol solvent, and their optical properties were characterised in solution and after adsorption onto a nanoporous titanium dioxide (TiO_2) film. Ultraviolet-visible-near-infrared (UV-Vis-NIR) spectra recorded from 230 to 1100 nm showed that all three extracts absorbed strongly in the ultraviolet (333 and 375 nm) and visible regions; the D. regia extract additionally exhibited a broad near-infrared band at 764 nm in solution which extended to 1028 nm after adsorption on TiO_2. From the measured absorbance, the absorption coefficient, an absorbance-based extinction parameter and the light-harvesting efficiency (LHE) were derived; the D. regia extract sustained an LHE of approximately 99% over 305-541 nm. Optical band gaps obtained from Tauc analysis, assuming a direct allowed transition, were 2.02 eV for D. regia, 1.98 eV for turmeric and 2.35 eV for the mixture. The results indicate that D. regia is the most promising single sensitiser of the three and that the 1:1 mixture is optically superior to the single turmeric extract, although co-pigmentation redistributes rather than simply superimposes the component bands. The dataset provides the optical baseline required for rational sensitiser selection and co-sensitisation.

Keywords: *dye-sensitised solar cell; natural dye; Delonix regia; Curcuma longa (turmeric); anthocyanin; curcumin; UV-Vis-NIR spectroscopy; optical band gap; light-harvesting efficiency; co-sensitisation*

1. Introduction

The global demand for clean and affordable energy continues to intensify as population growth, industrialisation and urbanisation place increasing pressure on conventional supplies. Fossil fuels remain the dominant energy source, yet their combustion releases carbon dioxide and other greenhouse gases that drive global warming and climate change (Reddy & Rao, 2017). Among the renewable alternatives, solar energy is the most abundant and the cleanest, delivering more power to the surface of the Earth in one hour than humanity consumes in a year (Lewis, 2007). The direct

conversion of sunlight into electricity through the photovoltaic effect therefore represents one of the most strategic responses to the twin challenges of energy security and environmental sustainability, particularly for a country such as Nigeria that combines abundant insolation with a persistent electricity deficit.

Silicon-based p-n junction solar cells presently dominate the photovoltaic market, but their high production cost, energy-intensive fabrication and reliance on high-purity, sometimes toxic, materials limit their affordability in developing regions (Nazeeruddin et al., 2011). Dye-sensitised solar cells (DSSCs), first reported by O'Regan & Grätzel (1991), belong to the third generation of photovoltaic technologies and offer a compelling low-cost alternative (Grätzel, 2005; Hagfeldt et al., 2010). A DSSC comprises a mesoporous wide-band-gap semiconductor (typically anatase TiO_2) coated with a light-absorbing dye, a redox electrolyte and a counter electrode; the dye harvests photons and injects electrons into the conduction band of the semiconductor, while the electrolyte regenerates the oxidised dye (Sharma et al., 2018). Because the light-harvesting and charge-transport functions are decoupled, DSSCs can be fabricated from low-to-medium purity materials by simple, low-temperature processes (Ahmad et al., 2017).

The photosensitiser defines the spectral window over which sunlight is captured. Ruthenium polypyridyl complexes remain the benchmark dyes, reaching efficiencies above 11%, but they are expensive, contain scarce heavy metals and require careful synthesis and purification (Nazeeruddin et al., 1993, 2011). Consequently, natural dyes extracted from the flowers, fruits, leaves, roots and bark of plants have attracted sustained attention as non-toxic, biodegradable and inexpensive sensitisers (Kumara et al., 2017; Narayan, 2012; Richhariya et al., 2017). The principal pigment families exploited for this purpose are the anthocyanins, chlorophylls, carotenoids, flavonoids, curcuminoids and tannins, each of which absorbs a characteristic portion of the solar spectrum and anchors to the TiO_2 surface through carbonyl, hydroxyl or carboxyl functional groups (Calogero et al., 2012; Gómez-Ortíz et al., 2010; Maldonado-Valdivia et al., 2013). Reviews of the field consistently conclude that, although natural-dye DSSCs remain modest in efficiency, they are valuable for education, indoor applications and as a route to low-cost, indigenous photovoltaics (Abdul Shukor et al., 2023; Hug et al., 2014; Rahman et al., 2023; Shalini et al., 2015).

Nigeria possesses an extensive and largely unexploited biodiversity of dye-bearing plants. Among these, Delonix regia (royal poinciana), whose brilliant red-orange flowers owe their colour to co-pigmentation between anthocyanins and carotenoids, and Curcuma longa (turmeric), whose rhizome yields the bright-yellow curcuminoid pigment curcumin, are widely available and inexpensive (Purohit et al., 2007; Wright, 2002). Both have been reported individually as DSSC photosensitisers (Godibo et al., 2015; Khalil et al., 2017; Kim et al., 2013), but a systematic optical comparison of their single extracts against a mixed (co-sensitised) extract prepared under identical conditions remains limited, particularly with respect to the absorption coefficient, extinction behaviour, light-harvesting efficiency and optical band gap that ultimately govern device performance.

