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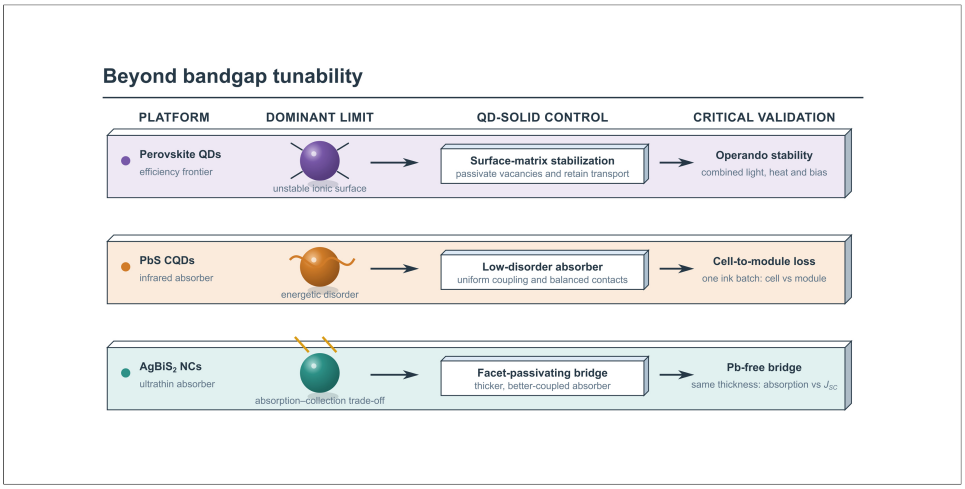
Beyond bandgap tunability: controlling quantum-dot solids for efficient solar cells

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Recent progress in solution-processed quantum-dot (QD) photovoltaics is represented by three absorber platforms: lead-halide perovskite QDs, lead sulfide (PbS) colloidal QDs (CQDs), and $AgBiS_2$ nanocrystals (NCs). Surface passivation, ligand-controlled coupling, energetic disorder and interfaces are already established as decisive in QD solids. Our contribution is not to restate that consensus, but to apply a common test across three distinct chemistries: which loss mechanism does a strategy remove, what limitation does it expose, and does the benefit survive operation and area scaling? This comparison highlights the distinct effects of disorder across material platforms: reducing energetic disorder improves charge transport and collection in PbS CQD solids, whereas controlled cation disorder can enhance optical absorption in $AgBiS_2$ nanocrystals. We use "reported power-conversion efficiency (PCE)" to denote the champion efficiency reported by a study, "stabilized PCE" to denote efficiency measured under stabilized operating conditions, and "certified PCE" to denote efficiency independently verified by a certification laboratory. Figure 1 presents selected efficiency trajectories with labels identifying the measurement and certification status of each value.

