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Research Article

A review of Zinc Oxide (ZnO) nanostructures application in Dye sensitize Solar Cells (DSSCs)

A. Adewole[a,b] & O. O. Daramola[a*]

[a]*Department of Physics, Lead City University, Ibadan, Oyo State Nigeria.*

[b]*Department of Physics Alayande University of education, Oyo, Oyo State, Nigeria.*

Abstract

The global demand for sustainable energy has accelerated research into next-generation photovoltaic technologies. Because of their affordability, versatility, and ease of manufacturing, dye-sensitized solar cells, (DSSCs) have become a viable substitute for traditional silicon-based solar cells. Among the various semiconductor materials employed as photoanodes in DSSCs, zinc oxide (ZnO) has garnered significant attention. Its unique properties, including a wide direct bandgap, high electron mobility, and diverse nano-structural forms, make it a compelling candidate for enhancing cell performance. This review provides a comprehensive overview of ZnO nanostructures, beginning with a discussion of various synthesis methods and their associated characterization techniques. We then delve into the fundamental of optical, electrical, and structural properties that make ZnO an ideal photoanode material. The core of this review analyzes the specific applications of ZnO in DSSCs, exploring its role in light absorption, dye interaction, and charge transport dynamics. Finally, we address the current challenges and limitations, such as recombination losses and stability issues, and outline future research directions aimed at harnessing the full potential of ZnO nanostructures for high-efficiency solar energy conversion.

Keywords: Zinc oxide (ZnO), Dye-sensitized solar cells (DSSCs), Nanostructures, Photovoltaics, Charge transport, solar energy conversion

1. Introduction

The global energy crisis remains one of the most critical issues of the 21st century, driven by increasing population growth, industrialization, and a heavy reliance on fossil fuels. Apart from concerns about depletion, fossil fuel combustion contributes significantly to greenhouse gas emissions, global warming, and environmental degradation. To ensure a sustainable future, there is a pressing need for transition toward renewable energy sources that are both clean and efficient.

Among the available alternatives, photovoltaic (PV) technology plays a central role by directly converting sunlight into electricity through the photovoltaic effect (Singh, 2021; Droepenu, et al, 2022). Despite decades of progress, traditional silicon-based solar cells face intrinsic limitations, such as thermalization losses (where excess photon energy is lost as heat), recombination losses (where electrons recombine with holes before reaching the external circuit), and transmission losses (where low-energy photons pass through the material without absorption). These inherent drawbacks restrict the theoretical efficiency of conventional PV devices and highlight the need for innovative materials and architectures to overcome these barriers (Fouda et al., 2023).

Technological innovation in nanostructured materials has paved the way for third-generation solar cells, which aim to combine high efficiency with low-cost and environmentally friendly production. Among them, dye-sensitized solar cells (DSSCs) have attracted significant attention. First introduced by Michael Grätzel and colleagues in 1991, DSSCs are often referred to as "bio-inspired" solar devices because they mimic natural photosynthesis (Singh, 2023; Kumar, 2021; Iswarya et al., 2025). In these systems, light absorption is carried out by a photosensitizing dye, which injects electrons into the conduction band of a

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*Corresponding author: O.O. Daramola
Email: daramola.olanrewaju@lcu.edu.ng (O.O, Daramola)
ORCiD: https://orcid.org/0000-0001-5548-4434 ↗

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nanostructured semiconductor, typically deposited as a porous film. The unique operating principle of DSSCs offers several advantages over conventional silicon solar cells. They are relatively inexpensive to fabricate, can be produced using flexible substrates, and demonstrate good performance under diffuse or low-light conditions. These attributes make them attractive for emerging applications such as building-integrated photovoltaics (BIPV), portable electronics, smart infrastructure, and wearable devices (Droepenu et al., 2022; Iswarya et al., 2025).

Within the landscape of semiconductor materials for solar energy applications, zinc oxide (ZnO) has emerged as a particularly promising candidate. ZnO is a wide-bandgap (~3.40 eV), n-type semiconductor with a high exciton binding energy (~60 meV), which is considerably greater than that of gallium nitride (GaN, ~24 meV) (Joshi et al., 2023). This high exciton binding energy contributes to enhanced luminescence efficiency and strong excitonic emission even at room temperature, features that are advantageous for optoelectronic and photovoltaic applications.