The optical characterisation of a candidate dye is a prerequisite for rational device engineering. The absorption spectrum reveals the wavelength range and intensity of light capture; the absorption and extinction coefficients quantify how strongly the dye attenuates light per unit path length; the

light-harvesting efficiency (LHE) expresses the fraction of incident photons absorbed; and the optical band gap, obtained from Tauc analysis, indicates the minimum photon energy required for electronic excitation and hence the threshold wavelength for photocurrent generation (Iswariya et al., 2017; Mphande & Pogrebnoi, 2014). Co-sensitisation, in which two or more dyes with complementary absorption ranges are combined, is a widely adopted strategy to broaden the spectral response and improve overall efficiency (Hussain et al., 2025; Pratiwi et al., 2017; Shah et al., 2023).

The present study reports a detailed optical investigation of natural dyes extracted from D. regia flower and turmeric, and of their 1:1 mixture, extracted with a 50:50 distilled water-methanol solvent. The specific objectives were: (i) to determine the UV-Vis-NIR absorption spectra of the dyes in solution and after adsorption on nanoporous TiO_2; (ii) to derive the absorption coefficient, an absorbance-based extinction parameter and the light-harvesting efficiency of each dye; and (iii) to evaluate the optical band gaps from Tauc plots and thereby assess the suitability of the dyes and their mixture as photosensitisers. The work provides the optical baseline that underpins the device-fabrication.

2. Theoretical Background

2.1 Photosensitisation and operating principle

In a DSSC, photons absorbed by the ground-state dye (S) promote electrons from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO), generating an excited dye (S*). The excited electron is injected into the conduction band of the mesoporous TiO_2, leaving the dye in its oxidised state (S^+). The injected electron percolates through the TiO_2 network to the transparent conducting substrate and performs work in the external circuit, while the oxidised dye is regenerated by the iodide/tri-iodide (I^-/I_3^-) redox couple (Hagfeldt et al., 2010; Sharma et al., 2018). For efficient operation the LUMO of the dye must lie above the conduction-band edge of TiO_2 and the HOMO must lie below the redox potential of the electrolyte (Nazeeruddin et al., 2011). The optical properties measured in this work - the absorption spectrum, absorption coefficient, extinction behaviour, light-harvesting efficiency and band gap - quantify the first of these steps and therefore set an upper bound on the photocurrent attainable from each sensitiser.

2.2 Optical parameters and their determination

The absorbance A of a dye solution is related to the incident and transmitted light intensities by the Lambert-Beer relation, $A = \log(I_0/I) = \varepsilon c l$, where ε is the molar extinction coefficient, c the molar concentration and l the optical path length. The absorption coefficient α is obtained from $\alpha = 2.303A/l$ and expresses the attenuation of light per unit thickness of the medium. A wavelength-dependent extinction coefficient k, an intrinsic property reflecting how strongly the dye absorbs, is related to α by $k = \alpha\lambda/4\pi$. The light-harvesting efficiency, which represents the fraction of incident photons absorbed at a given wavelength, is computed from the absorbance as $LHE = (1 - 10^{-A}) \times 100\%$ (Mphande & Pogrebnoi, 2014). The optical band gap E_g is evaluated from the Tauc relation, $(\alpha h\nu)^n = B(h\nu - E_g)$, where $h\nu$ is the photon energy, B a constant and $n = 2$ for a direct allowed transition; extrapolating the linear portion of a plot of $(\alpha h\nu)^2$ against $h\nu$ to the energy axis

yields E_g (Iswariya et al., 2017). A band gap in the range 1.8-2.4 eV corresponds to absorption thresholds in the visible region and is therefore well matched to photovoltaic sensitisation.

3. Materials and Methods

3.1 Plant collection and geo-referencing

Fresh *D. regia* flowers were collected from the premises of Kwali General Hospital, Kwali, Federal Capital Territory, Nigeria, and thoroughly washed with distilled water to remove dust and debris. The turmeric used in the optical experiments of the source study was processed *Curcuma longa* (turmeric) powder. In support of the biodiversity-mapping and voucher-documentation objective of the parent project, a fresh *C. longa* plant and its rhizomes were subsequently located and geo-referenced in the field using a Garmin GPSMAP 78sc handheld receiver (WGS-84 datum). Representative field photographs and the recorded coordinates are presented in Figures 1-3 and Table 1.

For this purpose, an in-situ, living C. longa plant along with its subsurface rhizomes was located and systematically geo-referenced. Spatial data acquisition was performed using a Garmin GPSMAP 78sc handheld receiver set to the WGS-84 coordinate datum. The definitive spatial provenance for the field-collected voucher material (Waypoint Identifier: 037 [“TUMERIC BC”]) was established at 06° 15.603′ N (6.260050° N) and 005° 35.287′ E (5.588124° E), at an approximate elevation of 22.4 m. Concurrently, the Delonix regia site was geo-referenced at the Kwali General Hospital premises, Kwali, FCT (Waypoint Identifier: 038 [“KWALI GH”]) at 08° 50.607′ N (8.843446° N) and 007° 00.771′ E (7.012850° E), at an elevation of 179 m. The in-situ botanical photographs and the corresponding spatial metrics for *C. longa* plant are cataloged in Figures 1-3 while Table 1 shows the tabulated coordinates read directly from the Garmin GPSMAP 78sc waypoint export for the two plants.

Table 1. Field collection and geo-referencing record for the plant sources (coordinate datum WGS-84; GPS receiver GARMIN GPSMAP 78sc).

