How components of Dye-sensitized solar cells contribute to efficient solar energy capture

---

ABSTRACT

Herein, we reviewed the main components of dye-sensitized solar cells (DSSCs) which are an emerging cheap and environmentally benign alternative for solar energy capture and conversion to electricity. The role of individual parts such as the semiconductor electrode, counter electrode, photosensitizer, electrolyte, and substrate and their contribution to the overall efficiency (η) of DSSCs is discussed. In addition, parameters such as short circuit current, open circuit voltage, and fill factor used to quantify the efficiency of DSSCs are addressed. The highest solar-to-electric energy conversion efficiency of 13 % has been achieved using titanium dioxide as a semiconductor electrode, a triiodide system as an electrolyte, and platinum counter electrodes. Semiconductors made of such as glass, carbon, conductive polymers and other metal oxides have lower efficiencies (< 8 %). In addition, synthetic photosensitizers especially ruthenium complexes have higher efficiencies (10-11 %) compared to natural dyes among which the highest efficiency (4.6 %) achieved using chlorophyll. The performance of natural dyes based on efficiency of the DSSC is generally in the order: chlorophyll > anthocyanins > carotenoids highly attributed to their structure which not dictates electron release and recombination but also attachment to other components. The DSSC performance is not fixed but rather tunable by variations in the components to achieve desired structural and electronic properties such as firm anchorage between the photosensitizer and the semiconductors, the reduction of the energy band gap by incorporation of other metal salts to extend the absorption range and use of additives that prevent electron recombination with the photosensitizer or any hindrances in the electrolyte redox reactions.

Keywords: synthetic dyes, photosensitizers, efficiency, photoanodes, counter electrodes

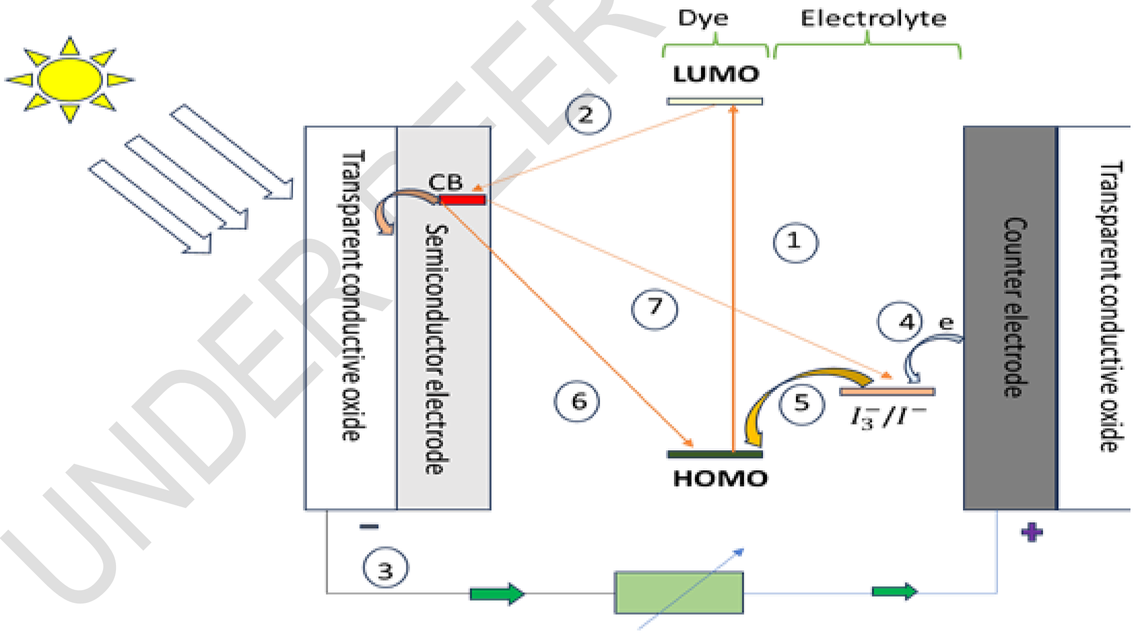
1. INTRODUCTION

Energy is crucial to the survival of mankind and sustainability of ecosystems by facilitation of key processes ranging from manufacturing to transportation. Green and renewable energy sources are cheap and environmentally benign alternatives to the commonly used coal and petroleum which are not only non-renewable but also contribute to global warming and the release of pollutants with detrimental effects on the environment and living organisms [1]. With the current trend in alternative renewable energy sources, it is estimated to account for 27 % of the total energy consumed by 2030 [2]. Renewable energy sources include hydroelectric power, wind, geothermal, and solar energy. Solar energy is key among the renewable energy source because it is non-toxic, quiet and require less sophisticated equipment to generate compared to all other forms of energy [3-5]. The energy from the sun amounts to $3.8x10^6$ Joules per year or $4.4x10^{16}$ watts making a potential source of energy [6].

Photovoltaics (PV) have been employed for decades to harness solar energy. The PV technology is generally classified into first, second, and third generations. The first-generation PV is made of silicon-based materials comprising either polycrystalline or monocrystalline or silicon which is abundant and cheap giving solar-to-electricity conversion between 12-16 % [7]. The second-generation solar cells also called thin film solar cells use amorphous silicon [8]. It has the advantage of reduced power loss due to low temperature coefficient [9]. They also contain other non-crystalline additives such as cadmium telluride (CDTe), copper indium gallium diselenide (CIGS) making the PV light and flexible, however, they have relatively low efficiencies [10] compared to the first generation solar cells. The CDTe solar cells have a module efficiency of 10.9 % and laboratory efficiency of 16.7 % however they are toxic and have low light tolerance [9]. On the other hand the CIGS have efficiencies of 13.5 % in the module and 19.9 % in laboratory with high durability, low cost and their band gap is tunable to achieve tandem cells [11, 12].

The third generation employs quantum dots (QDs) [13, 14], dye-sensitized solar cells (DSSCs) [5, 15], and perovskite solar cells (PSC) [16]. The cells are designed to create an electrical potential difference that push electrons to external circuits [17]. The use of DSSCs has found wide application since its fabrication by O’Regan and Grätzel in 1991 due to low production and design costs [18] and the ability to achieve ≈ 10 % efficiency compared to silicon solar cells [19].

The DSSCs comprise five major components which include the electrolyte [20], visible light adsorber dye [21], counter electrode [22], transparent conductive oxide substrate [23], and semiconductor [24] which are discussed in this review. The semiconductor supports the dye by anchorage and also facilitates electron transfer. It is made up of nanostructures which include the nanowires, nanotubes, nano horns, nanotubes, nano cones and nano sheets which are attached to the transparent conductive oxide [25]. The electrolyte acts as charge carriers as it collects electrons from the cathode and transports them back to the dye for restoration [15]. The photosensitizer which can be a synthetic or natural dye release electrons when struck by photons which enters semiconductor with a small band gap allowing electron transfer to the transparent conductive oxide that moves electrons to the load [26]. The counter electrode connected to load then transfer electrons to the electrolyte that acts as the mediator regenerating the oxidized dye and thus completing the circuit [27]. A simplified mode of operation of a DSSC is summarized in (Figure 1). It is worth noting that the efficiency DSSCs is greatly determined by the ability to regenerate the photosensitizer [28].



1. Photo excitation of the dye; 2. Electron injection into the conduction band of the semiconductor electrode; 3. Electron movement from transparent conductive oxide to the counter electrode; 4. Electrolyte reduction; 5. Dye regeneration and electrolyte oxidation; 6. Photoexcited electron recombination with oxidized dye and 7. Photoexcited electron recombination with oxidized electrolyte

Fig 1. Structure and operation of a dye-sensitized solar cell.

Factors that influence the performance dye-sensitized solar cells

Different characterization techniques are used to assess the performance of DSSCs and to monitor the different stages such as photon absorption and electron excitation, charge transfer, and photosensitizer regeneration [9, 29, 30]. Four common photochemical parameters used include short circuit current density (J_{sc}), open circuit voltage (V_{oc}), Fill Factor (FF), and conversion efficiency (η) [31]. The parameters are determined from a photocurrent density-voltage plot (J-V) curve at 1.5 standard global air mass (AM) (Figure 2) [32].

