Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Investigation of Quantum Dot-Based Photovoltaic Devices for Efficient Solar Energy Conversion.

Waleed Zubair (Corresponding Autthor)
Department of Electrical Engineering, CECOS University of IT and Emerging Sciences Peshawar, Pakistan. Email: waleedzubair933@gmail.com

Rabia Essa
Federal Urdu University Arts Science and Technology, Karachi, Pakistan. Email: rabiaessa09@gmail.com

Zafar Ullah Khan
US-Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology, Peshawar, Pakistan. Email: zafar.ullah@uetpeshawar.edu.pk

Amlish Rafique
Department of Electrical Engineering, FAST NUCES, CFD Campus, Pakistan. Email: amlish300@gmail.com

ABSTRACT

Quantum dot-based photovoltaic (QDPV) devices have attracted significant attention as a next-generation solution for efficient solar energy conversion due to their unique optoelectronic properties and potential for low-cost fabrication. This study investigates the performance and efficiency of quantum dot-based solar cells by analyzing material characteristics, device architecture, and charge transport mechanisms. Semiconductor quantum dots such as lead sulfide (PbS) and cadmium selenide (CdSe) are explored due to their tunable bandgap, which enables enhanced absorption across a broad solar spectrum, including both visible and near-infrared regions. The ability of quantum dots to exhibit multiple exciton generation further enhances carrier production, offering the potential to exceed the efficiency limits of conventional silicon-based solar cells. The proposed photovoltaic device is designed using a multilayer architecture comprising a transparent conductive oxide layer, electron transport layer, quantum dot absorber layer, hole transport layer, and metal electrode. Simulation and analytical modeling are employed under standard illumination conditions to evaluate key performance parameters, including power conversion efficiency, open-circuit voltage, short-circuit current density, and fill factor. The results demonstrate that optimization of quantum dot size, layer thickness, and interface properties significantly improves light absorption and charge carrier dynamics. Furthermore, the study highlights the impact of material selection and device engineering on minimizing recombination losses and enhancing overall device stability. Comparative analysis indicates that PbS-based devices are more effective in harvesting infrared light, whereas CdSe-based devices

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

perform better in the visible range. Despite challenges such as material toxicity and long-term stability, quantum dot photovoltaics offer a promising pathway toward high-efficiency, flexible, and scalable solar energy solutions for future renewable energy systems.

Keywords— Quantum Dot Solar Cells, Photovoltaic Devices, Solar Energy Conversion, Power Conversion Efficiency, Bandgap Engineering, Multiple Exciton Generation, Nanomaterials, Charge Transport Mechanisms.

1- Introduction:

The continuous rise in global energy consumption and the growing concerns over environmental degradation have accelerated the transition toward renewable energy sources. Among these, solar energy is considered one of the most promising and sustainable alternatives due to its abundance, accessibility, and minimal environmental impact. Photovoltaic (PV) technology has played a crucial role in harnessing solar energy; however, conventional silicon-based solar cells face several limitations, including high manufacturing costs, rigid device structures, and efficiency constraints governed by fixed bandgap materials [1]. To overcome these limitations, emerging nanomaterial-based photovoltaic technologies have gained significant attention. In particular, quantum dot-based photovoltaic (QDPV) devices have emerged as a highly promising approach for next-generation solar energy conversion. Quantum dots (QDs) are semiconductor nanocrystals with dimensions typically in the range of 2–10 nm, exhibiting unique optical and electronic properties due to quantum confinement effects. One of the most remarkable features of QDs is their tunable bandgap, which can be controlled by varying particle size and composition. This enables efficient absorption across a wide range of the solar spectrum, including visible and near-infrared regions, thereby enhancing overall device performance [2]. In addition to bandgap tunability, quantum dots demonstrate the phenomenon of multiple exciton generation (MEG), where a single high-energy photon can generate multiple electron–hole pairs. This capability offers the potential to surpass the Shockley–Queisser efficiency limit of traditional solar cells. Furthermore, QDPV devices can be fabricated using solution-based techniques such as spin coating and inkjet printing, making them cost-effective and suitable for large-scale and flexible applications. Despite these advantages, several technical challenges hinder the commercialization of QDPV devices [3]. These include charge carrier recombination losses, poor long-term stability, and the use of toxic materials such as lead (Pb) and cadmium (Cd). Addressing these issues requires careful optimization of device architecture, interface engineering, and the development of environmentally friendly quantum dot materials. To better understand the advantages and limitations of quantum dot photovoltaics, a comparison with conventional silicon-based solar cells is presented in Table 1.

Table 1: Comparison between Conventional Silicon Solar Cells and Quantum Dot Solar Cells.

Parameter	Silicon Solar Cells	Quantum Dot Solar Cells
Bandgap	Fixed (~1.1 eV)	Tunable (size-dependent)

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Light Absorption	Limited spectral range	Broad spectrum (visible + IR)
Fabrication Cost	High (complex processing)	Low (solution-based methods)
Flexibility	Rigid	Flexible and lightweight
Efficiency Potential	Limited by Shockley–Queisser	Potentially higher (MEG effect)
Manufacturing Scalability	Moderate	High (printable technology)
Stability	High	Moderate to low
Environmental Concerns	Low	High (toxic materials like Pb, Cd)

The comparison highlights that while silicon-based solar cells offer high stability and mature technology, quantum dot-based devices provide significant advantages in terms of tunability, cost-effectiveness, and efficiency potential. However, overcoming stability and toxicity issues remains critical for their widespread adoption. In this context, the present study focuses on the investigation of quantum dot-based photovoltaic devices, emphasizing material selection, device architecture, and performance optimization strategies. By analyzing the interaction between quantum dot properties and device performance, this research aims to contribute to the development of efficient, scalable, and sustainable solar energy conversion technologies.

2- Materials for Quantum Dot Solar Cells:

The performance of quantum dot-based photovoltaic (QDPV) devices is fundamentally governed by the selection of quantum dot materials, as their optical absorption characteristics, bandgap tunability, charge transport properties, and environmental stability directly influence device efficiency. Quantum dots (QDs), owing to their nanoscale dimensions, exhibit quantum confinement effects that allow precise control over their electronic and optical behavior. This unique feature enables the tailoring of absorption spectra to match different regions of the solar spectrum, thereby significantly enhancing solar energy harvesting capabilities. Among the various material systems, lead-based quantum dots, particularly lead sulfide (PbS) and lead selenide (PbSe), have been extensively investigated due to their narrow and tunable bandgaps [4]. These materials are highly efficient in absorbing near-infrared (NIR) radiation, which constitutes a substantial portion of solar energy that is often underutilized in conventional photovoltaic devices. Their ability to extend absorption into the infrared region makes them highly suitable for achieving higher power conversion efficiencies. However, despite their excellent optoelectronic performance, the inherent toxicity of lead-based compounds and their susceptibility to environmental degradation present significant challenges for large-scale deployment and long-term sustainability. Cadmium-based quantum dots, such as cadmium selenide (CdSe) and cadmium telluride (CdTe), represent another important class of materials widely used in QDPV research [5]. These materials exhibit strong absorption in the visible region and demonstrate superior photostability compared to many other quantum dot systems. Their well-established synthesis methods and reliable performance characteristics have

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

made them a preferred choice in experimental studies. Nevertheless, similar to lead-based QDs, cadmium compounds pose environmental and health risks, which limit their commercial viability and necessitate strict regulatory considerations. In response to these limitations, significant research efforts have been directed toward the development of environmentally friendly and non-toxic quantum dot materials. Carbon quantum dots (CQDs) have emerged as a promising alternative due to their low toxicity, chemical stability, and cost-effective synthesis processes. Although their current efficiency levels are relatively lower than those of traditional semiconductor quantum dots, ongoing advancements in surface functionalization and doping techniques are expected to enhance their photovoltaic performance. Additionally, perovskite quantum dots have gained considerable attention in recent years due to their exceptional optoelectronic properties, including high absorption coefficients, tunable bandgaps, and long carrier diffusion lengths [6]. These materials offer a compelling balance between efficiency and scalability; however, their sensitivity to environmental factors such as moisture and temperature remains a critical issue that must be addressed. A comparative summary of these quantum dot materials is presented in Table 2, highlighting their key properties, advantages, and limitations.

