Dye-sensitized solar cell: a promising renewable energy source to sustain global energy requirements

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Abstract: The present and future global energy needs in today's concern demand for the exploration of renewable and sustainable energy sources and the solar energy in this aspect is one of the most promising sources that can be easily exploited, being inexhaustible and abundant in supply. The dye-sensitized solar cell (DSSC) is a way front in this regard that is considered as new generation low cost solar (photovoltaic) cell exploiting the use of various light absorbing dye molecules absorbed on semiconductor nanoparticle to generate electricity from the sunlight. Being simple in structure and material composition, having low manufacturing cost, efficient energy convertor and eco-friendly, these DSSCs are the promising and sustainable solution to the future energy and environmental concerns. However, their exploitation as an efficient energy converter is linked to the various materials *viz.*, the transparent substrate for receiving sunlight, dye or sensitizers, conducting and counter-conducting electrode and an electrolyte which are used in its construction. This critical review thus investigated the various aspects regarding the material used in the construction/synthesis of these DSSCs, their various applications, and the challenges in their commercialization.

Keywords: dye-sensitized solar cell (DSSC), dye, electrode, electrolyte, sensitizer.

Introduction: The increasing energy demand and the depleting non-renewable energy sources are the alarming global issues which are to be addressed to find the alternate energy sources. Hence, to ensure the regular and sustainable supply of energy, we need to explore the renewable energy sources. It has been estimated that solar radiation amounts to 3.8 million EJ/year, which is approximately 10,000 times more than current energy needs [1]. Hence, solar energy offers a promising approach because of its abundance in availability, inexhaustible nature and easily exploitable properties. Moreover, these resources eliminate the environmental issues that were the major problems associated with the combustion of traditional fossil fuels [2]. Over the past decades, the production of solar cells exploiting the solar energy has been increased [3] and the market was mostly dominated by the first and second generation of solar cells based on crystalline silicon and semiconductor thin films, respectively, but they showed lower efficiencies and high production costs [4]. The third generation solar cells include the Dye-Sensitized Solar Cells (DSSCs), which were invented for the first time by Professor Michael Graetzel and Dr. Brian O'Regan [5]. These dye-sensitized nanocrystalline solar cells were low-cost, highly efficient solar cell based on dye-sensitized colloidal TiO_2 films with the conversion yield of 7.1 per cent. DSSC uses dye molecules adsorbed on the nanocrystalline oxide semiconductors such as TiO_2 to collect sunlight. Therefore the light absorption (by dyes) and charge collection processes (by semiconductors) are separated, mimicking the natural light harvest in photosynthesis [6].

Unlike the conventional solar cell systems in which semiconductors function as both photon absorber and charge carrier, DSSC separate these two functions into two different materials [7]. The process of charge generation is done by a sensitizer absorbing in the visible, which injects the charge into the semiconductor and that of charge transport is done by the semiconductor and the electrolyte.

In general, the ease of manufacturing, low production costs, and high photovoltaic conversion efficiency, these DSSCs make an attractive approach for large-scale solar energy conversion compared to other forms of the solar cell and have the wide range of applications both in indoor and outdoor. However, there are many challenges also which hampers its application outside the laboratory front. The main challenges included the improvement in the performance of DSSCs by using different approaches which addresses their higher efficiency, stability, and cost-effectiveness. This critical review was thus generated and summarized focusing the manufacture of these DSSCs exploiting the effective and stable components, applications of these cells and the challenges in their application as under following sub-heads:

Materials used for the construction/synthesis of DSSCs:

A typical DSSC consists of a transparent conductive oxide, semiconductor oxide, dye sensitizer, electrolyte and counter electrode [8]. Also, in an another mention [9] these cells were composed of four elements: Conducting electrode and counter conducting electrode, nanostructured metal oxide (usually TiO) layer, dye molecules, and electrolyte. Thus, to achieve high cell efficiency, the individual components in DSSCs are necessary to be optimized.

