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DESIGN AND PERFORMANCE EVALUATION OF ECO-FRIENDLY DYE-SENSITIZED SOLAR CELLS USING *Tinospora cordifolia* STEM AND *Allium Cepa* PEEL

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ABSTRACT

Owing to the low production costs, easy fabrication process, lightweight architecture and environmentally conscious qualities, dye-sensitised solar cells (DSSCs) are considered an especially promising substitute for traditional silicon-based solar cells. Therefore, they may find use in future sustainable and renewable energy applications. This study explores the use of natural dye extracted from the stem of Giloy (*Tinospora cordifolia*) and Onion peel (*Allium cepa*) as a sensitiser for DSSCs. The *Tinospora cordifolia* plant belongs to the Menispermaceae family, and Allium cepa belongs to the Amaryllidaceae family. Both the plant materials used in this research study are rich sources of primary and secondary metabolites. The TiO_2 nanoparticles were synthesised using the co-precipitation method and characterised using XRD and UV-VIS spectroscopy. The natural dyes were extracted using ethanol, and their photovoltaic performance was evaluated. The findings indicate that the Cocktail of the two extracted dyes (Dye-3) achieved the highest efficiency of 1.86%, exceeding the performance of the individual Giloy (1.38%) and onion peel (1.59%) extracts. The study emphasised the promising role of plant-based dyes as a sustainable and environmentally benign sensitiser for Dye-Sensitised Solar Cells, paving the way for advancements in eco-friendly solar energy technologies.

Keywords: Dye Sensitised Solar Cell, *Tinospora Cordifolia*, *Allium Cepa*, Photovoltaic Performance. Natural Dye, Titanium Dioxide

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INTRODUCTION

The growing demand for sustainable and renewable power sources has led to momentous advancements in solar cell technologies.[1] Dye-sensitized solar cells (DSSCs) have expanded extensively due to their low-cost, fabrication of cells without difficulties, and promoting sustainable development.[2,3] Unlike conventional silicon-based solar cells, DSSCs operate using a photosensitizer that absorbs sunlight and facilitates electron transfer, making them a promising alternative for next-generation photovoltaics.[4,5] One of the key components of DSSCs is the sensitiser dye, which plays a crucial role in absorbing light and initiating the photogeneration of electrons.[6] Despite their high efficiency, synthetic dyes like complexes based on ruthenium are costly, non-biodegradable, and pose environmental hazards .[7,8] Phyto-dyes, isolated from plant sources, present a sustainable alternative due to their abundance and ability to provide broad-spectrum light absorption.[9,10] These factors make natural dyes an attractive choice for the development of eco-friendly DSSCs. When dye molecules absorb sunlight, electrons in DSSC are stimulated from their ground state to an excited state.[6] An electric current is subsequently produced when these excited electrons move into a semiconductor's conduction band. By contributing electrons to the dye's regeneration, the electrolyte in the cell keeps the cell functioning continuously.[6] In DSSCs, co-sensitisation plays an essential role. A single dye often has a limited absorption range, restricting its ability to utilise the full spectrum of sunlight.

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By combining multiple dyes with complementary absorption spectra, co-sensitisation broadens the spectral response, leading to improved photocurrent generation. Additionally, it helps in reducing charge recombination, stabilising dye anchoring on the semiconductor surface, and enhancing the long-term stability of DSSCs. In this study, we explore the use of a natural dye derived from Giloy (*Tinospora cordifolia*) and onion peel (*Allium cepa*) as a sensitiser for DSSCs. Giloy plant is rich in bioactive compounds such as flavonoids, alkaloids, and tannins.[11,12] While onion peel contains anthocyanins and flavonoids, especially quercetin derivatives, which exhibit excellent dyeing properties, the ability to facilitate electron transfer and strong light-absorbing properties.[13,14] By combining these two natural extracts, the goal of this study is to improve the DSSC's stability and light-harvesting efficiency of sustainable photovoltaic technology.