Field	*Curcuma longa* (turmeric)	*Delonix regia* (flower)
Plant part used	Rhizome (dye from powder in experiments)	Flower petals
Collection location	Benin City, Southern Nigeria	Kwali General Hospital premises, Kwali, FCT
Latitude	06° 15.603′ N (6.260050° N)	08° 50.607′ N (8.843446° N)
Longitude	005° 35.287′ E (5.588124° E)	007° 00.771′ E (7.012850° E)
Elevation	≈ 22.4 m	179 m
Waypoint identifier	037 (“TUMERIC BC”)	038 (“KWALI GH”)
Coordinate datum	WGS-84	WGS-84
GPS receiver	GARMIN GPSMAP 78sc	GARMIN GPSMAP 78sc



Figure 1. Standing Curcuma longa (turmeric) plant at the field-collection site (original field photograph; GARMIN GPSMAP 78sc, WGS-84).



Figure 2. Freshly harvested C. longa rhizomes with roots and foliage (original field photograph).



Figure 3. Garmin GPSMAP 78sc handheld receiver displaying the on-site fix used to geo-reference the turmeric collection point (original field photograph).

3.2 Dye extraction

The extraction solvent was prepared by mixing distilled water and methanol in a 50:50 (v/v) ratio; both are protic solvents capable of hydrogen bonding and were selected to solubilise the polar anthocyanin and curcuminoid pigments. Fresh D. regia petals (9.3 g) were macerated with a mortar and pestle and diluted with 18.6 g of the solvent, giving a sample-to-solvent ratio of 1:2. The extract was centrifuged at 4000 rpm for 30 min to remove particulates, yielding a reddish-brown solution. In an identical manner, 9.3 g of turmeric powder was dissolved in 18.6 g of the solvent and centrifuged under the same conditions, yielding a bright-yellow solution. The 1:1 mixture was prepared by combining 2 mL of each single extract (volume ratio 1:1), giving a yellow solution. All extractions were carried out at room temperature and the extracts were stored away from direct sunlight prior to characterisation. The choice of solvent system is consistent with reports that extraction method and solvent polarity strongly influence the light absorbance of natural dyes (Mphande & Pogrebnoi, 2014; Popuri & Pagala, 2013), and with wider evidence that phytochemical screening and solvent selection determine the recoverable pigment and flavonoid fraction of plant extracts (Abiodun et al., 2011).

3.3 Preparation of nanoporous TiO_2 films and dye adsorption

Titanium dioxide paste (Ti-Nanoxide D/SP, Solaronix) was screen-printed onto cleaned soda-lime glass substrates over an active area of 1.0 cm^2 and annealed at 500 °C for 30 min to consolidate the anatase phase. After cooling to room temperature, the sintered nanoporous TiO_2 films were immersed in the single D. regia and turmeric extracts for 9 h, and in the mixed extract for 15 h, to allow dye adsorption. The films were then rinsed with the extraction solvent, dried in air and stored in the dark. The perceived colours of the sensitised films were purple (D. regia), yellow (turmeric) and pale yellow (mixture), consistent with anchoring of the pigments through carbonyl and hydroxyl groups to surface Ti-OH sites (Ahmad et al., 2017; Maldonado-Valdivia et al., 2013).

The adsorption of organic dye molecules onto porous natural and inorganic substrates is well documented and depends strongly on contact time and surface chemistry (Ofomaja et al., 2011).

3.4 Optical characterisation

The optical properties of the dye solutions and of the dyes adsorbed on TiO_2 were measured with a UV-Vis-NIR spectrophotometer (UV-750 series) over the wavelength range 230-1100 nm. From the recorded absorbance, the absorption coefficient, an absorbance-based extinction parameter and the light-harvesting efficiency were computed using the relations in Section 2.2, and the optical band gap was determined from the Tauc plot assuming a direct allowed transition (Iswariya et al., 2017; Mphande & Pogrebnoi, 2014). All spectra reported below are the original instrument traces from the source study; no smoothing, digitisation or synthetic reconstruction has been applied.

4. Results and Discussion

4.1 Absorption spectra of the dye solutions

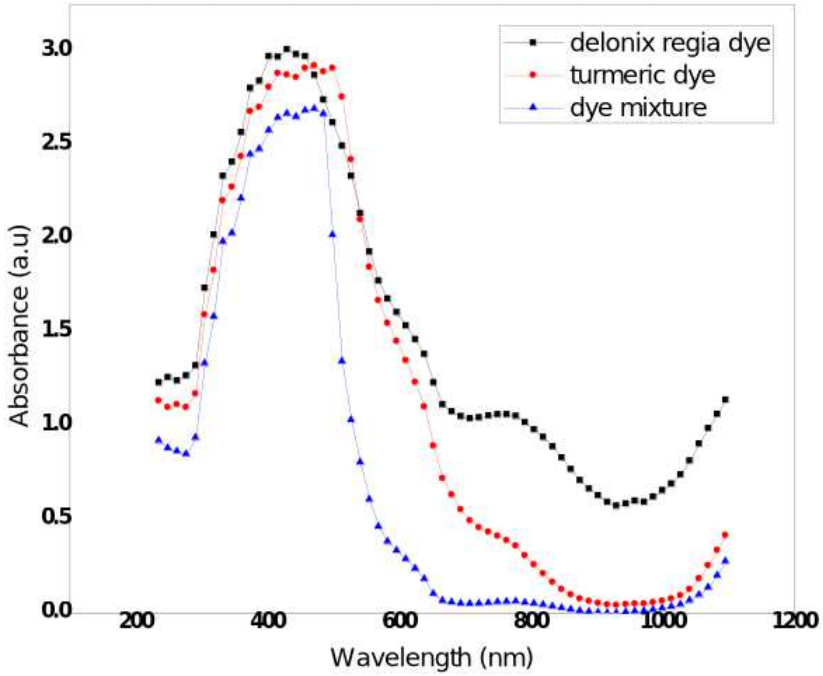


Figure 4. UV-Vis-NIR absorption spectra of the natural-dye solutions extracted from D. regia flower, turmeric and their 1:1 mixture