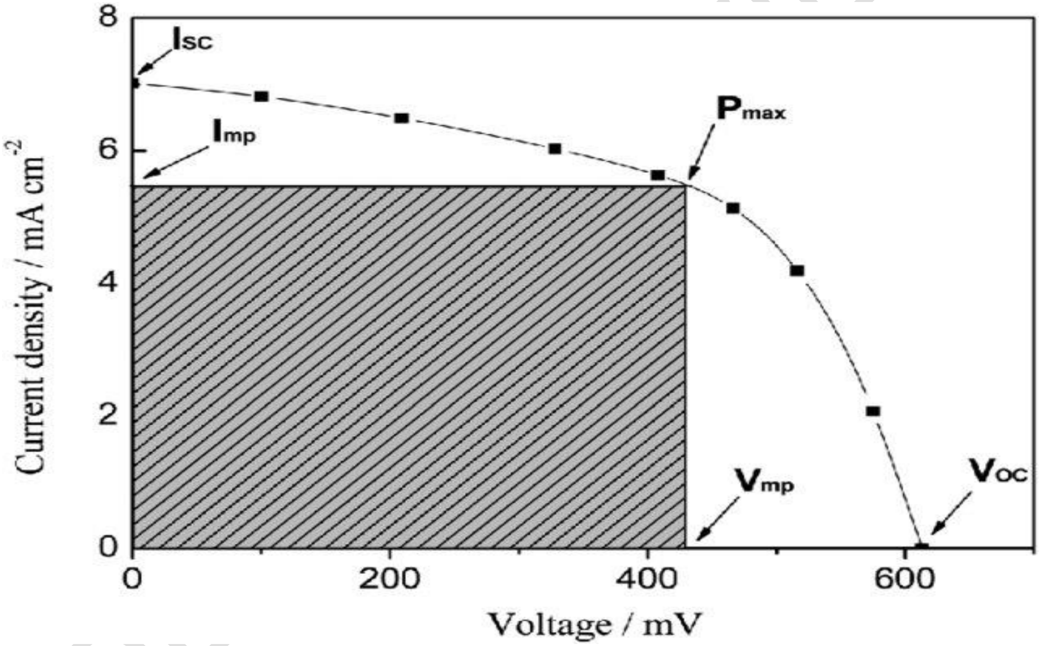


Fig 2. J-V characteristic curve of the DSSC performance [33].

The J_{sc} is estimated at zero potential difference and relatively low circuit irradiation [34] and it depends on the semiconductor-dye bond strength, ability of electron migration to the CB and ease of reducing the electrolyte. On the other hand, the V_{oc} is the potential difference when the current flowing through the circuit is zero [34]. It depends on the difference between the redox potential of the electrolyte and the conduction band Fermi level (E_{CB}) of the semiconductor electrode [34]. Further, the fill factor (FF) is the ratio of the experimental maximum power and the theoretical maximum power [32] which depends on the effects of resistance during ion transport and the resistance of the counter electrode. It should be noted that all components play role in solar capture and the efficiency is determined from the ratio of the maximum power output to the energy of incident photons of light [35]. The electrocatalytic activity and electrolytic conductivity that influence the DSSC performance depend on the counter electrode [36, 37] which have been fabricated using several techniques such as electrochemical deposition, chemical reduction, thermal decomposition, in situ polymerization, hydrothermal reaction and sputter deposition. The later technique is the commonly used because of high purity, uniformity, good adhesion, repeatability but also high melting point materials can be sputtered [38]. It has been observed that platinum electrodes give a relatively high efficiency [39] but have drawbacks such as high toxicity, less abundance, expensive and non-inertness reacting with redox mediators which corrodes the electrode observed from the formation of platinum iodide which hinders its application [40, 41]. Alternative electrodes made of conductive polymers, carbonaceous material, and carbides, nitrides, sulphides, and oxides of other metals have been used in DSSCs to replace platinum (Table 1).

Table 1. Counter electrode materials used in DSSCs.

Counter electrodes	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η %	Reference
Platinum	12.00	0.69	0.76	13.00	[19]
TiN nanotube	15.78	0.76	0.64	7.73	[42]
Glassy carbon	16.50	0.71	0.65	7.56	[43]
Polyoyrrole	11.00	0.79	0.64	7.77	[44]
$NiCO_2S_4$	14.11	0.72	0.60	6.10	[45]
$W_{18}O_{49}$	17.14	0.70	0.66	7.94	[46]

The efficiency of the counter electrode is determined by a rise in the fill factor (FF) which is influenced by the series resistance (SR) and charge transfer resistance (CTR) [47-49]. A reduction in the CTR increases SR which signifies a high electron movement from the counter electrode to the electrolyte enhancing reduction and thus electron continuity leading to high solar-to-electric energy conversion efficiency [48-50]. Brian O'Regan and Michael Grätzel [19] designed a DSSC with a platinum counter electrode which gave an efficiency of 12 % attributed to the morphology and the exposure of the surface facets [22]. Li et al [51] designed a counter electrode using titanium nitride nanoparticles with relatively close efficiency of 7.73 % attributed to interfacial active sites [52].

The solar conversion efficiency also depends on the electrolyte which should have a very fast charge carrier transfer rate from the semiconductor to the counter electrode to rapidly regenerate the oxidized dye [45, 53-55]. Three types of electrolytes have been used in DSSCs; solid-state, liquid, and quasi-solid electrolytes. A liquid electrolyte containing the redox couple of iodide/triiodide [56] and copper complex ($Cu^{+2/+1}$) has been widely with efficiencies >27 % [57]. However, the low redox couple-potential of iodide/triiodide causes a decrease in the Voc and thus energy loss [58]. The iodide/triiodide has an electrode potential of 0.35 V in comparison with the standard hydrogen electrode however the slow electron recombination as a result of low reduction kinetics of either I_2 or I_3^- is major drawback affecting the performance of DSSCs [59]. In addition, under low iodine concentration the electrolyte conductivity is low whereas high concentrations promote recombination reactions at semiconductor interface that decrease the efficiency [60]. Nevertheless, the recombination of the electrolyte with electrons can be reduced by additives such as methyl benzimidazole [61], 4-*tert*-butylpyridine [62] and guanidiumthiocyanate [63] which improve on the DSSC efficiency and stability. The alternative quasi-solid [64] and solid-state electrolytes [65] without electrolyte loss generally give less efficient DSSCs (Table 2).

Table 2. Type of electrolytes applied in DSSCs

Electrolyte	**J_{sc} (mA/cm^2)**	**V_{oc} (V)**	**FF**	**η (%)**	**Reference**
Solid state	15.1	0.64	0.72	6.95	[65]
Liquid	19.99	0.69	0.72	9.96	[56]
Quasi solid	15.53	0.77	0.77	8.25	[64]

Another key component determining the efficiency of a DSSC is the photoanode whose properties should match with those of other parts especially the dye molecule and the transparent conductive substrate to achieve high efficiency [66, 67]. In addition, it must have a high surface area to readily transfer the electron to the substrate, high resistance to corrosion by the electrolyte, and have excellent surface properties to firmly adsorb the photosensitizer dye [68, 69]. Titanium(IV) oxide (TiO_2) is the commonly used photoanode in DSSCs because of its, low toxicity and abundance, with sizes ranging from 15-30 nm and varying thickness (10-15 µm) making it a suitable material [70]. It exists in three crystalline forms; rutile, brookite, and anatase but the latter has found great application because of its high refractive index (n= 2.5), and band gap (3.2 eV) which enables fast movement of electrons [67, 71, 72] compared to ZnO, Zn_2SnO_4 and SnO_2. The band gaps of selected semi-conductors are summarized in (Figure 3). Research works have also reported use metal oxides such as WO_3 [73], $SrTiO_3$ [74], ZnO [75], Zn_2SnO_4 [76], and Nb_2O_5 [77] in DSSCs as shown in (Figure 4) [78, 79].

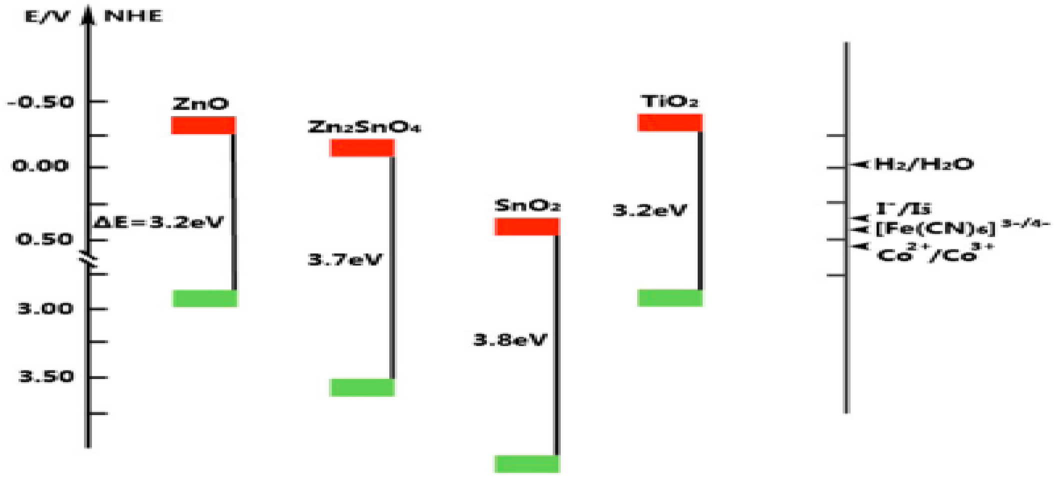


Fig 3. Band gaps of selected semiconductors with reference hydrogen.