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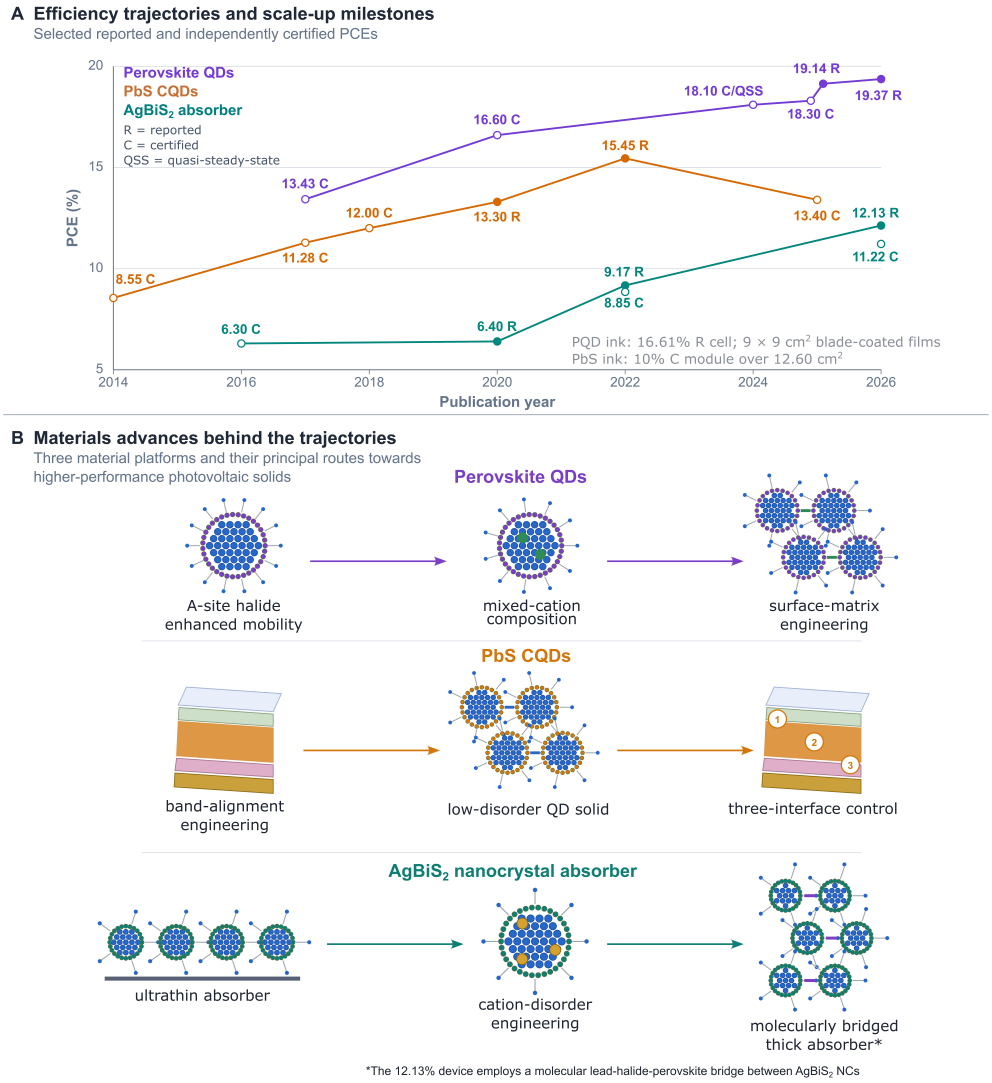


Figure 1. Selected progress in solution-processed QD photovoltaics. (A) Selected reported-R and certified-C PCEs from the cited primary studies; QSS identifies a quasi-steady-state value. Exact values are shown where reported. The annotations identify scale-up benchmarks for conductive perovskite-QD and stable PbS inks; (B) Principal materials advances associated with each trajectory. Schematics are not to scale; colors denote material platform and surface configuration rather than exact nanocrystal morphology. QD: Quantum dot; CQD: colloidal quantum dot; NC: nanocrystal; PCEs: power-conversion efficiencies; QSS: quasi-steady-state; PbS: lead sulfide.

Perovskite QDs currently define the efficiency frontier. A-site halide treatments doubled carrier mobility in $CsPbI_3$ QD films and enabled a certified PCE of 13.43% in 2017[1]. Ligand-assisted cation exchange subsequently produced $Cs_{1-x}FA_xPbI_3$ QDs with a certified 16.6% PCE, lower defect density, and suppressed phase segregation under illumination[2]. For $FAPbI_3$ QDs, alkyl-ammonium-iodide exchange displaced persistent oleyl ligands more effectively than conventional methyl-acetate treatment, giving an 18.1% independently certified quasi-steady-state PCE in 2024[3]. In 2025, potassium-hydroxide-assisted hydrolysis of methyl benzoate generated a denser population of short benzoate ligands, reducing trap density and particle agglomeration and yielding a certified 18.3% PCE[4]. In 2025, two distinct surface-engineering strategies achieved reported PCEs exceeding 19%: consecutive surface-matrix engineering yielded 19.14%, while PF_6^- exchange combined vacancy passivation with reduced interdot spacing to yield 19.01%, with 17.19% reported for a 1 cm^2 device[5,6]. Their convergence shows that 19% is not an isolated result, although neither value should be conflated with independently certified or stabilized performance. An *in situ* dual-ion surface-matrix solidification strategy subsequently compensated FA^+ and I^- vacancies while anchoring the surface lattice, producing a reported PCE of 19.37% in 2026[7].

The central tension in perovskite-QD films is between surface passivation and electronic coupling. Long ligands protect the nanocrystal surface but impede interparticle transport, whereas aggressive removal shortens the tunneling distance but can expose undercoordinated sites. Alkyl-ammonium-iodide exchange improves removal of oleyl ligands while stabilizing the photoactive phase[3]. Surface-matrix solidification instead targets purification-induced cation and anion vacancies, suppressing nonradiative recombination while anchoring the surface lattice[7]. These approaches share the need to preserve the surface during processing, but address ligand removal and lattice repair through different chemistries. We therefore favor exchange protocols that preserve both transport and phase stability, with the optimum judged in the operating device rather than by ligand removal alone.

PbS CQDs provide a longer record of how colloidal particles are converted into photovoltaic solids. Ligand-dependent band-alignment engineering produced a certified 8.55% efficiency in 2014 and maintained the performance of unencapsulated cells for more than 150 days in air[8]. Solution-phase ligand exchange with hybrid organic-inorganic precursors subsequently flattened the energetic landscape, increased packing density, and yielded a certified 11.28% PCE[9]. Two-dimensional matrix engineering reduced structural and energetic disorder, supported absorber layers approaching 600 nm, and delivered a certified 12.0% PCE in 2018[10]. Cascade surface modification then produced fully miscible n-type and p-type inks with complete surface passivation; the resulting bulk homojunction increased the carrier diffusion length by a factor of 1.5 and reached a reported 13.3% efficiency in 2020[11]. Coordinated passivation of the QD/QD, electron-selective, and hole-selective interfaces raised the reported PCE to 15.45% in 2022[12]. More recently, direct-synthesis inks with an iodine-rich charged surface shell suppressed aggregation and fusion-derived electronic states. These inks delivered a certified 13.40% PCE on 0.04 cm^2 cells and a certified 10% module efficiency over 12.60 cm^2[13].

Among these results, suppression of energetic disorder throughout the absorber is a particularly instructive PbS advance. Hybrid exchange and two-dimensional matrix engineering improve the uniformity of the assembled solid, reducing energy funneling and allowing charge collection through thicker absorbers[9,10]. This bulk improvement does not eliminate contact losses. In the three-interface study, excessive enhancement of electron extraction reduced the fill factor; coordinated hole-side modification restored extraction balance[12]. The design objective is therefore balanced collection with low recombination, rather than the fastest possible extraction at one contact. We regard absorber and contact optimization as interdependent, because improved transport inside the film can expose an extraction imbalance at its boundaries. Importantly, a non-record study showed that atomic-layer-deposited TiO_2 scarcely changed champion PCE but markedly narrowed device-to-device spread and eliminated shorted pixels[14]. Reproducibility can therefore be a more deployment-relevant advance than another isolated record.

$AgBiS_2$ NCs address a different limitation: combining strong absorption with charge collection through a defect-prone nanocrystal film. The first ambient-processed devices used an absorber only about 35 nm thick and reached a certified PCE of 6.3%[15]. A larger-NC synthesis subsequently improved carrier mobility, reduced trap-assisted recombination, and increased the reported PCE to 6.4%[16]. Cation-disorder engineering then enhanced the optical-transition strength sufficiently for a 30 nm absorber to reach a reported 9.17% efficiency (8.85% certified PCE)[17]. In 2026, molecular lead-halide-perovskite layers were grown epitaxially between $AgBiS_2$ NCs, passivating the (100) facets and strengthening interparticle transport. The resulting 185 nm absorber reached a reported 12.13% efficiency, with an independently certified value of 11.22%[18].