Table 2. Absorption-peak wavelengths of the dye solutions obtained from the UV-Vis-NIR spectra (Figure 4).

Dye source	UV region (nm)	Visible region (nm)	NIR region (nm)
D. regia flower	333, 375	402, 430, 458	764

Turmeric	333, 375	416, 458, 500	-
Mixture (1:1)	333, 375	430, 472	-

Figure 4 shows the UV-Vis-NIR absorption spectra of the three solutions, and the corresponding peaks are summarised in Table 2. All three extracts absorbed strongly in the ultraviolet (333 and 375 nm) and visible regions. The D. regia extract exhibited a broad visible band with a maximum near 430 nm and, notably, a second feature at 764 nm in the near-infrared, which widens its usable spectral window relative to the other extracts and is consistent with the carotenoid-anthocyanin co-pigment system of the flower (Calogero et al., 2012; Purohit et al., 2007). The turmeric extract absorbed principally between 416 and 500 nm, consistent with the curcuminoid chromophore (Kolev et al., 2005; Wright, 2002), while the mixture displayed visible peaks at 430 and 472 nm.

It is noteworthy that the near-infrared band of D. regia did not carry over into the spectrum of the mixture. This is attributed to the differing polarities of the two pigment-solvent systems in the combined solution, which produce a red-shift and re-distribution of the composite absorption rather than a simple superposition of the two single-dye spectra (Pratiwi et al., 2017). Although the mixture did not reproduce the long-wavelength feature, it retained significant absorption at 430 and 472 nm and therefore remains a viable sensitiser. The strong ultraviolet-visible absorption of all three extracts confirms their potential for DSSC sensitisation, with D. regia enjoying an additional advantage in the near-infrared (Kumara et al., 2017).

4.2 Absorption spectra of the dyes adsorbed on nanoporous TiO_2

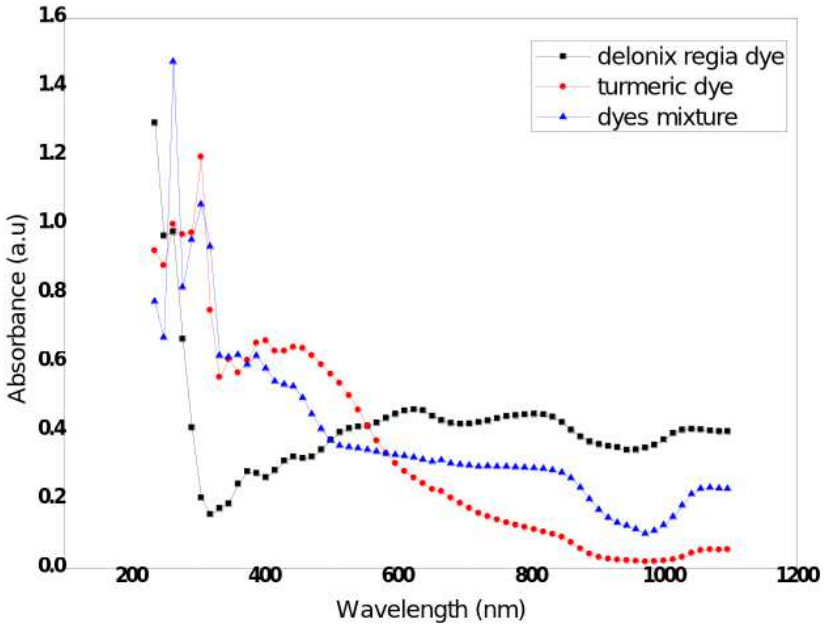


Figure 5. UV-Vis-NIR absorption spectra of the natural dyes after adsorption onto the nanoporous TiO_2 surface

Table 3. Absorption-peak wavelengths of the dyes after adsorption on the nanoporous TiO_2 surface (Figure 5).

Dye source	UV region (nm)	Visible region (nm)	NIR region (nm)
D. regia	236, 388	444, 528, 626	805, 1028
Turmeric	236, 277, 305, 347	402, 444	-
Mixture (1:1)	236, 263, 291, 305, 388	444	847

Adsorption onto the TiO_2 surface markedly modified the absorption behaviour of the dyes, as shown in Figure 5 and Table 3. The absorption onset advanced further into the ultraviolet, and the D. regia dye displayed the richest and broadest spectrum, with peaks spanning 236-388 nm (UV), 444-626 nm (visible) and 805-1028 nm (NIR). This broad, red-shifted response upon anchoring is consistent with electronic coupling between the pigment and TiO_2 through carbonyl and hydroxyl groups (Ahmad et al., 2017; Maldonado-Valdivia et al., 2013), and it identifies D. regia as the most promising candidate for photosensitisation among the three. The turmeric dye absorbed only weakly beyond the visible region, with peaks at 402 and 444 nm and no meaningful NIR response.

