JACS Au
AN OPEN ACCESS JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Aqueous Continuous Flow Synthesis of Cadmium Chalcogenide Quantum Dots: Opportunities and Challenges

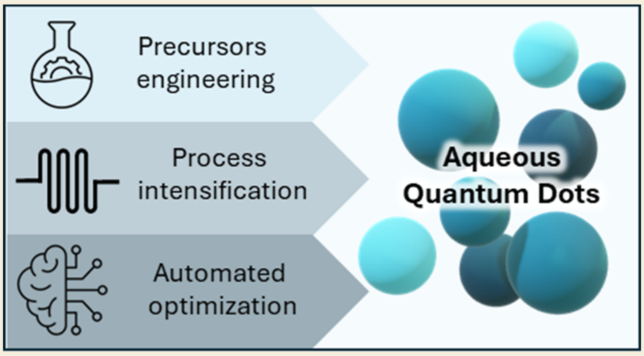
Published as part of JACS Au special issue "Continuous Flow Chemistry".

Carlotta Campalani, Guillaume Petit, and Jean-Christophe M. Monbaliu*

Cite This: https://doi.org/10.1021/jacsau.5c01449 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Cadmium chalcogenide quantum dots (CdX QDs, X = S, Se, Te) are among the most extensively studied semiconductor nanocrystals due to their size-tunable optical properties and wide potential applications in optoelectronics, bioimaging, and sensing. While early syntheses relied on high-temperature organometallic routes in organic solvents, the demand for safer, greener, and more biocompatible approaches has driven increasing interest in aqueous-based methods. These two strategies differ substantially in terms of precursor chemistry, surface passivation, and control over nanocrystal quality. In parallel, continuous flow technology has brought transformative assets to the field, offering precise reaction control, scalability, and reproducibility, which are essential for both fundamental studies and industrial translation. This review summarizes the evolution of CdX QDs synthesis, contrasting organic and aqueous batch approaches, and focuses on recent advances in aqueous continuous flow strategies. Finally, we highlight perspectives on the integration of automated machine learning and artificial intelligence approaches with continuous flow, which may accelerate the discovery, optimization, and scalable production of high-quality QDs for next-generation technologies.



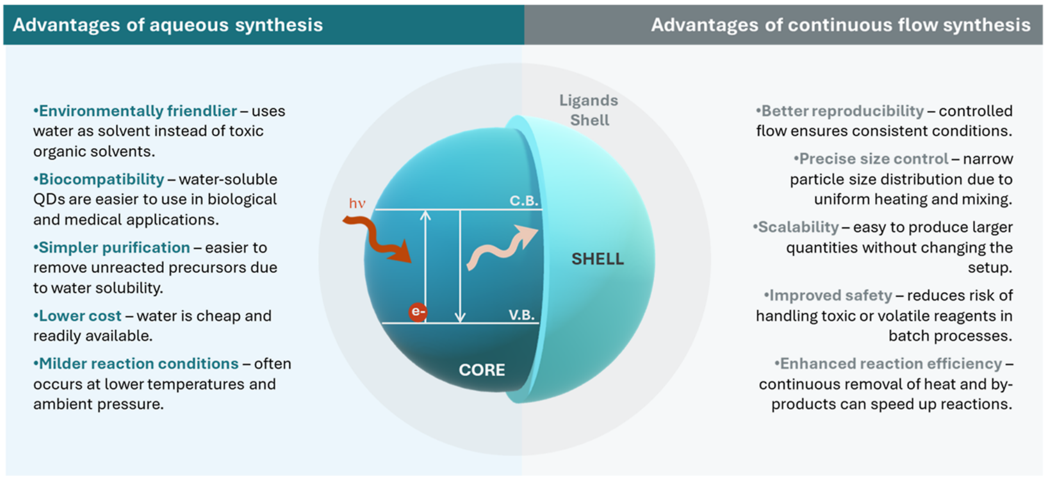
KEYWORDS: *quantum dots, continuous flow, aqueous, microfluidic, nanocrystals, cadmium chalcogenides*

1. INTRODUCTION

Quantum dots (QDs) are a unique class of semiconductor nanocrystals that have fascinated researchers since their discovery in the late 1980s, culminating in the 2023 Nobel Prize in Chemistry.[1−3] With diameters typically in the range of 2−10 nm, smaller than the exciton Bohr radius, they show pronounced quantum confinement effects. This results in discrete, size-dependent electronic states and an energy bandgap that widens as particle size decreases, giving rise to tunable photoluminescence and redox properties.[4−6] Such features, coupled with their high photoluminescence quantum yield (PLQY), photostability, and versatile surface chemistry, have established QDs as enabling materials for applications in photocatalysis,[7−10] drug delivery and bioimaging,[11,12] as well as in optoelectronics and energy devices.[13−15] Traditionally, QDs are composed of a semiconductor core, often coated with an additional semiconductor shell, and stabilized by an outer layer of organic ligands that ensure colloidal stability and facilitate charge mobility (Figure 1). In recent years, however, the field has expanded to include more complex architectures, such as alloyed nanocrystals, advanced core−shell configurations, and doped quantum dots.[16]

Cadmium chalcogenide QDs (CdX, X = S, Se, Te) have been especially prominent in these developments owing to their well-understood electronic structures, wide spectral tunability, and relative synthetic accessibility. Nevertheless, their preparation is not without challenges. Conventional syntheses in organic solvents, such as the hot-injection and heat-up methods, allow good control over size distribution, crystallinity, and heterostructure formation. Yet, they are hindered by issues of toxicity, high-temperature operation, limited scalability, batch-to-batch reproducibility and difficulties in adopting automated or continuous manufacturing. These are among the many bottlenecks that complicate both industrial translation and sustainable development. The need for precise control over nucleation and growth demands tight temperature, mixing, and feeding protocols, which are often batch-dependent and sensitive to operator conditions.

Received: October 30, 2025
Revised: December 5, 2025
Accepted: December 8, 2025


Advantages of aqueous synthesis

- **Environmentally friendlier** – uses water as solvent instead of toxic organic solvents.
- **Biocompatibility** – water-soluble QDs are easier to use in biological and medical applications.
- **Simpler purification** – easier to remove unreacted precursors due to water solubility.
- **Lower cost** – water is cheap and readily available.
- **Milder reaction conditions** – often occurs at lower temperatures and ambient pressure.

Advantages of continuous flow synthesis

- **Better reproducibility** – controlled flow ensures consistent conditions.
- **Precise size control** – narrow particle size distribution due to uniform heating and mixing.
- **Scalability** – easy to produce larger quantities without changing the setup.
- **Improved safety** – reduces risk of handling toxic or volatile reagents in batch processes.
- **Enhanced reaction efficiency** – continuous removal of heat and by-products can speed up reactions.

Figure 1. Simplified typical structure of QDs (V.B. = valence band, C.B. = conduction band and e^- = electron) with advantages of their synthesis in aqueous medium and in continuous flow.

Alongside these organic routes, aqueous syntheses have a long history, dating back to the pioneering work of Henglein and Fendler, and have since grown into a central branch of colloidal nanochemistry.[17−21] Although organic solvent methods often yield higher PLQYs and fewer defects, aqueous strategies remain highly appealing due to their sustainability, scalability, intrinsic safety and compatibility with biological and environmental applications. In particular, the use of water-soluble ligands, including biomolecules, has opened up possibilities for direct biofunctionalization and even biosynthetic approaches.[22−25]

In recent years, significant progress has been made in expanding the scope of aqueous synthesis. Chiral ligands have been introduced to impart size-dependent optical activity,[26] and nucleic acids have been employed to direct the formation of QDs with programmable and biocompatible surface chemistries.[27,28]

While high-quality III−V and Pb-based nanocrystals still rely on organic methods, many II−VI systems are now achievable through both aqueous and nonaqueous routes, with water-based approaches becoming increasingly competitive.[21]

Aqueous environments bring additional complexity, as factors such as pH, ionic strength, and solvation strongly affect precursor chemistry and surface passivation.[21] Nevertheless, these conditions can be harnessed to build heterostructures and even core/shell QDs with performances approaching those of organic counterparts.[29] Ongoing work in understanding nucleation, growth, and ligand interactions continues to enhance the quality of the resulting nanomaterials, moving the field closer to rational, application-driven design.

The earliest aqueous synthetic protocols involved simple precipitation reactions between ionic precursors in the presence of stabilizing additives. Early stabilizers included micelles, polymers, and phosphates, and these strategies were quickly extended from CdS to other chalcogenides such as ZnS, PbS, Cd_3P_2, Zn_3P_2, Cd_3As_2, and CdTe.[21] The introduction of thiol ligands was a decisive advance, as they proved exceptionally effective at stabilizing surfaces and enabled the isolation of ultrasmall CdS clusters with molecular-level precision.[30−32] The methodology was then broadened to CdSe and CdTe, the latter becoming particularly important due to its narrow bulk band gap (1.43 eV vs 2.45 eV for CdS). As mentioned, initial aqueous CdTe syntheses relied on Cd^{2+} and Na_2Te in the presence of polyphosphate,[33] later improved by adding thioglycerol (TGL) as a costabilizer.[34] A significant step forward was achieved by Rogach and colleagues, who used TGL or mercaptoethanol to obtain size-controlled CdTe QDs, although the PL efficiencies remained low (<3%).[35] Gao's group advanced the field by introducing mercapto acids such as thioglycolic acid (TGA) and mercaptopropionic acid (MPA), which produced CdTe with PLQY of 18% and 38%, respectively, and long-term colloidal stability.[36,37] Optimization of these protocols subsequently raised PLQYs to 50−80% and enabled access to a variety of anisotropic structures, including nanorods, nanowires, nanotubes, ribbons, and nanosheets.[38−42]

Advances in processing techniques further strengthened aqueous approaches. Hydrothermal conditions enhanced long-term stability, while microwave heating enabled faster, more reproducible syntheses with improved uniformity and photophysical quality, reducing reaction times from hours to minutes.[43−46]

As mentioned, the epitaxial growth of shells in water presents challenges that are distinct from core nucleation. Although aqueous synthesis of CdSe/CdS, CdTe/CdS, or multishell CdTe/CdS/ZnS QDs has been demonstrated, achieving high-quality shell growth requires careful ligand and precursor control to avoid undesirable homogeneous nucleation, hydrolysis, or uncontrolled growth, challenges that stem from the aqueous medium itself.[47,48] In aqueous environments, the higher dielectric constant and weaker ligand binding can further complicate growth, increasing the risk of surface etching or ripening. Yet, strategies such as thiolate-assisted precursor stabilization and the in situ generation of chalcogenide species have enabled successful aqueous core/shell structures.[49,50] For example, water-soluble CdTe/CdS have been prepared via stabilization using dual capping ligands (adenosine 5′-monophosphate and thiopropionic acid).[51] Optimized precursor design and passivation strategies therefore remain central to advancing high-quality aqueous core/shell Cd-chalcogenides.

What began as simple precipitation methods has thus matured into a versatile synthetic platform. Mercapto acid−based strategies, first optimized for CdTe, have since been extended to a broad spectrum of chalcogenides, including CdX, ZnX, PbX, HgX, AgX, $CuInS_2$ and $AgInS_2$.[21] This body of work has firmly established aqueous synthesis as a mainstream route for high-quality QDs. Nevertheless, batch processes still face challenges in reproducibility, scalability, and precise control over nucleation and growth.

To address these limitations, continuous flow chemistry has emerged as one of the most effective strategies for nanomaterial synthesis, enabling access to QDs with improved uniformity and tunability.[52,53] By allowing fine regulation of reaction parameters, flow systems not only enhance reproducibility but also improve safety through controlled handling of hazardous or toxic substances, while supporting more sustainable production.[54,55]

A notable example was provided by Jensen and co-workers, who engineered a stainless-steel tubular microreactor for the continuous preparation of QDs.[56] Their design incorporated a gas−liquid flow regime, which suppressed the parabolic residence time distribution typical of laminar flow and thereby produced nanocrystals with a remarkably narrow size distribution.

As said, continuous flow reactors and microfluidic platforms offer multiple intrinsic advantages that directly address many of the drawbacks of batch methods for the production of QDs:

- Improved mixing, heat, and mass transfer: In small channels or coils, diffusion times and convective flows are controlled more precisely. This allows sharper delineation between nucleation and growth phases, reducing the overlap that often broadens size distributions in batch systems.[57−59]
- Better reproducibility and narrower polydispersity: Because the reactor environment is fixed and decoupled from operator handling, batch-to-batch variation is reduced. Flow synthesis inherently ensures that every particle experiences the same history of temperature, concentration, and flow conditions.[60−62]
- Scalability and continuous production: Flow systems allow prolonged, uninterrupted operation, enabling high cumulative yields without repeated manual intervention. Scalability to larger scales can be addressed through either numbering up (operating several identical flow reactors in parallel) or scale-out (higher flow rates in larger internal volume flow reactors).This is especially advantageous for industrial translation.[62−65]
- Modularity, inline monitoring, and automation: Flow reactors easily integrate with real-time analytical probes (UV−vis, fluorescence, Raman, Infrared), feedback loops, and machine-driven optimization. This enables adaptive control and potentially closed-loop optimization of synthesis.[66,67]
- Safety, confinement, and reduced waste: Because flow reactors handle small reaction volumes continuously, hazards (e.g., hot reagents, evolving gases, toxic precursors) are confined, and heat or pressure excursions are easier to manage. Also, reaction byproducts and unreacted precursors can be handled downstream continuously, reducing waste and simplifying purification workflows. Moreover, microfluidic QDs syntheses often discard the need for inert gas protection or glovebox handling, as sealed channels reduce oxygen sensitivity, improving safety and reducing complexity.[66,68]

However, translating batch protocols into flow is not straightforward: clogging, fouling, precursor solubility, mixing times, and reactor design all pose obstacles. Moreover, transfer of optimized batch conditions to flow is often nontrivial and may require reoptimizing of process parameters, solvent systems, and precursor delivery schemes.[63]

Given these trade-offs, aqueous continuous flow synthesis of CdX QDs presents a compelling but underexplored area. By combining the sustainability and biocompatibility of water with the precision, reproducibility, and scalability of flow systems the field has an opportunity to push QDs production toward truly robust, large-scale, greener manufacturing (Figure 1).

Before delving into the synthesis of CdX QDs, it is important to acknowledge that, despite being among the most widely studied and best-performing QDs to date, the toxicity of Cd-based materials remains a critical concern. Their synthesis typically requires stringent experimental conditions, involves hazardous raw materials, and poses potential environmental risks, all of which may limit their commercial development. As a result, developing more environmentally friendly synthetic methods and identifying nontoxic alternatives have become major priorities in the field.

In this review, we start by comparing classical batch synthesis in organic solvents and in water and continue by summarizing the current state of aqueous continuous flow syntheses of CdX QDs discussing challenges in developing this emerging strategy. Although we chose to focus on Cd-based systems as a mean to improve the overall sustainability of their preparation, it is also worth noting the ongoing efforts aimed at developing safer, Cd-free materials, often using similar flow-based technologies. A brief discussion of aqueous continuous-flow syntheses of Cd-free QDs (including carbon and In-based QDs) is provided at the end of Section 3. Finally, we highlight perspectives for future integration of advanced tools such as machine learning and automated process control, which may accelerate the rational design of high-quality, sustainable QDs.

2. BATCH SYNTHESIS OF CDX QDS: ORGANIC VS AQUEOUS ROUTES

As mentioned in the introduction, among the various types of QDs, CdX QDs remain among the most widely produced, despite concerns regarding their toxicity.[3] These QDs are particularly valued for their narrow and tunable emission and excellent optical properties, such as high PLQY and narrow FWHM (full width at half maximum).[16,69] Batch synthesis can be performed in several ways, with protocols generally divided into solvo-/hydrothermal and hot-injection methods, which differ primarily in the order of reagent addition. In solvo- or hydrothermal syntheses (using organic solvents or water, respectively), the reagents are mixed at room temperature and the temperature is then gradually increased to generate the monomers.[70,71] A subcategory of these methods is microwave-assisted synthesis, where the reaction mixture is heated using microwaves.[72,73] By contrast, in hot-injection methods the solvent and/or one thermally stable precursor is first heated to a high temperature, followed by the rapid injection of the remaining precursors.[74] In Figure 2 an example for the synthesis of CdSe using the hot-injection method is illustrated.

Owing to these thermal requirements, solvothermal methods are generally more suitable for aqueous precursors, whereas organic solvents are typically preferred for hot-injection approaches.

From a chemical standpoint, the synthesis of CdX QDs is, in principle, as simple as reacting a Cd^{2+} precursor with a X^{2-} one (where X = S, Se, or Te) in the presence of ligands in the chosen solvent. In practice, however, solubility is a key parameter to consider, since both precursors and ligands must dissolve in the

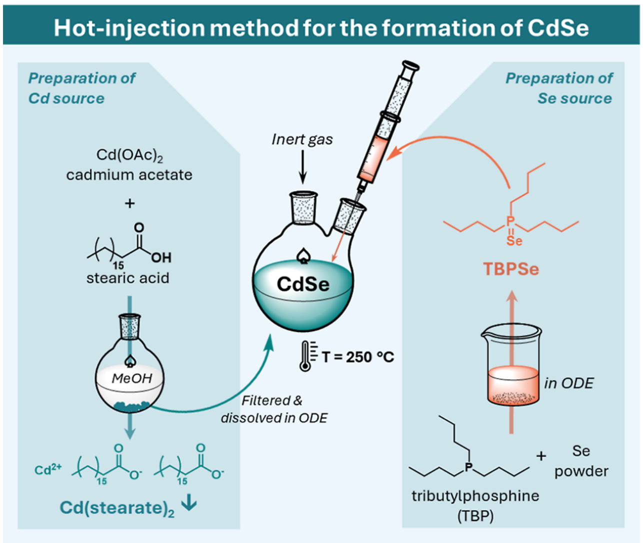


Figure 2. Example of a hot-injection synthetic protocol for the preparation of CdSe in an organic solvent (ODE = octadecene). The experimental protocol is from ref 78.

selected solvent. The resulting nanocrystals are accordingly soluble in either water or organic solvents; however, when a different solubility profile is required for the intended application, postsynthetic surface modification strategies such as ligand exchange can be employed to adjust the dispersibility of the QDs.[75−77]

The following sections explore recent advances in the batch, bottom-up synthesis of CdX QDs, with emphasis on the differences between protocols in organic solvents (Section 2.1) and aqueous routes (Section 2.2). For each approach, the choice of cadmium and chalcogen precursors, as well as the ligands, is discussed.

2.1. Organic Solvent-Based Synthesis

The pioneering work in QDs synthesis using organic solvents was reported by Bawendi et al. in 1993, who developed the hot-injection protocol that remained the gold standard for QDs preparation until the early 2000s.[2] Subsequent advances, notably the addition of a shell to the CdX core, significantly enhanced PLQY.[79]

Organic-solvent-based syntheses are typically conducted under harsh conditions, with reaction temperatures reaching up to 350 °C in hot-injection protocols. Consequently, these methods rely on high-boiling-point, weakly polar or nonpolar solvents such as octadecene (ODE), trioctylphosphine oxide (TOPO), fatty acids (e.g., stearic acid, lauric acid, oleic acid (OA), myristic acid), and hexadecylamine (HDA), some of which can act also as ligands. The structures of the main solvents used to prepare CdX, together with the principal ligands, cadmium sources and chalcogen precursors are illustrated in Figure 3.

Among cadmium precursors suitable for organic solvent-based syntheses, the first widely used source was dimethylcadmium ($Cd(Me)_2$). In the above-mentioned work from Bawendi and co-workers, indeed $Cd(Me)_2$ was used as the precursors to obtain CdS, CdTe and CdS nanocrystals as small as 1.2 nm.[2]

However, $Cd(Me)_2$ has several drawbacks, such as its extreme toxicity, pyrophoric nature, and tendency to decompose in the presence of TOPO at high temperature to form insoluble metallic cadmium. For these reasons numerous efforts have been done to find safer alternatives.[80]

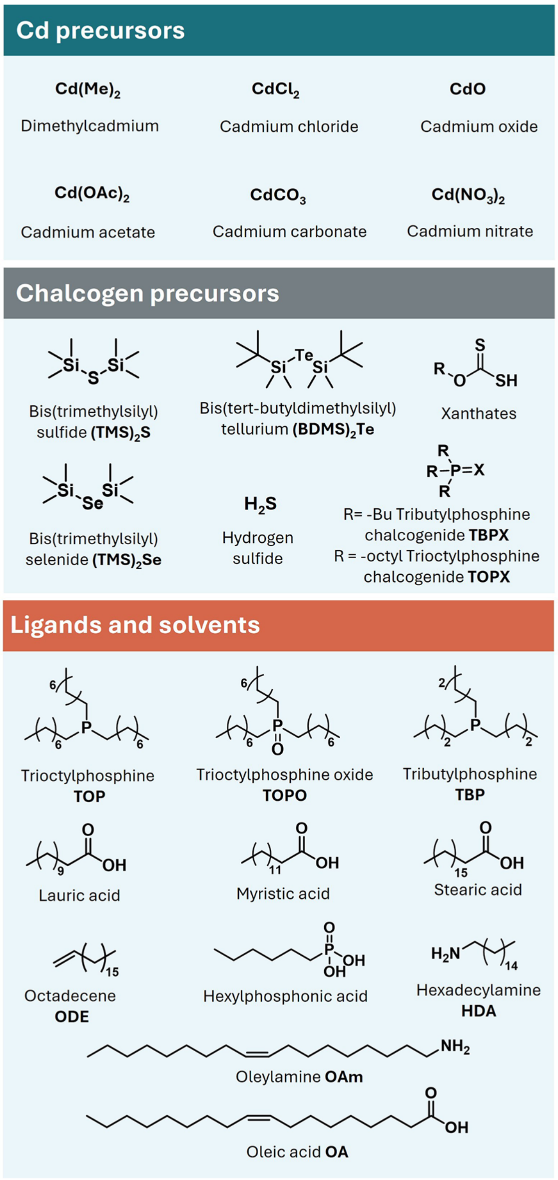


Figure 3. Structures of typical Cd precursors, chalcogen precursors (X = S, Se, