# Quantum dots Engineering for High-Efficiency Photovoltaics

## 1 Abstract

Quantum dot–based perovskite solar cells (QD-PSCs) represent a promising frontier in next-generation photovoltaic technologies, combining the exceptional optoelectronic properties of metal halide perovskites with the tunable quantum confinement effects of semiconductor nanocrystals. Quantum dots (QDs) are nanoscale materials with size-dependent bandgaps, enabling precise control over light absorption and emission. When integrated into solar cells, they serve multifunctional roles including defect passivation, energy level alignment, and enhancement of charge transport. These effects mitigate non-radiative recombination losses and improve crystallinity, thereby significantly increasing power conversion efficiency (PCE) and device stability .

Synthesis of QDs typically involves colloidal chemical methods, allowing fine control over size, composition, and surface ligands. In QDSCs, they can be incorporated as interfacial layers, embedded within a perovskite matrix, or used as standalone light-absorbing materials. Characterization techniques such as photoluminescence spectroscopy, electron microscopy, and current–voltage measurements show that QDs enhance carrier dynamics and suppress trap states, which are major limitations in conventional perovskite devices . In materials, QDs improve photovoltaic performance through bandgap engineering, multiple exciton generation, and intermediate-band formation, potentially enabling efficiencies beyond the traditional Shockley–Queisser limit .

From a sustainability perspective, QD-PSCs offer several advantages. Their solution-processability enables low-temperature fabrication, reducing energy input and manufacturing costs compared to silicon-based photovoltaics. Additionally, their compatibility with flexible substrates opens pathways for lightweight, portable, and building-integrated solar technologies. The tunability of QDs also allows better utilization of the solar spectrum, improving overall energy yield. However, challenges remain, particularly regarding long-term stability under environmental stress (moisture, UV exposure) and concerns over toxic elements such as lead and cadmium in some QD systems .

Recent progress has demonstrated rapid efficiency improvements and enhanced durability through interface engineering and compositional optimization, with QD-assisted devices approaching or exceeding the performance of conventional thin-film technologies . Future research directions emphasize the development of environmentally benign QDs, scalable fabrication methods, and advanced device architectures such as tandem and intermediate-band solar cells.

This presentation will go through the mechanisms used in solar cells devices and how these can be improved through the use of quantum dots.

# 2 References


- Neupane, K.; Kabel, J.; Uddin, J.; Dubey, R.; Ojha, R.; Zhang, D.; Yap, Y.K. Quantum Dot Solar Cells: Background, Progress, and Perspective. Micromachines 2026, 17, 474.

- Que, Meidan, Yuan Xu, Qizhao Wu, Jin Chen, Lili Gao and Shengzhong (Frank) Liu. "Application of advanced quantum dots in perovskite solar cells: synthesis, characterization, mechanism, and performance enhancement." Materials horizons (2025).

- Liu, AA., Cui, R., Zong, X. et al. Live-cell synthesis of biocompatible quantum dots. Nat Protoc 20, 1884–1914 (2025)

- Octavi E. Semonin, Joseph M. Luther, Matthew C. Beard, Quantum dots for next-generation photovoltaics, Materials Today

- H.K. Jun, M.A. Careem, A.K. Arof, Quantum dot-sensitized solar cells—perspective and recent developments: A review of Cd chalcogenide quantum dots as sensitizers, Renewable and Sustainable Energy Reviews

- Isomeric organic–inorganic indium bromide single crystals with delayed and dual colour emission, Haichao Zhou, Kiyonori Takahashi, Takuya Okamoto, Jianguo Pan and Vasudevanpillai Biju, Mater. Horiz., 2026, 13, 2802, DOI: 10.1039/D5MH02322J

- W.You, W.Zou, S.Jiang, J.Zhang, Y.Ge, G.Lu, D. W.Bahnemann, J. H.Pan, Carbon Neutralization2024;3:245–284

- Shockley, W., & Queisser, H. J. (1961). Detailed Balance Limit of Efficiency of p–n Junction Solar Cells. Journal of Applied Physics.

- E. Matioli, Semiconductor Devices I, EPFL course material

- Einstein, A. (1905). On a Heuristic Viewpoint Concerning the Production and Transformation of Light.