In addition to these electronic properties, ZnO exhibits high chemical stability, broad-spectrum absorption, and excellent photostability, which collectively make it suitable for use in a wide range of devices. Its multifunctional characteristics have supported its use in fields as diverse as pharmaceuticals, electronics, transparent conductive coatings, sunscreens, catalysts, and environmental remediation (Ranjitha et al 2020; Joshi et al., 2023). The versatility of ZnO lies in its ability to be synthesized in different forms, ranging from bulk polycrystalline structures to highly controlled nanostructures. One of the defining features of ZnO is the strong dependence of its properties on morphology. The performance of ZnO in various applications is closely tied to the shape and dimensions of its nanostructures. Morphologies such as nanorods, nanosheets, and nanobelts exhibit distinct surface areas, charge transport pathways, and light-scattering abilities. For instance, rod-like and wire-like nanostructures provide direct electron transport channels, which minimize recombination, whereas sheet-like or hierarchical structures enhance dye loading and light absorption. Such morphological control has enabled ZnO nanostructures to find application not only in DSSCs but also in other advanced technologies, including light-emitting diodes (LEDs), gas sensors, photocatalysts, and biological probes (Prajapati et al.,2023; Manabeng et al., 2022). Consequently, researchers continue to focus on optimizing the morphology of ZnO to meet the performance requirements of targeted applications.

In the specific context of DSSCs, ZnO has been widely investigated as an alternative to titanium dioxide (TiO2), the conventional photoanode material. Although TiO2 has been extensively studied and commercialized, ZnO presents several distinct advantages. Chief among them is its higher electron mobility, which enhances charge transport and reduces recombination losses, thereby improving the efficiency of the solar cell (Khosravi et al, 2017; Kainyu et al., 2022). Furthermore, ZnO can be synthesized into a broad range of nanostructures, including nanoparticles, nanorods, nanowires, nanoflowers, and hierarchical architectures (Iswarya et al., 2025; Prajapati et al., 2023). This flexibility allows for the design of photoanodes with optimized surface areas for maximum dye loading, as well as enhanced light-harvesting and electron transport properties. In particular, one-dimensional structures such as nanorods and nanowires provide direct pathways for electron transport, while three-dimensional hierarchical structures enhance light scattering and photon capture.

Beyond performance optimization, ZnO-based DSSCs offer additional benefits that position them as strong candidates for next-generation energy applications. Their fabrication is relatively low-cost compared to silicon-based devices, and the processes are compatible with flexible and lightweight substrates. Importantly, DSSCs incorporating ZnO exhibit superior performance under diffuse sunlight or indoor lighting, which extends their usability to non-traditional environments (Droepenu et al., 2022; Iswarya et al., 2025). These attributes make ZnO-based DSSCs highly attractive for emerging fields such as portable power sources, wearable devices, self-powered sensors, and integration into smart building materials. As global energy demands continue to raise, the combination of scalability, cost-effectiveness, and functionality positions ZnO nanostructures as key enablers of the transition toward sustainable solar energy technologies.

2. Crystal Structure of ZnO

Zinc oxide (ZnO) crystallizes predominantly in two main structures: wurtzite and zinc blende, with a third high-pressure form known as rock salt.

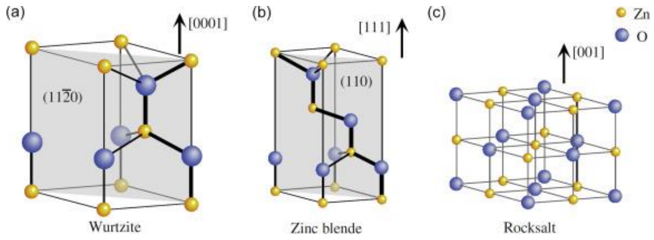

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Figure1. Crystal structures of ZnO: (A) wurtzite, (B) zinc blende, and (C) rock salt (Wu et al., 2023).

(i) The wurtzite phase, characterized by a hexagonal close-packed lattice, is the most thermodynamically stable and naturally occurring form of ZnO under ambient temperature and pressure. Its structure consists of alternating layers of zinc and oxygen atoms arranged along the c-axis, giving rise to strong piezoelectric and pyroelectric properties that are advantageous for various optoelectronic applications (Joshi et al., 2023; Wu et al., 2023).

(ii) The zinc blende phase, on the other hand, adopts a cubic crystal structure and is metastable under normal conditions. It can be synthesized and stabilized by epitaxial growth on substrates with a cubic lattice parameter closely matching that of ZnO, such as gallium arsenide (GaAs) or cubic silicon carbide (3C-SiC). This phase exhibits slightly different band structure characteristics compared to wurtzite, which can be exploited in specific device applications (Parihar et al., 2018; Wu et al., 2023).

