

# **Research Article**

# Enhancement of Optical Properties and Stability in CsPbBr<sub>3</sub> Using CQD and TOP Doping for Solar Cell Applications

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Cesium lead bromide (CsPbBr<sub>3</sub>) nanocrystals exhibit remarkable optoelectronic properties and exceptional stability. As a result, they have garnered significant interest for their potential applications in various fields, including solar cells, light-emitting devices, photodetectors, and lasers. Despite its resistance to moisture, oxygen, and heat compared to other perovskite materials, CsPbBr<sub>3</sub> still faces challenges maintaining its structural and optical stability over extended periods. This study proposes a robust solution to enhance and improve simultaneously the photoluminescence intensity and stability of CsPbBr<sub>3</sub> nanocrystals. The solution involves doping the perovskite precursor with green-synthesized carbon quantum dots (CQDs) and tri-n-octyl phosphine (TOP). The results indicate that the photoluminescence intensity of the perovskite nanocrystals (NCs) is sensitive to varying CQD ratios. A high photoluminescence intensity enhancement of 45% was achieved at the optimal CQDs ratio. The synthesized perovskite NCs/CQDs also demonstrated improved stability by adding TOP into the mixture. After storage in the air for 45 days, the mixed perovskite NCs maintained their performance, which was almost unchanged. Solar cell devices based on the modified perovskite NCs showed a power conversion of 7.74%. The devices also demonstrated a significant open-circuit voltage (VOC), with the most successful device achieving a VOC of 1.193 V, an Isc of 10.5748 mA cm<sup>-2</sup>, and a fill factor (FF) of 61%. This study introduces a cost-effective method for producing high-quality all-inorganic optoelectronic devices with enhanced performance and stability.

#### 1. Introduction

All-inorganic perovskite quantum dots have emerged as promising materials due to their exceptional electrooptical properties and stability. These quantum dots have demonstrated significant potential in various photovoltaic applications, including light-emitting diodes, solar cells, photoelectric detection, lasers, and more [1–4]. Perovskite nanocrystals (PNCs) exhibit a range of desirable photophysical characteristics, including the ability to tune their broadband gap, high molar extinction coefficients, strong charge-transfer capabilities [5], tolerance to defects, near-unity photoluminescence quantum yield [6], narrow emission spectrum, high absorption coefficient, long charge carrier diffusion length, low excitation binding energy, and low threshold for lasing [7–12].

PNCs represent a recently emerged class of perovskite materials that demonstrate substantial optoelectronic properties, such as highly pure photoluminescence (PL) emission and remarkably high photoluminescence quantum yield (PLQY) [13-15]. In contrast to PNCs incorporating organic cations, it is widely accepted that all-inorganic cesium lead bromide  $(CsPbX_3)$  (X = Cl, Br, I, or mixed Cl/Br and Br/I) NCs exhibit more excellent stability as a result of lacking volatile organic constituents within their crystal structures [16]. CsPbX<sub>3</sub> exhibits superior resistance to moisture and oxygen, maintains a high melting point, demonstrates remarkable thermal stability, and shows excellent resistance against photobleaching [17]. CsPbX<sub>3</sub> has gained considerable attention for its outstanding photoluminescence quantum yield and optical solid absorption, making it highly suitable for photovoltaic devices and other optoelectronic applications [18, 19].

