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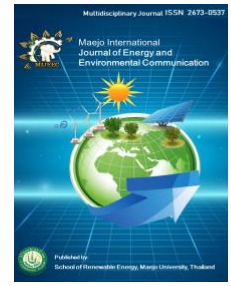

ARTICLE

# Dye-sensitized solar cells with nano $TiO_2$ quantum dots and foliar pigments: A review

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A B S T R A C T

The integration of plant pigments, quantum dots (QDs), and carbon nanotubes (CNTs) into dye-sensitized solar cells (DSSCs) is a notable progress in the effort to achieve carbon neutrality. Dye-sensitized solar cells (DSSCs) provide a sustainable alternative to conventional solar cells that depend on artificial dyes by utilizing renewable and environmentally friendly natural dyes produced from plant pigments. Quantum dots are employed to augment the effectiveness of light absorption in DSSCs, while carbon nanotubes promote electron transport and minimize charge recombination, resulting in a higher total efficiency. This integration not only decreases the environmental impact linked to the manufacturing of solar cells but also fosters a circular economy by utilizing agricultural by-products as sources of natural dyes. In addition, DSSCs have a reduced energy requirement for manufacturing compared to silicon-based solar cells, making them well-suited for widespread implementation in underdeveloped areas with insufficient infrastructure. Continued research and development efforts are focused on improving the performance and scalability of DSSCs. These technologies have the potential to be crucial in meeting global carbon neutrality targets and reducing the effects of climate change.

## 1. Introduction

In pre-industrial societies, energy requirements were mostly fulfilled by utilizing human and animal labor and wood combustion for heating, cooking, and metal smelting (Turnbull, 2021). The commencement of the Industrial Revolution signified a notable change, propelled by identifying plentiful coal resources and breakthroughs in mining techniques. Consequently, coal became extensively utilized to fuel steam engines, mechanize manufacturing processes, and enhance transportation systems (Wen, 2021). Oil exploration and exploitation experienced a surge in activity throughout the interwar period. Subsequently, during World War II, the availability of oil became a crucial concern. Following the war's end, oil played a significant part in the rapid increase in private automobile usage and the subsequent economic prosperity. Recently, natural gas has emerged as a significant catalyst for economic growth.

Global energy consumption is experiencing a swift rise due to the expansion in population and industrial advancement, especially in emerging countries (Cantarero, 2020). These nations have witnessed a population increase of 2 billion within a single generation. In the 21$^{st}$

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century, the need to prevent energy catastrophes has become urgent due to the increasing energy demand that strains world resources. Countries have implemented diverse tactics, plans, and regulations to ensure their energy requirements; nevertheless, the increasing population and economic progress are exhausting the Earth's resources. Fossil fuels, readily available and extensively utilized to fulfill global energy needs, provide a substantial contribution to environmental deterioration through the release of noxious gases (Khammee et al., 2021a; Tsai et al., 2023).

Following the onset of the Industrial Revolution, there has been a significant increase in the utilization of energy derived from fossil fuels, resulting in profound and detrimental effects on the environment. The ongoing release of carbon dioxide ($CO_2$) from industrial operations presents a significant environmental peril (Pimpimol et al., 2020). Fossil fuels, such as coal, petroleum, and natural gas, are finite resources that are being exhausted quickly and cannot be replenished within our lives. The utilization of these hydrocarbon fuels has resulted in the emission of greenhouse gases, contributing to global warming and posing a significant peril to both the Earth and mankind. Currently, the predominant source of global power generation is derived from non-renewable sources, which cannot be reused (Khammee et al., 2021b; Tsai et al., 2023).

The urgency for renewable and eco-friendly energy sources, such as solar, wind, and hydropower, has grown in response to these difficulties (Manmai et al., 2022). Solar energy has received considerable attention as a dependable and autonomous means of generating power. With almost 90% of energy sourced from petroleum-based resources, the exhaustion of these fuels and the resulting environmental harm have emphasized the need for alternative solutions (Jain et al., 2023). Sustainable energy sources such as wind, hydro, biofuels, solar, and geothermal energy provide feasible alternatives to conventional fossil fuels (Dussadee et al., 2022; Vu et al., 2022).

The pressing demand for renewable energy has hastened the exhaustion of fossil resources (Balakrishnan et al., 2023). According to current projections, the global oil reserves may be depleted in approximately 40 years, natural gas in about 60 years, and coal in around 200 years. The imminent shortage of these resources has spurred progress in renewable energy technologies. The European Union (EU) aims to get at least 27% of its energy from renewable sources by 2030 (Potrč et al., 2021). With the ongoing expansion in the world population, there is a greater need for energy in many forms. This has led energy specialists to concentrate on extracting energy from a wide range of renewable sources (Khammee et al., 2021).

### 1.1 The role of solar energy in mitigating climate change

Transportation and industrialization are significant factors in the accumulation of greenhouse gases in the atmosphere. The gases in question are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons (CFCs), and tropospheric ozone ($O_3$). As an illustration, the level of carbon dioxide has experienced a substantial increase over some time, going up from 288 parts per million (ppm) in 2003 to approximately 376 ppm (Nunes, 2023). Fossil fuels, such as coal, oil, and natural gas, mainly contribute to $CO_2$ emissions. Moreover, deforestation and the deliberate combustion of forests for land development result in the significant emission of $CO_2$ into the Earth's atmosphere. According to scientific predictions, the concentration of $CO_2$ in the atmosphere is expected to be twice as high as in the 1700s by the year 2050 (Nunes, 2023).

In addition to $CO_2$, the concentration of other trace gases linked to global climate change is also rising. The build-up of these anthropogenic gases in the atmosphere contributes to the increase in global temperatures, a process referred to as the greenhouse effect (Tsai et al., 2017). The impact of this phenomenon is becoming worrisome, as it has the potential to cause substantial and potentially detrimental alterations in the Earth's climate. In the face of these environmental challenges, the sun is the most plentiful and dependable energy source for civilization. The Earth receives an estimated 120,000 terawatts (TW) of solar energy, establishing it as a highly reliable source for natural and artificial processes (Salehabadi et al., 2023).

Plants utilize photosynthesis, a crucial biochemical process, to transform solar radiation into chemical energy, essential for the survival of almost all living forms on Earth (Tsai et al., 2015). Moreover, the sun's energy propels wind and tide patterns, underscoring its essential function in diverse forms of renewable energy (Bhuyar, 2021). Transitioning to renewable energy sources, specifically solar power, is crucial to reducing the negative consequences of greenhouse gas emissions and guaranteeing a sustainable future for the world, considering the increasing influence of climate change.

### 1.2 Renewable energy

Renewable energy is obtained from natural resources consistently renewed through natural processes. The resources encompassed in this category consist of sunlight, wind, flowing water, geothermal heat, biomass derived from energy crops, agricultural and industrial wastes, and urban garbage (Mejica et al., 2022). Renewable energy has various functions, such as producing electricity, powering transportation, and supplying heat for household and industrial uses. Renewable energy constitutes over 14% of the total world energy consumption. These energy types are particularly noteworthy for their environmentally friendly nature and greatly reduced influence on the ecosystem compared to typical fossil fuels (Tsai et al., 2012; Wang et al., 2024).

Solar power is a notable renewable energy source that offers a sustainable and ecologically friendly solution for generating cost-effective electricity. Solar energy is a fundamental source of other forms of renewable energy, including wind, hydroelectric power, and biofuels (Kumar et al., 2021). With the depletion of fossil fuel supplies, it is crucial to utilize solar energy's potential fully. The exploration of alternative energy sources enhances the standard of living by diminishing reliance on finite resources and fosters economic expansion by generating fresh job prospects across diverse industries (Onyemowo et al., 2023).

The worldwide proliferation of renewable energy production and distribution is continuously increasing. In the previous decade, substantial expenditures have been focused on advancing renewable energy due to substantial rises in oil prices and the effect on coal and gas prices (Khammee et al., 2020). Advancements in technology have allowed countries to produce increasing quantities of renewable energy at a lower cost. Given the negative and permanent effects of traditional energy extraction and usage, promoting and improving the availability and use of renewable energy sources is crucial.

### 1.3 Solar photovoltaic technology

A photovoltaic or solar cell or PV cell is a device that directly transforms solar radiation into electrical energy. A photovoltaic cell's main purpose is to catch solar radiation and convert it into electrical energy via the photovoltaic effect (Green, 2002). PV technology can be classified into two primary categories: wafer-based and thin-film. Wafer-based cells are fabricated on semiconductor wafers and do not require an extra substrate. They typically have a glass covering to enhance mechanical stability and provide protection. Thin-film cells, on the other hand, are produced by applying semiconducting films over a substrate composed of glass, plastic, or metal. These thin-film technologies are further classified into commercial and emergent categories (Maalouf, et al., 2023).

Photovoltaic cells provide numerous benefits, such as reduced energy production costs per unit area in comparison to traditional silicon solar cells, improved visual appeal, low levels of toxicity, high transparency, customizable colors, flexibility, and minimum power loss resulting from variations in the sun's angle of incidence. PV technology has specific characteristics that make it ideal for Building Integrated Photovoltaics (BIPV) (Dobrzañski et al., 2017). Solar PV technology is presently the most rapidly expanding sector in electricity production, showcasing the greatest power density among renewable energy sources, with an average global power density of 170 watts per square meter. The following factors drive the move from conventional fossil-fuel-based electricity generation to solar PV: The escalating expense and eventual exhaustion of fossil fuels, juxtaposed with the costless and limitless characteristic of solar energy.

Solar PV systems do not emit harmful pollutants during operation, unlike power units that rely on fossil fuels. Fossil fuels significantly contribute to global warming, but solar PV technology aids in alleviating this problem. The widespread presence and plentiful supply of solar energy compared to the finite availability of fossil fuel resources (Holechek et al., 2022). Reduced expenses for maintaining and operating solar PV installations. Solar PV provides the greatest power density among all renewable energy sources.

Solar cells are categorized into four generations based on their performance characteristics and technological advancements:

- First Generation: This category includes silicon-based solar cells, monocrystalline and polycrystalline silicon, and gallium arsenide (GaAs) cells.
- Second Generation: Comprising thin-film solar cells, this group includes technologies such as copper indium gallium selenide (CIGS) and cadmium telluride/cadmium sulfide (CdTe/CdS).
- Third Generation: This generation represents emerging photovoltaic technologies, including quantum dots, DSSCs, and organic polymer-based solar cells.
- Fourth Generation: This latest generation integrates the durability of organic-based nanomaterials like graphene, carbon nanotubes, and graphene derivatives with cost-effective thin-film polymers.

## 2. Overview of DSSCs

DSSCs represent a third-generation photovoltaic technology that differs fundamentally from traditional silicon-based solar cells. DSSCs mimic the natural process of photosynthesis, where light is absorbed by chlorophyll in plants to initiate a series of electron transfer reactions (Khammee et al., 2022). In a typical DSSC, a photosensitive dye adsorbed onto a porous semiconductor, typically $TiO_2$, captures sunlight and injects electrons into the semiconductor's conduction band. These electrons are then transported through the $TiO_2$ layer to the electrode, generating an electric current. The efficiency of DSSCs depends on factors such as the dye's light absorption properties, the $TiO_2$ layer's electron transport capabilities, and the overall cell design (Khammee et al., 2023).

Traditional DSSCs often use synthetic dyes, which are costly and unavailable. Researchers have explored using natural dyes derived from plant pigments, which offer advantages such as wide availability, low cost, and environmental compatibility. In solar cells, dyes perform a similar role to plant leaves in photosynthesis. They absorb sunlight, causing electrons to get excited. These excited electrons are then transferred through the anode to an external circuit; during photosynthesis, the energy absorbed produces glucose and oxygen. On the other hand, with DSSCs, the energy causes the release of electrons from the dye, which then initiates electricity production (Efurumibe et al., 2013). DSSCs are being recognized as a viable substitute for conventional silicon-based solar cells.

### 2.1 Characteristics of dyes in dye-sensitized solar cells

In order to get the best possible performance in DSSCs, dye sensitizers must possess the following properties:

- The capacity to assimilate light with wavelengths less than 920 nm.
- Intense adhesion to the surface of the oxide.
- The energy level of electrons that are excited and located near the conduction band of the oxide.
- Compatibility with an electrolyte exhibiting a high redox potential for dye/electron regeneration.

A minimal level of stability and longevity of around 20 years. The effectiveness of $TiO_2$ solar cells sensitized with natural dyes has reached 10.6% (Hug et al., 2014). This review study aims to improve the power conversion efficiency of DSSCs by employing nano $TiO_2$ quantum dots and foliar pigments extracted from plants.

### 2.2 DSSC: principles, performance, and technological advancements

DSSCs are a type of photovoltaic technology that belongs to the third generation. They function based on the electrochemical principle, in which dyes sensitive to incoming light are absorbed into the surface of a photoelectrode made of $TiO_2$. When light interacts with the dye molecules, they absorb the energy from the photons and convert it into electrical energy through a sequence of electron transfer processes within the cell (Asghar et al., 2024). DSSCs are renowned for their cost-effectiveness, eco-friendliness, and versatility. These machines can function effectively in many weather situations, and their small, lightweight structure ensures stability and longevity.

DSSCs are designed based on the functional mechanism of photosynthesis in plants, namely the Z-pathway, which imitates the light-dependent processes found in nature (Prabavathy et al., 2016).

The efficiency of a DSSC is impacted by the energy levels of its sensitizer, photoanode, and electrolyte. The photocurrent produced in a DSSC is determined by the energy gap between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) of the sensitizer (Lau et al., 2014). In addition, the open-circuit photovoltage (Voc), photogenerated current density under short-circuit conditions (Jsc), light irradiance (Io), and the fill factor (FF), which are influenced by the series and shunt resistances all contribute to the overall conversion efficiency of the solar cell (Lau et al., 2014).

DSSCs have attracted considerable global attention in the past twenty years because of their superior photoconversion efficiency and reduced production expenses compared to silicon and thin-film solar cells (Ashfaq et al., 2023). DSSCs that utilize nanostructured materials provide a cost-effective and highly efficient means of converting solar energy into electrical energy. When using $TiO_2$ as a photocatalyst in DSSCs, it is important to consider several key parameters (Hug et al., 2014). One of these factors is the capacity of $TiO_2$ to efficiently transport positive charges (holes) from the photosensitive dye and introduce electrons into its conduction band.

DSSCs employ a porous layer of wide-bandgap semiconductor oxide, usually $TiO_2$, altered with light-absorbing dye molecules (Figure 1). When light interacts with the dye, it absorbs energy and emits an electron, which is then transferred to the $TiO_2$ layer and transmitted to an electrode, producing electricity (Qu et al., 2012). DSSCs possess a porous structure that offers a greater surface area than conventional solar cells, enhancing light absorption. DSSCs depend on the electron injection and transport properties of nanocrystalline $TiO_2$ and a photoelectrochemical system consisting of a photosensitized anode, an electrolyte, and a platinum counter electrode. The main benefits of this technology are its inexpensive production, adaptability, lightweight structure, and excellent p

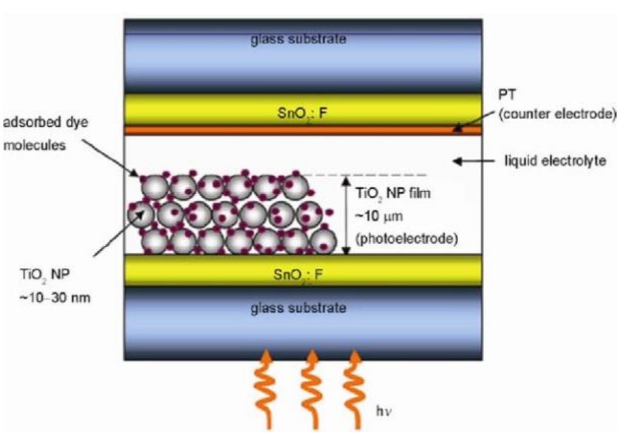


**Figure 1.** Structure of dye-sensitized solar cell (Qu et al., 2012)

### *2.2.1 Photoanode*

The photoanode is essential in DSSCs, primarily facilitating electron transport and supporting dye molecules (Figure 2). Optimizing electron transit is crucial for reducing electron-hole recombination and increasing conversion efficiency. The photoanode's extensive surface area enables efficient dye adsorption, while its shape, surface area, porosity, crystallinity, and conduction band properties greatly influence the conversion of light into electrical energy. Usually, a mesoporous $TiO_2$ layer is used as the photoanode on a fluorine-doped tin oxide (FTO) glass substrate (Susmitha et al., 2017). This architecture facilitates the absorption of dye and allows for the injection of photo-excited electrons into the conduction band of $TiO_2$. These electrons are gathered and sent over an external circuit to produce energy.