EXPERIMENTAL

Synthesis of TiO_2 Powder

At normal temperature, TiO_2 was synthesised using the co-precipitation technique. 1.82g of Cetyltrimethylammonium bromide (CTAB) was taken into the beaker and mixed with 12.5 mL of absolute C_2H_5OH and 50 mL of de-ionised H_2O, and then this mixture was rigorously agitated for 1.0 h. After that, 1.43 mL of titanium isopropoxide [$Ti[OCH(CH_3)_2)_4$] was added dropwise to the solution and regularly agitated for 24 h. The resulting milky colour solution was centrifuged, followed by three rounds of washing with de-ionised water and ethanol. The final product was dried for 12 h at 80 °C and then calcined for 2 h at 450 °C to remove any remaining organic material.[15]

Preparation of Natural Dye Sensitiser

Stems of Giloy (*Tinospora cordifolia*) were collected from the surrounding areas of Delhi, India. Onions (*Allium cepa*) were purchased from a local market in Delhi, and the peels were separated and stored for further use. The collected plant materials were thoroughly washed with deionised water and dried at room temperature. The shade-dried Giloy stems (50 g) were crushed and extracted with ethanol (150 mL) in a 1.0 L round-bottom flask using a water bath for 24 h. The extract was then filtered and concentrated under reduced pressure (Dye-1).[16-18] Similarly, onion peels (7 g) were crushed and extracted with ethanol (50 mL) under the same conditions. After 24 hours of extraction, the onion peel extract was also filtered and concentrated under reduced pressure (Dye-2). To prepare the Dye-3, equal amounts of both extracts were mixed thoroughly to ensure uniform composition and enhance light-harvesting efficiency.

Fabrication of Dye-Sensitised Solar Cells

The fabrication of DSSCs (Fig.-1) was carried out using the doctor blade technique to deposit the synthesized TiO_2 powder onto the conductive surface of a fluorine-doped tin oxide (FTO) glass slide.

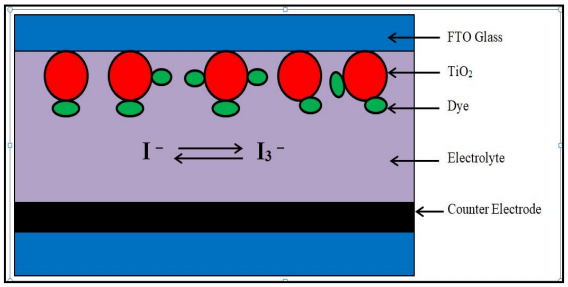

Fig.-1: Diagrammatic representation of Natural Dye-Sensitised Solar Cell

Initially, 0.5 g of TiO_2 powder was thoroughly throttled using 0.1 mL of acetylacetone. Next, 0.4 mL of Triton X-100 was added to a 1:1 mixture of deionised water and 100% ethanol to create a paste. Prior to coating, the FTO glass slides were cleaned with deionised water and subsequently sonicated in a methanol-acetone solution (1:1 ratio). The prepared TiO_2 paste was applied to the FTO glass using the doctor blade method, followed by calcination at 500 °C for 30 min. The TiO_2-laminated FTO glass plate was then immersed in a natural dye solution for 48 h to facilitate dye adsorption. After the immersion period, the slides were rinsed with deionised water. For the preparation of the counter electrode, graphite

carbon was scraped from a pencil onto the conductive surface of a separate FTO glass slide. An electrolyte solution was prepared by mixing 1mL of 5% Lugol's iodine solution with 10 mL of water. The DSSC assembly was completed by placing a few drops of the electrolyte between the photoanode and the counter electrode, with adhesive tape serving as a spacer. Lastly, the active working area of the solar cell was defined by placing a black cover with an open area on the leading edge of the TiO_2-laminated FTO glass slide.[20]

RESULTS AND DISCUSSION

FTIR Analysis of Extracts

The FTIR (SHIMADZU 8400S) spectrum of Dye-1 (Giloy extract) indicates the presence of aliphatic C-H (2990 cm^{-1}), carbonyl C=O (1750 cm^{-1}), aromatic C=C (1510, 1475 cm^{-1}), C-O stretching (1160 cm^{-1}) and aromatic C-H bending (735 cm^{-1}), suggesting the presence of flavonoids, terpenoids and phenolic compounds. Dye-2 (Onion peel extract) shows a broad peak at 3310 cm^{-1}, indicating the presence of the -O-H group, while a strong C=O stretching appeared at 1795 cm^{-1}. Aromatic -C=C- and C-O stretching appeared at 1460 cm^{-1} and 1110 cm^{-1}. All these data observed in the FTIR spectrum of dye-2 indicate the presence of flavonoids (such as quercetin derivatives), phenolic compounds, and possibly sulfur-containing phytochemicals. These functional groups confirm the presence of bioactive phytochemicals in both dyes (Fig-2).