Importantly, the mixture out-performed the single turmeric extract after adsorption, exhibiting peaks at 402, 444 and 847 nm; the appearance of a near-infrared feature at 847 nm demonstrates that combining the two dyes recovers part of the long-wavelength harvesting contributed by D. regia. From the standpoint of adsorbed-state absorption the ranking is therefore D. regia > mixture > turmeric, and co-sensitisation is beneficial relative to the weaker single dye (Hussain et al., 2025; Shah et al., 2023).

4.3 Absorption coefficient

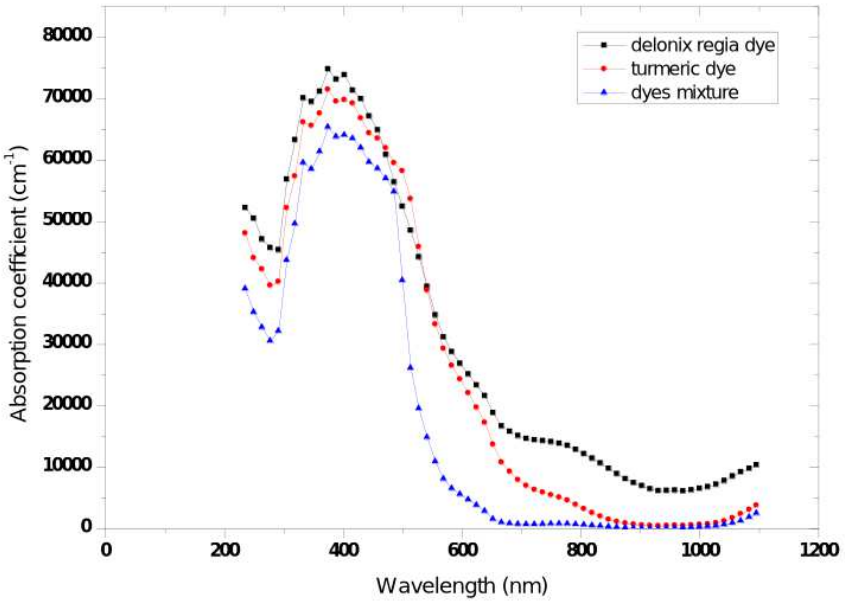


Figure 6. Absorption coefficient versus wavelength for the dye solutions of D. regia, turmeric and their 1:1 mixture

Table 4. Wavelengths of maximum absorption coefficient (α) of the dyes and their mixture (Figure 6).

Dye source	UV region (nm)	Visible region (nm)	NIR region (nm)
D. regia	333, 375	402	778
Turmeric	333, 375	402, 500	-
Mixture (1:1)	333, 375	402, 472	-

The variation of the absorption coefficient α with wavelength is presented in Figure 6, with characteristic wavelengths in Table 4. The three solutions have similar coefficients that rise from 333 to 375 nm in the ultraviolet, reaching a maximum near 375 nm, and then decline gradually through the visible region (402-500 nm for turmeric and 402-472 nm for the mixture). Only D. regia retains appreciable absorption at 778 nm in the near-infrared. All three dyes are therefore effective absorbers of ultraviolet and visible light, with D. regia offering an additional near-infrared contribution that is advantageous for photocurrent generation (Iswariya et al., 2017; Richhariya et al., 2017).

4.4 Extinction (absorbance-based) parameter

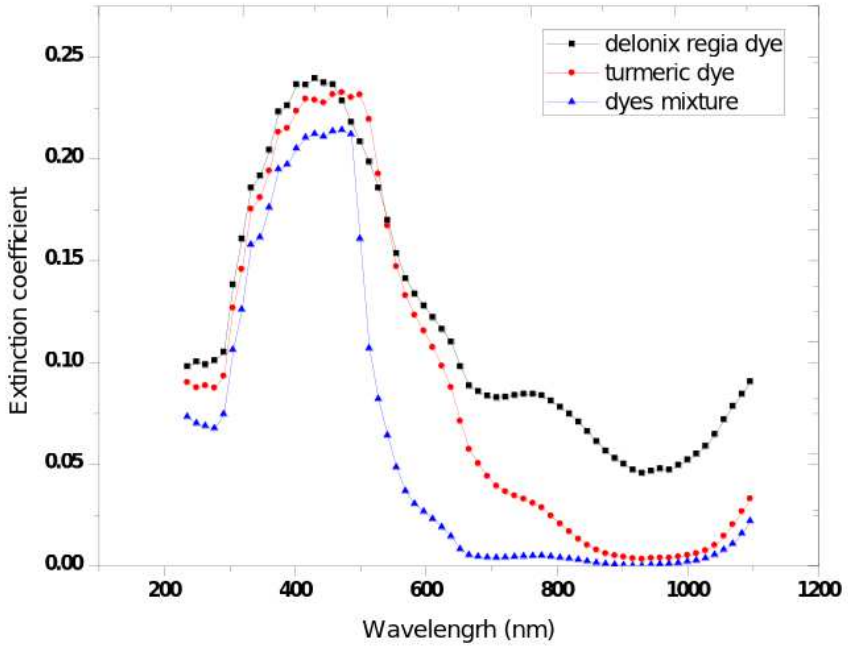


Figure 7. Absorbance-based extinction parameter versus wavelength for the dye solutions of D. regia, turmeric and their mixture

Table 5. Absorbance-based extinction values of the natural dyes reported in the source study (a.u.). See Section 2.2 editorial note.