An optimal photoanode must exhibit a significant surface area to provide maximum dye adsorption, efficient electron injection, suitable pore size for dye dispersion, exceptional resistance to photo-corrosion, ability to scatter light, and firm adherence to conductive substrates (Qu et al., 2012). Nanocrystalline $TiO_2$ is widely utilized for its abundant availability, non-toxic nature, and remarkable optoelectronic characteristics. The structure and features of the photoanode, such as light scattering and dye loading, significantly impact the photoelectric parameters of the DSSC.

The efforts to improve light absorption and mainly scattering concentrate on optimizing the $TiO_2$ coating. This is because chaotic crystalline structures and limited electron mobility might reduce efficiency (Susmitha et al., 2017). The smaller size of the $TiO_2$ nanoparticles enables excellent transparency across the solar spectrum, leading to optimal light absorption. When sunlight interacts with the DSSC, the dye molecules absorb photons, causing the electrons to become excited and then transfer them into the conduction band of $TiO_2$. Subsequently, these electrons traverse the $TiO_2$ sheet, ultimately reaching the conductive glass, where they are harnessed to energize devices or replenish batteries. Maximizing the performance of DSSC relies on the crucial and effective interaction between the $TiO_2$ photoanode and dye molecules.

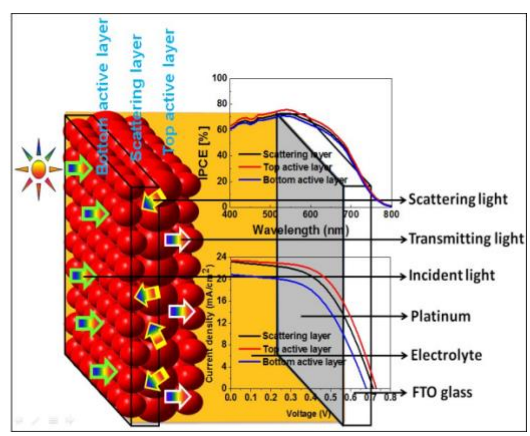


**Figure 2.** Photoanode architecture (Susmitha et al., 2017)

### *2.2.2 Electrolyte*

The electrolyte is an essential element in DSSCs, as it is crucial for dye regeneration and acts as the medium for transporting charges between electrodes. The electrolyte's characteristics substantially impact both the efficiency of converting light into electricity and the long-term stability of DSSCs (Bui et al., 2013). The three primary categories of electrolytes employed in DSSCs are solid-state conductors, quasi-solid electrolytes, and liquid electrolytes (Figure 3). In order to achieve the best possible performance, the electrolyte must satisfy multiple criteria:

- Efficient Charge Transport: The electrolyte must enable the effective movement of charge carriers between the photoanode and the counter electrode.
- Swift Dye Regeneration: The electrolyte must rapidly restore the dye to its original state after injecting electrons into the $TiO_2$ conduction band.
- Stable Interfacial Contact: The electrolyte must establish a reliable connection between the porous nanocrystalline layer and counter electrode, facilitating efficient diffusion of charge carriers.
- Long-Term Stability: The dye must demonstrate enduring chemical, thermal, optical, electrochemical, and interfacial stability to avoid deterioration and detachment from the oxide surface.
- Low Light Absorption: The electrolyte must not absorb much visible light to prevent interference with the effectiveness of light conversion.

Liquid electrolytes are widely utilized in DSSCs because they are easy to produce and have high conductivity, low viscosity, and strong interfacial wetting qualities. These attributes contribute to a notable increase in conversion efficiency since conventional DSSCs can achieve efficiency levels of up to 13%. Some examples of liquid electrolytes are ionic liquids, mediators without iodide/triiodide, and redox shuttles with iodide/triiodide. Essentially, the electrolyte plays a crucial role in improving the efficiency and endurance of dye-sensitized solar cells by facilitating charge transport, regenerating dye, ensuring stability, and reducing light absorption.

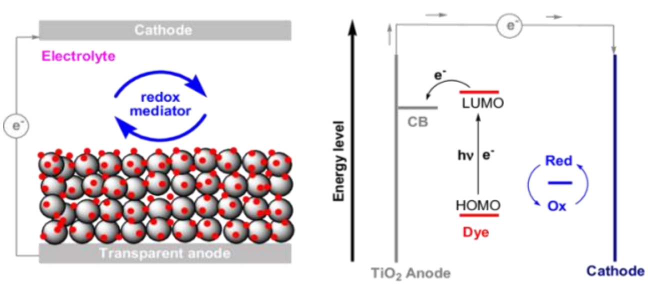


**Figure 3.** Structure of liquid electrolyte-based DSSC (Bui et al., 2013)

### *2.2.3 Counter electrode*

The counter electrode (CE) plays a crucial role in DSSCs, functioning as both a catalyst and a charge collector. The main purposes of it are (Figure 4):

- Catalysis: The counter electrode reduces redox species in the electrolyte, which helps restore the sensitizer (dye) after electron injection. This procedure is essential for ensuring the uninterrupted movement of electrons and optimizing the cell's overall efficiency.
- Charge Collection: In solid-state DSSCs, the counter electrode gathers holes from hole-transporting materials. In conventional DSSCs, electrons are transported from the external circuit back into the electrolyte, which completes the electrical circuit.

The counter electrode serves as a mirror, reflecting any light not absorbed back into the photoanode. This process enhances the efficiency of light harvesting in the cell. The counter electrode plays a crucial role in determining the fill factor (FF) and overall efficiency of the DSSC. Enhancing the counter electrode's composition might decrease the cell's series resistance (Rs), augmenting the fill factor (FF). The difference in energy levels between the Fermi levels of the counter electrode and the nanocrystalline $TiO_2$ layer determines the open-circuit voltage of the DSSC.

Essential characteristics for a highly efficient counter electrode in DSSCs comprise:

- High conductivity guarantees the effective movement of electrons and the durability of the electrolyte.
- Electrochemical Stability: Exhibits resistance to corrosion and chemical interactions with the dye or photoanode.
- High Electrocatalytic Activity: Enhances the speed of redox processes.
- Low electrical resistance reduces energy loss during the transmission of electrons.

Platinum is widely utilized as the preferred material for counter electrodes because of its exceptional catalytic activity and electrical conductivity (Lee et al., 2010). Additionally, researchers are investigating the possibility of various metals, carbon-based materials, transition metal complexes, conductive polymers, and composites for use in DSSCs.

Counter electrode preparation encompasses a range of processes, including thermochemical deposition, electrochemical deposition, chemical reduction, chemical vapor deposition, hydrothermal reaction, sputter deposition, and in situ polymerization. These techniques are designed to optimize the performance and stability of the counter electrode, hence increasing the efficiency of DSSCs.

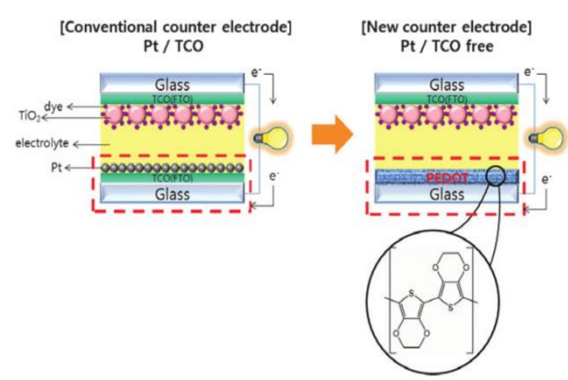


**Figure 4.** Structure of counter electrode (Lee et al., 2010)

### *2.2.4 Transparent conductive oxide*

Transparent conductive oxide (TCO)-coated glass is commonly used as the substrate for both the photoanode and counter electrode in DSSCs (Molla et al., 2014). The function of this layer is to serve as a current collector, which captures electrons emitted from the photoanode and transports them to the counter electrode via an external circuit. FTO and ITO are the most often utilized materials for TCO in DSSCs (Figure 5). The materials are chosen based on their low electrical resistance (about 20Ω at room temperature) and excellent transparency to solar radiation, which is crucial for effective light absorption.