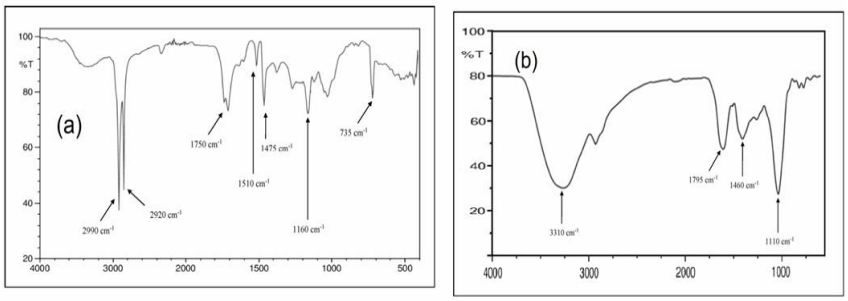

Fig.-2: FTIR Analysis of (a) Natural dye-1, (b) Natural dye-2

XRD Analysis of TiO_2

Rigaku, model: SMARTLAB instrument is used for the XRD analysis. Figure-3a displays the TiO_2 nanoparticle's XRD patterns. The positions of peak and comparative intensities are similar to the typical powder diffraction patterns of anatase-TiO_2, and the anatase phases of TiO_2 were in excellent accord with JCPDS card # 21-1272.[21.] Its primary summit is located at 24.9°, which is the (100) plane. The positions of the additional peaks at 37.6 ° (004), 48.3° (200), and 54.7 ° (105) correspond to the TiO_2 anatase phase. For TiO_2-based DSSCs to function well for electron transport and dye adsorption, this pure anatase structure of TiO_2 is essential.[22] This process yields a crystallite size of 23 nm.

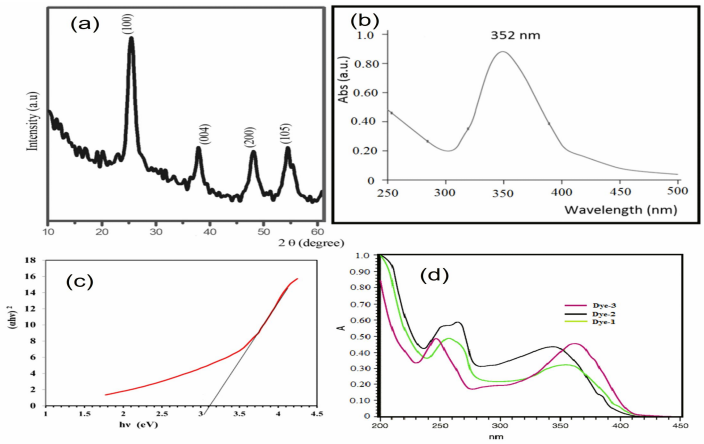

Fig.-3: (a) XRD of the TiO_2 Nanoparticles, (b) UV-Visible Spectra of the TiO_2, (c) Touc Plot of the TiO_2, (d) UV-Visible Spectra of Natural Extracted Dyes

The Debye-Scherrer formula.[23] Which is provided by equation 1, was used to determine the crystalline size.

$$D = K \lambda / (\beta \cos\theta) \qquad (1)$$

Here, "D = Crystallite size (nm); K = Scherrer constant or shape factor (0.89); λ = X-ray wavelength (λ=0.15406 nm); β = Full Width at Half Maximum of the diffraction peak; θ = Bragg angle".

UV-VIS Spectrum Analysis

The optical absorption performance (Fig.-3b) and band gap energy of TiO_2 (Fig.-3c) were investigated using UV-VIS spectroscopy (Shimadzu UV-1800).[24] TiO_2 nano powder was thoroughly dissolved in 10 mL of distilled water to record the UV-VIS absorption spectrum. UV absorption of TiO_2 nanoparticles is depicted in Fig.-4b. The optical absorption spectrum of TiO_2 was observed at 352 nm. The estimated band gap of TiO_2 is 3.1 eV. The band gap was estimated by applying the formula