Dye source	UV λ (nm) / A	Visible λ (nm) / A	NIR λ (nm) / A
D. regia flower	333 (0.19); 375 (0.22)	416-458 (0.24)	778 (0.08)
Turmeric	333 (0.18); 375 (0.21)	416-500 (0.23)	764 (0.03)
Mixture (1:1)	333 (0.16); 375 (0.19)	430-472 (0.21)	778 (0.05)

Figure 7 and Table 5 present the extinction behaviour reported in the source study. Within the visible region the dyes reach approximately constant values - 0.24 (a.u.) for D. regia between 416 and 458 nm, 0.23 for turmeric between 416 and 500 nm, and 0.21 for the mixture between 430 and 472 nm - before decreasing towards longer wavelengths. The D. regia extract exhibits the highest visible value and the strongest residual absorption in the near-infrared (0.08 at 778 nm). As noted in Section 2.2, the tabulated quantities are peak absorbances rather than the true wavelength-dependent extinction coefficient k; they are nonetheless a valid relative measure of light-absorbing strength and rank the dyes consistently with Figures 4-6 (Mphande & Pogrebnoi, 2014).

4.5 Light-harvesting efficiency

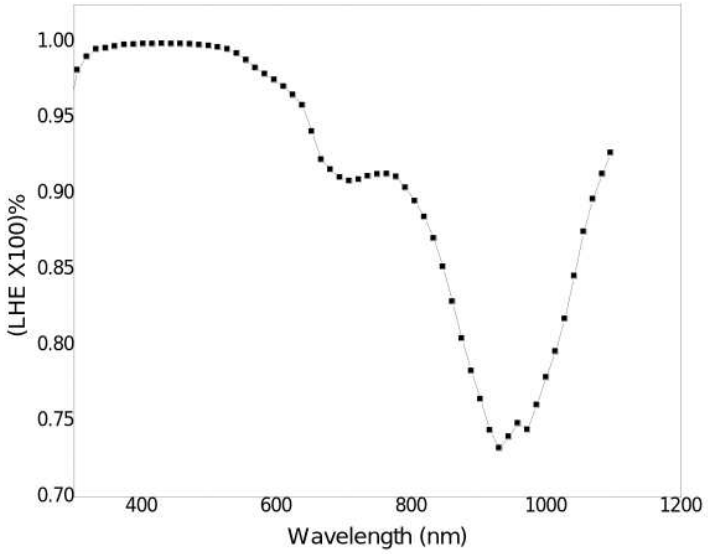


Figure 8. Light-harvesting efficiency (LHE) versus wavelength for the D. regia dye extract.

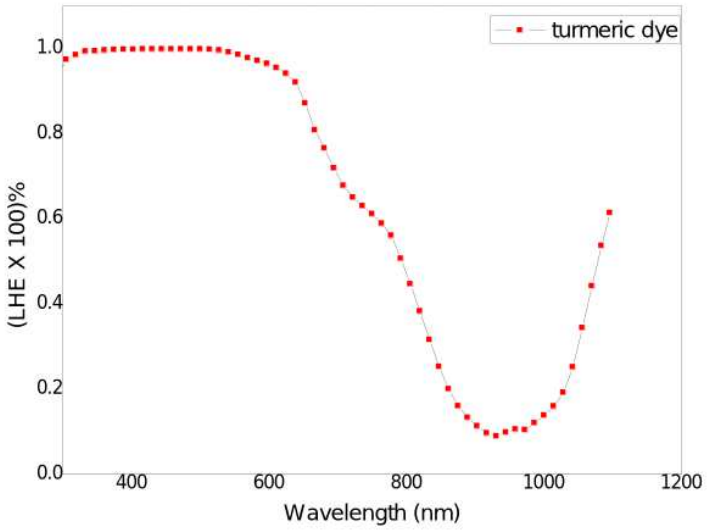


Figure 9. LHE versus wavelength for the turmeric dye extract.

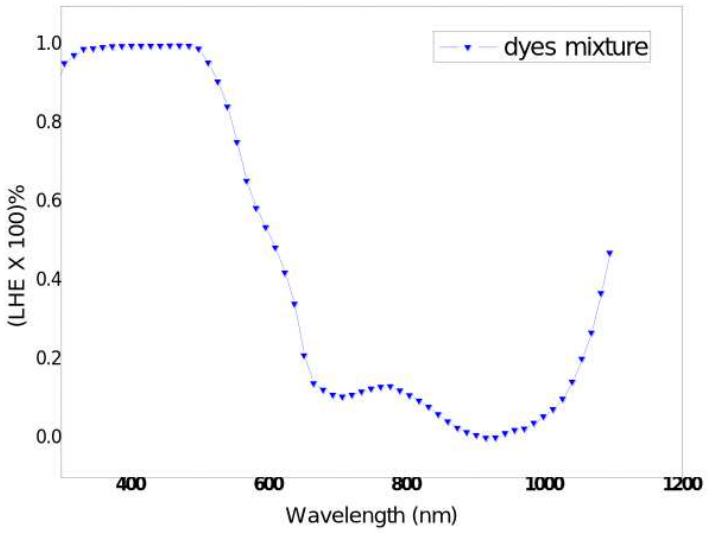


Figure 10. LHE versus wavelength for the 1:1 dye mixture.