Important aspects regarding TCO substrates in DSSCs:

The materials widely employed as Transparent Conductive Oxides (TCOs) include ITO and FTO, as well as alternatives such as Aluminum-Doped Zinc Oxide (AZO) and Antimony-Doped Tin Oxide (ATO).

- Performance: ITO is commonly favored because of its exceptional conductivity and transparency. Nevertheless, it is worth noting that the product consists of limited quantities of dangerous substances, which diminishes its desirability in terms of sustainability.
- Challenge: The compact oxide layer in these substrates, although it acts as an insulator, can hinder efficiency because of its limited surface area, which decreases the efficiency of light absorption and electron transport.

ITO is commonly employed in optoelectronic devices such as solar cells, plasma display panels, and liquid crystal displays due to its advantageous characteristics. Nevertheless, the pursuit of more environmentally friendly and economically efficient alternatives remains a primary priority in the field of DSSC research.

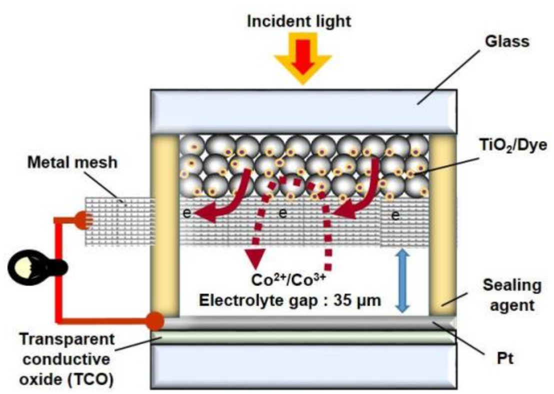


**Figure 5.** Transparent conductive oxide device structure (Molla et al., 2014)

The dye in DSSCs functions like the light-harvesting complexes in photosynthesis. When subjected to visible light, the dye is stimulated to a state of greater energy, resulting in the release of electrons and the oxidation of the dye. The presence of these emancipated electrons is essential for facilitating the electron injection and transfer mechanisms within the photoelectrode, which stimulates the production of electrical energy. Key Attributes of an Appropriate Photosensitizer for DSSCs:
The high adsorption coefficient guarantees excellent adherence of dye molecules to the surface of the photoelectrode.

- Wide range of light absorption: Collects sunlight from different wavelengths.
- Energy Alignment: The dye's LUMO energy level must exceed the photoelectrode's conduction band energy level.
- Intense Chemical Adsorption: Anchoring groups such as hydroxyl or methoxy groups strengthen the interaction between the photoelectrode and other substances.
- Optimal viscosity: Facilitates efficient dye regeneration.

This technology effectively reduces electron recombination with its high thermal stability and quick regeneration. A high molar extinction coefficient increases the ability of a dye to be adsorbed. In the case of DSSCs, the dye functions as a molecular electron pump. When the dye molecules absorb visible light, they undergo a transition from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO), resulting in the generation of excited electrons. The electrons are an electron's immigration completes the circuit traverses the photoelectrode, producing an electric current. The redox pair in the electrolyte subsequently restores the oxidized dye to its original state, concluding the cycle and guaranteeing uninterrupted energy conversion without any lasting chemical alterations.
Reactions in dye-sensitized solar cells:

$$\mathbf{DTiO_2} + h\nu \xrightarrow{\text{Photon Excitation}} \mathbf{D^{*}ITiO_2} \qquad [.]$$

$$\mathbf{D^{*}ITiO_2} \xrightarrow{\text{Electron Injection}} \mathbf{D^{+}|TiO_2 + e^{-}|TiO_2} \qquad [.]$$

$$\mathbf{D^{+}|TiO_2 + RE} \xrightarrow{\text{Dye Regeneration}} \mathbf{D|TiO_2 + OX} \qquad [.]$$

$$\mathbf{OX + e^{-} \mid CE} \xrightarrow{\text{Electrolyte Regeneration}} \mathbf{RE} \qquad [.]$$

$$\mathbf{e^{-}\left|\begin{matrix}TiO_2\\+D^{+}\end{matrix}\right| TiO_2} \xrightarrow{\text{Recombination by } D^{+}\text{,Dark Reaction}} \mathbf{D|TiO_2} \qquad [.]$$

$$\mathbf{e^{-} \mid TiO_2 + OX} \xrightarrow{\text{Recombination by Ox,D ark reaction}} \mathbf{RE} \qquad [.]$$

## 2.3 Operating principle of DSSC

The operating principle of dye-sensitized solar cells is based on converting light energy into electrical energy (Figures 6 and 7). DSSCs, unlike first-generation and second-generation solar cells, operate in a manner that closely resembles the process of natural photosynthesis in plants. This involves using certain chemicals to absorb light and transport charge carriers (Bai et al., 2021). The basic mechanisms of DSSCs include the following:

- The sensitizer is photoexcited by incident light, resulting in the production of an excited dye.
- When an electron is introduced into the conduction band of the metal oxide, it causes the dye to undergo oxidation.
- The transfer of electrons from an external circuit to the anode and the counter electrode.
- The oxidized dye is regenerated by utilizing electrons from the reduced redox pair.
- The oxidized redox pair replenishes itself at the counter electrode by assimilating electrons from the photoanode.
- Providing electrons to the oxidized dye in order to facilitate electron recombination.
- Providing electrons to the oxidized redox pair for electron recombination.
- The excited dye is returned to its ground state through a non-radiative decay mechanism (Dobrzañski et al., 2017).

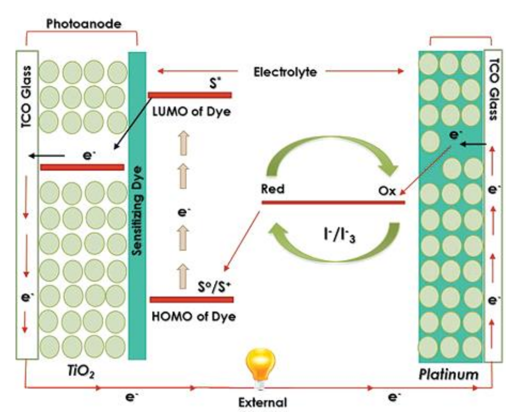


**Figure 6.** Operating principle of DSSC (Bai et al., 2021)

## 2.4 Plant pigments

Pigments are elemental compounds found in plants that can absorb visible light, resulting in the manifestation of their characteristic hues.

These pigments are present not just in plant parts like leaves, fruits, and flowers but also in animal tissues like skin and eyes and microorganisms like bacteria and fungi. They have a crucial function in several biological processes, such as forming animal structures and attracting pollinators while protecting against environmental stressors (Delgado-Vargas et al., 2000).

Pigments can be classified into three categories: inorganic, synthetic, or natural. In this context, the primary subject of interest is natural pigments, originating in plants, animals, fungi, and microorganisms. The brilliant hues of these pigments are obtained through the utilization of the chromophore element, which absorbs energy and stimulates electrons (Table1.). These pigments play a crucial role in a range of applications, such as photosynthesis and DSSCs (Ngamwonglumlert et al., 2017).

#### *2.4.1. Chlorophyll*

Chlorophyll is a pigment found in plants responsible for the green coloration of leaves and stems. It plays a crucial role in photosynthesis, the process by which plants. Chlorophyll, the primary pigment in photosynthesis, is a complex molecule in green plants, cyanobacteria, and algae. Photosynthesis is a vital process that involves the absorption of solar energy, its conversion into chemical energy, and the transmission of electrons (Mejica et al., 2022). Chlorophyll-a is the main form of chlorophyll, while chlorophyll-b acts as an additional pigment, absorbing light in distinct parts of the spectrum. Chlorophyll captures light in the blue (420-460 nm) and red (650-700 nm) wavelengths while reflecting green light, which results in plants appearing green in color (Khammee et al., 2020, 2021a,b; 2022; 2023).