(iii) The rock salt phase, another cubic modification, is a high-pressure polymorph of ZnO that forms when subjected to pressures typically above GPa. This structure is not stable under standard atmospheric conditions and reverts to the wurtzite form upon decompression. Although rarely encountered in practical devices, the rock salt phase is of interest in high-pressure physics and material science studies due to its distinct bonding and density characteristics (Morkoç & Özgür , 2009)

3. Synthesis of Zinc Oxide Nanostructures

The properties and performance of ZnO nanostructures are highly dependent on their synthesis method. A variety of techniques, both chemical and physical, have been developed to control the size, shape, and morphology of the nanostructures (Iswarya et al., 2025; Parihar et al., 2018; Ranjitha & Vijayalakshmi, 2020).

Table 1: A comparative table summarizing ZnO's three crystal structures

Structure	Crystal System	Coordination	Stability & Notes
Wurtzite	Hexagonal	Tetrahedral (4-fold)	Most stable at ambient conditions; commonly found form (Wu *et al*., 2023)
Zinc Blende	Cubic	Tetrahedral (4-fold)	Metastable; achievable via epitaxial growth on cubic substrates (Wu *et al*., 2023)
Rock Salt	Cubic	Octahedral (6-fold)	High-pressure phase (~10 GPa); reverts to wurtzite when pressure is released (Morkoç & Özgür , 2009)

3.1. Chemical Methods

3.1.1. Sol-gel method

This versatile wet-chemical technique is a bottom-up approach that allows for the creation of ZnO nanostructures from a colloidal suspension. The process involves two primary steps: hydrolysis and condensation. A zinc precursor, such as zinc acetate or zinc nitrate, is dissolved in a solvent (often an alcohol) (Ranjitha & Vijayalakshmi, 2020; Singh et al., 2025). This solution undergoes hydrolysis to form reactive monomers, which then condense to form a colloidal suspension, known as a sol. Over time, these particles aggregate to form a continuous, three-dimensional network, or a gel. After drying and calcination at elevated temperatures, the organic components are removed, and the final crystalline ZnO nanostructures are obtained. This method is praised for its simplicity, cost-effectiveness, and ability to produce high-purity nanoparticles and thin films.

3.1.2. Hydrothermal synthesis

This is a powerful, solution-based method for growing highly crystalline and well-ordered ZnO nanostructures, particularly one-dimensional morphologies like nanorods and nanowires. The process is conducted in a sealed vessel, or autoclave, containing an aqueous solution of a zinc precursor (e.g., zinc nitrate hexahydrate) and a hydroxide source (e.g., hexamethylenetetramine or HMT). The solution is heated to a temperature above the ambient boiling point of water, creating a high-pressure and high-temperature environment. Under these conditions, the ZnO spontaneously precipitates and grows on a substrate. The key advantage of this method is the ability to grow nanorods and nanowires directly on a conducting substrate, which creates a highly efficient, direct pathway for electron transport, bypassing the tortuous paths inherent in nanoparticle-based films (Khosrav et al., 2017; Ranjitha; Vijayalakshmi 2020).

3.1.2. Precipitation and Solvothermal Methods

These are similar solution-based techniques that offer precise control over morphology and crystallinity. Precipitation involves the controlled addition of a precipitating agent (like NaOH or NH4OH) to an aqueous zinc precursor solution to form a ZnO precipitate (Ramesh et al., 2015). This method is often used with surfactants, such as cetyltrimethylammonium bromide (CTAB) or Pluronic, which act as capping agents to control the growth and morphology of the nanocrystals, allowing for the synthesis of various shapes like plates, flowers, and rods. The solvothermal method is a variation that uses a non-aqueous solvent, such as ethanol or ethylene glycol, and is conducted at high temperatures and pressures. This non-aqueous environment can lead to higher crystallinity and more uniform nanostructures compared to the aqueous precipitation method, as it can suppress rapid particle growth and aggregation (Ranjitha & Vijayalakshmi 2020).

3.2. Physical Methods

Physical methods for synthesizing ZnO nanostructures typically involve vapor-phase or solid-phase processes. These techniques are often used to produce highly oriented thin films and single crystals, which are crucial for optoelectronic applications wastewater, specifically focusing on indicator organisms whose presence signals fecal contamination and potential health risks.

Table 2. Comparison of Common ZnO Nanostructure Synthesis Methods

Method	Description	Pros	Cons
Sol-gel	Wet-chemical, bottom-up approach using colloidal suspension.	Simple, low-cost, produces high-purity particles.	Difficult to control morphology, risk of aggregation.
Hydrothermal	Solution-based growth in a sealed, high-pressure, high-temperature vessel.	Produces highly crystalline, well-ordered nanorods/nanowires.	Energy-intensive, slow, not easily scalable.
Sputtering	Physical vapor deposition using energetic ion bombardment.	Excellent control over film thickness and stoichiometry.	High-cost equipment, not suitable for high-volume production.
Green Synthesis	Uses natural biological agents (e.g., plant extracts) for reduction and capping.	Eco-friendly, low-cost, produces biocompatible materials.	Less control over morphology and crystallinity, inconsistent performance.