Being an all-inorganic perovskite, CsPbBr<sub>3</sub> perovskite exhibits superior stability compared to other inorganic perovskites as well as organic-inorganic hybrid perovskites, which are known to suffer from stability issues in humid and ambient conditions [20]. A broad range of effective strategies have been pursued to manipulate the inherent properties of CsPbBr<sub>3</sub> perovskite crystals to improve their electrooptical properties and stability performance in optoelectronic applications. For example, surface passivation using long-chain ligands or silver complexes has significantly enhanced the photoluminescence quantum yield and stability of all-inorganic perovskite nanocrystals [21, 22]. Previous studies have found that it suppresses charge recombination and enhances hole extraction using interfacial engineering, enhancing efficiency and stability [23]. Doping becomes the most emerging strategy because it improves optoelectronic properties such as structure, optical properties, morphology control, carrier behavior, and related optoelectronic and photovoltaic properties [24, 25]. Several studies found that doping impurity ions into CsPbX<sub>3</sub> perovskite structure or lattice enhanced photoluminescence performance and improved phase stability [26] through the partial substitution of foreign ions for intrinsic ions [27, 28]. Cation doping, focusing on the replacement of cations within the A-site and B-site of the perovskite lattice, is a popular doping method for modulating electrooptical properties and improving phase stability simply by incorporating smaller metal cations into the perovskite lattice [24, 29]. In addition, cation B-site doping has been proven to tune band gap, enhance photoluminescence quantum yield, and improve the stability of perovskites, for example, by partially or completely substituting the  $Pb^{2+}$  ion at the B-site with another cation, such as  $Sn^{2+}$ , Ge<sup>2+</sup>, Bi<sup>3+</sup>, and FeCl<sub>2</sub> [30–32].

One of the main issues regarding the CsPbX<sub>3</sub> perovskite crystal is its stability [33]. Despite its stability against moisture, oxygen, and heat compared to other perovskite materials, CsPbX<sub>3</sub> still faces challenges in maintaining its structural and optical stability over extended periods. Researchers have tried to improve the stability of CsPbBr<sub>3</sub> by employing surface passivation techniques, such as using organic ligands and embedding them into a polymer matrix, to protect the crystal from environmental factors. Recently, Guan found that CQDs doped into CsPbBr<sub>3</sub> films improved their water stability and photoinduced charge transfer properties [4]. The CQDs-CsPbBr3@PVDF film demonstrated excellent water stability, with its fluorescence (FL) intensity remaining steady at about 85% of its original value even after being immersed in water for 50 days, according to the study [4]. Even after being immersed in harsh environments such as water, strong acid, strong base, and salty water for more than several months, excellent optical properties have been realized based on the fluorine elastomer polymer matrix [34]. The Pb<sup>2+</sup> ion can accept electron pairs from Lewis bases containing S, N, and O [35].

Consequently, CQDs, which contain an important amount of -OH, -C<sup>1</sup>/4O, and -COOH groups, can function as Lewis bases and effectively form complexes with  $Pb^{2+}$  ions [36]. Hence, it is possible that the presence of CQDs as dopants for PNCs can enhance both the stability of PNCs and their ability to improve charge separation at perovskite/

polymer interfaces. The CQDs were injected into the precursors of CsBr and  $PbBr^{2-}$  simultaneously. The -OH, -C<sup>1</sup>4O, and -COOH functional groups visible on CQDs can interact with  $Pb^{2+}$  ions, which stabilizes PNCs [37].

In addition, there have been reports indicating that phosphine functional groups can improve both the PLQY and the stability of PNCs. Liu et al. introduced a hot-injection synthesis method utilizing tri-n-octyl phosphine (TOP) to successfully fabricate phase-stable CsPbI<sub>3</sub> NCs with a PL efficiency approaching 100% [38]. In a novel example of a method devoid of acids and amines, the utilization of TOP was employed for surface modification [39], resulting in the production of CsPbBr<sub>3</sub> NCs exhibiting improved resistance to light, air, ethanol, moisture, and heat [10, 40].

These findings collectively suggest that doping strategies, including introducing impurity ions and surface modifications, can effectively enhance the electrooptical properties and stability of CsPbBr<sub>3</sub> perovskite crystals in optoelectronic applications. Herein is a simple process for creating CsPbBr<sub>3</sub> films with improved stability and electron transport characteristics utilizing CQDs as dopants. Our research aimed to comprehensively investigate the stability of CsPbBr<sub>3</sub> NCs in toluene, employing spectroscopic techniques across different experimental conditions [41].