#### *2.4.2 Carotenoids*

Carotenoids are prevalent pigments that play a crucial role in photosynthesis by absorbing light that chlorophyll cannot capture. They are predominantly present in algae, plants, and specific fungi, and are distinguished by their yellow-orange hue (Khammee et al., 2022). Carotenoids protect plants against excessive light by transferring energy to chlorophyll and releasing surplus energy as heat, reducing leaf damage (Khammee et al., 2023).

#### *2.4.3 Anthocyanins*

Anthocyanins are a class of pigments that give plants red, purple, and blue colors. Hydrophilic pigments provide vibrant red, blue, or violet hues to various plant structures such as petals, fruits, and stems (Mejica et al., 2022). Plant pigments have an aesthetic purpose and are crucial in attracting pollinators. Moreover, there is a growing inclination toward utilizing natural anthocyanins as a substitute for artificial food colorings owing to their advantageous effects on health (Ngamwonglumlert et al., 2017).

#### *2.4.4 Betalains*

Betalains are hydrophilic pigments that exhibit a reddish-purple or yellow coloration, contingent upon their molecular arrangement. Initially extracted from beetroot, betalains are utilized in food and can be found in many plant components, such as leaves, flowers, and stems. The pigments can be categorized into two primary groups: betaxanthins, yellow, and betacyanins, which have a red-purple hue. Betacyanins dominate pigments (Awolu et al., 2021; Ngamwonglumlert et al., 2017).

#### *2.4.3. Flavonoids*

Flavonoids are flower pigments that contribute to their vibrant colors and play a crucial role in plant reproduction by attracting pollinators. Flavonoids not only aid in pollination but also protect plants from ultraviolet B radiation, facilitate communication with microorganisms, and regulate the transfer of auxin (Mejica et al., 2022). They primarily absorb light in the 280–315 nm. This overview emphasizes the variety and significance of pigments in plants, both in their role in biological processes and their prospective applications, such as in dye-sensitized solar cells. ome in various colors (for instance, purple maize, red onions, grapes, and butterfly peas): orange, red, or blue.

Anthocyanins that do not contain sugar molecules are known as anthocyanidins (Ngamwonglumlert et al., 2017). Furthermore, there is a growing interest in using natural anthocyanin colors instead of damaging synthetic dyes due to the health advantages of anthocyanins and concerns over synthetic food pigments. Many fruits, vegetables, and flowers contain this pigment, giving them red, purple, blue, and pink hues. It also aids in photosynthesis and pollination by luring pollinators.

#### *2.4.5 Betalains*

Betalains are water-soluble pigments that are either reddish-purple or yellow, depending on the structure of the pigment. It is an essential natural pigment first created from beetroot for use in the food sector (Awolu et al., 2021). Various foods, vegetables, and flowers contain these pigments, such as red beetroot and aizoaceae. Betalains are found in various plant components, such as leaves, flowers, stems, and bracts, in addition to the eatable sections of plants (Ngamwonglumlert et al., 2017). Based on their structural differences, betalains are divided into two groups:

- betaxanthins (a yellow pigment).
- betacyanin (a red-purple pigment)

However, betacyanin makes up most of these pigments and shows an absorbance peak at wavelengths close to 536 nm.

#### *2.4.6 Flavonoids*

All plants that produce flowers contain floral pigments called flavonoids. This group of pigments gives flower petals appealing hues visible in the light spectrum (Delgado-Vargas et al., 2000). Insects are the primary pollinators of plants, and they are drawn to plants by flavonoids, which are present not just in the flowers but also in other parts of the plant (Mejica et al., 2022). In addition, they support plant defense against ultraviolet B radiation, communication with plant microbes, and auxin transport regulation. Flavonoids absorb visible light in the range of 280-315 nm. Table 1 captures the essential details about each type of pigment, its function, color range, and relevant applications.

**Table 1.** Key information on plant pigments on DSSC

| Pigment Type | Description | Role/Function | Color Range | Applications |
|---|---|---|---|---|
| **Chlorophyll** | Found in green plants, cyanobacteria, and algae. Involved in photosynthesis. | Absorbs solar energy, converts it into chemical energy, and transmits electrons. | Green (absorbs blue and red light) | Photosynthesis, DSSCs |
| **Carotenoids** | Prevalent in algae, plants, and some fungi. Protects against excessive light. | Absorbs light that chlorophyll cannot, transfers energy to chlorophyll, and releases excess energy as heat. | Yellow to orange | Photosynthesis, DSSCs |
| **Anthocyanins** | Found in petals, fruits, and stems. Provides red, purple, or blue hues. | It attracts pollinators, offers health benefits, and is a natural food coloring substitute. | Red, purple, blue | Aesthetic role, pollination, natural food coloring |
| **Betalains** | Water-soluble pigments are found in plants such as leaves, flowers, and stems. | Provides color: betaxanthins (yellow) and betacyanins (red-purple) pigments. | Reddish-purple, yellow | Food industry, aesthetic role in plants |
| **Flavonoids** | Found in all flowering plants. It contributes to flower color, attracts pollinators, and protects against UV radiation. | Absorbs light, attracts pollinators, supports plant defense, and regulates auxin transport. | Various (depending on type) | Photosynthesis, UV protection, pollination, DSSCs |

**2.5 Utilization of natural dyes**

Plant-derived natural dyes provide a sustainable substitute for costly and limited Ruthenium (II) complexes in DSSCs. They are preferred due to their positive environmental impact, cost-effectiveness, high absorption rates, ease of extraction, and widespread availability. In contrast to synthetic dyes, natural dyes such as chlorophyll, carotenoids, betalains, and flavonoids are easier to manufacture and have a lower environmental impact (Figure 7). They perform exceptionally under different lighting situations (Anis et al., 2021; Salimian et al, 2022).

The pigments derived from foliage, blossoms, fruits, roots, and bark are both harmless and economical. Efficient electron transport is made possible by their ability to cling strongly to the photoanode surface and their broad absorption spectra in the visible range. Chlorophyll and carotenoids are natural dyes that have been extensively researched for their applications in DSSC. Chlorophyll is mainly found in green plants, while carotenoids have numerous functions in photosynthesis and protection. These dyes have been examined in detail by Al-Alwani et al. (2017) and Khammee et al. (2020).

Natural dyes used as sensitizers in DSSCs generally show lower photoconversion efficiency than synthetic dyes. This is primarily due to their weaker attachment to the semiconductor oxide layer, which limits the mobility of excited electrons and reduces overall cell efficiency. However, chlorophyll, being both abundant and biodegradable, presents a promising, eco-friendly alternative. Studies have demonstrated its potential as an effective sensitizer in DSSCs (Al-Alwani et al., 2017).

For instance, DSSCs using natural dyes extracted from roselle flowers and *Carica papaya* leaves achieved power conversion efficiencies (PCEs) of 0.046% and 0.022%, respectively (Danladi et al., 2016). Another study showed PCEs of 0.17% and 0.21% using dyes from flame trees and *Bougainvillea glabra* flowers, respectively. Introducing water-extracted co-sensitizers further enhanced the efficiency to 0.24% (Isah et al., 2017). Remarkably, DSSCs incorporating a dye derived from Inthanin bok achieved a PCE of 1.138%, marking a significant performance improvement (Khammee et al., 2020; Salimian et al, 2022).