The light-harvesting efficiencies were computed from the absorbance using LHE = $(1 - 10^{-A}) \times 100\%$ and are shown in Figures 8-10 (Mphande & Pogrebnoi, 2014). The D. regia extract sustained an LHE of approximately 99% over 305-541 nm, declining to about 91% between 694 and 764 nm and to about 73% in the near-infrared before rising again at longer wavelengths (Figure 8). The turmeric extract maintained about 99% LHE between 318 and 555 nm, falling to about 10% near 944 nm and then recovering to about 61% at longer wavelengths (Figure 9). The mixture retained about 99% LHE from 320 to 500 nm, dropping from about 90% at 538 nm to about 12% at 680 nm before increasing to about 47% in the infrared (Figure 10). All three dyes therefore harvest visible light very efficiently, differing mainly in their long-wavelength behaviour, where D. regia is clearly superior (Kumara et al., 2017; Shalini et al., 2015).

4.6 Optical band gap

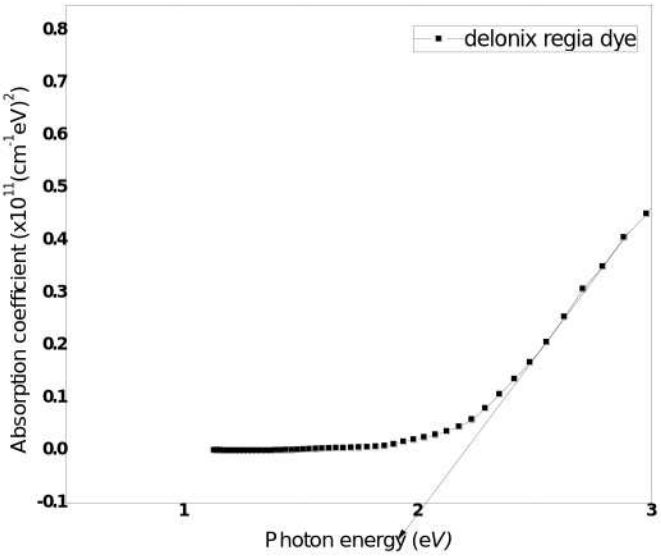


Figure 11. Tauc plot of $(\alpha h\nu)^2$ versus photon energy for the D. regia dye extract (direct allowed transition assumed).

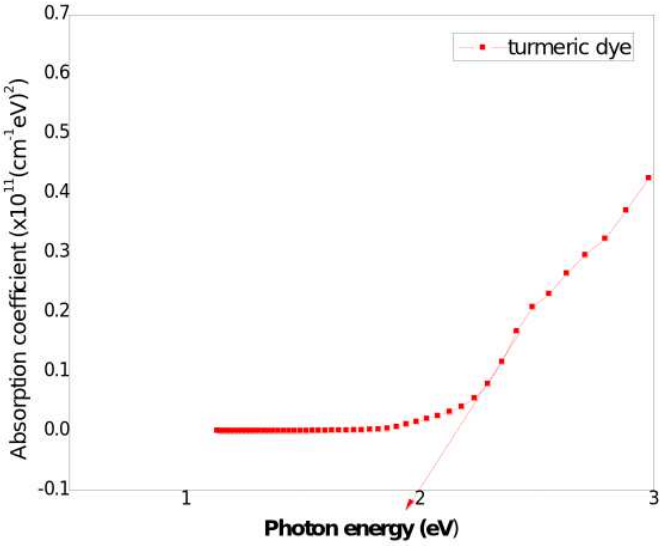


Figure 12. Tauc plot of $(\alpha h\nu)^2$ versus photon energy for the turmeric dye extract.

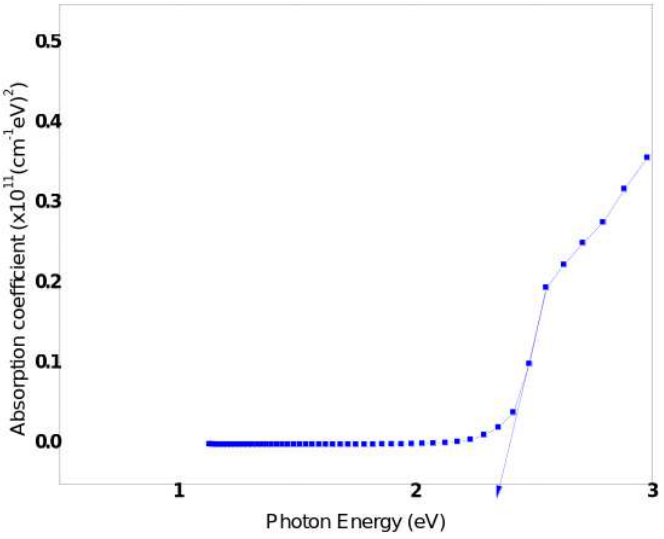


Figure 13. Tauc plot of $(\alpha h\nu)^2$ versus photon energy for the 1:1 dye mixture.