3.2.1. Sputtering

This is a physical vapor deposition technique where atoms are ejected from a solid target by bombarding it with energetic ions in a vacuum chamber. Plasma of an inert gas, such as argon, is created, and the positively charged ions are accelerated towards a negatively biased ZnO target. The collision with the target causes ZnO atoms and clusters to be "sputtered" off and deposited as a thin, uniform film on a heated substrate. Sputtering is highly versatile and allows for the precise control of film thickness and stoichiometry (Borowski, & Myśliwiec, 2025).

3.2.2. Pulsed Laser Deposition (PLD)

PLD is a powerful technique that uses a high-power laser beam to ablate material from a ZnO target in a vacuum. The laser pulse vaporizes the target material, creating a high-energy plasma plume that expands rapidly towards a substrate. The ablated species condense on the substrate to form a highly crystalline thin film. PLD is particularly advantageous for its ability to produce high-quality, epitaxial (single-crystal) films and its fine control over deposition parameters.

3.2.3. Electron Beam Evaporation

In this method, a high-energy electron beam is directed at a ZnO source material in a high-vacuum environment. The kinetic energy of the electrons is converted to thermal energy upon impact, causing the ZnO to sublimate or evaporate. The resulting vapor travels through the vacuum and condenses on a cooler substrate to form a thin film. This technique is known for its simplicity and for producing high-purity films by minimizing contamination from the heating element.

3.3. Biological Methods

Biological synthesis, or "green synthesis," is a growing field that leverages natural biological agents to produce ZnO nanostructures. This approach is gaining popularity due to its eco-friendly nature, cost-effectiveness, and the avoidance of harsh, toxic chemicals.

3.3.1. Green Synthesis

This method uses living organisms or extracts from them, such as bacteria, fungi, yeast, algae, or plant extracts, to act as both reducing and stabilizing agents. For example, plant extracts from mint leaves, aloe vera, or tea contain various biomolecules (e.g., proteins, amino acids, polyphenols, flavonoids) that interact with zinc precursor ions (like zinc nitrate). These biomolecules perform a dual function: they reduce the zinc ions to form ZnO nanoparticles and simultaneously cap the growing particles, preventing uncontrolled aggregation and dictating their final size and shape. The specific biomolecules present in the extract influence the morphology, leading to the formation of different shapes. Green synthesis is a highly promising sustainable alternative to traditional chemical methods, as it produces biocompatible and non-toxic materials (Fouda et al, 2023; Singh et al., 2025).

4. Characterization Techniques for ZnO Nanostructures

To understand and optimize the synthesized materials, various characterization techniques are employed. These methods provide critical information about the material's structural, optical, and chemical properties, which directly influence its performance in DSSCs.

Table 3. Characterization Techniques and Their Applications for ZnO (Geremew, 2024)

Technique	Purpose	Information Gained
X-ray Diffraction (XRD)	Determine crystalline structure and phase purity.	Crystal phase (e.g., wurtzite), crystallite size, and presence of impurities.
Electron Microscopy (SEM/TEM)	Visualize morphology and internal structure.	Surface topography, overall shape (rods, flowers, etc.), size, internal defects, and crystallinity.
UV-Vis Spectroscopy	Measure optical properties.	Bandgap energy (Eg), absorption/transmission properties.
Photoluminescence (PL) Spectroscopy	Investigate electronic band structure.	Near-band-edge emission (UV peak) and deep-level defects (visible peak).
FTIR Spectroscopy	Identify chemical bonds and functional groups.	Confirmation of Zn-O bonds, presence of organic residues or surface-passivating agents.

4.1. Biological Methods

XRD is a powerful, non-destructive technique used to determine the crystalline structure, phase purity, and crystallite size of the material. The technique is based on Bragg's Law, which describes how X-rays are diffracted by a crystalline solid. When a beam of monochromatic X-rays interacts with the planes of atoms in a crystal, they are scattered. Constructive interference occurs when the path difference between the scattered waves is an integer multiple of the X-ray wavelength. Bragg's Law describes this condition in Eq. 1 (Dowsett et al., 2021).

$$n\lambda = 2d \sin\theta \tag{1}$$

Where,

n is an integer representing the order of diffraction.

λ is the wavelength of the incident X-rays.

d is the distance between adjacent parallel planes of atoms in the crystal lattice. θ is the angle of incidence of the X-rays.

By analyzing the angles and intensities of the diffracted X-rays, a unique diffraction pattern is generated. This pattern, which is essentially a fingerprint of the material's crystalline structure, can be compared to known patterns to identify the material and its crystalline phase (e.g., wurtzite ZnO). The sharpness of the diffraction peaks is also a key indicator of crystallinity; a sharper, narrower peak signifies a material with higher crystallinity and larger crystallites.

The peak broadening can be used to calculate the average crystallite size using the Scherrer equation Eq.2:

$$\tau = \frac{K\lambda}{\beta \cos\theta} \tag{2}$$

where:

τ is the average size of the crystallites (in nanometers or Ångströms).

K is the shape factor, a dimensionless constant that is typically close to 0.9 for spherical crystallites.

λ is the X-ray wavelength (for a common Cu Kα radiation source, λ=0.15418 nm).

β is the full width at half maximum (FWHM) of the diffraction peak, measured in radians. This value accounts for the peak broadening due to small crystallite size. θ is the Bragg angle (in degrees).

4.2. Electron Microscopy (SEM and TEM)

4.2.1. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) provides high-resolution images of the surface morphology and topography. It is essential for visualizing the overall shape and arrangement of the nanostructures (e.g., films, rods, flowers) and confirming the successful synthesis of the desired morphology.

4.2.2. Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) offers significantly higher resolution than SEM, allowing for the detailed observation of individual nanostructures. TEM can reveal internal features, such as crystal defects, stacking faults, and the degree of crystallinity. It provides crucial information on the size, shape, and internal structure of the nanomaterials at the atomic level.

4.3. Optical Spectroscopy (UV-Vis and Photoluminescence)

4.3.1. UV-Vis Spectroscopy

UV-Vis Spectroscopy is used to measure the absorption, transmission, and reflection of light as a function of wavelength. This technique is crucial for determining the optical properties of the material, particularly the bandgap energy (Eg). The bandgap can be estimated from the absorption spectrum using the Tauc plot method. For a direct bandgap semiconductor like ZnO, the relationship between absorption coefficient (α) and photon energy (hv) is given by:

$$(\mathrm{ahv})^2 = A(\mathrm{hv} - \mathrm{Eg}) \tag{3}$$

where A is a constant. By plotting $(\mathrm{ahv})^2$ versus hv and extrapolating the linear region to the x-axis, the bandgap energy can be determined.

4.3.1. Photoluminescence (PL)

Photoluminescence (PL) Spectroscopy is a highly sensitive technique used to investigate the electronic band structure and defect levels within the ZnO nanostructures. PL spectra typically show two main emission bands: a strong, sharp UV peak corresponding to the near-band-edge (NBE) emission from the recombination of excitons, and a broader, less intense peak in the visible range associated with deep-level defects, such as oxygen vacancies or zinc interstitials.

4.4. Fourier-Transform Infrared (FTIR) Spectroscopy

FTIR Spectroscopy is employed to identify the chemical bonds and functional groups present in the material. It can confirm the successful formation of ZnO by identifying characteristic Zn-O vibrational modes, typically around 400 − 500 cm−1. FTIR is also valuable for detecting impurities, adsorbed molecules (like dye or solvent residues), or the presence of surface-passivating agents.

5. Properties of Zinc Oxide Nanostructures

The performance of ZnO in DSSCs is directly tied to its intrinsic properties, which can be tuned by controlling the synthesis process (Kainyu, 2022; Joshi et al., 2023).

5.1. Fourier-Transform Infrared (FTIR) Spectroscopy

ZnO has a wide direct bandgap of approximately 3.37 eV to 3.40 eV at room temperature. This large bandgap means it primarily absorbs ultraviolet (UV) light, which is a small fraction of the solar spectrum. This is a crucial distinction from traditional solar cells; ZnO is not the main light absorber in a DSSC. Instead, its wide bandgap makes it an excellent transparent semiconductor, allowing the dye to handle the absorption of visible light effectively. The bandgap can be precisely tuned through doping, a process of intentionally introducing small amounts of other elements into the ZnO crystal lattice. For example, doping with elements like aluminum (Al), gallium (Ga), or indium (In) can increase the carrier concentration and modify the band structure. This is particularly useful for creating transparent conducting oxide (TCO) films that are both highly conductive and optically transparent (Tripathi & Ridhi, 2023).

5.2. Electrical Properties

One of the most significant advantages of ZnO is its exceptionally high electron mobility, which can reach up to 1000 cm2/Vs. This is considerably higher than that of the traditional photoanode material, TiO2 (0.1−4 cm2/Vs) (Khosravi et al., 2017; Kainyu, 2022). Electron mobility can be thought of as the speed at which an electron can move through the material when an electric field is applied. In a DSSC, high electron mobility is a critical factor for two main reasons:

(i) **Rapid Charge Transport**: It facilitates rapid electron transport from the dye-semiconductor interface to the collecting electrode. The electrons injected by the dye travel quickly through the ZnO nanostructure, reducing the overall transport time.

(ii) **Minimized Recombination Losses**: By speeding up the electron transport, high mobility minimizes the time an electron spends in the ZnO film. This reduces the likelihood of it recombining with oxidized dye molecules or the electrolyte, which would waste the generated charge and lower the cell's efficiency. The wurtzite crystal structure of ZnO is also a key factor, as the growth of nanorods and nanowires along the polar c-axis creates a direct, uninterrupted path for electron transport, further enhancing mobility and collection efficiency.disinfection may be necessary to effectively remove ARB and ARGs before the effluent is discharged or reused.

5.3. Structural Properties and Morphology Control

The morphology (shape and structure) of ZnO nanostructures plays a critical role in DSSC performance, acting as a trade-off between maximizing dye adsorption and optimizing electron transport (Iswarya et al., 2025; Prajapati et al., 2023; Datye & DeLaRiva 2023; Agrawal et al., 2024). The various shapes of ZnO nanostructures, such as flowers, wires, rods, and combs, are visualized in Figure 2.

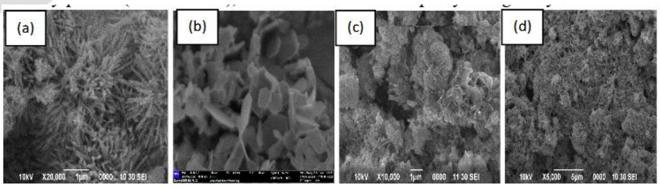

Figure 2. Various Morphologies of Zinc Oxide Nanostructures (Harish et al., 2022).

5.3.1. Nanoparticles

This morphology offers an extremely high surface area for dye adsorption. However, the electron transport path is tortuous and indirect, forcing electrons to hop from one nanoparticle to the next. This increases the transit time and the probability of recombination losses.

Nanorods and Nanowires: These one-dimensional nanostructures are often called "superhighways" for electrons. Because they are grown epitaxially along the c-axis, they provide a direct, continuous, and highly conductive pathway to the collecting electrode. This directional transport significantly reduces recombination and enhances charge collection efficiency (Khosravi et al., 2017).

The main trade-off is their limited surface area compared to nanoparticles, which can lead to lower dye loading and, consequently, a reduced short-circuit current (JSC).

5.3.2. Nanoflowers and Nanosheets

These complex, interconnected structures are an attempt to combine the best features of nanoparticles and nanorods. They provide a high surface area for dye adsorption while offering improved inter-particle connectivity and a more direct transport pathway for electrons, often leading to enhanced performance. The porous nature of these structures also allows for better infiltration of the dye and electrolyte.

5.4. Surface Properties

A large, porous surface area is essential for maximizing dye adsorption, as it allows more dye molecules to attach to the ZnO surface and absorb incoming photons. The surface roughness and pore size of the nanostructure film are also crucial. A highly porous and rough surface allows for the efficient infiltration of the liquid electrolyte, ensuring good contact with the dye-coated ZnO. This optimal contact is vital for the regeneration of the oxidized dye and the overall functioning of the cell.

6. Applications of Zinc Oxide Nanostructures in DSSCs

The application of ZnO in DSSCs centers on its function as a photoanode, where it serves as a scaffold for the dye and a pathway for electron transport. The mechanism of energy conversion in a DSSC involves a series of coordinated events.

6.1. Electron Transport and Recombination Dynamics

The process begins with the absorption of a photon by a dye molecule. This excites the dye from its ground state (S) to an excited state (S∗).

$$\boldsymbol{S + ZnO \rightarrow S^*} \qquad (4)$$

The excited electron is then rapidly injected from the dye molecule into the conduction band (CB) of the ZnO nanostructure. This is an ultrafast process, typically occurring in the femtosecond to picosecond timescale.

$$S^* + ZnO \rightarrow S^+ + ZnO(e_{CB}^-) \qquad (5)$$

Once in the ZnO conduction band, the electron begins its journey through the nanostructure to the transparent conducting oxide (TCO) electrode. For this to be efficient, the electron must be transported faster than it can recombine. As mentioned in section 1.0, the high electron mobility of ZnO nanorods and nanowires provides a direct, one-dimensional pathway for this transport, reducing the transit time and minimizing recombination.

Meanwhile, the oxidized dye (S+) is regenerated back to its ground state by accepting an electron from the electrolyte, which typically contains a redox couple like I^-/I_3^- in Eq. (6)

$$S^+ + I^- \rightarrow S + \tfrac{1}{2}I_3^- \qquad (6)$$

The electrolyte, now containing the triiodide ion (I_3^-), diffuses to the counter electrode, where it is reduced back to iodide (I^-) in Eq. (7).

$$I_3^- + 2e^- \rightarrow 3I^- \qquad (7)$$

Recombination is the main factor limiting the efficiency of DSSCs. It represents the loss of electrons before they can be collected, reducing the overall current. The three main recombination pathways are:

(i) **Recombination at the FTO/electrolyte interface**: Electrons that reach the TCO electrode can be "siphoned off" and recombine with oxidized species in the electrolyte.

(ii) **Recombination at the ZnO/electrolyte interface**: Electrons within the ZnO conduction band can directly recombine with oxidized species in the electrolyte. This pathway is particularly significant in ZnO-based DSSCs because ZnO has a higher chemical instability in acidic dye solutions, which can create defect states on the surface that act as recombination centers.

6.2. Recombination with the oxidized dye

An electron in the ZnO conduction band can transfer back to the oxidized dye molecule, a process that competes with dye regeneration by the electrolyte.

(i) **Performance Metrics:** The performance of a DSSC is evaluated using its current-voltage (I-V) characteristic curve, measured under standard illumination conditions shown in Figure 3. This curve provides a comprehensive picture of the cell's efficiency and its key operating parameters.

(ii) **Short-Circuit Current (JSC):** This is the maximum current density generated by the cell when the voltage is zero (i.e., the external circuit is shorted). It is a direct measure of the

(iii) number of electrons collected per unit area and is dependent on the amount of light absorbed and the efficiency of electron injection and collection. A high JSC indicates efficient light harvesting and charge transport.

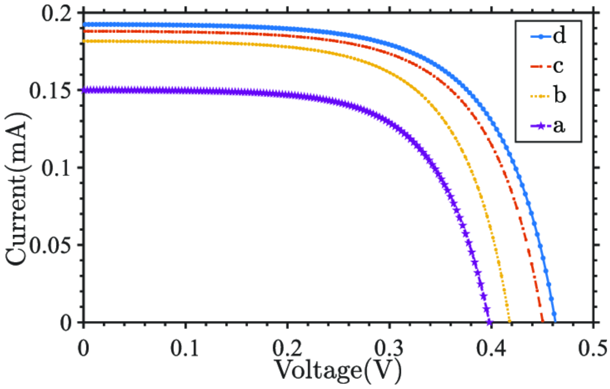

Figure 3: Typical Current-Voltage (I-V) Curve of a Dye-Sensitized Solar Cell (Okello et al., 2017).

(iv) **Open-Circuit Voltage (VOC):** This is the maximum voltage generated by the cell when the current is zero (i.e., the circuit is open). VOC is a measure of the difference between the Fermi level of the ZnO photoanode and the redox potential of the electrolyte. Minimizing recombination losses is crucial for achieving a high VOC.

(v) **Fill Factor (FF):** The fill factor is a measure of the "squareness" of the I-V curve and represents the ratio of the actual maximum power output to the theoretical maximum power. It is calculated using Eq. (8):

$$FF = \frac{V_{MAX} \times J_{MAX}}{V_{OC} \times J_{SC}} \qquad (8)$$

A high FF indicates that the internal resistance of the cell is low and that the charge collection is highly efficient at the maximum power point. A low FF suggests significant resistance or high recombination rates.

6.3. Power Conversion Efficiency (η)

The overall power conversion efficiency is the most important metric, as it quantifies the percentage of incident solar power that is converted into electrical power. It is calculated as:

$$\eta = \frac{P_{MAX}}{P_{IN}} = \frac{V_{OC} \times J_{SC} \times FF}{P_{IN}} \qquad (9)$$

Where, P_{IN} is the intensity of the incident light (typically 1000 W/m^2 for standard test conditions). Studies have shown that ZnO-based DSSCs can achieve comparable, and in some cases higher, efficiencies than their TiO_2counterparts, particularly when using well-ordered nanostructures with high electron mobility (Kumar, 2021; Iswarya *et al.*, 2025; Khosravi *et al., 2017*)

6.4. Challenges and Limitations

Despite its advantages, the use of ZnO in DSSCs faces several challenges that limit its widespread commercialization (Kumar, 2021).These challenges are rooted in the material's inherent chemical and physical properties, and overcoming them is a primary focus of recent researches.

Recombination Losses

While the high electron mobility of ZnO nanostructures is a significant advantage, it is often overshadowed by increased recombination losses compared to TiO_2. The primary reason for this is the positioning of the conduction band minimum (CBM) of ZnO, which is slightly higher (more negative) than that of TiO2 on the energy scale. This can lead to a slightly lower Vocfor ZnO-based DSSCs.