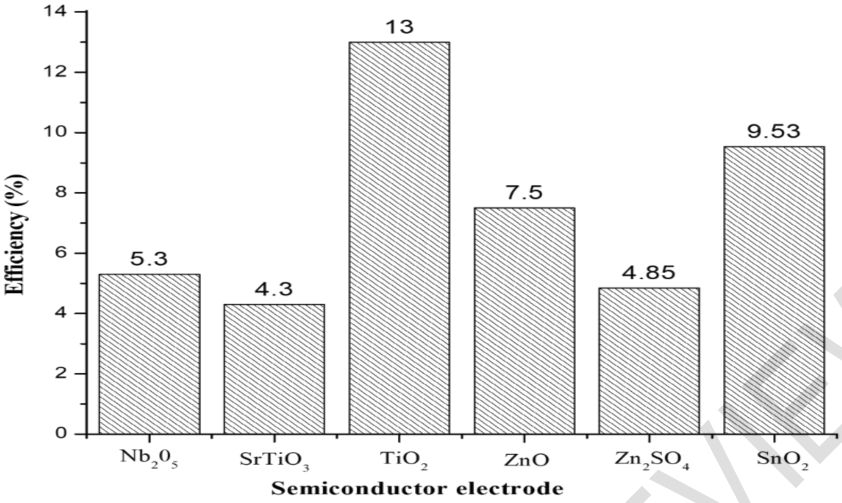


Fig 4. Comparison of the highest-performing semiconductor electrodes.

Photoanodes are fabricated using a number of techniques which include hydrothermal, spin coating, spray pyrolysis, chemical vapour deposition and sol gel are employed in synthesis [80]. These techniques give a variety of nanostructures such as the nanowires, nanorods, nanoparticles, nanosheets and nanotubes [81]. It is worth mentioning that the structures high depend on pH and temperature used during fabrication. Barbé et al [82] designed a method is used to prepare TiO_2 nanoparticles by hydrolysis of a titanium precursor such as titanium (IV) alkoxide with excess water catalyzed by an acid or base followed by hydrothermal growth and crystallization. Under acidic conditions, transmission electron microscopy revealed that the nanoparticles mainly consisting of anatase phase had 101 surfaces. Under basic condition, Hore et al. reported semiconductors with mesoporous layers which resulted into low recombination rates, high Voc with weak dye-semiconductor bonds [83].

Mathew et al [84] fabricated a DSSC containing TiO_2 achieving a conversion efficiency of 13 % which is the highest compared to other semiconductor electrodes. The low efficiency compared to silicon solar cells was attributed to slow electron mobility in addition to light absorption only in the UV region [28]. Nevertheless enhancement of DSSC performance has been achieved by metal doping using aluminium (Al) [85], lanthanum (La) [86], niobium (Nb) [87], tungsten (W) [88], nickel (Ni) [89], and the used of non-metal additives such as carbon (C) [90], fluorine (F) [91], nitrogen (N) [92] and sulphur (S) [93] to modify the energy band gap. The transparent conductive oxides have found great application in DSSCs and they include fluorine-doped tin oxide (FTO) and indium-doped tin oxide (ITO) both of which are transparent and have a wide band gap [94]. The oxides have high optical activity in the visible and near infrared regions [95]. However, FTO has a slight edge in that it more transparent allowing photons to strike the dye with ease and also has a higher thermal capacity, better electrical conductivity and higher corrosion resistance [94]. The transparent conductive oxide is normally prepared using two methods which include sputter deposition and chemical vapour deposition [96]. ITO has a high optical transparency and conductivity compared to FTO [95]

It is worth noting that the most crucial component of DSSCs is the dye sensitizer (DS) responsible for absorbing photons that excite its electrons excitation followed by a jump to the conduction band starting the electricity generation process [8]. The efficiency of the DS is enhanced by the presence of several functional groups such as carboxyl and hydroxyl that enable anchoring onto the photoanode. The three common categories of DS include synthetic metal- and metal-free organic dyes, and natural dyes. Ruthenium complexes have found wide application since they have a high solar-to-electric energy conversion efficiency of 11% in the presence of sunlight at 1.5 AM standardized global air mass [97]. The commonly used ruthenium dyes include N719, N749 (black dye), and N3 (red dye) [98] with 10-11% efficiencies. The three ruthenium dyes have been used in numerous studies through the modification of their two bipyridyl moieties while leaving the rest of the molecule unchanged [99]. Grätzel et al described the synthesis of numerous ruthenium complexes and modification the substituents enhanced efficiency and interaction between the semiconductor and dye [19, 100]. The N-Chlorosuccinimide groups of ruthenium that help in diffusion of the surface holes and the bipyridyl ligands whose role is to carry out electron transport [101]. The methyl and phenyl groups have been found to increase the absorption coefficients of the metal-ligand once they are bonded at the appropriate positions [19, 100]. However, ruthenium dyes have major drawbacks such as tedious synthetic processes, high costs, and toxicity to the environment and living organisms [8]. Current research has shifted focus to natural dyes as photosensitizers for DSSCs because they are readily available, generally cheap, easy to extract, and have no detrimental effect on man and the environment. Commonly used dye extracts used in DSSCs contain anthocyanins [102], flavonoids [103], chlorophyll [104], and carotenoids [105]. It has been observed that natural dyes show absorb visible light (400-700 nm) [97]. (Figure 5) shows the efficiencies of the commonly used dyes and the synthetic dyes have the highest conversions.

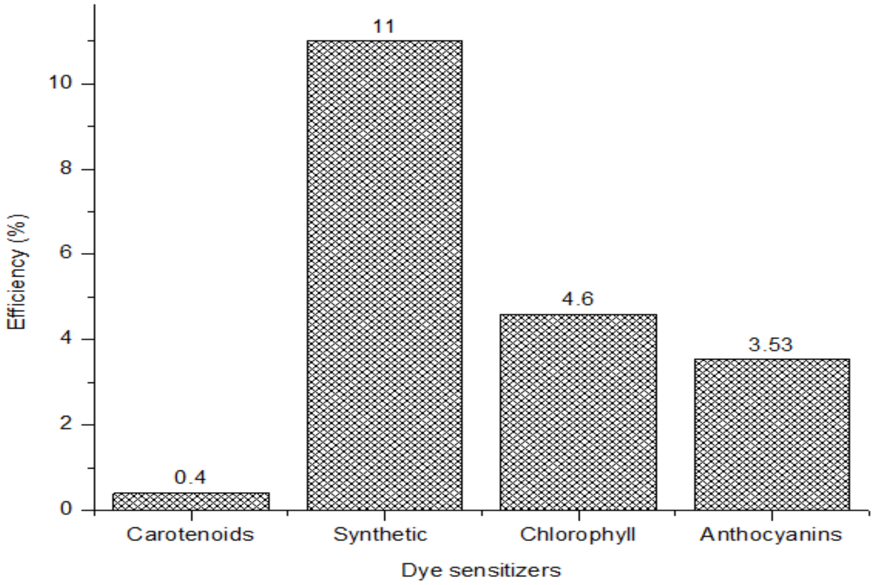


Fig 5. DSSC efficiency using synthetic [106] and natural photosensitizers Carotenoids [107], Chlorophyll [108] and Anthocyanins [109].

Chlorophylls have a magnesium ion is a porphyrin group containing four pyrrole rings [110, 111] responsible for the absorption of light facilitated by an extensive aromatic system [112]. Chlorophyll absorbs in the visible region 420-460 nm (Blue) and 650-700 nm (Red) and reflects green light observed by humans [70]. There are two types of chlorophyll which differ with methyl and acetal groups attached to carbon at position 7 in chlorophyll a and b, respectively. Recently, Mejica et al [113] used chlorophyll extracted from *Strobilanthes cusia* as a dye photosensitizer and the recorded V_{oc}, J_{sc}, FF, and η values were 0.306 V, 0.0155 mA cm^{-2}, 0.462, and 0.039 %, respectively which were relative low compared to the synthetic dye N719 [98]. In similar research works Jaafar et al used chrophyll extracted from *Spinacia oleracea* and the obtained V_{oc}, J_{sc}, FF, and η were 0.33 V, 3.74 mA cm^{-2}, 0.47 and 0.58 %, respectively [114]. In both works, the low J_{sc} is likely due to the weak attachment of the dye to the semiconductor caused by long hydrophobic chain alkyl group which decreases the chances of electron injection in to the consuction band and due to the high possibily of the electron combining with the cation of the dye. Other chlrophyll extracts from brown seaweed [108], moss bryophyte [115], cream leaves [116], *Pandannus amaryllifolius* [117], *Azadirachta indica* [118], *Zizyphus* sp leaves [119], *Ficus rectus linn* [120], and microalgae [121] have been used in DSSCs (Table 3). The measured parameters J_{sc}, V_{oc} and FF vary with each component of the DSSC making it difficult to attribute the overall performance on any one due to the uncorrelated fluctuations in values with respect to the efficiency. Nevertheless, some factors such as the FF can be ruled out in determining the overall efficiency and to a fair prediction, high J_{sc} values result to higher efficiencies as observed with the different classes of photosentitizers, electrolytes and electrode materials in Tables 1-3.