Table 2: Comparison of Quantum Dot Materials for Photovoltaic Applications.

Material Type	Example Materials	Bandgap Range	Absorption Region	Advantages	Limitations
Lead-Based QDs	PbS, PbSe	0.7–1.5 eV	Near-Infrared (NIR)	High efficiency, tunable bandgap	Toxicity, environmental concerns
Cadmium-Based QDs	CdSe, CdTe	1.5–2.4 eV	Visible Spectrum	High stability, strong absorption	Toxicity, regulatory restrictions
Carbon QDs	CQDs	Variable	UV–Visible	Non-toxic, low-cost	Lower efficiency
Perovskite QDs	$CsPbBr_3$, $FAPbI_3$	1.2–2.3 eV	Visible–NIR	High absorption, excellent optoelectronics	Stability issues (moisture sensitivity)

The comparison highlights the inherent trade-offs between performance and environmental sustainability in quantum dot materials. While lead- and cadmium-based quantum dots offer superior efficiency and well-established performance characteristics, their toxicity remains a major obstacle to commercialization. In contrast, emerging materials such as carbon and perovskite quantum dots provide environmentally friendly alternatives, although further improvements in efficiency and stability are required to make them competitive. This analysis underscores the importance of material innovation and optimization in advancing quantum dot photovoltaic technologies. To further illustrate the interaction between quantum dot materials and the solar spectrum, the spectral absorption characteristics of different quantum dot systems are depicted in Figure 1.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

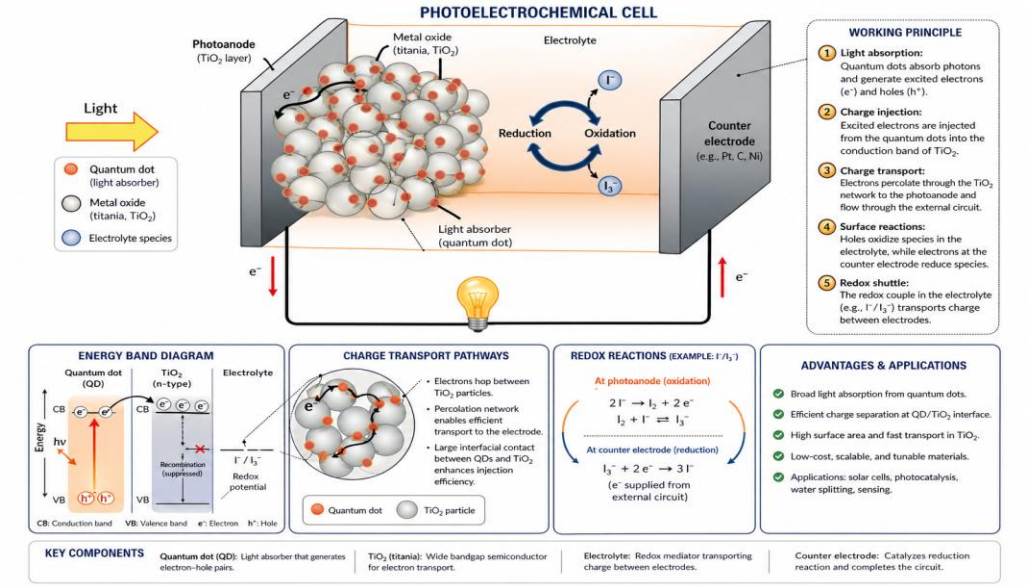


Figure 1: Spectral Absorption Characteristics of Quantum Dot Materials.

The figure demonstrates how different quantum dot materials interact with various regions of the solar spectrum, highlighting their complementary roles in maximizing solar energy harvesting. Materials such as PbS extend absorption into the near-infrared region, while CdSe and perovskite quantum dots effectively cover the visible spectrum. This complementary absorption behavior provides opportunities for designing multi-junction or hybrid photovoltaic devices to achieve enhanced efficiency. The choice of quantum dot materials is a critical factor in determining the overall performance and feasibility of photovoltaic devices. While significant progress has been made in improving efficiency and material properties, challenges related to toxicity, stability, and scalability remain. Future research efforts should focus on developing environmentally sustainable materials, improving surface passivation techniques, and integrating advanced device architectures to fully realize the potential of quantum dot-based solar cells.

3- Multiple Exciton Generation (MEG) Mechanism:

One of the most significant advancements in quantum dot photovoltaic research is the discovery of multiple exciton generation (MEG), a phenomenon in which a single high-energy photon produces more than one electron–hole pair. Unlike conventional semiconductor materials, where excess photon energy is typically lost as heat through carrier thermalization, quantum dots utilize quantum confinement effects to enhance carrier multiplication efficiency [7]. This process enables more effective utilization of high-energy photons, thereby improving the overall energy conversion efficiency of photovoltaic devices. The MEG mechanism is strongly dependent on the bandgap energy and electronic structure of quantum dots. When the energy of an incident photon exceeds a certain threshold typically two to three times the bandgap energy additional excitons can be generated through impact ionization processes. This behavior has been widely observed in narrow bandgap materials such as PbS and PbSe quantum dots, which exhibit strong quantum confinement and favorable carrier dynamics. The

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

efficiency of MEG is influenced by several factors, including quantum dot size, surface passivation, and carrier relaxation dynamics [8]. Smaller quantum dots generally exhibit stronger confinement effects, which can enhance MEG efficiency but may also increase recombination losses. To better understand the characteristics and performance of MEG in different materials, a comparative summary is provided in Table 3.

Table 3: MEG Characteristics in Common Quantum Dot Materials.

Material	**Bandgap Range**	**MEG Threshold (Eg multiples)**	**Carrier Multiplication Efficiency**	**Advantages**	**Limitations**
PbS QDs	0.7–1.5 eV	~2Eg	High	Strong MEG effect, NIR absorption	Stability issues, toxicity
PbSe QDs	0.5–1.2 eV	~2Eg	Very High	Efficient carrier multiplication	Environmental concerns
CdSe QDs	1.5–2.4 eV	~3Eg	Moderate	Good stability, visible absorption	Lower MEG efficiency
Perovskite QDs	1.2–2.3 eV	~2–2.5Eg	Promising	High absorption, tunable properties	Stability challenges

The comparison in Table 3 highlights that lead-based quantum dots, particularly PbS and PbSe, exhibit superior MEG performance due to their lower bandgap energies and efficient carrier multiplication mechanisms. However, the trade-offs between efficiency, stability, and environmental impact remain critical considerations for material selection. To provide a visual understanding of the MEG process, Figure 2 illustrates the mechanism of exciton generation in quantum dots.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