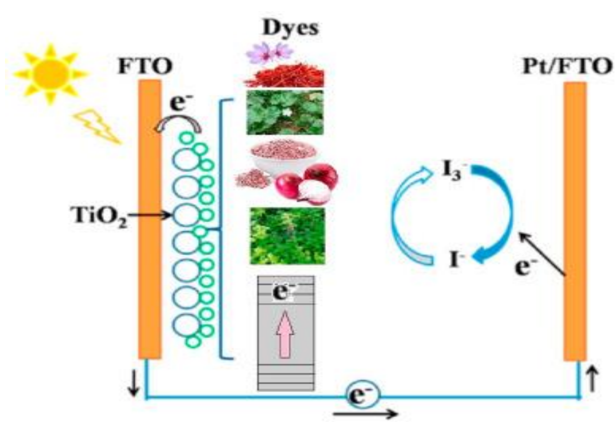


**Figure 7.** Schematic of a natural dye DSSC (Salimian et al, 2022)

**2.6 Carbon nanotubes**

Carbon nanotubes (CNTs) have attracted much interest because of their remarkable structural, mechanical, and electrical characteristics, which make them highly promising for enhancing DSSCs. Although the photoconversion efficiencies of DSSCs have reached as high as 12.3%, there is still scope for improvement, especially by fully using the capabilities of CNTs (Yella et al., 2011). The main obstacles in DSSCs involve enhancing electron transit and minimizing charge recombination. CNTs, due to their excellent electrical conductivity and ability to store electrons, provide a promising solution to these difficulties (Du et al., 2013; Cai et al., 2015).

Current studies have concentrated on integrating carbon nanomaterials and noble metals with $TiO_2$ in order to alter DSSCs. Studies have demonstrated that the use of these materials improves the movement of electrons, increases the efficiency of electron collection, and prevents recombination, resulting in an overall enhancement of cell performance (Arla et al., 2020). Out of the various categories of CNTs, MWCNTs are very economical for producing $TiO_2$/CNT nanocomposites. MWCNTs exhibit a wide spectrum of light absorption, ranging from 300 to 700 nm. This characteristic renders them highly useful in light-harvesting applications such as DSSCs.

The incorporation of MWCNTs into the photoanode, together with $TiO_2$, leads to a highly optimized interface between the $TiO_2$ and the dye molecules. The integration of this process results in the formation of two separate pores inside the structure. This leads to a notable increase in the amount of surface area that is available for the absorption of dye (Isah et al., 2017). Consequently, this enhances the absorption of light and improves the efficiency of energy conversion.

### 2.11 Quantum dots

Quantum dots (QDs) are nanoscale semiconductor materials, typically ranging from 2 to 10 nm in size, that exhibit unique optical and electrical properties due to quantum confinement effects. First synthesized by Louis E. Brus in the 1980s, QDs have become a focal point of research in nanotechnology and materials science (Deshmukh et al., 2023). Their ability to emit light of specific colors based on size makes them valuable in applications such as biological imaging, photovoltaics, and lighting (Figure 8).

One of the key characteristics of QDs is their tunable bandgap, which can be adjusted by controlling their size, allowing for customized light absorption and emission properties. This tunability enhances the light-harvesting capabilities of solar cells, improving their efficiency (Sanglee et al., 2020). In QDs, the absorption of a photon creates an exciton, a bound state of an electron and a hole, which then emits a photon as it relaxes to its ground state. The energy of the emitted photon corresponds to the size of the QD, making QDs highly versatile for various applications (Sanchez-Dominguez & Rodriguez-Abreu, 2016).

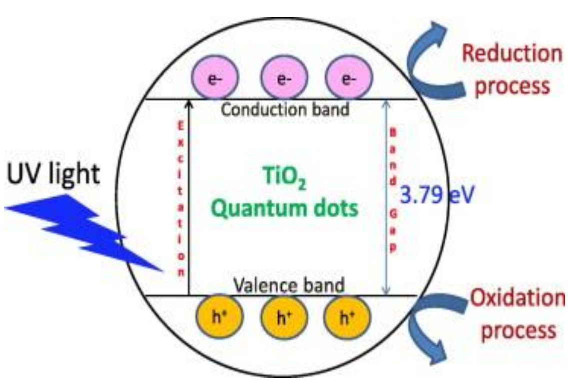


**Figure 8.** Schematic Structure of $TiO_2$ Quantum Dots (Sanchez-Dominguez & Rodriguez-Abreu, 2016).

Quantum dots offer several advantages, including easy material processing, cost-effectiveness, and flexibility in device fabrication (Figure 8). They have a high absorption coefficient, can generate multiple excitons for enhanced quantum yield, and possess significant intrinsic dipole moments that facilitate rapid charge separation. These features make QDs promising materials for applications in electronics, energy, and medicine, and they continue to be an active area of research and development (Sanglee et al., 2020).

## 3. Role of Plant Pigments in Photosynthesis and Applications in Dye-Sensitized Solar Cells with Quantum Dots

Examining the pigment composition in plant leaves is a crucial method for comprehending plant development, categorization, and relationships with the surroundings. Pigments, such as chlorophyll and carotenoids, have a fundamental function in photosynthesis. They capture light energy and transform it into chemical energy, which is essential for the synthesis of organic matter in plants. Chlorophyll-a is the main pigment that carries out this conversion, whereas chlorophyll-b serves as an additional pigment, assisting in the absorption of light and transferring it to chlorophyll-a. The abundance of these pigments in plant leaves dictates the efficacy of light assimilation, impacting the plant's capacity to flourish under different lighting circumstances. Carotenoids, a notable category of pigments, can absorb light in the blue-green region and are accountable for the vivid colors of plant tissues (Khammee et al., 2020, 2021a, b; 2022; 2023).

Analysis of pigment content using a spectrophotometer indicated that mahogany and inthanin leaves contained larger quantities of chlorophyll-a compared to chlorophyll-b and carotenoids. This indicates a greater degree of greenness in mahogany leaves, which is probably because they contain more chlorophyll-a. The choice of solvent employed during the extraction process is a crucial factor in influencing the ratio of chlorophyll to carotenoid concentration.

Pigments have a role that goes beyond their contribution to photosynthesis (Tsai et al., 2015). For example, the relationship between the amounts of chlorophyll-a and chlorophyll-b can be used to determine the level of light intensity that a plant is exposed to. A larger ratio indicates greater exposure to light and more efficient movement of electrons. Carotenoids serve a dual purpose in plants by both absorbing light and safeguarding against excessive light, functioning as antioxidants (Khammee et al., 2023). Examining the pigment composition offers vital insights into the environmental adaptations and physiological well-being of plants.

In the realm of DSSCs, natural pigments such as chlorophyll and carotenoids hold promise as photosensitizers because of their capacity to absorb light and produce electrons. The study investigated the effectiveness of DSSCs that included $TiO_2$QD and natural dye extracts derived from different plant sources (Vu et al., 2023). The findings indicated that the utilization of $TiO_2$QD greatly augmented the ability to capture light and facilitate the movement of charges in DSSCs, resulting in enhanced photoconversion efficiency. The correlation between $TiO_2$QD and dye molecules was determined to be important in enhancing the overall efficiency of the solar cells (Powar et al., 2020).

By incorporating quantum dots into the structure of the DSSC, electron recombination was effectively prevented, resulting in increased electron mobility and improved efficiency of solar energy conversion. The long-term stability of the DSSCs, particularly those enhanced with $TiO_2$QD, was remarkable, as they consistently maintained a high degree of light-induced electricity generation

(Castillo-Robles et al., 2021). The efficient extraction of electrons by $TiO_2$QD resulted in a decrease in charge recombination, hence enhancing the stability and efficiency of the DSSCs.

Moreover, the study emphasized the significance of fine-tuning the concentration and synthesis conditions of $TiO_2$QD in order to optimize the efficiency of DSSCs. The crucial factor in achieving better current density and overall efficiency was the photoanode's capacity to effectively absorb dye molecules and promote electron transfer (Ammar et al., 2019). The investigation of combined dye extracts and the integration of MWCNTs with $TiO_2$ photoanodes also showed promise in enhancing DSSC efficiency. Co-sensitization tactics, which involve the amalgamation of many dyes, have been demonstrated to augment light absorption across a wider range of wavelengths, resulting in heightened current generation and overall efficiency. MWCNTs in the photoanode decreased electron recombination, leading to an increase in open-circuit voltage (Voc) and enhancement of photoconversion efficiency (Onyemowo et al. 2024). Overall, the study highlights the importance of natural pigments in plant physiology and their potential applications in renewable energy (Sabarikirishwaran et al., 2022). The results highlight the possibility of using natural dye extracts and modern materials such as $TiO_2$QD and MWCNTs in DSSCs to attain improved efficiency and stability. Table 2 show the enhances the progress of sustainable energy technology by investigating novel methods to efficiently capture solar energy.