This study thoroughly investigates how green-synthesized CQDs and TOP can enhance the PL and stability of inorganic perovskite nanocrystals (CsPbBr<sub>3</sub>) using a hot-injection technique. Adding green-synthesized CQDs [42] to the perovskite precursor solution significantly increases the PL of the prepared perovskite NCs. The enhancement is most significant at a certain concentration of CQDs, beyond which it decreases. We also show that adding TOP to the perovskite/CQDs precursor solution improves the stability of the resultant perovskite without affecting the PL emission of the perovskite NCs. Moreover, we have studied the influence of CQDs and TOP inclusion on the efficiency and stability of the fabricated perovskite solar cell device. Our research provides an important foundation for further improving perovskite materials' optical properties and photostability, especially in solar cell devices.

#### 2. Materials and Methods

2.1. Materials. The chemicals used, including cesium carbonate ( $Cs_2CO_3$ , 99.9%) and lead bromide (PbBr<sub>2</sub>, 98%) from Sigma-Aldrich, 1-octadecene (ODE, 90%), oleic acid (OA, 90%), and oleylamine (OAm, 80–90%) from new material China, toluene 99.8%, and hexane 99%, were obtained from Biochem. No additional purification was necessary as all the chemicals were utilized in their initial form.

#### 2.2. Methods

2.2.1. Preparation of Cs-Oleate. The hot-injection technique synthesizes  $CsPbBr_3$  perovskite nanoparticles [43]. A 100 mL three-necked flask is used to carry out the synthesis, where 100 mg of  $Cs_2CO_3$ , 4 mL of ODE, and 0.5 mL of OA are combined and stirred in a nitrogen (vacuum)

environment at 120°C for 1 hour. Subsequently, the mixture is heated under  $N_2$  to a temperature of 150°C until the reaction between  $Cs_2CO_3$  and OA is complete. This results in a clear solution of Cs-OA. Before use, the solution must be preheated to ensure solubility. At room temperature, Csoleate tends to precipitate out of the ODE solution; hence, it is necessary to heat it to 100°C before injection.

2.2.2. Synthesis and Purification of CsPbBr<sub>3</sub> Nanoparticles. Alternatively, in a separate 100 mL three-necked flask, 5 mL of ODE and 69 mg of PbBr<sub>2</sub> are introduced and stirred under nitrogen at a temperature of 120°C for 1 hour. Following this step, a solution of 0.5 mL of OA, 0.5 mL of OAm and 0.5 ml of TOP is added to the above three-necked flask as posttreatment. As soon as PbBr<sub>2</sub> fully dissolves, the reaction temperature increases to 150°C. The three-necked flask was promptly filled with 0.4 mL of the Cs-OA solution obtained earlier. After a five-second interval, the mixture is rapidly chilled using ice water to initiate the crystallization process of CsPbBr<sub>3</sub> nanoparticles. The unrefined mixture is centrifuged at 1500 rpm for 10 minutes to eliminate any sizable particles. Next, the supernatant was subjected to another centrifugation process at 12000 rpm for 10 minutes, and it was subsequently washed twice with toluene. The resulting precipitate was collected and resuspended in toluene to enable further characterization [43].