$$E_g = hc / \lambda$$

Hear: "E_g stand for Band gap energy, h is Planck's constant (6.626 x 10^{-34} Joules/sec), C is velocity of the light, λ = Absorbance of the sample, 1 eV = 1.6 x 10^{-19} Joules". The UV-VIS absorbance data (Fig.-3d) indicates that Dye-1 exhibits absorption maxima at 260 nm (48% absorbance) and 360 nm (32% absorbance), suggesting the presence of flavonoids and phenolic compounds. Dye-2 (Onion peel extract) shows multiple absorption peaks at 255 nm (56%), 265 nm (60%), and 340 nm (46%), indicating a higher concentration of conjugated compounds, likely flavonoids (such as quercetin derivatives) and other phenolics. Dye-3, a 1:1 combination of the two extracts, retains absorption at 250 nm (50%) and 360 nm (48%), suggesting a synergistic effect in which compounds from both extracts contribute to the absorbance pattern. The increase in absorbance at 360 nm compared to Dye-1, along with the maintained UV absorption at lower wavelengths, suggests possible interaction or enhancement of chromophoric groups. This data confirms that both dyes contain bioactive phytochemicals with strong UV-absorbing properties, which are useful for dyeing and photoprotective applications.

Field Emission Scanning Electron Microscopy

The FESEM (JEOL JSM-7800F) of FTO+TiO_2(Fig.-4a) reveals a uniform distribution of TiO_2 nanoparticles (~23 nm). Upon dye adsorption, FTO+TiO_2+Dye-1 (Fig.-4b) and FTO+TiO_2+Dye-2 (Fig.4c) show increased surface roughness, while FTO+TiO_2+Dye-3 (Fig.-4d) displays a more homogeneous layer, ensuring improved charge transport and reduced recombination losses.

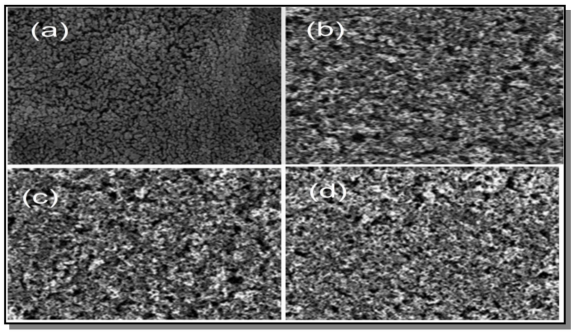

Fig.-4: FESEM of (a) FTO+TiO_2, (b) FTO+TiO_2+ Dye-1, (c) FTO+TiO_2+Dye-2, (d) FTO+ TiO_2+ dye-3

Efficiency Measurements of DSSC

The Circuit diagram (Fig.-5) was used for the measurement of the I-V value.
Efficiency (η) of the DSSC is estimated by applying formula:[25-28]

$$\eta = P_o / P_{in}$$

Here: "P_o is output power from the cell; P_{in} is input power given to the cell"

"Power per unit area (P_o) is estimated by applying the formula"

$$P_o = V I / A$$

Here: "V is open circuit voltage; I is short circuit voltage; A is the Effective area of the cell".

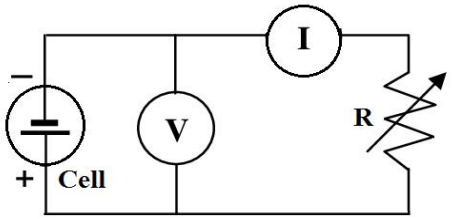

Fig.-5: Circuit of I-V Characteristic Measurement

Table-1: Identification of the Efficacy of DSSC for "Dye-1, Dye-2, and Dye-3"

Dyes	Voltage (V)	Current (mA)	Area (cm^2)	Output power(P_0)	Input power (P_{in}) (mW/cm^2)	Efficiency (η) (%)
Dye-1	0.48	5.2	3	0.832	60	1.38
Dye-2	0.53	5.4	3	0.954	60	1.59
Dye-3	0.57	5.7	3	1.121	60	1.86

Ethanol Extract of Giloy stem: Dye-1; Ethanol Extract of Onion peel: Dye-2; 1:1 ratio of both the extracts (Giloy stem and Onion peel): Dye-3 Source meter model Agilent B2900A Series: B2901/02/11/12A is used to identify I & V of DSSC, and it was observed that at noon, when the sun's intensity was at its highest (610 W/m^2), the current flow was at its highest level. Intensity of sunlight is measured using MP-100: Silicon-Cell Pyranometer and a solarimeter made by HTC.