Table 3. Photochemical parameters of chlorophylls

Chlorophyll	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
Microalgae	2.53	0.551	0.65	0.90
Brown sea weed	13.80	0.57	0.58	4.60
Moss bryophite	5.96	0.58	0.58	2.00
Cream leaves	2.28	0.61	0.44	0.61
Pandannus amaryllifolius	0.40	0.55	0.61	0.10
Azadirachta indica	0.43	0.40	0.40	0.72
Zizyphus sp leaves	1.50	0.68	0.40	0.40
Ficus rectus linn	7.85	0.52	0.29	1.18

Natural dyes containing flavonoids have also been used in DSSCs. They have phenolic structures with low molecular weight and are abundant in fruits, flowers, and a few beverages [122]. Anthocyanins have the longest absorption 500-600 nm which lies in the visible range [123]. They are substituted glycoside salts of phenyl-2-benzopyrilium whose chromane bears another aromatic ring B at carbon 2 where the hydroxylated points are attached to sugar molecules [124-126]. These pigments have loosely bound electrons that easily jump to the semiconductor electrode thus enhancing the conversion efficiency [127]. The hydroxyl groups of anthocyanins strongly anchor the DS onto the semiconductor electrode (Figure 6) [128] facilitating the transfer of electrons into its conduction band [129].

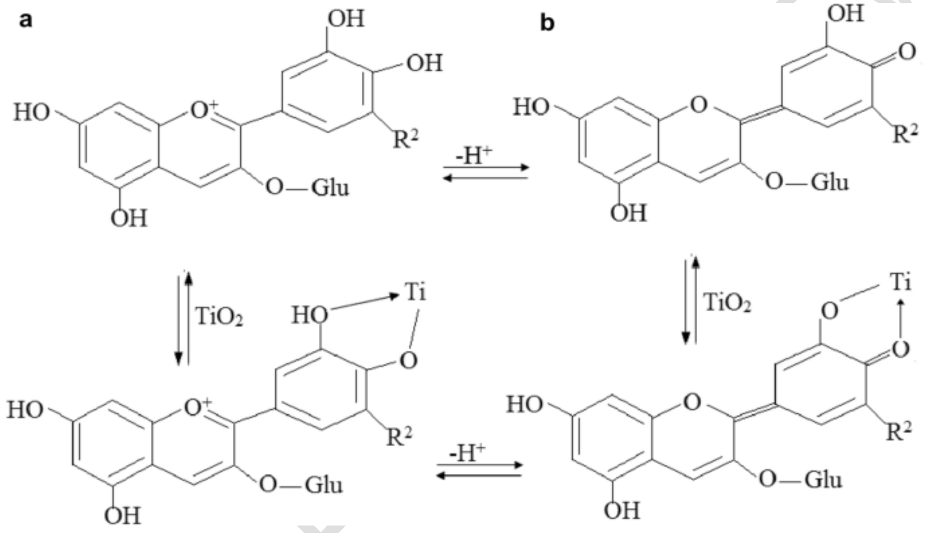


Fig 6. Schematic representation of the interaction between cyanidine-3-glucoside (anthocyanin) and TiO_2 [130].

Al Batty et al investigated Ber and Blackberry fruits containing anthocyanins and managed to obtain the highest efficiency of 1.194 % with J_{sc} of 5.71 $mAcm^{-2}$, V_{oc} of 0.4 V, and FF of 0.523% using Ber extract compared to an efficiency of 1.059 % with a J_{sc} of 5.25 $mAcm^{-2}$, V_{oc} of 0.4 V, and FF of 0.504 using the Blackberry fruit extract (Table 4) [131]. The higher performance of the Ber extract is attributed to the high anthocyanin concentration. Other anthocyanin extracts Poinsettia bracts [132], dragon fruit [133], Rose myrite [109], pomegranate [134], spinach [135], *Opuntia dillenii* [136], red sicilian orange [137] and hibiscus flowers [138] used as photosensitizers in DSSCs are shown in (Table 5).

Table 4. The Photochemical parameters of a combination of Blackberry/Ber [131]

Combination of dyes	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)
Blackberry: Ber (1:1)	3.50	0.35	0.46	0.57
Blackberry: Ber (1:2)	4.50	0.36	0.51	0.83
Blackberry: Ber (2:1)	2.70	0.32	0.41	0.35

Table 5. Photochemical parameters of anthocyanins

Dyes	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	η (%)	Reference
Poinsettia bracts	0.40	0.60	0.40	1.74	[132]
Dragon fruit	0.20	0.22	0.30	0.22	[133]
Pomenganate	12.20	0.39	0.410	2.00	[134]
Spinach	1.11	0.58	0.46	0.29	[135]
Opuntia dillenii	1.09	0.52	0.69	0.47	[136]
Rose myrite	8.77	0.50	0.29	3.53	[109]
Red sicilian orange	5.13	0.33	0.59	1.01	[137]
Hibiscus flower	0.96	0.27	0.43	0.11	[138]
Blueberry	0.96	0.39	0.47	0.17	[139]
Tamarindus indica	0.35	0.53	0.67	0.14	[136]

Carotenoids are also another important group of natural pigments used in DSSCs. They are normally found in the chloroplast and chromoplast and are responsible for the orange, red, and yellow colour which are characteristic of most fruits and flowers [70]. They have a C_{40} backbone structure [140] and are grouped into the xanthophylls that contain oxygen, and carotenes with only hydrogen and carbon (Figure 7) [141]. Carotenoids are derivates of lycopene which are produced through reactions such as dehydrogenation, methyl migration, cyclization, hydrogenation, chain elongation and hydrogenation [142].

(Table 6) shows the performance of DSSCs using carotenoid extracts from achiote seeds [105], *Curcuma longa* [143], golden trumpet [107], gardenia yellow [144], tomatoes [145], *Syngonium* sp [146], walnuts [147] and Gardenia blue [144] as photosensitizers. The relative poor performance of DSSCs containing carotenoids as DS is likely due to the extensive conjugated double bond system that can hold the excited electron by formation of many stable resonance forms there by reducing the chance of electron jump to the photoanode.

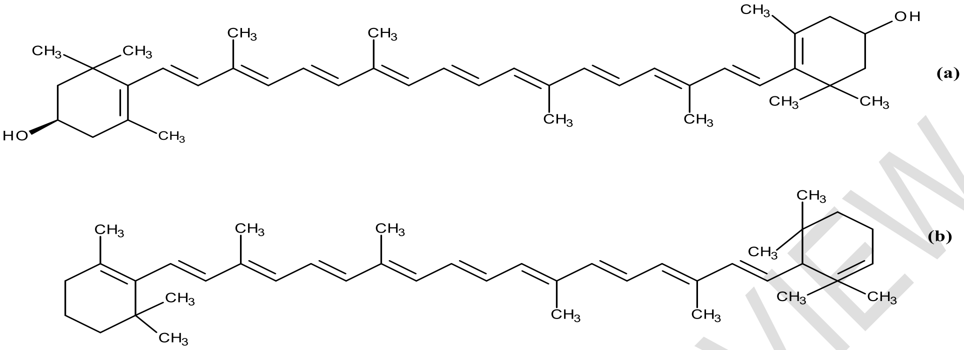


Fig 7. The structure of xanthophyll (a) and carotene (b) molecules

Table 6. Photochemical parameters of carotenoids

Carotenoids	J_{sc} ($mAcm^{-2}$)	V_{oc} (V)	FF	η (%)	Reference
Achiote seeds	1.10	0.57	0.59	0.37	[105]
Curcuma longa	0.20	0.28	0.65	0.36	[143]
Golden trumpet	0.88	0.41	0.54	0.40	[107]
Gardenia yellow	0.96	0.54	0.62	0.32	[144]
Tomatoes	0.51	0.14	0.37	0.03	[145]
Syngonium sp	0.27	0.40	0.69	0.07	[146]
Walnuts	0.73	0.30	0.39	0.01	[147]
Gardenia blue	0.53	0.44	0.69	0.16	[144]

CONCLUSIONS

Dye-sensitive solar cells are a promising cheap and green alternative energy source. The efficiecy of the cells depends on the interdependent-components each playing a crucial role from the process of electron release and transfer to the load and back to the DSSC system. Synthetic dyes are better photosensitizer giving relatively higher efficiencies than natural dyes. The structure of the photosentizer aid in its anchorage to the photoanodes that determines the extent of electron jump. In addtion, it determines the chances of electronic release to the photoanode where photosensitizers with cations or conjugated pi-electron system can hold the excited electron causing the generally reduced low efficiencies of DSSCs. Photoanodes can be improved by metal doping to lower and expland the band gap increasing the chances of electron reaching the conduction band. In general, the structural and electronic properties of individual components influence the performance of DSSCs. Functional groups of natural photosensitizers enable grip to semicoonductors which enhances stability of the system and also facilitates electron transfer. The performance increases with concentration of DS while other factors such as pH and temperature directly affect electron release and recombination. For electrolytes, the performance of quasi solids lies midway between liquid and solid phase with the former having a slight edge.