2.2.3. Process of Device Fabrication. The FTO glass substrate was cleaned with an ultrasonic cleaning using acetone, isopropanol, deionized water, and ethanol for 20 minutes each. The FTO substrate conducted oxygen treatment to remove any residual organic matter on the surface. A focused layer of TiO<sub>2</sub> was applied using a spin-coating technique, utilizing a 0.15 M solution in 1-butanol, with a rotation speed of 2000 rpm for 20 s. The substrate drying process at 100°C for 10 min, followed by an annealing process at a temperature of 450°C for 30 min in dry air. A solution containing 1 mL of CsPbBr<sub>3</sub> was applied onto the TiO<sub>2</sub> layer using a spin-coating technique at a speed of 2000 rpm for 20 s. The substrate underwent annealing for 5 minutes at a temperature of 100°C. Following that, a solution of Spiro-OMeTAD was prepared and applied to the CsPbBr<sub>3</sub> perovskite layer using a spin-coating technique. The Spiro-OMeTAD solution consisted of 50 mg of Spiro-OMeTAD,  $22.5 \,\mu\text{L}$  of 4-tertbutylpyridine, and  $22.5 \,\mu\text{L}$  of acetonitrile solution containing  $170 \text{ mg} \cdot \text{mL}^{-1}$  of lithium bis(trifluoromethyl sulfonyl)imide in 1 mL of chlorobenzene. The spin-coating process was carried out at 3000 rpm for 25 s within a glove box filled with nitrogen gas to ensure a controlled environment. Ultimately, the use of silver electrodes was achieved using the process of spray coating, which involved depositing them into the film.

2.2.4. Characterization of Inorganic Perovskite Nanocrystal. Various characterization techniques have been used to investigate the structural, optical, compositional, and surface properties of inorganic perovskite nanocrystals (specifically,

CsPbBr<sub>3</sub>). To analyze the optical characteristics, the wavelength range spanning from 190 to 900 nm has been examined by exploiting a CECIL CE 7200, 7000 series UV-vis. PL was recorded and analyzed using a homemade fluorescence spectrophotometer (a tunable light source and spectrometer from SCEINCETECH 9702 (Canada)). In addition, the crystal phase data of the films was examined using a PAN X-Pert from the United Kingdom. X-ray powder diffraction (XRD) with a copper target radiation source ( $\lambda = 1.54$  Å). To examine the NC morphology and size using a TEM TEC9G20, FIE, USA, a single droplet of the sample was applied onto a copper grid coated with carbon and subsequently allowed to air-dry for 12 hours. The scanning electron microscopy (SEM) technique was employed to examine the morphologies and shapes of the nanocrystals. Moreover, the study used the Fourier transform infrared spectrophotometer (Thermo Scientific, USA) to examine the removal of ligands from NCs throughout the procedure.

#### 3. Results and Discussion

3.1. Structure, Morphology, and Composition of CsPbBr<sub>3</sub> Nanoparticles. To determine the phases of perovskite CsPbBr<sub>3</sub> crystalline, the XRD spectrum is displayed in Figures 1(a) and 1(b). The XRD patterns of the nanostructures for investigation indicate a cubic phase structure of CsPbBr<sub>3</sub> [44]. The primary diffraction peaks are observed at angles of 15.3°, 21.5°, 31°, 35.4°, and 50.7°, corresponding to the crystallographic planes denoted as (100), (110), (200), (210), and (031). Moreover, the diffraction peaks of CsPbBr3-CQDs are seen at angles of 21.5°, 31°, 35.4°, and 50.7°, which correspond to the crystallographic planes labelled as (110), (200), (210), and (031), respectively, the material is characterized by being indexed according to a cubic crystal system (Joint Committee on Powder Diffraction Standards (JCPDS) Portable Document Format (PDF) #54-0752) [45]. There were no additional peaks detected. Furthermore, the TOP has no impact on the crystal structure phase. The presence of only the cubic structure CsPbBr<sub>3</sub> was observed in the solution of CQDs-CsPbBr<sub>3</sub>-TOP. The diffraction peaks exhibit a high degree of sharpness and narrowness, which indicates a better degree of crystallinity in the material [4]. The XRD patterns exhibited by both samples are comparable, indicating the presence of a similar crystal lattice structure. It is observed that the X-ray diffraction patterns of all the shapes are identical due to the constant temperature maintained during the growth process. In contrast, the study conducted by Peng et al. demonstrated the influence of increasing temperature on the structural characteristics, morphology, and overall size of perovskite nanostructures [46].