**Table 2.** J-V Performance of different DSSCs based on nano $TiO_2$ and MWCNT/$TiO_2$ photoanode

| Dye Solution | Photoanode Material | $V_{OC}$ (V) | $J_{SC}$ (mA/cm$^2$) | FF (%) | Efficiency (η) | Reference |
|---|---|---|---|---|---|---|
| **Spinach** | Nano$TiO_2$ | 0.59 | 0.41 | 58.00 | 0.17 | Castillo-Robles et al. (2021) |
| **Inthanin bok** | Nano$TiO_2$ | 0.09 | 0.81 | 3.71 | 1.14 | Khammee et al. (2021) |
| **Purple cabbage** | Nano$TiO_2$ | 0.48 | - | 46.00 | 0.15 | Castillo-Robles et al. (2021) |
| **Red cabbage** | Nano$TiO_2$ | 0.51 | 0.21 | 46.61 | 0.06 | Ammar et al. (2019) |
| **Onion** | Nano$TiO_2$ | 0.34 | 0.24 | 46.63 | 0.06 | Ammar et al. (2019) |
| **Malabar spinach** | Nano$TiO_2$ | 0.17 | 0.01 | 0.19 | 0.002 | Mejica et al. (2020) |
| ***A. xylocarpa*** | Nano$TiO_2$ | 0.73 | 0.03 | 64.00 | 0.3 | Onyemowo et al. (2024) |
| ***Coleus*** | Nano$TiO_2$ | 0.73 | 0.06 | 32.00 | 0.2 | |
| ***S. koetjape*** | 0.03(wt%)MWCNT/$TiO_2$ | 0.069 | 0.029 | 0.56 | 0.069 | Sabarikirishwaran et al. (2022) |
| ***Coleus*** | MWCNT/$TiO_2$ | 0.78 | 0.23 | 67.00 | 0.5 | Onyemowo et al. (2024) |
| | MWCNT/$TiO_2$ | 0.74 | 0.18 | 46 | 0.3% | |

## 4. Exploration of future applications of plant pigments in dye-sensitized solar cells with quantum dots for carbon neutralization

The future of renewable energy hinges on pioneering strategies that integrate sustainability, efficiency, and scalability. DSSCs exhibit considerable promise owing to their affordability, simplicity of production, and capacity to function in many lighting environments (Ulusu et al., 2021). This section explores the potential future uses of plant pigments in DSSCs, particularly when combined with QDs and carbon nanotubes CNTs, and examines their contribution to the advancement of carbon neutralization initiatives (Carambo, 2023).

### 4.1. Utilizing Plant Pigments for Renewable Energy

Natural pigments, such as chlorophyll, carotenoids, anthocyanins, and betalains, are found in large quantities in plant leaves, flowers, and fruits (Castillo-Robles et al., 2021; Onyemowo et al., 2024). These pigments offer a renewable and environmentally benign option as an alternative to the synthetic dyes typically employed in DSSCs. These pigments provide numerous benefits:

- Plant pigments, unlike synthetic colors, are obtained from renewable resources and are biodegradable, which reduces their environmental impact.
- Plant pigments have a broad absorption spectrum, which means they can absorb light across a wide range of wavelengths. This makes plants highly efficient in gathering solar energy. Chlorophyll mostly absorbs light in the blue and red regions, whereas carotenoids absorb light in the blue-green region, which complements the absorption of chlorophyll.
- Plant pigments offer a cost-effective and easily accessible solution for producing huge quantities of DSSCs.

Genetic engineering and new extraction processes have the potential to improve these natural dyes for greater stability, longevity, and higher light absorption in future applications. The integration of these pigments with contemporary substances, such as quantum dots, has the potential to enhance the efficiency of DSSCs.

### 4.2 Utilizing quantum dots to improve photoconversion efficiency

Quantum dots (QDs) are tiny particles made of semiconductors that have optical and electrical properties that vary depending on their size (Archana et al., 2020; Carambo, 2023). Their exceptional capacity to adjust the bandgap by manipulating their size renders them very suitable for enhancing the effectiveness of DSSCs:

- Researchers can manipulate the bandgap of QDs by altering their size, which enables them to optimize light absorption by aligning it with the solar spectrum. This tunability enhances the efficiency of light absorption in QDs.

- Numerous Exciton Generation refers to the ability of QDs to produce numerous electron-hole pairs, known as excitons, from a single photon. This characteristic has the potential to increase QDs' quantum efficiency.
- Quantum dots exhibit a significant capacity for light absorption since they possess high extinction coefficients. This characteristic allows them to absorb a greater amount of light per unit surface area in comparison to conventional materials.

Combining quantum dots with plant pigments in DSSCs has the potential to improve the cells' ability to capture light, resulting in a substantial boost in photoconversion efficiency. Continual research is being conducted to create hybrid systems that merge the most advantageous characteristics of QDs with natural dyes. This advancement aims to bring the efficiency of DSSCs closer to that of conventional silicon-based solar cells.

### 4.3 Utilizing carbon nanotubes to enhance electron transport

A primary obstacle in DSSCs is the effective conveyance of electrons from the energized dye molecules to the external circuit (Mohammadnezhad et al., 2020). CNTs, renowned for their exceptional electrical conductivity and mechanical robustness, provide a viable solution:

- CNTs offer improved conductivity by creating a highly conductive route for electrons, hence minimizing electron recombination and enhancing the efficiency of electron transportation.
- MWCNTs coupled with $TiO_2$ increase the surface area, leading to enhanced dye adsorption, improved light absorption, and increased energy conversion.
- Enhanced Stability: CNTs can improve the stability of DSSCs by offering a strong and durable structure that prevents degradation over time.

The inclusion of CNTs in the photoanode material, coupled with quantum dots and natural pigments, can greatly enhance the overall efficiency of DSSCs. This method not only enhances the efficiency of the cells but also aids in the advancement of adaptable and lightweight solar panels, ideal for many applications, ranging from portable gadgets to photovoltaic integration in buildings.

### 4.4 Enhancing carbon neutrality initiatives

The incorporation of plant pigments, quantum dots, and carbon nanotubes in DSSCs directly contributes to the objective of achieving carbon neutrality (Chapman et al., 2022):

- Minimization of Carbon Footprint: The utilization of natural dyes diminishes the dependence on energy-intensive synthetic dyes, hence reducing the carbon footprint associated with the production of solar cells.
- Circular Economy: Utilizing agricultural by-products to obtain natural dyes fosters a circular economy, transforming waste materials into valuable components that generate energy.
- Enhanced efficiency of DSSCs can help decrease reliance on fossil fuels, supporting worldwide initiatives to shift towards sustainable energy sources.

Moreover, the minimal energy demands of DSSCs compared to traditional silicon-based solar cells render them a compelling choice for widespread implementation in underdeveloped areas, where the potential reduction in carbon emissions might be significant. The future of DSSCs hinges on the creative integration of natural plant colors, quantum dots, and carbon nanotubes. This technique offers the potential to improve solar cells' effectiveness, durability, and expandability, positioning them as a crucial element in the worldwide transition to renewable energy. As research progresses in these fields, DSSCs have the potential to make a substantial contribution towards attaining carbon neutrality. They offer a clean, cost-effective, and sustainable energy alternative for the future.

## 5. Boosting carbon neutrality with dye-sensitized solar cells

The incorporation of plant pigments, QDs, and CNTs into DSSCs is a notable step forward in achieving carbon neutrality. By utilizing these materials, DSSCs not only improve their efficiency but also contribute to wider environmental and economic objectives, such as decreasing carbon emissions, developing a circular economy, and encouraging sustainable energy production (Spinelli et al., 2023). Here is a detailed analysis of how these advancements contribute to achieving carbon neutrality, with the support of specific instances.