REFERENCE

1. Grossman, G.M. and A.B. Krueger, Economic growth and the environment. The quarterly journal of economics, 1995. **110**(2): p. 353-377.
2. Halicioglu, F. and N. Ketenci, Output, renewable and non-renewable energy production, and international trade: Evidence from EU-15 countries. Energy, 2018. **159**: p. 995-1002.
3. Faninger, G., The potential of solar heat in the future energy system. Faculty for Interdisciplinary Research and Continuing Education, IFF-University of Klagenfurt, Austria, 2010.
4. Ye, M., X. Wen, M. Wang, J. Iocozzia, N. Zhang, C. Lin, et al., Recent advances in dye-sensitized solar cells: from photoanodes, sensitizers and electrolytes to counter electrodes. Materials Today, 2015. **18**(3): p. 155-162.
5. Sharma, K., V. Sharma, and S. Sharma, Dye-sensitized solar cells: fundamentals and current status. Nanoscale research letters, 2018. **13**: p. 1-46.
6. Hasan, M.A. and K. Sumathy, Photovoltaic thermal module concepts and their performance analysis: a review. Renewable and sustainable energy reviews, 2010. **14**(7): p. 1845-1859.

7. Pandey, A.K., V. Tyagi, A. Jeyraj, L. Selvaraj, N. Rahim, and S. Tyagi, Recent advances in solar photovoltaic systems for emerging trends and advanced applications. Renewable and Sustainable Energy Reviews, 2016. **53**: p. 859-884.

8. Richhariya, G., A. Kumar, P. Tekasakul, and B. Gupta, Natural dyes for dye sensitized solar cell: A review. Renewable and Sustainable Energy Reviews, 2017. **69**: p. 705-718.

9. Hagfeldt, A., G. Boschloo, L. Sun, L. Kloo, and H. Pettersson, Dye-sensitized solar cells. Chemical reviews, 2010. **110**(11): p. 6595-6663.

10. Green, M.A., Crystalline and thin-film silicon solar cells: state of the art and future potential. Solar energy, 2003. **74**(3): p. 181-192.

11. Repins, I., M. Contreras, M. Romero, Y. Yan, W. Metzger, J. Li, et al., Characterization of 19.9% Efficient CIGS Absorbers (Presentation). 2008, National Renewable Energy Lab.(NREL), Golden, CO (United States).

12. Green, M., Prog. Photovoltaics 17 320 Green MA, Emery K, Hishikawa Y and Warta W 2009. Prog. Photovoltaics, 2009. **18**: p. 144.

13. Kouhnavard, M., S. Ikeda, N. Ludin, N.A. Khairudin, B. Ghaffari, M. Mat-Teridi, et al., A review of semiconductor materials as sensitizers for quantum dot-sensitized solar cells. Renewable and Sustainable Energy Reviews, 2014. **37**: p. 397-407.

14. Meng, K., P.K. Surolia, O. Byrne, and K.R. Thampi, Quantum dot and quantum dot-dye co-sensitized solar cells containing organic thiolate–disulfide redox electrolyte. Journal of Power Sources, 2015. **275**: p. 681-687.

15. Gong, J., J. Liang, and K. Sumathy, Review on dye-sensitized solar cells (DSSCs): Fundamental concepts and novel materials. Renewable and Sustainable Energy Reviews, 2012. **16**(8): p. 5848-5860.

16. Jung, H.S. and N.G. Park, Perovskite solar cells: from materials to devices. small, 2015. **11**(1): p. 10-25.

17. Nelson, J.A., The physics of solar cells. 2003: World Scientific Publishing Company.

18. Bella, F., C. Gerbaldi, C. Barolo, and M. Grätzel, Aqueous dye-sensitized solar cells. Chemical Society Reviews, 2015. **44**(11): p. 3431-3473.

19. O'regan, B. and M. Grätzel, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films. nature, 1991. **353**(6346): p. 737-740.

20. Bella, F. and R. Bongiovanni, Photoinduced polymerization: an innovative, powerful and environmentally friendly technique for the preparation of polymer electrolytes for dye-sensitized solar cells. Journal of photochemistry and photobiology C: photochemistry reviews, 2013. **16**: p. 1-21.

21. Qin, Y. and Q. Peng, Ruthenium sensitizers and their applications in dye-sensitized solar cells. International Journal of Photoenergy, 2012. **2012**.

22. Thomas, S., T. Deepak, G. Anjusree, T. Arun, S.V. Nair, and A.S. Nair, A review on counter electrode materials in dye-sensitized solar cells. Journal of Materials Chemistry A, 2014. **2**(13): p. 4474-4490.

23. Kawashima, T., T. Ezure, K. Okada, H. Matsui, K. Goto, and N. Tanabe, FTO/ITO double-layered transparent conductive oxide for dye-sensitized solar cells. Journal of Photochemistry and Photobiology A: Chemistry, 2004. **164**(1-3): p. 199-202.

24. Roy, P., D. Kim, K. Lee, E. Spiecker, and P. Schmuki, TiO2 nanotubes and their application in dye-sensitized solar cells. Nanoscale, 2010. **2**(1): p. 45-59.

25. Mir, N. and M. Salavati-Niasari, Photovoltaic properties of corresponding dye sensitized solar cells: effect of active sites of growth controller on TiO2 nanostructures. Solar Energy, 2012. **86**(11): p. 3397-3404.

26. Sugathan, V., E. John, and K. Sudhakar, Recent improvements in dye sensitized solar cells: A review. Renewable and Sustainable Energy Reviews, 2015. **52**: p. 54-64.

27. Carella, A., F. Borbone, and R. Centore, Research progress on photosensitizers for DSSC. Frontiers in chemistry, 2018. **6**: p. 481.

28. Ahmad, M.S., A.K. Pandey, and N. Abd Rahim, Advancements in the development of TiO2 photoanodes and its fabrication methods for dye sensitized solar cell (DSSC) applications. A review. Renewable and Sustainable Energy Reviews, 2017. **77**: p. 89-108.

29. Halme, J., P. Vahermaa, K. Miettunen, and P. Lund, Device physics of dye solar cells. Advanced materials, 2010. **22**(35): p. E210-E234.

30. Listorti, A., B. O'regan, and J.R. Durrant, Electron transfer dynamics in dye-sensitized solar cells. Chemistry of Materials, 2011. **23**(15): p. 3381-3399.

31. Ebenezer Anitha, A. and M. Dotter, A Review on Liquid Electrolyte Stability Issues for Commercialization of Dye-Sensitized Solar Cells (DSSC). Energies, 2023. **16**(13): p. 5129.

32. Nazeeruddin, M.K., E. Baranoff, and M. Grätzel, Dye-sensitized solar cells: A brief overview. Solar energy, 2011. **85**(6): p. 1172-1178.

33. Wu, J., Z. Lan, J. Lin, M. Huang, Y. Huang, L. Fan, et al., Counter electrodes in dye-sensitized solar cells. Chemical Society Reviews, 2017. **46**(19): p. 5975-6023.

34. Muñoz-García, A.B., I. Benesperi, G. Boschloo, J.J. Concepcion, J.H. Delcamp, E.A. Gibson, et al., Dye-sensitized solar cells strike back. Chemical Society Reviews, 2021. **50**(22): p. 12450-12550.

35. Kumara, N., A. Lim, C.M. Lim, M.I. Petra, and P. Ekanayake, Recent progress and utilization of natural pigments in dye sensitized solar cells: A review. Renewable and Sustainable Energy Reviews, 2017. **78**: p. 301-317.

36. Halme, J., M. Toivola, A. Tolvanen, and P. Lund, Charge transfer resistance of spray deposited and compressed counter electrodes for dye-sensitized nanoparticle solar cells on plastic substrates. Solar Energy Materials and Solar Cells, 2006. **90**(7-8): p. 872-886.

37. Kang, S.H., S.H. Choi, M.S. Kang, J.Y. Kim, H.S. Kim, T. Hyeon, et al., Nanorod-based dye-sensitized solar cells with improved charge collection efficiency. Advanced materials, 2008. **20**(1): p. 54-58.

38. Moraes, R., E. Saito, D. Leite, M. Massi, and A. da Silva Sobrinho, Optical, electrical and electrochemical evaluation of sputtered platinum counter electrodes for dye sensitized solar cells. Applied Surface Science, 2016. **364**: p. 229-234.

39. Theerthagiri, J., A.R. Senthil, J. Madhavan, and T. Maiyalagan, Recent progress in non-platinum counter electrode materials for dye-sensitized solar cells. ChemElectroChem, 2015. **2**(7): p. 928-945.

40. Olsen, E., G. Hagen, and S.E. Lindquist, Dissolution of platinum in methoxy propionitrile containing LiI/I2. Solar Energy Materials and Solar Cells, 2000. **63**(3): p. 267-273.

41. Syrrokostas, G., A. Siokou, G. Leftheriotis, and P. Yianoulis, Degradation mechanisms of Pt counter electrodes for dye sensitized solar cells. Solar Energy Materials and Solar Cells, 2012. **103**: p. 119-127.

42. Jiang, Q., G. Li, and X. Gao, Highly ordered TiN nanotube arrays as counter electrodes for dye-sensitized solar cells. Chemical communications, 2009(44): p. 6720-6722.

43. Xu, S., Y. Luo, and W. Zhong, Investigation of catalytic activity of glassy carbon with controlled crystallinity for counter electrode in dye-sensitized solar cells. Solar energy, 2011. **85**(11): p. 2826-2832.

44. Jeon, S.S., C. Kim, J. Ko, and S.S. Im, Spherical polypyrrole nanoparticles as a highly efficient counter electrode for dye-sensitized solar cells. Journal of Materials Chemistry, 2011. **21**(22): p. 8146-8151.

45. Lin, J.-Y. and S.-W. Chou, Highly transparent NiCo2S4 thin film as an effective catalyst toward triiodide reduction in dye-sensitized solar cells. Electrochemistry communications, 2013. **37**: p. 11-14.

46. Zhou, H., Y. Shi, Q. Dong, Y. Wang, C. Zhu, L. Wang, et al., Interlaced W 18 O 49 nanofibers as a superior catalyst for the counter electrode of highly efficient dye-sensitized solar cells. Journal of Materials Chemistry A, 2014. **2**(12): p. 4347-4354.

47. Koide, N., A. Islam, Y. Chiba, and L. Han, Improvement of efficiency of dye-sensitized solar cells based on analysis of equivalent circuit. Journal of Photochemistry and Photobiology A: chemistry, 2006. **182**(3): p. 296-305.

48. Yin, X., Z. Xue, and B. Liu, Electrophoretic deposition of Pt nanoparticles on plastic substrates as counter electrode for flexible dye-sensitized solar cells. Journal of Power Sources, 2011. **196**(4): p. 2422-2426.

49. Chen, C.-M., C.-H. Chen, and T.-C. Wei, Chemical deposition of platinum on metallic sheets as counterelectrodes for dye-sensitized solar cells. Electrochimica Acta, 2010. **55**(5): p. 1687-1695.

50. Park, S., H. Boo, and T.D. Chung, Electrochemical non-enzymatic glucose sensors. Analytica chimica acta, 2006. **556**(1): p. 46-57.

51. Li, G.r., F. Wang, Q.w. Jiang, X.p. Gao, and P.w. Shen, Carbon nanotubes with titanium nitride as a low-cost counter-electrode material for dye-sensitized solar cells. Angewandte Chemie International Edition, 2010. **49**(21): p. 3653-3656.

52. Gregg, B.A., Interfacial processes in the dye-sensitized solar cell. Coordination Chemistry Reviews, 2004. **248**(13-14): p. 1215-1224.

53. Su’ait, M.S., M.Y.A. Rahman, and A. Ahmad, Review on polymer electrolyte in dye-sensitized solar cells (DSSCs). Solar Energy, 2015. **115**: p. 452-470.

54. Najm, A.S., S.A. Alwash, N.H. Sulaiman, M. Chowdhury, and K. Techato, N719 dye as a sensitizer for dye-sensitized solar cells (DSSCs): A review of its functions and certain rudimentary principles. Environmental Progress & Sustainable Energy, 2023. **42**(1): p. e13955.

55. Iftikhar, H., G.G. Sonai, S.G. Hashmi, A.F. Nogueira, and P.D. Lund, Progress on electrolytes development in dye-sensitized solar cells. Materials, 2019. **12**(12): p. 1998.

56. Kumar, R., S.S. Nemala, S. Mallick, and P. Bhargava, High efficiency dye sensitized solar cell made by carbon derived from sucrose. Optical Materials, 2017. **64**: p. 401-405.

57. Freitag, M., J. Teuscher, Y. Saygili, X. Zhang, F. Giordano, P. Liska, et al., Dye-sensitized solar cells for efficient power generation under ambient lighting. Nature Photonics, 2017. **11**(6): p. 372-378.

58. Chiba, Y., A. Islam, Y. Watanabe, R. Komiya, N. Koide, and L. Han, Dye-sensitized solar cells with conversion efficiency of 11.1%. Japanese journal of applied physics, 2006. **45**(7L): p. L638.

59. Jena, A., S.P. Mohanty, P. Kumar, J. Naduvath, V. Gondane, P. Lekha, et al., Dye sensitized solar cells: a review. Transactions of the Indian Ceramic Society, 2012. **71**(1): p. 1-16.

60. Zanni, M.T., B.J. Greenblatt, A.V. Davis, and D.M. Neumark, Photodissociation of gas phase I 3− using femtosecond photoelectron spectroscopy. The Journal of chemical physics, 1999. **111**(7): p. 2991-3003.

61. Figgemeier, E. and A. Hagfeldt, Are dye-sensitized nano-structured solar cells stable? An overview of device testing and component analyses. International journal of photoenergy, 2004. **6**: p. 127-140.

62. Boschloo, G., L. Häggman, and A. Hagfeldt, Quantification of the effect of 4-tert-butylpyridine addition to I-/I3-redox electrolytes in dye-sensitized nanostructured TiO2 solar cells. The Journal of Physical Chemistry B, 2006. **110**(26): p. 13144-13150.

63. Kopidakis, N., N.R. Neale, and A.J. Frank, Effect of an adsorbent on recombination and band-edge movement in dye-sensitized TiO2 solar cells: evidence for surface passivation. The journal of physical chemistry B, 2006. **110**(25): p. 12485-12489.

64. Jiao, S., Z. Sun, J. Wen, Y. Liu, F. Li, Q. Miao, et al., Development of rapid curing SiO2 aerogel composite-based quasi-solid-state dye-sensitized solar cells through screen-printing technology. ACS Applied Materials & Interfaces, 2020. **12**(43): p. 48794-48803.

65. Fang, Y., W. Xiang, X. Zhou, Y. Lin, and S. Fang, High-performance novel acidic ionic liquid polymer/ionic liquid composite polymer electrolyte for dye-sensitized solar cells. Electrochemistry communications, 2011. **13**(1): p. 60-63.

66. Nazeeruddin, M.K., P. Pechy, and M. Grätzel, Efficient panchromatic sensitization of nanocrystalline TiO 2 films by a black dye based on a trithiocyanato–ruthenium complex. Chemical Communications, 1997(18): p. 1705-1706.

67. Park, N.-G., J. Van de Lagemaat, Frank, and AJ, Comparison of dye-sensitized rutile-and anatase-based TiO2 solar cells. The Journal of Physical Chemistry B, 2000. **104**(38): p. 8989-8994.

68. Li, B., L. Wang, B. Kang, P. Wang, and Y. Qiu, Review of recent progress in solid-state dye-sensitized solar cells. Solar energy materials and solar cells, 2006. **90**(5): p. 549-573.

69. Wang, X.-F., A. Matsuda, Y. Koyama, H. Nagae, S.-i. Sasaki, H. Tamiaki, et al., Effects of plant carotenoid spacers on the performance of a dye-sensitized solar cell using a chlorophyll derivative: enhancement of photocurrent determined by one electron-oxidation potential of each carotenoid. Chemical physics letters, 2006. **423**(4-6): p. 470-475.

70. Adedokun, O., K. Titilope, and A.O. Awodugba, Review on natural dye-sensitized solar cells (DSSCs). International Journal of Engineering Technologies IJET, 2016. **2**(2): p. 34-41.

71. Mehmood, U., S.-u. Rahman, K. Harrabi, I.A. Hussein, and B. Reddy, Recent advances in dye sensitized solar cells. Advances in Materials Science and Engineering, 2014. **2014**.

72. Wu, J., Z. Lan, S. Hao, P. Li, J. Lin, M. Huang, et al., Progress on the electrolytes for dye-sensitized solar cells. Pure and Applied Chemistry, 2008. **80**(11): p. 2241-2258.

73. Hara, K., Z.-G. Zhao, Y. Cui, M. Miyauchi, M. Miyashita, and S. Mori, Nanocrystalline electrodes based on nanoporous-walled WO3 nanotubes for organic-dye-sensitized solar cells. Langmuir, 2011. **27**(20): p. 12730-12736.

74. Gholamrezaei, S., M. Salavati Niasari, M. Dadkhah, and B. Sarkhosh, New modified sol–gel method for preparation SrTiO 3 nanostructures and their application in dye-sensitized solar cells. Journal of Materials Science: Materials in Electronics, 2016. **27**: p. 118-125.

75. Redmond, G., D. Fitzmaurice, and M. Graetzel, Visible light sensitization by cis-bis (thiocyanato) bis (2, 2'-bipyridyl-4, 4'-dicarboxylato) ruthenium (II) of a transparent nanocrystalline ZnO film prepared by sol-gel techniques. Chemistry of Materials, 1994. **6**(5): p. 686-691.