Table-2: Current (I) & Voltage (V) Estimation of Dye-Sensitised Solar Cells

Dye-1				Dye-2				Dye-3			
Intensity (w/m^2)	V	I (mA)	Time	Intensity (w/m^2)	V	I (mA)	Time	Intensity (w/m^2)	V	I (mA)	Time
510	0.36	3.09	10:30	510	0.37	3.18	10:30	510	0.39	3.22	10:30
530	0.39	3.17	11:30	530	0.42	3.23	11:30	530	0.43	3.25	11:30
540	0.41	3.83	12:30	540	0.44	3.92	12:30	540	0.45	3.93	12:30
575	0.46	4.71	13:30	575	0.47	4.73	13:30	575	0.52	4.75	13:30
610	0.48	5.20	14:30	610	0.53	5.40	14:30	610	0.59	5.70	14:30
560	0.44	4.28	15:30	560	0.45	4.53	15:30	560	0.47	4.16	15:30
490	0.32	2.81	16:30	490	0.35	3.01	16:30	490	0.37	3.09	16:30

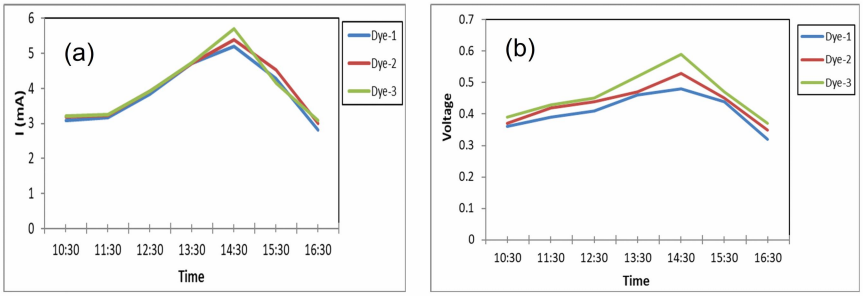

Fig.-6: (a) Current vs Time Study of Prepared DSSCs, (b) Voltage vs Time Study of Prepared DSSCs

CONCLUSION

This study successfully demonstrated the fabrication and performance evaluation of a natural dye-sensitised solar cell using the stem of Giloy and Onion peel extracts as sensitizers. Dye-3 shows the highest efficiency **(**1.86%**)** compared to dye-1 **(**1.38%**)** and dye-2 **(**1.59%**)** due to its superior light absorption and co-sensitisation effect. The combination of Giloy stem and Onion peel extracts provides complementary absorption spectra, reducing charge recombination and improving electron injections. The XRD and UV-VIS analysis confirmed the anatase phase of TiO_2 and its suitable optical properties for DSSC applications. The findings emphasise the viability of plant-based dyes as cost-effective and

environmentally friendly alternatives to synthetic sensitisers in DSSCs, paving the way for further research in sustainable solar energy solutions.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-7: Affordable and Clean Energy*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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REFERENCES

1. L.P.S.S. Panagoda, R.A.H.T. Sandeepa, W.A.V.T. Perera, D.M.I. Sandunika, S.M.G.T. Siriwardhana, M.K.S.D. Alwis, S.H.S. Dilka, *Journal of Research Technology & Engineering*, **30**, 30(2023).
2. N.S.M.N. Izam, Z. Itam, W.L. Sing, A. Syamsir, *Energies*, **8**, 2790 (2022), https://doi.org/10.3390/en15082790
3. O.B. Ogundipe, A.C. Okwandu and S.A. Abdulwaheed, *GSC Advanced Research and Reviews*, **1**, 159-175 (2024), https://doi.org/10.30574/gscarr.2024.20.1.0259
4. D. Zheng, X. Yang, L. Čuček, J. Wang, T. Ma and C. Yin, *Journal of Cleaner Production*, **464**, 142717 (2024), https://doi.org/10.1016/j.jclepro.2024.142717
5. S. Rahman, A. Haleem, M. Siddiq, M. K. Hussain, S. Qamar, S. Hameed and M. Waris, *RSC Advances*, **28**, 19508(2023), https://doi.org/10.1039/D3RA00903C
6. M.A. Al-Alwani, A.B. Mohamad, N.A. Ludin, A.A.H. Kadhum and K. Sopian, Renewable *and Sustainable Energy Reviews*, **65**, 183(2016), https://doi.org/10.1016/j.rser.2016.06.045
7. J. Bhattacharjee and S. Roy, Chemical *Papers*, **15**, 8077(2024), https://doi.org/10.1007/s11696-024-03657-2
8. I. Arora, H. Chawla, A. Chandra, S. Sagadevan and S. Garg, *Inorganic Chemistry Communications*, **143,** 109700 (2022), https://doi.org/10.1016/j.inoche.2022.109700
9. M. Dhorkule, P. Lamrood, S. Ralegankar, S. P. Patole, S. S. Wagh and H.M. Pathan, *ES Food & Agroforestry*, **16**, 1086 (2024), http://dx.doi.org/10.30919/esfaf1086
10. N. Mariotti, M. Bonomo, L. Fagiolari, N. Barbero, C. Gerbaldi, F. Bella e C. Barolo, *Green Chemistry*, **21**, 7168(2020), https://doi.org/10.1039/D0GC01148G
11. A.Gupta, P. Gupta and G. Bajpai *Heliyon*, **4,**1(2024), https://doi.org/10.1016/j.heliyon.2024.e26125
12. P.Kumar, D.K. Verma, G. Kimmy, P.P Srivastav and K.S. Sandhu, 2021,Phytochemicals in Giloy (Tinospora cordifolia L.): Structure, Chemistry, and Health Benefits. In *Phytochemicals in Food and Health,* Apple Academic Press, pp. 127-150.