### 5.1 Reduction of carbon footprint

Utilizing natural dyes to reduce carbon emissions: The manufacturing of artificial colors usually entails energy-intensive procedures, such as the extraction of raw materials, chemical synthesis, and purification (Carambo, 2023). These processes make a substantial contribution to the release of greenhouse gases. On the other hand, natural colors obtained from plant pigments, such as chlorophyll, anthocyanins, and carotenoids, necessitate only a little amount of energy and are obtained from sustainable sources. For instance, the process of obtaining anthocyanins from red cabbage or betalains from beets utilizes uncomplicated solvent extraction methods that are significantly less carbon-intensive compared to the production of metal-based artificial hues.

For instance: In a study conducted by Calogero et al. (2021), it was found that the carbon footprint associated with the production of chlorophyll-based dye for DSSCs was up to 80% reduced compared to typical ruthenium-based dyes. The solar industry may effectively reduce carbon emissions from dye production by repurposing agricultural waste, such as spinach leaves or carrot tops, which contain abundant chlorophyll and carotenoids. This process transforms low-value by-products into valuable resources.

### 5.2. Circulare conomy

A circular economy refers to an economic system that aims to minimize waste and maximize resource use by promoting the continual reuse, recycling, and regeneration of products and materials. Utilizing agricultural by-products as natural dye supplies promotes a circular economy, wherein waste materials are transformed into valuable resources. This strategy decreases waste and decreases the necessity for additional land, water, and chemical inputs generally needed for making synthetic materials. By incorporating natural dyes derived from agricultural waste into DSSC technology, enterprises can establish a self-contained system in which the products are either recycled or biodegraded at the end of their useful life, thus minimizing the environmental impact (Schoden et al., 2022).

In Thailand, researchers have investigated the utilization of rice husk ash, a residue produced during the process of rice milling, as a source of silicon dioxide ($SiO_2$) to fabricate a mesoporous framework for $TiO_2$ photoanodes in DSSCs. This approach not only decreases the requirement for extracting and treating silica but also repurposes a plentiful agricultural waste product in accordance with the principles of the circular economy (Sawasdee & Pisutpaisal, 2022). Rice husk ash characterization and utilization as a source of silica material. Chemical Engineering Transactions, 93, 79-84.). By utilizing natural dyes derived from readily accessible plants such as mango leaves, which are abundant in flavonoids, these DSSCs offer a cost-effective and ecologically friendly substitute for traditional solar technologies.

### 5.3 Sustainable energy generation

DSSCs can be utilized as an effective means to decrease our reliance on fossil fuels. DSSCs have the ability to replace energy sources that rely on fossil fuels, making them a valuable tool in achieving carbon neutrality (Francis & Ikenna, 2021). Conventional solar cells, such as those composed of crystalline silicon, necessitate the use of high-purity silicon, a resource-intensive material to manufacture (Aslam et al., 2020). DSSCs, in contrast, can be produced at lower temperatures and with reduced energy requirements, especially when utilizing natural dyes and photoanodes improved with CNTs.

An experimental initiative was conducted in rural India to introduce DSSCs utilizing natural colors derived from marigold flowers cultivated in the local area. (Reddy, 2017). These dyes contain carotenoids and were further improved by including CNTs. The utilization of DSSCs enabled the operation of small-scale irrigation systems, thereby diminishing the need on diesel generators. The project documented a 60% decrease in carbon emissions in comparison to traditional energy sources. Moreover, the utilization of indigenous resources and uncomplicated manufacturing methods rendered the concept financially feasible and adaptable to different areas.

### 5.4 Minimal energy demands and capacity to expand in size

Feasibility for widespread implementation in underdeveloped areas: DSSCs have minimal energy requirements, making them well-suited for large-scale deployment, particularly in developing regions with limited infrastructure for traditional solar cell manufacture (Mohammadnezhad et al., 2020). DSSCs can be manufactured using readily available local ingredients and low-temperature procedures, unlike silicon-based solar cells that necessitate energy-intensive purifying methods (Francis & Ikenna, 2021). This decreases the total energy input needed for production, hence reducing the carbon footprint even more.

In Sub-Saharan Africa, where the availability of energy is still limited, a community-led project employed DSSCs created using natural dyes extracted from native hibiscus flowers and quantum dots to generate electricity for illumination and charging stations for mobile phones (Charles et al., 2018). The project, backed by international non-governmental organizations, showcased the feasibility of local experts assembling and maintaining DSSCs, therefore empowering communities and diminishing reliance on diesel generators. DSSCs not only served as a sustainable energy source, but also bolstered local economies through the creation of employment opportunities in solar cell assembly and maintenance.

**Table 2.** Key points regarding the advancement of carbon neutralization efforts through the integration of plant pigments, quantum dots, and carbon nanotubes in DSSCs

| Aspect | Details | Example |
|---|---|---|
| **Reduction of Carbon Footprint** | Natural dyes, such as chlorophyll and anthocyanins, require minimal energy for production compared to synthetic dyes, resulting in lower greenhouse gas emissions. | A study showed that chlorophyll-based dye for DSSCs has a carbon footprint up to 80% lower than traditional ruthenium-based dyes. Agricultural waste like spinach leaves can be repurposed for high-value materials, reducing carbon emissions. |
| **Circular Economy** | Using agricultural by-products as sources for natural dyes supports a circular economy, reducing waste and minimizing the need for additional resources like land and water. | In Thailand, rice husk ash is used as a source of silicon dioxide for $TiO_2$ photoanodes in DSSCs. Combined with natural dyes from mango leaves, these DSSCs are low-cost and sustainable alternatives to conventional solar technologies. |
| **Sustainable Energy Generation** | DSSCs can replace fossil fuel-based energy sources by offering a low-energy, low-cost alternative to traditional silicon-based solar cells. | A pilot project in rural India used DSSCs with natural dyes from marigold flowers and CNTs to power irrigation systems, reducing carbon emissions by 60% compared to diesel generators. |
| **Low Energy Requirements and Scalability** | DSSCs have low energy requirements for production, making them suitable for large-scale deployment in developing regions with limited infrastructure for traditional solar cell production. | In Sub-Saharan Africa, DSSCs made with hibiscus flowers and quantum dots provided renewable energy for lighting and phone charging, reducing dependence on diesel generators and creating local job opportunities. |

Combining plant pigments, quantum dots, and carbon nanotubes in dye-sensitized solar cells is an effective approach to enhance carbon neutralization endeavors (Table 2). DSSCs provide a feasible route towards achieving a low-carbon future by minimizing the environmental impact of solar cell manufacturing, supporting a circular economy, and facilitating the production of sustainable energy. As ongoing research and development efforts improve the efficiency and durability of solar cells, their use in both developed and developing regions might have a crucial impact on reducing climate change and attaining global carbon neutrality objectives.

The integration of plant pigments, quantum dots, and carbon nanotubes in DSSCs is a significant step toward carbon neutralization. These technologies reduce the carbon footprint, promote a circular economy, and enable sustainable energy generation. Continued research and development will further enhance the efficiency and durability of DSSCs, making them a viable solution for achieving global carbon neutrality goals.

## 6. Conclusion

The transition from pre-industrial energy sources to fossil fuels has greatly propelled humanity forward while simultaneously giving rise to environmental issues, such as the emission of greenhouse gases and the depletion of resources. Given the increasing need for energy due to population increase and industrialization, there is an urgent want for sustainable and renewable energy options. Solar energy offers a hopeful and potential answer, particularly when harnessed using DSSCs. DSSCs, which are a type of third-generation photovoltaic technology, imitate the process of natural photosynthesis. Using plant pigments, QDs, and CNTs optimizes efficiency, diminishes carbon emissions, promotes a circular economy, and augments sustainable energy production. Utilizing natural dyes reduces the carbon emissions associated with solar cells, while QDs enhance light absorption, and CNTs improve electron transport, resulting in increased efficiency. The progress made in DSSC technology is essential for tackling the worldwide energy crisis and attaining carbon neutrality. DSSCs possess advantageous characteristics such as low energy requirements and scalability, making them suitable for implementation in developing areas. They provide a sustainable and economically efficient energy alternative. Combining plant pigments, quantum dots, and carbon nanotubes in DSSCs is essential to achieving a low-carbon future. As research progresses, DSSCs are poised to have a pivotal role in worldwide endeavors to mitigate climate change.

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