76. Tan, B., E. Toman, Y. Li, and Y. Wu, Zinc stannate (Zn2SnO4) dye-sensitized solar cells. Journal of the American Chemical Society, 2007. **129**(14): p. 4162-4163.

77. Ou, J.Z., R.A. Rani, M.-H. Ham, M.R. Field, Y. Zhang, H. Zheng, et al., Elevated temperature anodized Nb2O5: a photoanode material with exceptionally large photoconversion efficiencies. ACS nano, 2012. **6**(5): p. 4045-4053.

78. Kumavat, P.P., P. Sonar, and D.S. Dalal, An overview on basics of organic and dye sensitized solar cells, their mechanism and recent improvements. Renewable and Sustainable Energy Reviews, 2017. **78**: p. 1262-1287.

79. Ahmad, M.S., A. Pandey, and N. Abd Rahim, Towards the plasmonic effect of Zn nanoparticles on TiO2 monolayer photoanode for dye sensitized solar cell applications. Materials Letters, 2017. **195**: p. 62-65.

80. Raj, C.C. and R. Prasanth, A critical review of recent developments in nanomaterials for photoelectrodes in dye sensitized solar cells. Journal of Power Sources, 2016. **317**: p. 120-132.

81. Sengupta, D., P. Das, B. Mondal, and K. Mukherjee, Effects of doping, morphology and film-thickness of photo-anode materials for dye sensitized solar cell application–A review. Renewable and Sustainable Energy Reviews, 2016. **60**: p. 356-376.

82. Barbé, C.J., F. Arendse, P. Comte, M. Jirousek, F. Lenzmann, V. Shklover, et al., Nanocrystalline titanium oxide electrodes for photovoltaic applications. Journal of the American Ceramic Society, 1997. **80**(12): p. 3157-3171.

83. Hore, S., E. Palomares, H. Smit, N.J. Bakker, P. Comte, P. Liska, et al., Acid versus base peptization of mesoporous nanocrystalline TiO 2 films: functional studies in dye sensitized solar cells. Journal of Materials Chemistry, 2005. **15**(3): p. 412-418.

84. Mathew, S., A. Yella, P. Gao, R. Humphry-Baker, B.F. Curchod, N. Ashari-Astani, et al., Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers. Nature chemistry, 2014. **6**(3): p. 242-247.

85. Ko, K.H., Y.C. Lee, and Y.J. Jung, Enhanced efficiency of dye-sensitized TiO2 solar cells (DSSC) by doping of metal ions. Journal of colloid and interface science, 2005. **283**(2): p. 482-487.

86. Zhang, J., Z. Zhao, X. Wang, T. Yu, J. Guan, Z. Yu, et al., Increasing the oxygen vacancy density on the TiO2 surface by La-doping for dye-sensitized solar cells. The Journal of Physical Chemistry C, 2010. **114**(43): p. 18396-18400.

87. Lü, X., X. Mou, J. Wu, D. Zhang, L. Zhang, F. Huang, et al., Improved-performance dye-sensitized solar cells using Nb-doped TiO2 electrodes: efficient electron injection and transfer. Advanced Functional Materials, 2010. **20**(3): p. 509-515.

88. Zhang, X., F. Liu, Q.-L. Huang, G. Zhou, and Z.-S. Wang, Dye-sensitized W-doped TiO2 solar cells with a tunable conduction band and suppressed charge recombination. The Journal of Physical Chemistry C, 2011. **115**(25): p. 12665-12671.

89. Wang, Y., Y. Hao, H. Cheng, J. Ma, B. Xu, W. Li, et al., The photoelectrochemistry of transition metal-ion-doped TiO2 nanocrystalline electrodes and higher solar cell conversion efficiency based on Zn2+-doped TiO2 electrode. Journal of Materials Science, 1999. **34**: p. 2773-2779.

90. Chu, D., X. Yuan, G. Qin, M. Xu, P. Zheng, J. Lu, et al., Efficient carbon-doped nanostructured TiO 2 (anatase) film for photoelectrochemical solar cells. Journal of Nanoparticle Research, 2008. **10**: p. 357-363.

91. Song, J., H.B. Yang, X. Wang, S.Y. Khoo, C. Wong, X.-W. Liu, et al., Improved utilization of photogenerated charge using fluorine-doped TiO2 hollow spheres scattering layer in dye-sensitized solar cells. ACS applied materials & interfaces, 2012. **4**(7): p. 3712-3717.

92. Kang, S.H., H.S. Kim, J.-Y. Kim, and Y.-E. Sung, Enhanced photocurrent of nitrogen-doped TiO2 film for dye-sensitized solar cells. Materials Chemistry and Physics, 2010. **124**(1): p. 422-426.

93. Sun, Q., J. Zhang, P. Wang, J. Zheng, X. Zhang, Y. Cui, et al., Sulfur-doped TiO2 nanocrystalline photoanodes for dye-sensitized solar cells. Journal of Renewable and Sustainable Energy, 2012. **4**(2).

94. Sobti, R.C., N.K. Arora, and R. Kothari, Environmental biotechnology: for sustainable future. 2018: Springer.

95. Yahya, M., A. Bouziani, C. Ocak, Z. Seferoğlu, and M. Sillanpää, Organic/metal-organic photosensitizers for dye-sensitized solar cells (DSSC): Recent developments, new trends, and future perceptions. Dyes and Pigments, 2021. **192**: p. 109227.

96. Minami, T., Present status of transparent conducting oxide thin-film development for Indium-Tin-Oxide (ITO) substitutes. Thin Solid Films, 2008. **516**(17): p. 5822-5828.

97. Ludin, N.A., A.A.-A. Mahmoud, A.B. Mohamad, A.A.H. Kadhum, K. Sopian, and N.S.A. Karim, Review on the development of natural dye photosensitizer for dye-sensitized solar cells. Renewable and Sustainable Energy Reviews, 2014. **31**: p. 386-396.

98. Krawczak, E., Dye photosensitizers and their influence on dssc efficiency: A review. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, 2019. **9**(3): p. 86-90.

99. Basheer, B., D. Mathew, B.K. George, and C.R. Nair, An overview on the spectrum of sensitizers: the heart of dye sensitized solar cells. Solar Energy, 2014. **108**: p. 479-507.

100. Nazeeruddin, M.K., A. Kay, I. Rodicio, R. Humphry-Baker, E. Müller, P. Liska, et al., Conversion of light to electricity by cis-X2bis (2, 2'-bipyridyl-4, 4'-dicarboxylate) ruthenium (II) charge-transfer sensitizers (X= Cl-, Br-, I-, CN-, and SCN-) on nanocrystalline titanium dioxide electrodes. Journal of the American Chemical Society, 1993. **115**(14): p. 6382-6390.

101. Rillema, D.P. and K.B. Mack, The low-lying excited state in ligand. pi.-donor complexes of ruthenium (II): mononuclear and binuclear species. Inorganic Chemistry, 1982. **21**(10): p. 3849-3854.

102. Alhamed, M., A.S. Issa, and A.W. Doubal, Studying of natural dyes properties as photo-sensitizer for dye sensitized solar cells (DSSC). Journal of electron Devices, 2012. **16**(11): p. 1370-1383.

103. Sinha, K., P.D. Saha, and S. Datta, Extraction of natural dye from petals of Flame of forest (Butea monosperma) flower: Process optimization using response surface methodology (RSM). Dyes and Pigments, 2012. **94**(2): p. 212-216.

104. Hao, S., J. Wu, Y. Huang, and J. Lin, Natural dyes as photosensitizers for dye-sensitized solar cell. Solar energy, 2006. **80**(2): p. 209-214.

105. Gómez-Ortíz, N., I. Vázquez-Maldonado, A. Pérez-Espadas, G. Mena-Rejón, J. Azamar-Barrios, and G. Oskam, Dye-sensitized solar cells with natural dyes extracted from achiote seeds. Solar Energy Materials and Solar Cells, 2010. **94**(1): p. 40-44.

106. Nazeeruddin, M.K., F. De Angelis, S. Fantacci, A. Selloni, G. Viscardi, P. Liska, et al., Combined experimental and DFT-TDDFT computational study of photoelectrochemical cell ruthenium sensitizers. Journal of the American Chemical Society, 2005. **127**(48): p. 16835-16847.

107. Narayan, M. and A. Raturi, Investigation of some common Fijian flower dyes as photosensi-tizers for dye sensitized solar cellsabstract. Applied Solar Energy, 2011. **47**: p. 112-117.

108. Wang, X.-F., C.-H. Zhan, T. Maoka, Y. Wada, and Y. Koyama, Fabrication of dye-sensitized solar cells using chlorophylls c1 and c2 and their oxidized forms c1′ and c2′ from Undaria pinnatifida (Wakame). Chemical physics letters, 2007. **447**(1-3): p. 79-85.

109. Siregar, N., Motlan, J.H. Panggabean, M. Sirait, J. Rajagukguk, N.S. Gultom, et al., Fabrication of dye-sensitized solar cells (DSSC) using Mg-doped ZnO as photoanode and extract of rose myrtle (Rhodomyrtus tomentosa) as natural dye. International Journal of Photoenergy, 2021. **2021**: p. 1-7.

110. Leite, A.C., A.M. Ferreira, E.S. Morais, I. Khan, M.G. Freire, and J.A. Coutinho, Cloud point extraction of chlorophylls from spinach leaves using aqueous solutions of nonionic surfactants. ACS sustainable chemistry & engineering, 2018. **6**(1): p. 590-599.

111. Scheer, H., Chlorophylls and carotenoids. 2013.

112. Taniguchi, M. and J.S. Lindsey, Synthetic chlorins, possible surrogates for chlorophylls, prepared by derivatization of porphyrins. Chemical reviews, 2017. **117**(2): p. 344-535.

113. Mejica, G.F.C., Y. Unpaprom, and R. Ramaraj, Fabrication and performance evaluation of dye-sensitized solar cell integrated with natural dye from Strobilanthes cusia under different counter-electrode materials. Applied Nanoscience, 2023. **13**(2): p. 1073-1083.

114. Jaafar, H., L. Magesvaran, N. Ameram, and A. Ali, Studies on the Optical and Photoelectric Properties of Anthocyanin and Chlorophyll as Dihybrid Sensitizer in Dye Sensitized Solar Cell (DSSC). Orbital, 2023.

115. Hassan, H., Z. Abidin, M. Careem, and A. Arof, Chlorophyll as sensitizer in I−/I3−-based solar cells with quasi-solid-state electrolytes. High Performance Polymers, 2014. **26**(6): p. 647-652.

116. Taya, S.A., T.M. El-Agez, K.S. Elrefi, and M.S. Abdel-Latif, Dye-sensitized solar cells based on dyes extracted from dried plant leaves. Turkish Journal of Physics, 2015. **39**(1): p. 24-30.

117. Al-Alwani, M.A., A.B. Mohamad, H.K. Abd Amir, N.A. Ludin, N. Safie, M. Razali, et al., Natural dye extracted from Pandannus amaryllifolius leaves as sensitizer in fabrication of dye-sensitized solar cells. International Journal of Electrochemical Science, 2017. **12**(1): p. 747-761.

118. Swarnkar, A., S. Sahare, N. Chander, R.K. Gangwar, S. Bhoraskar, and T.M. Bhave, Nanocrystalline titanium dioxide sensitised with natural dyes for eco-friendly solar cell application. Journal of Experimental Nanoscience, 2015. **10**(13): p. 1001-1011.

119. Abdel-Latif, M.S., M.B. Abuiriban, T.M. El-Agez, and S.A. Taya, Dye-sensitized solar cells using dyes extracted from flowers, leaves, parks, and roots of three trees. International Journal of Renewable Energy Research, 2015. **5**(1): p. 294-298.

120. Lai, W.H., Y.H. Su, L.G. Teoh, and M.H. Hon, Commercial and natural dyes as photosensitizers for a water-based dye-sensitized solar cell loaded with gold nanoparticles. Journal of Photochemistry and Photobiology A: Chemistry, 2008. **195**(2-3): p. 307-313.

121. Mohammadpour, R., S. Janfaza, and F. Abbaspour-Aghdam, Light harvesting and photocurrent generation by nanostructured photoelectrodes sensitized with a photosynthetic pigment: A new application for microalgae. Bioresource technology, 2014. **163**: p. 1-5.

122. Panche, A.N., A.D. Diwan, and S.R. Chandra, Flavonoids: an overview. Journal of nutritional science, 2016. **5**: p. e47.

123. Narayan, M.R., Dye sensitized solar cells based on natural photosensitizers. Renewable and sustainable energy reviews, 2012. **16**(1): p. 208-215.

124. Delgado-Vargas, F., A. Jiménez, and O. Paredes-López, Natural pigments: carotenoids, anthocyanins, and betalains—characteristics, biosynthesis, processing, and stability. Critical reviews in food science and nutrition, 2000. **40**(3): p. 173-289.

125. Counsell, J., G. Jeffries, and C. Knewstubb, Some other natural colors and their applications. Natural Colors for Foods and Other Uses. Appl. Sci., London, 1979: p. 122-151.

126. Bate-Smith, E. and T. Swain, Comparative biochemistry. Eds. Mason, HS, Florkin, M, 1962. **3**: p. 764.

127. Singh, P.K. and V.K. Shukla, Widening spectral range of absorption using natural dyes: Applications in dye sensitized solar cell. Materials Today: Proceedings, 2022. **49**: p. 3235-3238.

128. Yazie, A.N., A.D. Worku, and Y.A. Tsigie, Recent advances in anthocyanin dyes extracted from plants for dye sensitized solar cell. Materials for Renewable and Sustainable Energy, 2020. **9**(4).

129. Prior, R.L. and X. Wu, Anthocyanins: structural characteristics that result in unique metabolic patterns and biological activities. Free radical research, 2006. **40**(10): p. 1014-1028.

130. Amogne, N.Y., D.W. Ayele, and Y.A. Tsigie, Recent advances in anthocyanin dyes extracted from plants for dye sensitized solar cell. Materials for Renewable and Sustainable Energy, 2020. **9**: p. 1-16.

131. Al Batty, S., S.M. Al-Jubouri, M. Wali Hakami, A. Sarief, and S.M. Haque, Innovative economic anthocyanin dye source for enhancing the performance of dye-sensitized solar cell. Journal of Taibah University for Science, 2022. **16**(1): p. 415-422.

132. Prakash, P., B. Janarthanan, M. Ubaidullah, A.M. Al-Enizi, S.F. Shaikh, N.B. Alanazi, et al., Optimization, fabrication, and characterization of anthocyanin and carotenoid derivatives based dye-sensitized solar cells. Journal of King Saud University-Science, 2023. **35**(4): p. 102625.

133. Ali, R.A.M. and N. Nayan, Fabrication and analysis of dye-sensitized solar cell using natural dye extracted from dragon fruit. International Journal of Integrated Engineering, 2010. **2**(3).

134. Ghann, W., H. Kang, T. Sheikh, S. Yadav, T. Chavez-Gil, F. Nesbitt, et al., Fabrication, optimization and characterization of natural dye sensitized solar cell. Scientific reports, 2017. **7**(1): p. 41470.

135. Taya, S.A., T.M. El-Agez, H.S. El-Ghamri, and M.S. Abdel-Latif, Dye-sensitized solar cells using fresh and dried natural dyes. International Journal of Materials Science and Applications, 2013. **2**(2): p. 37-42.

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

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

138. Hemamali, G. and G. Kumara, Dye-sensitized solid state solar cells sensitized with natural pigment extracted from the grapes. International Journal of Scientific and Research Publications, 2013. **3**(11): p. 2250-3153.

139. Ahmadian, R., Estimating the impact of dye concentration on the photoelectrochemical performance of anthocyanin-sensitized solar cells: a power law model. Journal of photonics for energy, 2011. **1**(1): p. 011123-011123-11.

140. Davies, K., Plant pigments and their manipulation. 2004: Blackwell publishing.

141. Shalini, S., R. Balasundaraprabhu, T.S. Kumar, N. Prabavathy, S. Senthilarasu, and S. Prasanna, Status and outlook of sensitizers/dyes used in dye sensitized solar cells (DSSC): a review. International Journal of Energy Research, 2016. **40**: p. 1303 - 1320.

142. Zhang, W., X. Hu, L. Wang, and X. Wang, Reconstruction of the carotenoid biosynthetic pathway of Cronobacter sakazakii BAA894 in Escherichia coli. PLoS One, 2014. **9**(1): p. e86739.

143. Al-Bat'hi, S.A., I. Alaei, and I. Sopyan, Natural photosensitizers for dye sensitized solar cells. International Journal of Renewable Energy Research, 2013. **3**(1): p. 138-143.

144. Park, K.H., T.Y. Kim, J.Y. Park, E.M. Jin, S.-H. Yim, J.G. Fisher, et al., Photochemical properties of dye-sensitized solar cell using mixed natural dyes extracted from Gardenia Jasminoide Ellis. Journal of Electroanalytical Chemistry, 2013. **689**: p. 21-25.

145. Supriyanto, A., F. Nurosyid, and A. Ahliha. Carotenoid pigment as sensitizers for applications of dye-sensitized solar cell (DSSC). in IOP Conference Series: Materials Science and Engineering. 2018. IOP Publishing.

146. Halidun, W.O.N.S., E.C. Prima, and B. Yuliarto. Fabrication Dye Sensitized Solar Cells (DSSCs) Using β-Carotene Pigment Based Natural Dye. in MATEC Web of Conferences. 2018. EDP Sciences.

147. El-Agez, T.M., A.A. El Tayyan, A. Al-Kahlout, S.A. Taya, and M.S. Abdel-Latif, Dye-sensitized solar cells based on ZnO films and natural dyes. International Journal of Materials and Chemistry, 2012. **2**(3): p. 105-110.