Transparent conducting substrate: The first crucial component of a DSSC is the surface which directly receives the solar energy and to allow maximum passage of sunlight to the active area of a DSSC, this surface should be highly transparent so as to receive maximum sunlight [10]. Transparent conducting oxides (TCO) were reported as an efficient light receiving area of various photovoltaic cells. In general, fluorine-doped tin oxide (FTO) has been a common choice of TCO due to its greater thermal reception and lower costs. Transparent double-layered conductive oxide films that consisted of fluorine-doped tin oxide film coated on indium–tin oxide film were developed for dye-sensitized solar cells with 3.7 per cent energy conversion efficiency [11]. Later, ZnO heavily doped with Ga or Al came as an attractive option for the generation of these transparent conductive oxides with enhanced efficiency in many of these solar based cells [12]. Moreover, there are coming new DSSCs that eliminated these expensive TCO and the conventional glass substrates were replaced with flexible plastic substrates and these flexible DSSC fabricated on a plastic substrate recorded an efficiency of 8.10 per cent [13].

Also, the DSSCs which were fabricated using a 10 mm TiO_2mesoporous layer and sensitized with N719 dye when used a flexible glass, demonstrated a power conversion efficiency of 4.53 per cent compared to the 3.09 per cent as obtained from those which were based on a traditional ITO coated thick glass [14].

Dye or sensetizer:

Dye is considered as another important component of these photovoltaic cells. The dye after absorbing the photon creates an electron that allows the electron to be injected into the conduction band of the semiconductor. These dyes or 'sensitizers' actually are responsible for the conversion of sunlight into electricity and as soon as the dye is 'energized' by solar radiation, there is the generation of electricity which then 'flows' from the dye to the metal oxide surface [15]. There are in general two classes of dyes used in various DSSCs that include organometallic and organic dyes [16]. Earlier the transition metal complexes like Ru-based sensitizers have been widely used because of their better efficiency and high durability, however, they involved more production cost and are also susceptible to degradation by water [17]. Hence, the new approaches uses natural plant based organic dyes that not only has enhanced efficiency but at the same time are cost-effective and safe. Curcumin based dye extract showed a high level of absorbance in the utra-violet and visible regions of the solar spectrum and was successfully exploited sensitizer with high absorbance in a typical nanoporous TiO_2based DSSC [9]. Natural dyes *viz.,* anthocyanin (extracted from red cabbage) and chlorophyll (extracted from palm leaf) when used in the traditional DSSCs (fabricated with TiO_2 nanoparticle semiconductor) showed a light absorbance at 550 nm and 420, 664 nm, respectively and the respective conversion efficiency of 0.502 and 0.892 per cent [18].

Metal oxide as a conducting electrode:
After the successful absorption of photons by the dye, the electrons are exposed to the conducting oxide (semiconductor band) which is generally consisted of a mesoporous layer of metal oxide semiconductor typically TiO_2. Various nanoparticle films were used as semiconductor oxides as they provided a large surface area for light-harvesting absorption molecules to accept electrons from the excited dye [19]. The *d* - block binary metal oxides *viz.*, TiO_2, ZnO, and NbO_3 are the best candidates as photoelectrode due to the dissimilarity in orbitals constituting their conduction band and valence band [20]. Earlier, TiO_2 was the most commonly exploited metal oxide in various DSSCs. Many studies revealed the use of TiO_2 nano tubes in successful application of various DSSCs [21,22,23]. ZnO offered an another option of metal oxide as it showed much higher electron diffusivity than TiO_2, a high electron mobility, a large excitation binding energy, is available at low-cost, and stable against photo-corrosion [24,25,26]. Thus, nano based ZnO is an alternative candidate for high efficiency of these DSSCs.