The decisive $AgBiS_2$ bottleneck is the absorption-collection trade-off. Cation-disorder engineering strengthens optical transitions, enabling efficient absorption within a short collection distance[17]. The molecular bridge combines facet passivation with interparticle transport and also permits annealing that

increases cation disorder and absorption. Its benefit therefore cannot be assigned solely to shorter interparticle spacing. The two strategies address different constraints, but their optical and transport effects overlap. A thicker film is useful only while the additional absorbed light produces collected charge. However, the lead-containing bridge also weakens the platform's environmental claim: an absorber with a reported Pb content of 754 ppm is not strictly lead-free[18]. A Pb-free bridge that preserves charge collection is a useful next target, although lattice matching alone would not establish suitable band alignment or defect passivation.

Taken together, the three platforms do not support a universal ligand recipe. Their common objective is carrier survival with efficient extraction, but the mechanisms differ: perovskite treatments stabilize ionic surfaces, PbS benefits from reduced variations in interparticle spacing and site energy, and homogenized cation disorder in $AgBiS_2$ can strengthen absorption. Thus, neither stronger coupling nor less disorder is a universal rule; the physical origin and device consequence must be identified. Processability is also part of material design: conductive perovskite and stable direct-synthesis PbS inks show that surface chemistry must survive ink preparation, storage and deposition[13,19].

Commercialization should be judged against incumbent photovoltaics. Commercial crystalline-silicon modules average 22.7% efficiency and sell near US$0.10 W^{-1}, while commercial CdTe modules approach 20% efficiency[20]. All three QD platforms therefore remain precommercial: the 9 × 9 cm^2 perovskite coating is not an interconnected module; the certified 10% PbS module over 12.60 cm^2 is the strongest scale demonstration reviewed here but remains 3.4 percentage points below its paired small cell; and no comparable $AgBiS_2$ module is reported. Although perovskite-QD devices have undergone stability testing for 1,200 h under illumination at open circuit and 300 h at 80 °C[3], and bridged $AgBiS_2$ devices have undergone 500 min of maximum-power-point tracking[18], these tests do not substitute for module qualification and outdoor testing. Solution coating may reduce process temperature, but nanocrystal synthesis yield, purification, solvent recovery, encapsulation and lead recovery still determine cost and toxicity per delivered kilowatt-hour. On present evidence, QD photovoltaics are unlikely to displace silicon or CdTe in mainstream power generation. More credible roles are complementary: perovskite QDs in printable tandem or lightweight devices, PbS as an infrared-absorbing subcell, and $AgBiS_2$ in ultrathin lightweight devices if Pb-free transport bridges and scalable deposition are achieved. For tandems, bandgap complementarity is only the entry condition; current matching and a low-loss, stable interconnection determine whether the spectral advantage survives stacking[21].

Progress should be judged by stabilized module efficiency, cell-to-module loss, batch reproducibility and cost per watt over a defined service life. Priorities are operando surface and phase tracking for perovskites, same-ink cell/module comparisons for PbS, and Pb-free $AgBiS_2$ bridges tested at matched thickness. Operando measurements should distinguish reversible ligand or ion rearrangement from irreversible defect and phase evolution under combined light, heat and bias; ex situ before/after measurements cannot establish that sequence[22]. These comparisons would reveal whether a strategy removes or merely relocates a bottleneck. Bandgap tunability defines the opportunity; QD-solid control determines its realization.

DECLARATIONS

Authors' contributions

Conceptualization, literature investigation, and writing: Ullah MI
Supervision, critical revision, and correspondence: Duan C

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool ChatGPT (version ChatGPT-6 Astra, released 2026-09-03) was used solely for language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

Duan C is an Editorial Board Member of the Journal of *Energy Materials*, but was not involved in any steps of editorial processing, notably including reviewer selection, manuscript handling, and decision-making, while the other author has declared no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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