Furthermore, Figures 1(c) and 1(e) display the morphology, phase structure, and composition characteristics of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs. Figures 1(c) and 1(e) present a TEM image showing the CsPbBr<sub>3</sub> NCs. The image indicates morphology, demonstrating the particle sizes of the CsPbBr<sub>3</sub> quantum dots and core-shell CQD-CsPbBr<sub>3</sub> to be 1.8 nm and 2.4 nm, respectively. Figures 1(d) and 1(f) illustrate the size and distribution of CsPbBr<sub>3</sub> QDs and CQD-CsPbBr<sub>3</sub> QDs, respectively [6, 47].



FIGURE 1: (a) XRD pattern of CsPbBr<sub>3</sub>, (b) XRD pattern of CsPbBr<sub>3</sub>-CQDs, (c) TEM of CsPbBr<sub>3</sub>, (d) particle size of CsPbBr<sub>3</sub> and its histogram, (e) TEM of CsPbBr<sub>3</sub>-CQDs, and (f) particle size of CsPbBr<sub>3</sub>-CQDs and its histogram.

Moreover, these particles demonstrate a uniform cubic morphology. The EDAX patterns of CsPbBr<sub>3</sub> depicted in Figures 2(a) and 2(b) demonstrate an atomic ratio of Cs/Pb/ Br as 9.2:48.3:40.6 and for CsPbBr<sub>3</sub>-CQDs, an atomic ratio of Cs/Pb/Br/C/O as 7.1:50.002:34.7:3.6:2.59. This change in observation suggests that the effect of CQDs has appeared.



FIGURE 2: (a) EDX of perovskite CsPbBr<sub>3</sub>, (b) EDX of perovskite CsPbBr<sub>3</sub>-CQDs, and (c) FTIR spectra of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs NCs.

3.2. Surface Chemistry Composition of CsPbBr<sub>3</sub> Nanoparticles. To oversee the assembly process, we analyzed the ligand species present on the NC samples utilizing FT-IR spectroscopy. The interaction between CQDs and CsPbBr3 was investigated using FT-IR. The study aimed to explore the synthesis of CQDs-CsPbBr<sub>3</sub>. The characteristic peaks observed in the CsPbBr<sub>3</sub> PNCs in Figure 2(c) are approximately 462.39, 726, 1463, 1609, 1715, 2689, and 2949 cm<sup>-1</sup>. The study on the surface modification for improving the photoredox activity of CsPbBr<sub>3</sub> nanocrystals has identified various vibrational bands that provide valuable insights into the molecular structure and functional groups present in the modified nanocrystals. These bands include the characteristic C-H asymmetric and symmetric stretching vibration observed at 2924 cm<sup>-1</sup> (from 2850 to 310), which is attributed to corresponding to oleylamine and oleic acid [48, 49]. The C=O stretching vibration is prominent at  $1715 \text{ cm}^{-1}$ , assignable to the oleic acid [50]. The other FTIR peaks at 1465 cm<sup>-1</sup> are attributed to the C-H bending vibration [49]. The peak at  $725-465 \text{ cm}^{-1}$  is to be attributed to the CsPbBr<sub>3</sub>-OAm complexes [51].

3.3. Optical Properties of CsPbBr<sub>3</sub> Nanoparticles. The PL and absorption spectra of CsPbBr<sub>3</sub>, TOP-CsPbBr<sub>3</sub>, CsPbBr<sub>3</sub>-CQDs, and TOP-CsPbBr<sub>3</sub>-CQDs are depicted in Figure 3. According to the data presented in Figure 3, the absorption peaks of CsPbBr<sub>3</sub>, TOP-CsPbBr<sub>3</sub>, CsPbBr<sub>3</sub>-CQDs, and TOP-CsPbBr<sub>3</sub>, CsPbBr<sub>3</sub>-CQDs, and TOP-CsPbBr<sub>3</sub>-CQDs were observed at wavelengths of 501.272 nm, 501.272 nm, 509.3 nm, and 513 nm, respectively. The observed red shift in the absorption peaks can be attributed to the absorption of NCs on the surface of TOP and the subsequent formation of slightly larger particles [52].