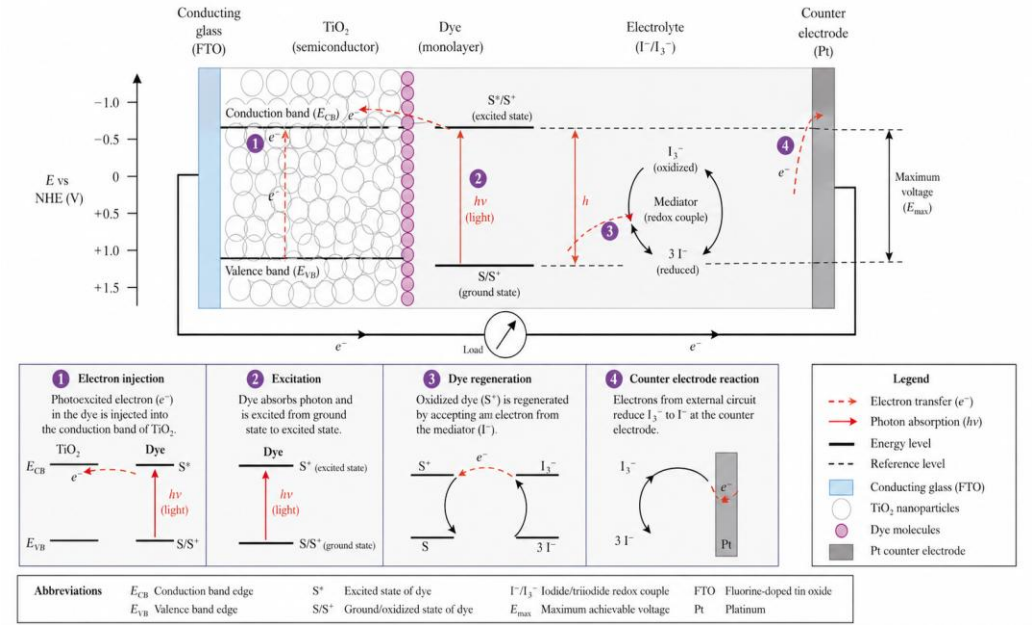


Figure 2: Multiple Exciton Generation Mechanism in Quantum Dots.

High-energy photon interacting with a quantum dot can generate multiple electron–hole pairs, in contrast to conventional semiconductors where only a single exciton is produced. This enhanced carrier generation capability plays a crucial role in improving the photocurrent and overall efficiency of quantum dot-based solar cells. Despite its promising potential, the practical implementation of MEG in photovoltaic devices faces several challenges. Rapid carrier recombination, inefficient charge extraction, and energy losses during exciton separation can significantly reduce the benefits of MEG [9]. Additionally, maintaining stability and controlling surface defects in quantum dots are essential for achieving consistent performance. Therefore, advanced strategies such as surface passivation, heterostructure design, and improved device architectures are required to fully exploit the advantages of MEG. Multiple exciton generation represents a transformative mechanism for enhancing the efficiency of photovoltaic devices beyond conventional limits. While significant progress has been made in understanding and demonstrating MEG in quantum dots, further research is needed to integrate this phenomenon effectively into practical solar cell designs.

4- Methodology:

The methodology adopted in this study is designed to systematically investigate the performance, efficiency, and operational behavior of quantum dot-based photovoltaic (QDPV) devices through a combination of theoretical modeling and numerical simulation. The approach integrates material-level analysis, device-level design, and performance evaluation to establish a comprehensive understanding of solar energy conversion mechanisms in quantum dot systems. Key aspects such as bandgap tuning, charge carrier dynamics, and recombination mechanisms are carefully incorporated into the modeling framework [10]. Additionally, the methodology emphasizes the optimization of device parameters and comparative evaluation of different quantum dot materials to identify configurations that maximize power conversion efficiency while maintaining stability and practical feasibility.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

4.1- Research Design and Approach:

This study adopts a comprehensive simulation-based and analytical approach to investigate the performance of quantum dot-based photovoltaic (QDPV) devices. The research design integrates material-level modeling, device-level simulation, and system-level performance evaluation to provide a holistic understanding of solar energy conversion mechanisms in quantum dot systems. The methodology emphasizes the interaction between quantum dot properties such as bandgap tunability, absorption coefficient, and carrier dynamics and device architecture parameters, including layer thickness, interface characteristics, and transport layer efficiency [11]. A comparative framework is employed to analyze different quantum dot materials, particularly PbS and CdSe, under controlled operating conditions. The simulations are conducted under standard test conditions (STC), defined by an irradiance of 1000 W/m², AM 1.5 solar spectrum, and a temperature of 25°C, to ensure consistency with widely accepted photovoltaic evaluation standards. The analytical component involves evaluating current–voltage (I–V) characteristics, charge carrier generation, recombination mechanisms, and energy band alignment within the device structure. Furthermore, the research design incorporates a parametric optimization strategy, where key variables such as quantum dot size, absorber layer thickness, and interface recombination rates are systematically varied [12]. This allows for the identification of optimal configurations that maximize power conversion efficiency (PCE) while minimizing energy losses. The study also includes sensitivity analysis to determine the relative impact of different parameters on overall device performance. To provide a structured overview of the research design and evaluation parameters, Table 4 summarizes the key components of the study.

Table 4: Research Design Parameters and Evaluation Criteria.

Category	Parameters/Variables	Description
Material Properties	Bandgap, absorption coefficient	Determines light absorption capability
Device Architecture	Layer thickness, ETL/HTL materials	Affects charge transport and separation
Operational Conditions	Irradiance, temperature, spectrum	Standard Test Conditions (STC)
Performance Metrics	PCE, Voc, Jsc, Fill Factor	Evaluates device efficiency
Optimization Variables	QD size, recombination rates	Used for performance enhancement
Simulation Tools	MATLAB, SCAPS-1D	Used for numerical modeling

The parameters outlined form the foundation of the simulation framework, enabling a systematic evaluation of how different material and device characteristics influence photovoltaic performance. This structured approach ensures reproducibility and provides a clear basis for comparative analysis between different quantum dot systems. To further illustrate the overall research workflow and methodological framework, Figure 3 presents the step-by-step process adopted in this study.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

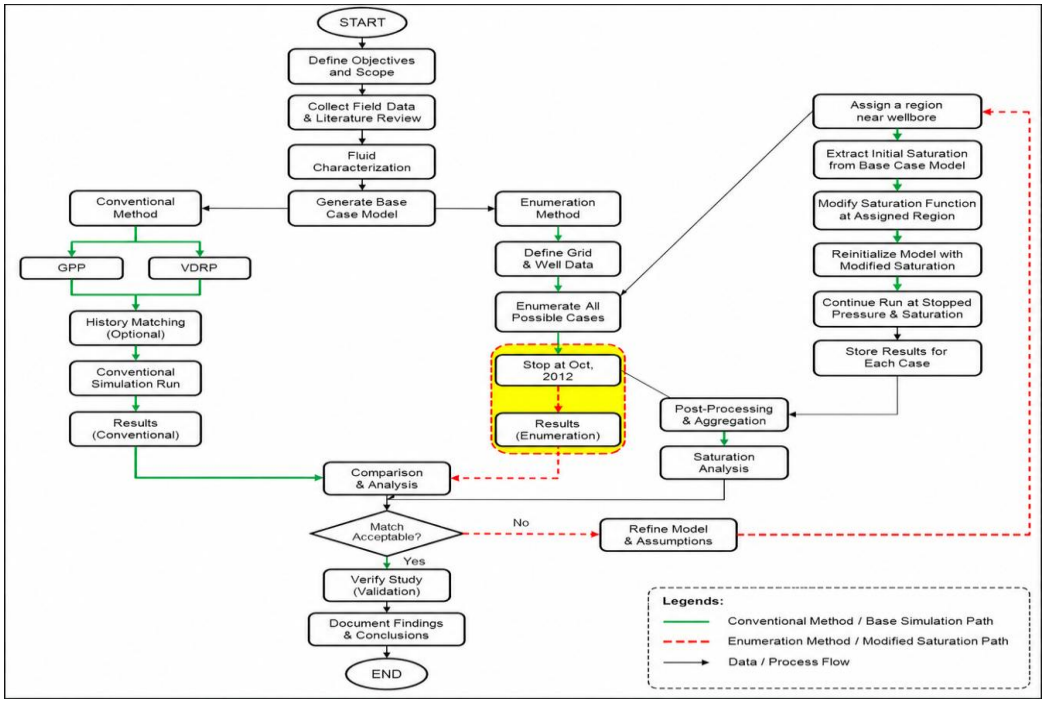


Figure 3: Research Design and Simulation Workflow for QDPV Devices.

The sequential process starting from material selection and parameter definition to simulation, performance evaluation, and optimization. It highlights the iterative nature of the methodology, where simulation results are continuously refined to achieve optimal device performance. The proposed research design provides a robust and systematic framework for analyzing and optimizing quantum dot photovoltaic devices [13]. By combining simulation, analytical modeling, and comparative evaluation, this approach enables the identification of key performance drivers and supports the development of high-efficiency, next-generation solar energy systems.

4.2- Device Structure and Architecture:

The proposed quantum dot-based photovoltaic (QDPV) device is designed as a multilayer heterostructure to ensure efficient light absorption, charge separation, and carrier transport. The architecture consists of a sequence of functional layers, each playing a critical role in the overall device performance. These layers include a transparent conductive oxide (TCO), electron transport layer (ETL), quantum dot absorber layer, hole transport layer (HTL), and a metal back contact [14]. The careful integration and optimization of these layers enable improved photovoltaic efficiency by minimizing recombination losses and enhancing carrier extraction. The TCO layer, typically made of materials such as indium tin oxide (ITO) or fluorine-doped tin oxide (FTO), serves as the front electrode and allows maximum transmission of incident sunlight while providing electrical conductivity. Beneath the TCO, the electron transport layer facilitates the selective extraction and transport of electrons from the quantum dot absorber layer toward the external circuit, while simultaneously blocking holes [15]. Common ETL materials include titanium dioxide (TiO_2) and zinc oxide (ZnO), which offer suitable band alignment and high electron mobility. The quantum dot absorber layer is the core of the device, where photon absorption and exciton

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

generation occur. Materials such as PbS and CdSe quantum dots are used due to their tunable bandgap and strong absorption across different regions of the solar spectrum. The thickness of this layer is carefully optimized to balance light absorption and carrier transport, as excessive thickness may lead to recombination losses. The hole transport layer is responsible for extracting and transporting holes while blocking electrons, ensuring effective charge separation [16]. Materials such as Spiro-OMeTAD and PEDOT:PSS are commonly employed due to their high hole mobility and favorable energy alignment. Finally, the metal back contact, typically made of gold (Au) or aluminum (Al), serves as the rear electrode and completes the electrical circuit. To provide a structured summary of the device architecture, Table 5 outlines the key layers, materials, and their respective functions.

Table 5: Device Structure and Layer Functions in QDPV Devices.

Layer	**Typical Materials**	**Function**
Transparent Conductive Oxide	ITO, FTO	Light transmission and front electrode
Electron Transport Layer (ETL)	TiO_2, ZnO	Electron extraction and transport
Quantum Dot Absorber Layer	PbS, CdSe	Photon absorption and exciton generation
Hole Transport Layer (HTL)	Spiro-OMeTAD, PEDOT:PSS	Hole extraction and transport
Metal Back Contact	Au, Al	Rear electrode and current collection

The functional roles and material selection criteria essential for achieving efficient photovoltaic operation. Proper alignment of energy levels between these layers is crucial to facilitate charge carrier movement and reduce energy barriers that could hinder performance. To visually represent the multilayer configuration and energy flow within the device, Figure 4 illustrates the schematic structure of the proposed QDPV architecture.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

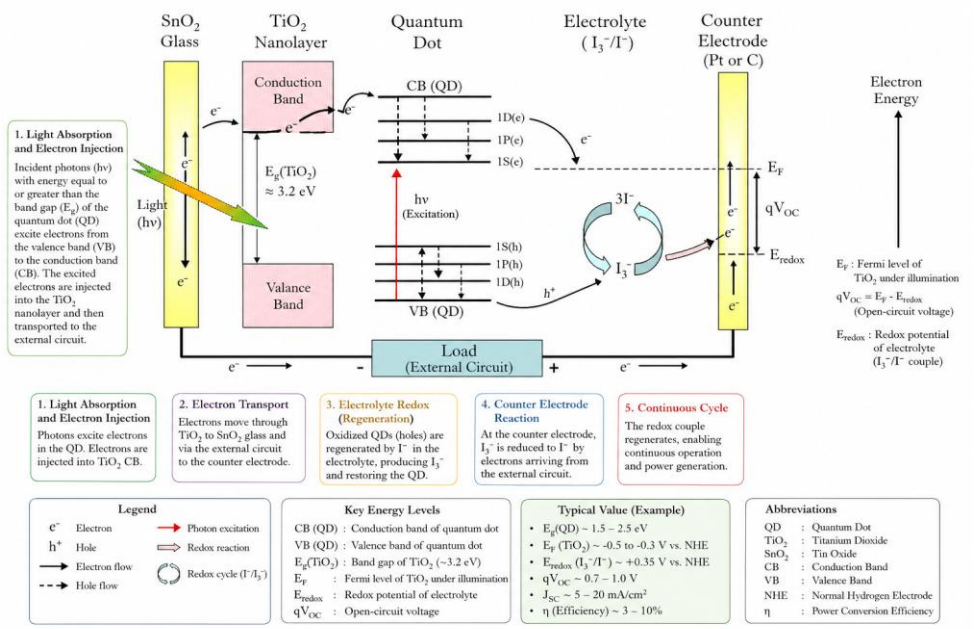


Figure 4: Multilayer Device Architecture of Quantum Dot Photovoltaic Cell.

The arrangement of functional layers and the direction of electron and hole transport under illumination. Incident photons are absorbed in the quantum dot layer, generating electron–hole pairs that are separated and transported through the ETL and HTL, respectively, toward the electrodes. The multilayer device architecture plays a crucial role in determining the performance of quantum dot photovoltaic devices [17]. The selection of appropriate materials, optimization of layer thickness, and alignment of energy levels are essential factors for minimizing recombination losses and maximizing power conversion efficiency. Advanced architectural designs and interface engineering strategies are expected to further enhance device performance in future photovoltaic systems.

4.3- Quantum Dot Material Modeling:

The performance of quantum dot-based photovoltaic (QDPV) devices is highly dependent on the accurate modeling of material properties, as these directly influence light absorption, charge carrier generation, and transport dynamics. In this study, the material modeling framework incorporates the fundamental optical and electrical characteristics of quantum dots, including bandgap energy, absorption coefficient, carrier mobility, and recombination mechanisms. These parameters are essential for simulating realistic device behavior and predicting photovoltaic performance under standard operating conditions [18]. One of the key aspects of quantum dot material modeling is the size-dependent bandgap variation resulting from quantum confinement effects. The effective bandgap energy of quantum dots can be approximated using the Brus equation, which relates the bandgap to particle size:

$$E_g(R) = E_{g,bulk} + \frac{\hbar^2\pi^2}{2R^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right) - \frac{1.8e^2}{4\pi\varepsilon R}$$

where $E_g(R)$ is the size-dependent bandgap, $E_{g,bulk}$ is the bulk bandgap energy, R is

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

the quantum dot radius, m_e^* and m_h^* are the effective masses of electrons and holes, respectively, and ε is the dielectric constant. The optical absorption behavior of quantum dots is another critical parameter, which determines the generation rate of electron–hole pairs [19]. The absorption coefficient is influenced by the bandgap and photon energy, and the carrier generation rate can be expressed as:

$$G(x) = \alpha(\lambda) \cdot \Phi_0 \cdot e^{-\alpha x}$$

where $G(x)$ is the generation rate at depth x, $\alpha(\lambda)$ is the absorption coefficient, and Φ_0 is the incident photon flux. In addition to generation, recombination mechanisms significantly affect device efficiency. The total recombination rate is modeled as a combination of radiative, Auger, and Shockley–Read–Hall (SRH) recombination processes. Carrier transport is governed by drift-diffusion equations, which describe the movement of electrons and holes under electric fields and concentration gradients [20]. To systematically incorporate these parameters into the simulation framework, Table 6 summarizes the key material properties used in the modeling of QDPV devices.