13. M.K. Samota, M. Sharma, K. Kaur, Sarita, D.K. Yadav, A. K. Pandey and H.Rani, Frontiers *in Nutrition*, **9,** 917617(2022), https://doi.org/10.3389/fnut.2022.917617
14. S. Chadorshabi, S. Hallaj-Nezhadi and Z. Ghasempour, *Food Chemistry*, **386**, 132737(2022), https://doi.org/10.1016/j.foodchem.2022.132737
15. A.Karami, *Journal of the Iranian Chemical Society*, **7(Suppl 2)**, S154(2010), https://doi.org/10.1007/BF03246194
16. S. Hao, J. Wu, Y. Huang and J. Lin, *Solar Energy*, **80(2)**, 209(2006), https://doi.org/10.1016/j.solener.2005.05.009
17. M. Alhamed, A.S. Issa and A.W Doubal, *Journal of Electron Devices*, **16(11)**, 1370(2012).
18. C. Cari, K. Khairuddin, T.Y. Septiawan, P. M. Suciatmoko, D. Kurniawan and A.Supriyanto, In *AIP Conference Proceedings* (2018), AIP Publishing, https://doi.org/10.1063/1.5054510
19. M.S. Ahmad, A.K. Pandey and N. Abd Rahim, *Renewable and Sustainable Energy Reviews*, **77**, 89(2017), https://doi.org/10.1016/j.rser.2017.03.129
20. G.Richhariya, B.C. Meikap and A.Kumar, *Environmental Science and Pollution Research*, **29(11)**, 15233(2022), https://doi.org/10.1007/s11356-021-18049-2
21. S. Sathyajothi, R.Jayavel, A. C. Dhanemozhi, *Materials Today: Proceedings*, **4(2)**, 668(2017), https://doi.org/10.1016/j.matpr.2017.01.071
22. T.Theivasanthi and M. Alagar, *arXiv preprint arXiv,***1307**,1091(2013), https://doi.org/10.48550/arXiv.1307.1091
23. S.Fatimah, R. Ragadhita, D.F. Al Husaeni and A.B.D. Nandiyanto, *ASEAN Journal of Science and Engineering*, **2(1)**, 65(2022), http://dx.doi.org/10.%2017509/xxxxt.vxix
24. W. Khan, S. Ahmad, M.M Hassan and A.H. Naqvi, *Optical Materials*, **38**, 278(2014), https://doi.org/10.1016/j.optmat.2014.10.054
25. K.Takagi, S. Magaino, H Saito, T. Aoki and D. Aoki, *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, **14**, 1(2013), https://doi.org/10.1016/j.jphotochemrev.2012.08.003
26. N. Mittal, R. K. Soni, V. Sharma, D. Prakhar, V. Sharma, B. P. Singh, R. K. Sharma, *Solar Compass*, **18**, 100161(2026), https://doi.org/10.1016/j.solcom.2026.100161
27. E. S. Esakki, G. Deepa, P. Vivek, S. M. Sundar, *Solid State Communications*, **371**, 115266 (2023), https://doi.org/10.1016/j.ssc.2023.115266
28. J. Ohshita, S. Kangai, H. Yoshida, A. Kunai, S. Kajiwara, Y. Ooyama, Y. Harima, *Journal of Organometallic Chemistry*, **692(4)**, 801(2007), https://doi.org/10.1016/j.jorganchem.2006.10.016

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