Furthermore, a critical issue is the chemical instability of ZnO in the acidic dye solutions that are commonly used (e.g., N3 or N719 dyes containing carboxylic acid anchor groups). The acidic environment can cause the dissolution of ZnO, forming a zinc-dye complex (Zn^{2+}-dye) on the surface of the photoanode. This complex can create additional recombination pathways for the injected electrons, severely reducing both Jscand Voc. This reaction is particularly detrimental because it not only promotes electron recombination but also destabilizes the entire photoanode, leading to device degradation.

To mitigate this, researchers are exploring two main strategies:

(i) **Surface Passivation:** Coating the ZnO nanostructures with a thin, protective layer of an inert material, such as alumina (Al_2O_3) or zirconia (ZrO_2), can prevent direct contact between the ZnO surface and the acidic dye/electrolyte.

(ii) **Using Non-Acidic Dyes:** Developing new classes of metal-free organic dyes or other sensitizers that do not contain strongly acidic anchor groups can prevent the dissolution of the ZnO photoanode.

6.5. Stability

The long-term operational stability of a DSSC is crucial for its commercial viability, and ZnO-based cells often exhibit poor stability compared to TiO_2-based ones. The chemical instability in the presence of the iodide/triiodide (I^-/I^{3-}) redox couple in the electrolyte is a significant factor. The iodide ions can facilitate the dissolution of ZnO through the following reaction:

$$ZnO + 2I^- + H_{20} \rightarrow ZnI_2 + 2OH^- \qquad (10)$$

This degradation not only reduces the thickness and porosity of the photoanode film but also contaminates the electrolyte with zinc ions, which can further affect the performance and stability of the cell. High temperatures and prolonged exposure to light can accelerate this degradation process.

6.6. Scalability

While lab-scale synthesis of high-quality ZnO nanostructures is well-established, transitioning these methods to large-scale, cost-effective commercial production remains a significant challenge. Many of the most effective synthesis techniques, such as the hydrothermal and vapor-phase methods, are slow, energy-intensive, and difficult to scale up.

(i) **Hydrothermal Synthesis:** This method, while excellent for producing highly ordered nanorods, requires a high-pressure, high-temperature environment in an autoclave, which is not easily scalable for continuous, roll-to-roll manufacturing.

(ii) **Physical Vapor Deposition (PVD):** Techniques like sputtering and PLD are highly effective for producing high-quality thin films but are also expensive and not suited for high-volume production.

(iii) **Green Synthesis:** While environmentally friendly and low-cost, green synthesis methods often result in materials with less control over morphology and crystallinity, leading to inconsistent performance. Simple and reproducible synthesis methods are needed to make ZnO-based DSSCs a viable commercial technology (Seth, & Meena, 2024).

6.6. Future Directions

The field of ZnO nanostructures in DSSCs is ripe with opportunities for future research and development (Kumar, 2021; Iswarya *et al.*, 2025).

6.6.1. Innovative Synthesis Methods

Future research will probably concentrate on creating innovative, affordable, and scalable synthesis techniques that give exact control over the shape of nanostructures and the concentration of defects. The aim is to create architectures that maximize dye loading while providing rapid, direct electron transport (Seth, & Meena, 2024).

6.6.2. Hybrid Systems

The combination of ZnO with other semiconductor materials, such as perovskites, is an exciting area of research. Perovskite-ZnO hybrid solar cells could leverage the high electron mobility of ZnO and the excellent light-absorbing properties of perovskites to create next-generation high-efficiency devices (Simandl *et al.*, 2023; Manabeng *et al.*, 2022).

6.6.3. Environmental Impact

Assessing the full life-cycle environmental impact of ZnO fabrication and usage is crucial for developing sustainable technologies. Research into "green" synthesis methods and the recyclability of materials will be a priority (Masood *et al.*, 2021; Manabeng *et al.*, 2022).

7. Conclusion

Zinc oxide nanostructures have proven to be a highly promising alternative to conventional TiO_2been use as photoanodes in Dye-Sensitized Solar Cells. Their unique properties such as high electron mobility, tunable morphology, and ease of synthesis offer significant advantages for enhancing cell performance. While challenges related to recombination losses, stability, and scalability must be addressed, ongoing research into innovative synthesis techniques and hybrid systems points to a bright future. The continued exploration of ZnO nanostructures holds immense potential for the development of highly efficient and sustainable solar energy conversion technologies.

Abbreviations

DSSC's	Dye Sensitized Solar Cells
PVD-	Physical Vapor Deposition
V_{oc}-	Open Circuit Voltage
FF-	Fill Factor
CBM	Conducting Band Minimum
J_{sc}-	Short Circuit Current Density
P_{IN}-	Power In

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Conflicts of Interest

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