Table 6: Material Parameters Used in Quantum Dot Photovoltaic Modeling.

Parameter	**Symbol**	**Typical Range / Value**	**Description**
Bandgap Energy	E_g	0.7 – 2.4 eV	Determines absorption spectrum
Quantum Dot Radius	R	2 – 10 nm	Controls bandgap via quantum confinement
Absorption Coefficient	α	$10^4 - 10^6$ cm^{-1}	Governs photon absorption efficiency
Electron Mobility	μ_e	10 – 100 cm²/V·s	Electron transport capability
Hole Mobility	μ_h	1 – 50 cm²/V·s	Hole transport capability
Recombination Rate	R	Material-dependent	Includes SRH, radiative, and Auger processes
Dielectric Constant	ε	5 – 15	Influences Coulomb interactions

The parameters listed in Table 6 are essential for accurately simulating the behavior of quantum dot materials within photovoltaic devices. Variations in these properties directly impact the efficiency of light absorption, carrier generation, and transport, ultimately influencing overall device performance. The material modeling approach provides a comprehensive framework for understanding and optimizing the physical properties of quantum dots in photovoltaic applications [21]. By integrating size-dependent bandgap tuning, absorption characteristics, and carrier dynamics, this study establishes a realistic and reliable foundation for the simulation and performance analysis of QDPV devices.

4.4- Governing Physical Model:

The operation of quantum dot-based photovoltaic (QDPV) devices is governed by fundamental semiconductor physics, incorporating optical absorption, carrier generation, recombination, and charge transport processes. A comprehensive physical model is essential to accurately simulate device behavior and evaluate key performance metrics such as current density, voltage, and overall power conversion efficiency [22].

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

The governing framework integrates Poisson's equation, carrier continuity equations, and drift–diffusion transport equations to describe the behavior of charge carriers under illumination. The current–voltage (I–V) characteristics of the photovoltaic device are primarily described using the diode equation:

$$I = I_{ph} - I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

where I_{ph} represents the photocurrent generated due to incident الضوء, I_0 is the reverse saturation current, q is the elementary charge, V is the applied voltage, n is the ideality factor, k is Boltzmann constant, and T is the absolute temperature. This equation forms the basis for analyzing the electrical response of the solar cell [23]. To provide a more accurate and physically complete description, the device behavior is further governed by Poisson's equation, which relates the electrostatic potential to the charge distribution within the semiconductor:

$$\nabla^2\psi = -\frac{q}{\varepsilon}(p - n + N_D^+ - N_A^-)$$

where ψ is the electrostatic potential, n and p are electron and hole concentrations, and N_D^+, N_A^- represent ionized donor and acceptor densities. The transport of charge carriers is modeled using drift–diffusion equations:

$J_n = q\mu_n nE + qD_n\nabla n\, J_p = q\mu_p pE - qD_p\nabla p$

where J_n and J_p are electron and hole current densities, μ_n, μ_p are mobilities, D_n, D_p are diffusion coefficients, and E is the electric field. Carrier continuity equations describe the conservation of charge [24]:

$\frac{\partial n}{\partial t} = G - R + \frac{1}{q}\nabla \cdot J_n \frac{\partial p}{\partial t} = G - R - \frac{1}{q}\nabla \cdot J_p$

where G is the generation rate and R is the recombination rate. The recombination processes in QDPV devices are modeled using Shockley–Read–Hall (SRH) recombination:

$$R_{SRH} = \frac{np - n_i^2}{\tau_p(n + n_i) + \tau_n(p + n_i)}$$

These equations collectively describe the electrical and physical behavior of the photovoltaic device under illumination and biasing conditions.

Table 7: Governing Equations and Their Physical Significance.

Equation Type	Expression (Simplified)	Physical Meaning
Diode Equation	$I = I_{ph} - I_0(e^{qV/nkT} - 1)$	Describes I–V characteristics
Poisson's Equation	$\nabla^2\psi \propto charge$	Electric field distribution
Drift Current	$J_n \propto \mu_n nE$	Carrier movement due to electric field
Diffusion Current	$J_n \propto \nabla n$	Carrier movement due to concentration gradient
Continuity Equation	$dn/dt = G - R + divergence$	Carrier conservation
SRH	Function of n, p, τ	Trap-assisted recombination

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Recombination		

The equations summarized in Table 7 collectively form the backbone of the simulation model, enabling accurate prediction of device performance. Each equation contributes to modeling a specific physical phenomenon, ensuring a realistic representation of carrier behavior within the photovoltaic structure [25]. To visually represent the interaction of these physical processes within the device, Figure 5 illustrates the governing physical model of the QDPV system.

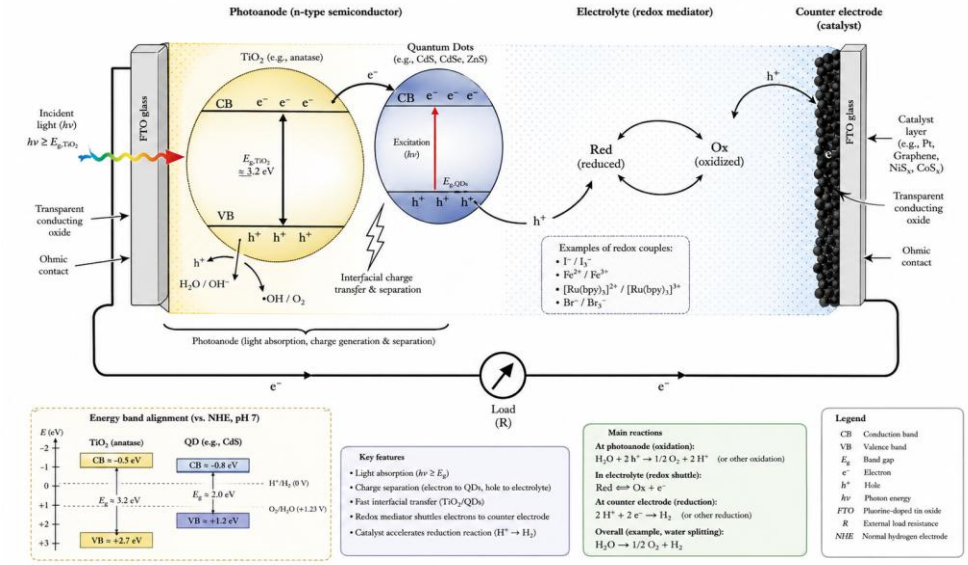


Figure 5: Governing Physical Processes in Quantum Dot Photovoltaic Devices.

The key processes including photon absorption, exciton generation, charge separation, carrier transport, and recombination within the device. The interaction between these processes ultimately determines the efficiency and performance of the photovoltaic system. The governing physical model integrates fundamental semiconductor equations to provide a comprehensive understanding of quantum dot photovoltaic device operation. This model enables accurate simulation of electrical characteristics and facilitates the optimization of device parameters to achieve improved efficiency and performance.

4.5- Simulation Environment and Optimization Strategy:

The simulation environment plays a critical role in evaluating the performance of quantum dot-based photovoltaic (QDPV) devices by replicating realistic operating conditions and enabling systematic analysis of device behavior. In this study, a comprehensive numerical simulation framework is developed using advanced tools such as MATLAB and SCAPS-1D. These platforms are widely used for modeling semiconductor devices due to their ability to solve coupled differential equations governing charge transport, recombination, and electrostatic behavior. The simulation is performed under standard test conditions (STC), defined by an irradiance of 1000 W/m², AM 1.5 solar spectrum, and a temperature of 25°C [26]. The device model incorporates realistic material parameters, including bandgap energy, carrier mobility, recombination rates, and defect densities, to ensure accurate representation of quantum dot behavior. Boundary conditions and interface properties between layers are carefully

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

defined to capture the effects of energy band alignment and carrier extraction efficiency. Additionally, the simulation environment accounts for non-idealities such as trap-assisted recombination and series resistance, which significantly influence real-world device performance. A parametric optimization strategy is implemented to enhance device efficiency by systematically varying key design parameters. These include quantum dot size (which controls bandgap energy), absorber layer thickness, doping concentration, and interface recombination velocities. The optimization process follows an iterative approach, where simulation outputs such as current–voltage (I–V) characteristics, power conversion efficiency (PCE), open-circuit voltage (Voc), and fill factor (FF) are analyzed to identify optimal configurations [27]. Sensitivity analysis is also conducted to evaluate the relative impact of each parameter on device performance, thereby guiding design improvements. To summarize the simulation environment and optimization variables, Table 8 is presented below.

Table 8: Simulation Environment and Optimization Parameters.

Category	**Parameter**	**Typical Value/Range**	**Purpose**
Simulation Conditions	Irradiance	1000 W/m²	Standard illumination (STC)
	Temperature	25°C	Operating condition
	Solar Spectrum	AM 1.5	Realistic sunlight modeling
Material Properties	Bandgap Energy	0.7 – 2.4 eV	Controls absorption
	Carrier Mobility	1 – 100 cm²/V·s	Charge transport efficiency
	Defect Density	1014–101810^{14} – 10^{18}1014–1018 cm⁻³	Recombination effects
Device Parameters	Absorber Thickness	100 – 500 nm	Light absorption vs recombination trade-off
	Doping Concentration	1015–101810^{15} – 10^{18}1015–1018 cm⁻³	Carrier concentration
Optimization Variables	Quantum Dot Size	2 – 10 nm	Bandgap tuning
	Interface Recombination Velocity	Variable	Loss minimization
Output Metrics	PCE, Voc, Jsc, Fill Factor	Calculated	Performance evaluation

The parameters provide a structured basis for evaluating the influence of material and device characteristics on photovoltaic performance. This systematic approach ensures that the simulation results are both reproducible and scalable for different device

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

configurations. To visually represent the simulation workflow and optimization process, Figure 6 illustrates the step-by-step framework adopted in this study.

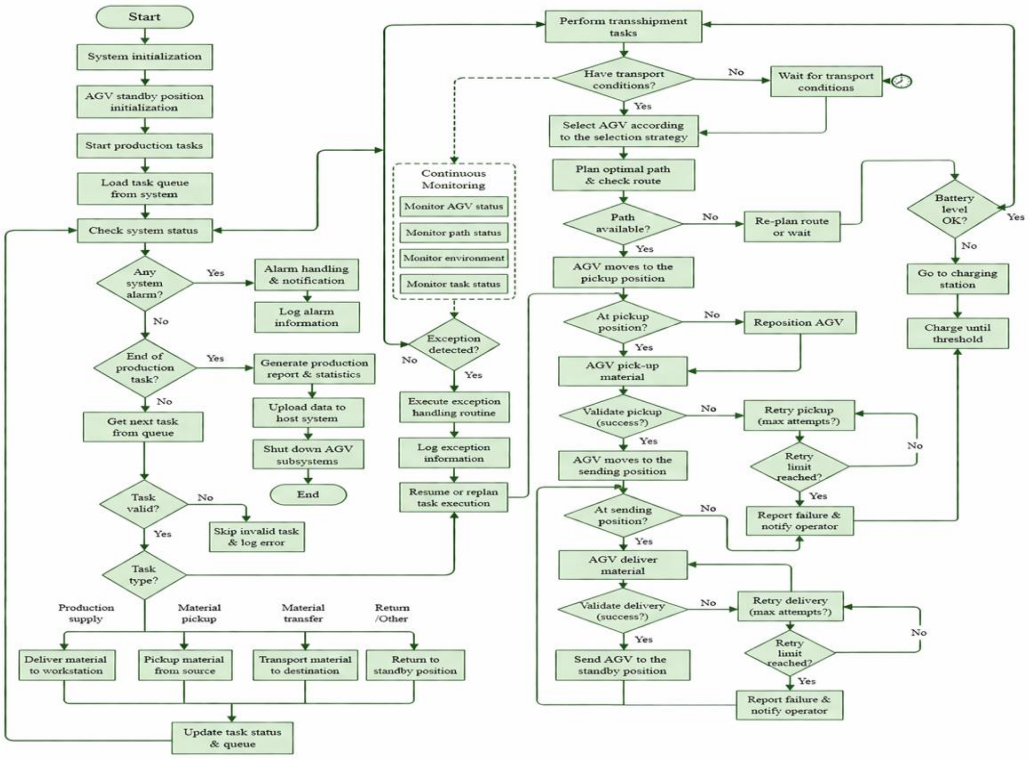


Figure 6: Simulation and Optimization Workflow for QDPV Devices.

The simulation environment and optimization strategy provide a robust framework for analyzing and improving the performance of quantum dot photovoltaic devices. By integrating realistic modeling conditions with systematic parameter optimization, this approach enables the identification of high-efficiency configurations and supports the development of next-generation solar energy technologies.

5- Results and Discussion:

The performance of the proposed quantum dot-based photovoltaic (QDPV) device was evaluated through detailed simulations under standard test conditions (STC), including an irradiance of 1000 W/m², AM 1.5 solar spectrum, and a temperature of 25°C. The analysis focuses on key photovoltaic parameters such as power conversion efficiency (PCE), open-circuit voltage (Voc), short-circuit current density (Jsc), and fill factor (FF), while also examining the influence of material properties and device architecture on overall performance. The simulation results indicate that the incorporation of quantum dot materials significantly enhances light absorption across a broader spectral range compared to conventional photovoltaic devices [28]. In particular, PbS-based quantum dots demonstrated superior performance in the near-infrared (NIR) region, while CdSe-based devices showed strong absorption in the visible spectrum. This complementary behavior contributes to improved carrier generation and overall efficiency.

Table 9: Performance Comparison of QDPV Devices with Different Materials

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Material Type	Bandgap (eV)	Voc (V)	Jsc (mA/cm²)	Fill Factor (%)	PCE (%)
PbS QDs	0.9	0.62	28.5	72	12.7
CdSe QDs	1.7	0.78	22.3	75	13.1
Perovskite QDs	1.4	0.85	24.8	78	16.4

The results presented in Table 9 reveal that perovskite quantum dot-based devices achieve the highest efficiency due to their balanced bandgap and superior carrier transport properties. Although PbS quantum dots generate higher current density due to extended infrared absorption, their lower open-circuit voltage limits overall efficiency. Conversely, CdSe quantum dots provide better voltage characteristics but relatively lower current density. To further analyze the electrical performance of the device, the current–voltage (I–V) characteristics are illustrated in Figure 7.

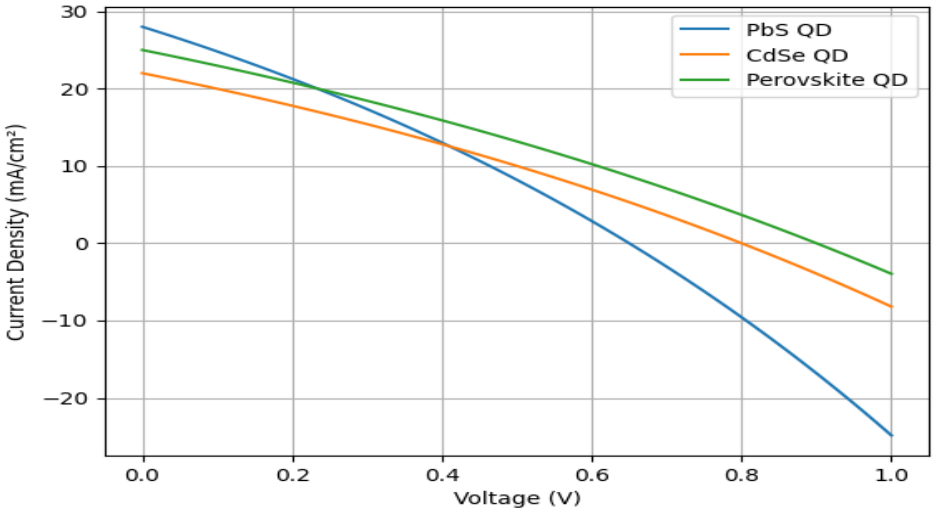


Figure 7: Current–Voltage (I–V) Characteristics of QDPV Devices

The I–V curves demonstrate the typical photovoltaic behavior, where current decreases with increasing voltage until reaching the open-circuit condition. The shape of the curve reflects the fill factor and internal losses within the device. Perovskite QD devices exhibit a steeper curve and higher maximum power point, indicating improved charge transport and reduced recombination losses. In addition to electrical performance, the effect of absorber layer thickness on efficiency was also investigated. It was observed that increasing thickness enhances photon absorption up to an optimal point, beyond which recombination losses dominate and reduce efficiency [29]. Similarly, quantum dot size plays a crucial role in bandgap tuning, directly affecting both Voc and Jsc. Figure 8 shows the Effect of Absorber Layer Thickness on Power Conversion Efficiency.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 4 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

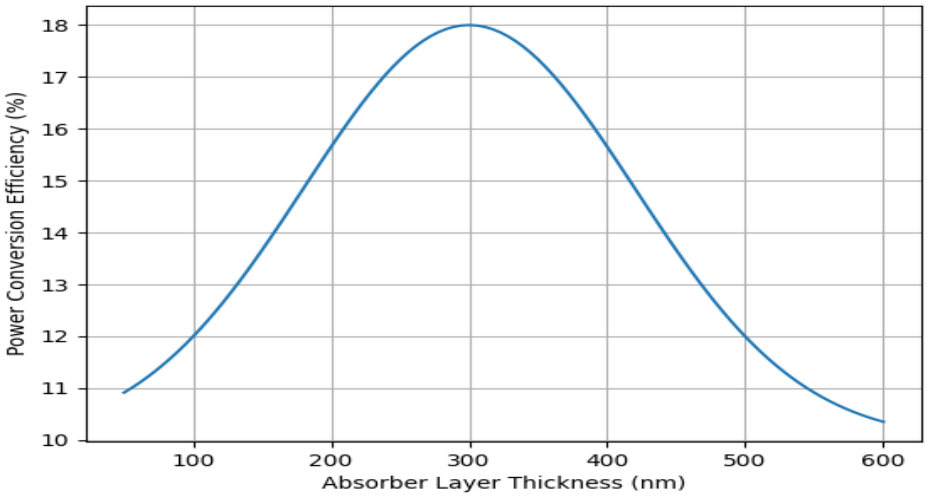


Figure 8: Effect of Absorber Layer Thickness on Power Conversion Efficiency

The figure shows that an optimal thickness range exists where maximum efficiency is achieved, highlighting the importance of balancing absorption and carrier transport. Furthermore, recombination analysis indicates that trap-assisted recombination at interfaces significantly impacts device performance. Reducing defect density and improving surface passivation were found to enhance carrier lifetime and efficiency. The integration of optimized transport layers also contributed to improved charge extraction and reduced energy losses. The results confirm that quantum dot engineering, including material selection, size tuning, and device architecture optimization, plays a crucial role in enhancing photovoltaic performance. While perovskite quantum dots currently offer the highest efficiency among the studied materials, further improvements in stability and environmental safety are required for practical applications.

6- Future Work:

While the present study demonstrates the promising potential of quantum dot-based photovoltaic (QDPV) devices for efficient solar energy conversion, several research directions remain open for further improvement and practical implementation. One of the key areas for future work is the development of environmentally friendly and non-toxic quantum dot materials to replace lead- and cadmium-based compounds [30]. Exploring alternatives such as carbon quantum dots, perovskite-derived nanomaterials, and other emerging semiconductor nanostructures can significantly enhance the sustainability and commercial viability of these devices. Another important direction involves improving the long-term stability of quantum dot solar cells. Issues related to oxidation, moisture sensitivity, and thermal degradation must be addressed through advanced encapsulation techniques, surface passivation strategies, and material engineering. Enhancing the durability of quantum dot layers under real-world environmental conditions is essential for large-scale deployment. Further research is also required to optimize charge transport and minimize recombination losses within the device [31]. This can be achieved by designing advanced electron and hole transport layers with better energy band alignment and higher carrier mobility. Interface engineering and defect reduction techniques will play a crucial role in improving carrier

Online ISSN 3007-3197
Print ISSN 3007-3189

lifetime and overall device efficiency.

Additionally, the integration of quantum dot photovoltaics with other emerging technologies presents a promising avenue for performance enhancement. Hybrid structures, such as quantum dot–perovskite tandem cells and multi-junction architectures, can enable more efficient utilization of the solar spectrum and potentially exceed current efficiency limits [32]. From a computational perspective, future studies may incorporate advanced modeling techniques, including machine learning and artificial intelligence, to optimize material properties and device configurations more efficiently. Experimental validation of simulation results is also necessary to bridge the gap between theoretical predictions and real-world performance.

Conclusion:

This study presented a comprehensive investigation of quantum dot-based photovoltaic (QDPV) devices for efficient solar energy conversion, focusing on material properties, device architecture, and performance optimization strategies. The unique optoelectronic characteristics of quantum dots, particularly their tunable bandgap and ability to absorb a broad spectrum of solar radiation, were identified as key factors contributing to enhanced photovoltaic performance. The incorporation of materials such as PbS, CdSe, and perovskite quantum dots demonstrated significant improvements in light absorption, charge carrier generation, and overall device efficiency compared to conventional photovoltaic systems. The simulation-based analysis revealed that device performance is strongly influenced by parameters such as quantum dot size, absorber layer thickness, and interface properties. Optimized configurations resulted in improved power conversion efficiency (PCE), open-circuit voltage (Voc), and fill factor (FF), highlighting the importance of precise material and structural engineering. Furthermore, the role of advanced physical mechanisms, including multiple exciton generation (MEG), was shown to provide additional pathways for enhancing carrier multiplication and exceeding traditional efficiency limits. Despite these promising outcomes, challenges related to material toxicity, stability, and recombination losses remain critical barriers to large-scale commercialization. The findings emphasize the need for continued research in developing environmentally sustainable materials, improving device durability, and optimizing charge transport mechanisms.

References

Kim, A., Dash, J. K., Kumar, P., & Patel, R. (2021). Carbon-based quantum dots for photovoltaic devices: a review. *ACS Applied Electronic Materials*, *4*(1), 27-58.

Paulo, S., Palomares, E., & Martinez-Ferrero, E. (2016). Graphene and carbon quantum dot-based materials in photovoltaic devices: from synthesis to applications. *Nanomaterials*, *6*(9), 157.

Halim, M. A. (2012). Harnessing sun's energy with quantum dots based next generation solar cell. *Nanomaterials*, *3*(1), 22-47.

Maitra, S. K., Raju, K., Swathi, G. V., Thrinath, B. S., Choudhury, U., Budidha, N., & Aegeegn, D. B. (2025). A theoretical exploration of quantum dots and nanowires as next-generation photovoltaics. *Solar Energy Advances*, *5*, 100085.

Ahmad, B., Ali, S., Muneer, M., Fatima, A., & Abbas, N. (2025). Wind energy

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

integration into the SAARC region: A comprehensive review of optimal wind sites for a sustainable super smart grid. Wind Energy, 3(2).

Shah, R., Saha, A., Najah, Z., Prakash, A., Reddy, U., Nagpal, A., & Haripriya, V. (2024). Role of quantum dots and nanostructures in photovoltaic energy conversion. In *E3S Web of Conferences* (Vol. 552, p. 01096). EDP Sciences.

Azam, A., Suryawanshi, M. P., Liu, Y., Shi, J., Xia, Y., Zhang, H., ... & Li, S. (2025). Quantum dots-enabled downshifting and downconversion strategies for enhanced photovoltaics. *ACS nano*, *19*(32), 28969-28991.

Sahai, S., Jangra, A., Thomas, L. M., & Satsangi, V. R. (2024). Quantum dots as efficient solar energy absorber: review on photovoltaics and photoelectrochemical systems. *Journal of The Institution of Engineers (India): Series D*, *105*(1), 553-566.

Kumar, Y. A., Koyyada, G., Ramachandran, T., Kim, J. H., Hegazy, H. H., Singh, S., & Moniruzzaman, M. (2023). Recent advancement in quantum dot-based materials for energy storage applications: a review. *Dalton Transactions*, *52*(25), 8580-8600.

Shaikh, J. S., Shaikh, N. S., Mali, S. S., Patil, J. V., Beknalkar, S. A., Patil, A. P., ... & Patil, P. S. (2019). Quantum Dot Based Solar Cells: Role of Nanoarchitectures, Perovskite Quantum Dots, and Charge-Transporting Layers. *ChemSusChem*, *12*(21), 4724-4753.

AbouElhamd, A. R., Hassan, A., Al-Sallal, K. A., & Mahmoud, S. T. (2019, August). Quantum dots solar cells in solar system to convert light into electricity. In *Renewable Energy and Sustainable Buildings: Selected Papers from the World Renewable Energy Congress WREC 2018* (pp. 859-868). Cham: Springer International Publishing.

Kumar, S., Bharti, P., & Pradhan, B. (2023). Performance optimization of efficient PbS quantum dots solar cells through numerical simulation. *Scientific Reports*, *13*(1), 10511.

Baytar, O., Şahin, Ö., Horoz, S., & Kutluay, S. (2024). Solar cell efficiency enhancement via mulberry molasses-based carbon quantum dot-supported CdS and CdS-Mn nanomaterials. *Waste and Biomass Valorization*, *15*(7), 4395-4404.

Lesyuk, R., Lesnyak, V., Herguth, A., Popovych, D., Bobitski, Y., Klinke, C., & Gaponik, N. (2017). Simulation study of environmentally friendly quantum-dot-based photovoltaic windows. *Journal of Materials Chemistry C*, *5*(45), 11790-11797.

Ahmad, B., Majeed, M. K., Soomro, A. A., & Jillani, S. A. (2026, January). Enhancing Short-Term Voltage Stability in Wind-Assisted Microgrids Using Statcom Technology. In 2026 1st International Conference on Innovations in Information and Communication Technologies (IICT) (pp. 1-6). IEEE.

Arellano-Ramírez, I. D., Santiago, L. B., Rebaza, A. G., Amaya-Roncancio, S., & Restrepo-Parra, E. (2025). The Frontier of Solar Energy: Quantum Dots and Density Functional Theory Insights. *Journal of Scientometric Research*, *14*(2), 424-436.

Song, J. H., & Jeong, S. (2017). Colloidal quantum dot based solar cells: from materials to devices. *Nano Convergence*, *4*(1), 21.

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Wang, L., Wang, Y., Wang, H., Xu, G., Doring, A., Daoud, W. A., ... & Zi, Y. (2020). Carbon dot-based composite films for simultaneously harvesting raindrop energy and boosting solar energy conversion efficiency in hybrid cells. *ACS nano*, *14*(8), 10359-10369.

Mistry, B., Machhi, H. K., Vithalani, R. S., Patel, D. S., Modi, C. K., Prajapati, M., ... & Kane, S. R. (2019). Harnessing the N-dopant ratio in carbon quantum dots for enhancing the power conversion efficiency of solar cells. *Sustainable Energy & Fuels*, *3*(11), 3182-3190.

Kamat, P. V. (2008). Quantum dot solar cells. Semiconductor nanocrystals as light harvesters. *The Journal of Physical Chemistry C*, *112*(48), 18737-18753.

Yuan, J., Yang, X., Zheng, D., Guo, J., Lin, W., Liao, J., ... & Tang, Q. (2023). Perovskite quantum dot-based tandem triboelectric-solar cell for boosting the efficiency and rain energy harvesting. *Nano Energy*, *110*, 108341.

Johansson, E. M., & Andruszkiewicz, A. (2022). Combining quantum dot and perovskite photovoltaic cells for efficient photon to electricity conversion in energy storage devices. *Energy Technology*, *10*(10), 2200598.

Dong, H., Xu, F., Sun, Z., Wu, X., Zhang, Q., Zhai, Y., ... & Sun, L. (2019). In situ interface engineering for probing the limit of quantum dot photovoltaic devices. *Nature nanotechnology*, *14*(10), 950-956.

Ahmad, B., Jillani, S. A., Rafique, M., & Soomro, A. A. (2026, January). Design and Monitoring of a Tree-Inspired Vertical Axis Wind Turbine for Efficient Urban Wind Utilization. In 2026 1st International Conference on Innovations in Information and Communication Technologies (IICT) (pp. 1-6). IEEE.

Parravicini, J., Trapani, F. D., Nelson, M. D., Rex, Z. T., Beiter, R. D., Catelani, T., ... & Di Vece, M. (2020). Quantum confinement in the spectral response of n-doped germanium quantum dots embedded in an amorphous Si layer for quantum dot-based solar cells. *ACS Applied Nano Materials*, *3*(3), 2813-2821.

El-Ballouli, A. A. O., Bakr, O. M., & Mohammed, O. F. (2019). Compositional, processing, and interfacial engineering of nanocrystal-and quantum-dot-based perovskite solar cells. *Chemistry of materials*, *31*(17), 6387-6411.

Shah, R., Saha, A., Najah, Z., Prakash, A., Reddy, U., Nagpal, A., & Haripriya, V. (2024). Role of quantum dots and nanostructures in photovoltaic energy conversion. In *E3S Web of Conferences* (Vol. 552, p. 01096). EDP Sciences.

Azam, A., Suryawanshi, M. P., Liu, Y., Shi, J., Xia, Y., Zhang, H., ... & Li, S. (2025). Quantum dots-enabled downshifting and downconversion strategies for enhanced photovoltaics. *ACS nano*, *19*(32), 28969-28991.

Sahai, S., Jangra, A., Thomas, L. M., & Satsangi, V. R. (2024). Quantum dots as efficient solar energy absorber: review on photovoltaics and photoelectrochemical systems. *Journal of The Institution of Engineers (India): Series D*, *105*(1), 553-566.

Kumar, Y. A., Koyyada, G., Ramachandran, T., Kim, J. H., Hegazy, H. H., Singh, S., & Moniruzzaman, M. (2023). Recent advancement in quantum dot-based materials for energy storage applications: a review. *Dalton Transactions*, *52*(25), 8580-8600.

Paulo, S., Palomares, E., & Martinez-Ferrero, E. (2016). Graphene and carbon

Online ISSN 3007-3197
Print ISSN 3007-3189

quantum dot-based materials in photovoltaic devices: from synthesis to applications. *Nanomaterials*, *6*(9), 157.

Halim, M. A. (2012). Harnessing sun's energy with quantum dots based next generation solar cell. *Nanomaterials*, *3*(1), 22-47.