PL spectra of CsPbBr<sub>3</sub> and TOP-CsPbBr<sub>3</sub> are illustrated in Figure 3(b), both at an equivalent concentration. At the excitation wavelength of 405 nm, the PL intensity of CsPbBr<sub>3</sub> was slightly lower than that of TOP-CsPbBr<sub>3</sub>, and the latter exhibited a small redshift. The emission wavelength of CsPbBr<sub>3</sub> QDs in their pure form was measured to be 515 nm, while the emission wavelength of QDs doped with TOP-CsPbBr<sub>3</sub> was found to be 521 nm. A red shift of 6 nm was observed, which could be attributed to the enlarged dimensions of the TOP in its interaction with CsPbBr<sub>3</sub>.



FIGURE 3: (a) UV-visible absorption spectra of PNCs. (b) PL spectra of CsPbBr<sub>3</sub> with doped by CQD and TOP. (c) PL emission spectrum of the concentration of CQDs in CsPbBr<sub>3</sub>. (d) Relation of CsPbBr<sub>3</sub> with CQD.

PL spectra of CsPbBr<sub>3</sub> and CQD-CsPbBr<sub>3</sub> are illustrated in Figure 3(b), both at an equivalent concentration. At the excitation wavelength of 405 nm, the PL intensity of CsPbBr<sub>3</sub> was lower compared to CQD-CsPbBr<sub>3</sub>, and the latter exhibited a red shift. The emission wavelength of CsPbBr<sub>3</sub> NCs in their pure form was measured to be 515 nm, while the emission wavelength of NCs doped with CQD-CsPbBr<sub>3</sub> was found to be 533 nm. A red shift of 18 nm was observed, which could be attributed to the enlarged dimensions of the CQDs in its interaction with CsPbBr<sub>3</sub>.

Figure 3(b) shows the normalized PL spectra of CsPbBr<sub>3</sub> and CQDs-CsPbBr<sub>3</sub>, respectively. A distinct absorption peak was detected at a wavelength of 515 nm for CsPbBr<sub>3</sub>, indicating a bandgap energy of 2.4 eV. Upon doping CQDs, it was observed that the absorption peak experienced a shift towards 527 nm, while the band gap increased to 2.35 eV. Furthermore, integrating CQDs led to a redshift in the emission peak of CsPbBr<sub>3</sub> [53].

This observation indicates that CQDs can impede the growth of CsPbBr<sub>3</sub>, which aligns with the aforementioned characterization using TEM. In addition, it can be observed from Figure 3(b) that the FWHM of the emission band of CsPbBr<sub>3</sub> was approximately 25 nm. The introduction of CQDs-CsPbBr<sub>3</sub> increased the wavelength to 28 nm. The phenomenon of spectral diffusion has been recognized as a factor that influences the broadening of emission linewidth [54], thereby playing a crucial role in determining the colour purity of CsPbBr<sub>3</sub> [55].

The emission spectra of a solution containing CQDs-CsPbBr<sub>3</sub> with different concentrations as a posttreatment of CQDs are presented in Figures 3(c) and 3(d). The obtained CsPbBr<sub>3</sub> demonstrated exceptional green emission



8000 7600 7000 7400 6000 7200 5000 7000 Intensity (a.u) Intensity (a.u) 6800 4000 6600 3000 6400 2000 6200 1000 6000 0 5800 480 500 540 560 460 520 580 600 620 50 150 200 250 300 350 400 450 500 100 550 Wavelength (nm) Laser Power (mW) 100 mw 350 mw 150 mw 400 mw 200 mw 450 mw 250 mw 500 mw 300 mw (e) (f)

FIGURE 4: (a) Stability of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs and (b) the stability of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs with TOP as treatment. (c) Error bars stability of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs and (d) error bars stability of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs with TOP as treatment. (e) PL spectra of CsPbBr<sub>3</sub> with different laser power and (f) the relation between intensity and laser power in the CsPbBr<sub>3</sub>.

performance, as evidenced by the presence of a highly symmetric band centred at 533 nm in each sample. The PL emission peak intensity of CsPbBr<sub>3</sub> increased with the increment in CQDs. The maximum peak was observed at a CQD concentration of 0.18 mg/ml. The observed increase in PL intensity indicates a reduced occurrence of nonradiative recombination events, charge carriers, and diffusion charges. The small nonradiative recombination loss observed in this study can be attributed to the passivation defect caused by CQDs. Increasing the quantity of CQDs in the solution would reduce the PL intensity. This phenomenon can be attributed to an abundance of charge-quenching defects within the composite material, which serve as nonradiative recombination centres. Consequently, the PL intensity is decreased.

3.4. Stability of CsPbBr<sub>3</sub>. The stability of perovskite materials is crucial due to their susceptibility to several environmental factors, including heat, light, oxygen, and humidity. The stability of perovskite has been studied using the measurement of the PL in both CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs as depicted in Figures 4(a) and 4(b). The stability of CsPbBr<sub>3</sub> is seen to have a duration of less than 4 hours, while the stability of CsPbBr<sub>3</sub>-CQDs is estimated to be approximately 6.5 hours. Moreover, we investigate an easy way to significantly enhance the stability of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs by using TOP as a part of the postsynthesis process. Without the addition of TOP, the stability duration is shorter, typically ranging from 4 to 6.5 hours. The addition of TOP immediately after the synthesis process results in the maintenance of the optical characteristics of CsPbBr<sub>3</sub> in

solution for a duration over one month (45 days) as shown in Figures 4(a) and 4(b). This result provides novel perspectives on addressing the issue of instability in these materials.

3.5. Effect of Laser Power on the PL of CsPbBr<sub>3</sub>. To understand the photoinduced recombination mechanism in the CsPbBr<sub>3</sub> NCs, we measure the PL spectra at various excitation laser powers at room temperature as illustrated in Figures 4(e) and 4(f) [56]. The excitation power of the incoming light ranges from 100 to 500 mW. No significant change in the position of the single PL peak at 515 nm was found across a range of excitation power at ambient temperature. The PL intensity of the perovskite structures exhibits a superlinear relationship with the laser power. The increase in the power of the carrier laser results in the saturation of nonradiative recombination centres, enhancing the effective internal quantum efficiency [44]. Zhang et al. demonstrated that the PL of CsPbBr<sub>6</sub> microdisks exhibit a linear relationship with laser energy. In addition, when the laser power is increased, the full-width high maximum (FWHM) remains constant at around 25 nm as illustrated in Figure 4(e).

#### 4. The Performance of CsPbBr<sub>3</sub> Perovskite Solar Cell Devices

The current density versus voltage (I–V) curves are recorded to investigate the effect of CQDs on the PSC performance. The device arrangement of a CsPbBr<sub>3</sub> PSC comprising FTO/ TiO<sub>2</sub>/CsPbBr<sub>3</sub>/Spiro-OMeTAD/Ag layers [57] is illustrated in Figure 5(b). The structure under examination combines



FIGURE 5: (a) I-V characterization of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQD, (b) schematic of the energy level of PNCs, (c, d) the diagram of the cell of CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs, and (e, f) SEM of the both CsPbBr<sub>3</sub> and CsPbBr<sub>3</sub>-CQDs.

the utilization of a CsPbBr<sub>3</sub> film as the light-absorbing layer, TiO<sub>2</sub> contact surfaces, Spiro-OMeTAD as the hole transport layer (HTL), and Ag electrodes as the anode. Figure 5(a) presents the I–V curves and PCEs of the CsPbBr<sub>3</sub> PSCs with and without CQDs. By introducing CQDs, current density (I) is improved compared to the undoped CsPbBr<sub>3</sub> PSC. It is visible that I for pristine CsPbBr<sub>3</sub> PSC is 7.8 mA/cm<sup>2</sup>, while for CsPbBr<sub>3</sub>PSC-doped CQDs, it is 10.5 mA/cm<sup>2</sup>. In another word, the PCE of the CsPbBr<sub>3</sub> PSC is observed to be greater by including CQDs compared to the PSC without CQDs. Specifically, by CQDs, the PCE increases from 5.61% to 7.741%. The results indicate that using CQDs improves the device's ability to extract carriers [58].

The operational mechanism of a device, including the FTO/TiO<sub>2</sub>/CsPbBr<sub>3</sub>/Spiro-OMeTAD/Ag structure, collectively with the related energy level diagram is illustrated in Figure 5(b). The light-absorbing matter employed in this configuration is a perovskite layer composed of CsPbBr<sub>3</sub>. Spiro-OMeTAD is a widely recognized HTL that functions by facilitating the movement of holes throughout the device [59].

In addition, it serves as an electron-blocking layer (EBL) to prevent charge recombination. Titanium dioxide (TiO<sub>2</sub>) was applied onto the surface of an FTO substrate to create the photoanode. A compact layer composed of TiO<sub>2</sub> was employed to reduce the occurrence of electrode shorting. The generation of an exciton, which is a pair consisting of an electron and a hole, occurs within the active layer as a result of the absorption of light. The exciton should undergo separation at the interfaces, generating charge carriers, specifically electrons and holes. Collecting free electrons and holes by the electrodes is necessary to generate an electric current before recombining through either radiative or nonradiative processes. The conduction band of TiO<sub>2</sub> has a lower energy level in comparison to that of CsPbBr<sub>3</sub>, therefore facilitating the transport of electrons from CsPbBr3 to TiO2. The valence band of Spiro-OMeTAD exhibits a higher energy level compared to that of CsPbBr<sub>3</sub>, hence facilitating the transfer of holes from CsPbBr3 to Spiro-OMeTAD. Consequently, it is believed that most electrons will be transferred from the perovskite material to TiO<sub>2</sub>, whereas most holes will be sent to Spiro-OMeTAD [60].

### 5. Conclusion

This study successfully enhanced the optical properties and stability improvement of CsPbBr<sub>3</sub> nanocrystals at room temperature by CQD doping and the addition of TOP. Our study shows that the PL intensity is sensitive to the concentration of CQDs and provides 45% enhancement. In addition, we demonstrated that adding a few amounts of TOP in the perovskite-CQD precursors boosts the stability of the perovskite, retaining most of its performance after 45 days. Importantly, the application of the enhanced capabilities of the CQDs-CsPbBr<sub>3</sub>-TOP facilitated its dependable operation in perovskite solar cell devices. The device exhibited power conversion efficiency (PCE) of 5.61% and 7.741.

Moreover, the devices demonstrated a significant opencircuit voltage (VOC), with the most successful device achieving a VOC of 1.193 V, an Isc of 10.5748 mA cm<sup>-2</sup>, and a fill factor (FF) of 61%. Interestingly, we also demonstrated that the photoluminescence (PL) intensity of CsPbBr<sub>3</sub> can be increased by lighting it with a 532 nm laser. The stability test results indicate that the long-term stability of CsPbBr<sub>3</sub> was explored after subjecting it to storage at room temperature with a humidity level of 20%. This study offers additional strategies for attaining stable and efficient optoelectronic devices that exhibit exceptional performance.

#### **Data Availability**

The article contains all underlying data; thus, no further source data are needed.

#### Disclosure

The authors are employees of the Department of Physics, College of Science, and University of Zakho/Iraq.

#### **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

#### **Authors' Contributions**

Chiayee Salih Ajaj researched, proposed, and edited the study as well as the essay. Diyar Sadiq performed the technique, supervision, and article editing.

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