Electrolyte: To regenerate the dye after electron injection into the conduction band of the semiconductor, the electrolytes are used and they also act as a charge transport medium for the transfer of positive charge toward the counter electrodes [10]. Thus, an electrolyte is an indispensable component of dye the DSSCs which is known to exert significant influence on the efficiency and stability of these solar cells. The conventional solvents used as electrolyte were some organic solvents such as c-butyrolactone, acetonitrile and 3-methoxypropionitrile. However, all of them were normally poisonous and volatile, which limits the DSSC industrialization. The mixed ratios of lithium ion (Li^+), 1,2-dimethyl-3-propylimidazolium ion ($DMPI^+$), tetra-*n*-butylammonium ion (TBA^+) cations were optimized as an electrolyte, and the performance of these DSSCs showed the highest conversion efficiency with the given electrotyle which was constituted of 75 per cent Li^+ with 25 per cent other cations [27]. A non-nitrile solvent, acetylacetone has been explored as a promising electrolyte solvent for these DSSCs [28]. The printable electrolytes containing I^-/I_3^- redox couples were prepared based on a 3-methoxypropionitrile liquid electrolyte that also made use of poly (ethylene oxide) and poly (vinylidene fluoride) resulted in high performance of DSSC in terms of its conversion efficiency (6.45 %) as revealed from the study [19].

Moreover, the liquid based electrolyte are now being substituted by solid polymer based electrolyte in various DSSCs that had proven itself as a novel alternative [30,31] and thus the new arena opens the gate for using various biodegradable polymer as electrolyte in these photovoltaic cells.

Counter electrode: The last crucial component of DSSC is the counter electrode that collects electrons from the external circuit and catalyzes the redox reduction in the electrolyte, which has a significant influence on the photovoltaic performance, long-term stability and cost of the devices [32]. In simple terms, the counter electrodes are mainly used to regenerate the electrolyte by transporting the electron that arrives from the external circuit back to the redox electrolyte system [8,10]. Platinum (Pt) was considered as a preferred material for counter-electrode to fabricate efficient DSSCs since it showed good catalytic activity for the reduction of oxidized electrolyte [33]. Various studies depicted the efficient use of Platinum as a counter electrode [34,35]. However, Pt is a rare and expensive metal, and some studies reported that Pt erodes via reaction with I_3^- in the electrolyte to form PtI_4 [36]. So, the new approaches continued to find the suitable substitutes that replace these high cost Pt based counter electrodes. Carbon is now coming as an effective low-cost alternative for these Pt based counter electrode as it offers sufficient conductivity and heat resistance in addition to corrosion resistance and electrocatalytic activity for I_3^- reduction [37]. Graphene nanosheets were used in placed of platinum as a counter electrode and these DSSCs exhibited the high conversion efficiency up to 6.81 per cent [38]. Carbon black thin films when used as counter electrodes in a DSSC achieved the conversion efficiencies of 8.27–8.35 per cent which were comparable to cells that used Pt [39]. In an another study, dye sensitized solar cells had been fabricated with the few layered graphene based composite conducting inks, which were formulated with multi walled carbon nanotubes and carbon black in polyimide matrix and these graphene composite coated on steel substrates served as the back electrodes and at the same time encouraged the catalytic activity for the redox reaction of I^-/I_3^- redox mediator [40]. Metal Selenides are also coming as an efficient substitute to the Pt based counter electrode as depicted in the study where it used the in situ-grown $Co_{0.85}Se$ nanosheet and $Ni_{0.85}Se$ nanoparticle films as CE [41].

Application and challenges of DSSCs: The first commercial application of DSSC created by G24 innovations was in 2009 where these were used in backpacks and bags (Hong Kong-based consumer electronics bag manufacturer, Mascotte Industrial Associates) and they could harvest solar energy to power mobile phones, cameras, and portable LED lighting systems for camping. Presently, DSSC has found its application in portable charging and building integrated photovoltaic (BIPV) modules [42,43]. DSSCs though have made several advancements in all their material composition that has overcomed the drawbacks associated with the traditional photovoltic systems and resulted in hastened efficiency, improved stability etc., still there is a dilemma that hampered its outdoor practical application and commericialization. The future challenge is thus to explore and generate more efficient, stable and low cost DSSCs that enables their application outfront to the indoor and outdoor, thus making them as a more reliable sustainable energy source which would lessen the burden of increasing global energy demand.

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