Table 6. Optical band gaps of the dye solutions from Tauc analysis (direct allowed transition).

Dye source	Optical band gap, E_g (eV)	Equivalent onset (nm)
D. regia flower	2.02	≈ 614
Turmeric	1.98	≈ 626
Mixture (1:1)	2.35	≈ 528

Optical band gaps were obtained by extrapolating the linear portion of $(\alpha h\nu)^2$ versus $h\nu$ to the energy axis (Figures 11-13), assuming a direct allowed transition (Iswariya et al., 2017). The values were 2.02 eV for D. regia, 1.98 eV for turmeric and 2.35 eV for the mixture (Table 6). All lie within the 1.8-2.4 eV window associated with visible-light absorption and are therefore suitable for photovoltaic sensitisation (Calogero et al., 2012; Shalini et al., 2015). The larger band gap of the mixture is consistent with the re-distribution of its absorption towards shorter wavelengths noted in Section 4.1 and with the loss of the D. regia near-infrared band on mixing. The equivalent onset wavelengths in Table 6 are calculated from E_g using $\lambda = 1240/E_g$ and are provided only as a convenience; they are not independent measurements.

4.7 Implications for photosensitisation and co-sensitisation

Taken together, the optical data establish a clear ranking of the three sensitisers. The D. regia extract combines strong visible absorption, the highest visible extinction value, near-99% light-harvesting efficiency across a broad visible window and a uniquely useful near-infrared band, making it the most promising single natural sensitiser of the three. The turmeric extract is a competent visible absorber but lacks long-wavelength response. The 1:1 mixture does not simply add the two spectra; instead, co-pigmentation and solvent-polarity effects redistribute the composite absorption, so that the mixture is optically superior to single turmeric yet inferior to single D. regia (Pratiwi et al., 2017; Shah et al., 2023). This behaviour underlines a central lesson of co-sensitisation research: complementary dyes, matched ratios, pH control and co-adsorbents

are required for additive spectral gains, and these variables are increasingly guided by TD-DFT modelling of dye-TiO_2 interactions (Hussain et al., 2025). The present results provide the experimental optical baseline against which such optimisation, and the device performance reported, can be judged (Imoni-Ogbe et al., 2025; Ogo et al., 2024).

4.8 Comparison with the literature

Table 7. Reported optical band gaps and absorption maxima for representative natural-dye sensitisers, for context. Direct comparison is limited by differences in solvent, concentration and instrumentation.

Sensitiser system	Band gap / λ_max	Reference
D. regia flower (this work)	2.02 eV; 430, 764 nm	This work
Turmeric/curcumin (this work)	1.98 eV; 416-500 nm	This work
1:1 mixture (this work)	2.35 eV; 430, 472 nm	This work
Curcumin (Curcuma longa)	≈ 420-430 nm max	(Kim et al., 2013)
Anthocyanin/betalain pigments	visible 470-550 nm	(Calogero et al., 2012)
Fruit-extract sensitisers	2.6-2.9 eV	(Iswariya et al., 2017)
Chlorophyll-anthocyanin mixture	broadened visible	(Pratiwi et al., 2017)

The band gaps and absorption maxima obtained here fall within the ranges reported for other natural-dye sensitisers, supporting the suitability of all three extracts for DSSC sensitisation while confirming the optical superiority of the anthocyanin-carotenoid-rich D. regia flower. As the footnote to Table 7 indicates, quantitative comparison across studies is constrained by differences in solvent polarity, dye concentration, film thickness and spectrophotometer, and the comparison is therefore qualitative.

5. Conclusion

Natural dyes were extracted from D. regia flower and turmeric, and from their 1:1 mixture, using a 50:50 distilled water-methanol solvent, and their optical properties were characterised in solution and after adsorption on nanoporous TiO_2. All three extracts absorbed strongly in the ultraviolet and visible regions, with D. regia uniquely absorbing in the near-infrared (764 nm in solution, extending to 1028 nm on TiO_2). The D. regia extract showed the highest visible absorbance, near-99% light-harvesting efficiency across a broad visible window and an optical band gap of 2.02 eV; turmeric and the mixture had band gaps of 1.98 and 2.35 eV, respectively. The mixture was optically superior to single turmeric but inferior to single D. regia, because co-pigmentation redistributes rather than superimposes the component bands. These results identify anthocyanin-carotenoid-rich D. regia as an excellent indigenous single sensitiser and provide the optical baseline for the co-sensitisation. The principal limitation of the study is that the optical measurements were conducted as single runs. Future work should therefore include independent experimental replicates, uncertainty estimates, and complementary chemical identification of the principal pigment components.

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Author Contributions (CRediT)

O. M. Osiele: Conceptualisation, Methodology, Supervision, Project administration, Funding acquisition, Writing - review and editing. A. S. Olayinka: Funding acquisition, Formal analysis, Data curation, Software, Visualisation, Writing - original draft, Writing - review and editing. S. A. Uzoekwe: Methodology (dye extraction and chemical characterisation), Validation, Writing - review and editing. B. U. Osolobri: Investigation (fabrication and measurement), Data curation.

Data Availability Statement

The optical datasets (UV-Vis-NIR spectra and derived parameters) supporting this article are available from the corresponding author on reasonable request. The GPS waypoint export for the turmeric collection point is retained by the authors.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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