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Review on the Use of Dyestuff for Enhancement of Dye-Sensitized Solar Cell Efficiency

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ABSTRACT: Dye-sensitized solar cells (DSSCs) have high energy conversion efficiency and environmental friendliness. Consequently, the aim of this paper is to review the use of dyestuff for the enhancement of dye sensitive solar cell efficiency. For this reason, this paper gives a background of dye stuff, types and limitations and investigates the important criteria which are considered for selecting dye to enhance DSSC efficiency.

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At present, the main method of utilization of solar energy is the conversion of solar energy into other energy sources. In 1954 the silicon solar cell developed by Bell marks that human can cause solar energy to be converted into electrical energy for use (Chapain *et al.*, 2014). However, it is not suitable for large-scale usage, since this type of cell has stringent requirements for raw materials and production process. Although the subsequent development of polysilicon and amorphous silicon solar cells was relatively simple in production process, its high prices limited its use on a large scale. In most cases, solar cells are manufactured on a silicon material. Its proportion represents 40% of world-wide semiconductor solar cells production. Pure silicon material is founded directly in solid silica by electrolysis. The production of silicon by processing silica (SiO₂) needs very high energy and more efficient methods of synthesis. Also, the most prevalent silicon solar cell material is crystalline silicon (c-Si) or amorphous silicon (a-Si). Crystalline silicon can be separated into multiple categories according to its crystallinity and its crystal size. These include: monocrystalline silicon, poly or multicrystalline silicon, Ribbon silicon and new structures. In 1991, Gratzel reported a new low-cost chemical solar cell by

the successful combination of nanostructured electrodes and efficient charge injection dyes, known as Gratzel cells or dye-sensitized solar cells which gave a photoelectric conversion efficiency of 7% under simulated sunlight irradiation (O'Regan and Gratzel, 1991). It was designed to imitate photosynthesis, the natural process through which plants convert sunlight into energy by sensitizing a nanocrystalline TiO₂ film using novel ruthenium (Ru) bipyridyl complex. In dye sensitized solar cell, charge separation is accomplished by kinetics competition like in photosynthesis leading to photovoltaic action. The organic dye monolayer in the photoelectrochemical or dye sensitized solar cell replaces light absorbing pigments (chlorophylls). The wide bandgap nanostructured semiconductor layer replaces oxidized dihydro-nicotinamideadenine-dinucleotide phosphate (NADPH), and carbon dioxide acts as the electron acceptor. Moreover, the electrolyte replaces the water while oxygen as the electron donor and oxidation product, respectively (Lagref *et al.*, 2008). It has been shown that DSSCs are promising classes of low cost and moderate efficiency solar cells based on organic materials (Haruna *et al.*, 2015). In addition, Hagfeldt *et al.*, (2010) recorded that the DSSC promises extremely cheap photovoltaic energy

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production by combining the advantages of none vacuum processing, extremely low costs components, low embodied energy of production and superior performance compared to silicon solar cells under diffuse light conditions. Never the less, the technology still suffers from a number of technical challenges that has hindered large-scale deployment, notably, difficulty in scale-up and stability. Advances in the synthesis of materials and experimental tools have led to an improvement of more than 12% (Yella *et al.*, 2011). Because of the simple production process, much lower cost relative to silicon cells, this type of cells provides a feasible approach for large-scale utilization of solar energy (Yen, *et al.*, 2011). Natural dyes have become a viable alternative to expensive and rare organic sensitizers because of their low cost, easy attainability and abundance in supply in the environment (Adedokun, *et al.*, 2016). Various components of a plant such as the flower petals, leaves and bark have been tested as sensitizers. The nature of these pigments together with other parameters has resulted in varying performances. In order to be familiar with dye-stuff in the DSSC a concise overview will be summarized about different type of dye-stuff, its role in DSSC, relations with colours and lights, classification according to application and structure. Therefore, the objective of this paper is to provide a brief review of the use of dyestuff for the enhancement of dye sensitive solar cell efficiency.

Classification of dyes: There are several ways for classifying dyes. It should be noted that each class of dye has a very unique chemical structure and particular way of bonding. While some dyes can react chemically with the substrates forming strong bonds in the process, others can be held by physical forces. One of the prominent ways of several classifications which is more effective to our application is chemical classification, based on the nature of chemical structure.

Different types of dyes

- Natural Dye: These are simply dye substances extracted from natural sources
- Synthetic Dye: Dyes derived from organic or inorganic compounds are known as synthetic dyes. Examples are direct, acid, basic e.t.c.
- Azonic dye: Azo dyes contain at least one azo group (-N=N-) attached to one or often two aromatic rings. Others are:
 - Nitro Dye
 - Disperse Dye
 - Vat Dye
 - Mordant Dye
 - Solvent Dye
 - Sulfur Dye

The setup of a dye-sensitized solar cell is shown in fig 1.

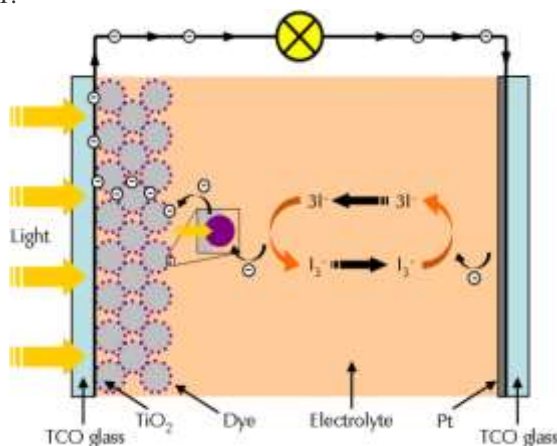


Fig 1. Simplified Setup of a Dye-sensitized Solar Cell

The anode of a DSSC consists of a glass plate which is coated with a transparent conductive oxide (TCO) film. Indium tin oxide (ITO) or fluorine doped tin oxide are most widely used. A thin layer of titanium dioxide (TiO₂) is applied on the film. The semiconductor exhibits a high surface area because of its high porosity. The anode is soaked with a dye solution which bonds to the TiO₂. The dye – also called photosensitizers – is mostly a ruthenium complex or various organic metal free compounds. For demonstration purposes, also plain fruit juice (such as from blackberries or pomegranates) can be used. They contain pigments which are also able to convert light energy into electrical energy. The cathode of a DSSC is a glass plate with a thin Pt film which serves as a catalyst. An iodide/triiodide solution is used as the electrolyte. Both electrodes are pressed together and sealed so that the cell does not leak. An external load can be powered when light shines on the anode of the dye solar cell.

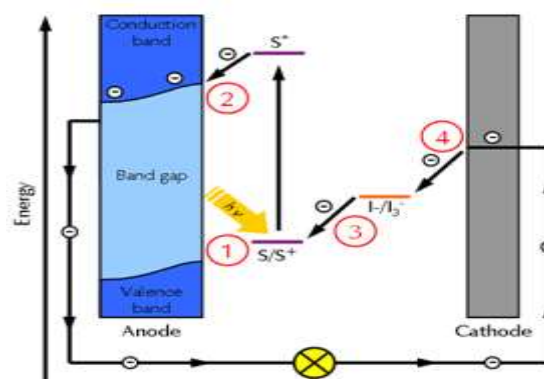


Fig 2. Energy diagram of a Dye-sensitized solar cell

Principle of a dye-sensitized solar cell: As the name implies, the mechanism of dye solar cells is based on the photo electrochemical processes as depicted in the

energy diagram in Figure 2.

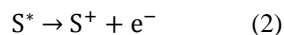
Step 1: The dye molecule is initially in its ground state (S). The semiconductor material of the anode is at this energy level (near the valence band) non-conductive.

When light shines on the cell, dye molecules get excited from their ground state to a higher energy state (S*), see equation 1.



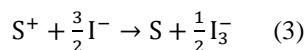
The excited dye molecule has now a higher energy content and overcomes the band gap of the semiconductor.

Step 2: The excited dye molecule (S*) is oxidized (see equation 2) and an electron is injected into the conduction band of the semiconductor. Electrons can now move freely as the semiconductor is conductive at this energy level.

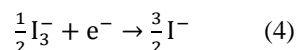


Electrons are then transported to the current collector of the anode via diffusion processes (Smestad and Gratzel, 1998). An electrical load can be powered if connected.

Step 3: The oxidized dye molecule (S⁺) is again regenerated by electron donation from the iodide in the electrolyte (Hagfeldt and Gratzel, 1995) (equation 3).



Step 4: In return, iodide is regenerated by reduction of triiodide on the cathode (equation 4).



Similarities between DSSCs and photosynthesis

Both DSSCs and plants both harvest energy from sunlight. Photovoltaic solar cells collect sunlight and change it to electricity. Plant leaves gather sunlight and convert it into stored chemical energy. Both DSSCs and plants are utilizing dye to convert light energy into another sort of energy, but they do it in different ways.

Photosynthesis, the effectiveness of the light conversion in plant's leaves in which chlorophyll acts as the dye corresponds to the sensitizer dye in DSSCs

shown in Figure 3.

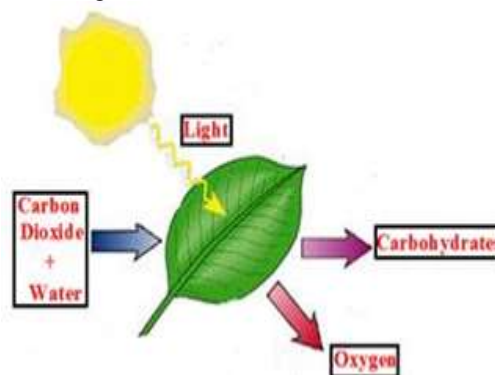


Fig. 3 Conversion of light energy into potential energy in the leaves

Light energy transfers (in plant) into chemical reaction forming formaldehyde (from $CO_2 + H_2O + h\nu = HCHO + O_2$) which polymerized to glucose ($6HCHO = C_6H_{12}O_6$) then starch ($C_6H_{10}O_5$) in or cellulose polymers, while light energy converted to electric current in DSSC. So, the DSSC is designed based on photosynthesis phenomena.

Dye as photo sensitizer: In spite of several elements combining the DSSC (2 electrodes, dye, electrolyte, sealing). The dye which acts as sensitizers in DSSCs plays an essential task in absorption and conversion of incident light ray into electricity (Hara and Arakawa, 2003). Dye is considered as a promising element for getting more performance to DSSC.

Why dyes are coloured: Dyes possess color because they:

- Absorb light in the visible spectrum (400–700 nm),
- Have at least one chromophore (colour-bearing chemical group),
- Have a conjugated system, i.e. a structure with alternating double and single bonds, and
- Exhibit resonance of electrons, which is a stabilizing force in organic compounds.

When any one of these features is lacking from the molecular structure the colour is lost. In addition to chromophores, most dyes also contain groups known as auxochromes (colour developers), examples of which are carboxylic acid, sulfonic acid, amino, nitro, and hydroxyl groups.

While these are not responsible for colour, their presence can shift the colour of a colourant and they are most often used to influence dye solubility. Table 1 shows the relationships between wavelength of visible (observed) color and absorbed colour (complementary colours).

Table 1. Wavelength of light absorption versus color in organic dyes

Wavelength Absorbed (nm)	Colour Observed	Colour Absorbed
400-435	Yellow- Green	Violet
435-480	Yellow	Blue
480-490	Orange	Green-Blue
490-500	Red	Blue-Green
500-560	Purple	Green
560-580	Violet	Yellow- Green
580-595	Blue	Yellow
595-605	Green-Blue	Orange
605-700	Blue-Green	Red

Source: Edoardo (2000)

The important factors to be considered when designing a dye. When designing a dye for DSSC application, there are many important factors that need to be taken into consideration, such as:

i. A high extinction coefficient will enable the use of thinner semiconductor films and keep a high degree of absorbed photons as shown in Figure 4.

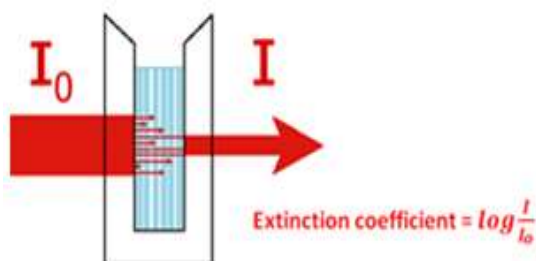


Fig.4. Absorption of photons

ii. It must bind strongly to the semiconductor surface for long term stability.

iii. The energy levels should match the conduction band of the semiconductor and the redox potential of the hole-conductor, as shown in Figure 5.

iv. Easy and straightforward synthesis for future large scale production.

v. Low toxicity and possibility to recycle.

vi. High photo-stability to sustain at least 20 years of use.

If the energy exceeds the band gap of the semiconductor, the photon can be absorbed and an electron will be excited from the valence band to the conduction band. Electrons in the conduction band can move, which allows for electric current, as shown in Figure 6. The difference between the photon energy and the band gap will end up as heat.

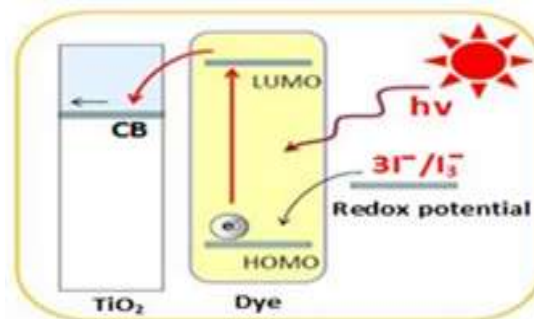


Fig.5. Excitation of electrons

A common way of designing organic dyes is the D- π -A strategy where the molecule is built up of an electron donor, a conjugated linker, and an electron acceptor, as illustrated in Figure 6. This structure will yield an intramolecular charge separation upon excitation which is desired for DSSCs.

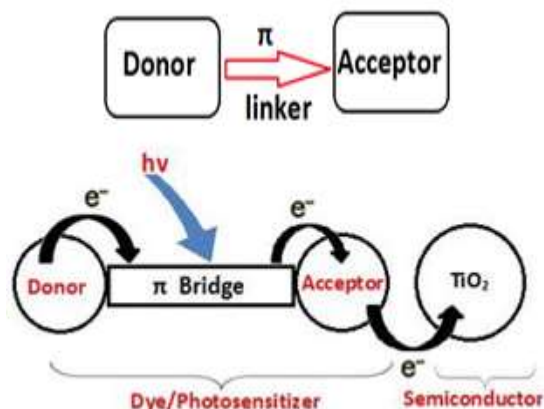


Fig.6. Transportation of charge carriers

Conclusion: This review article presented the role of dye in DSSC in order to formulate basic guidelines and strategies for improving of dye-sensitized solar cells. Also, this paper reviewed the important criteria which are considered for selecting dye to enhance DSSC efficiency, and it has been shown that there are a great number of factors that need to be kept in mind such as temperature, PH and storage time. Energy harvested from solar source by DSSC using photovoltaic solar cells and changed into electricity can ameliorate cases of power outages in developing economies.

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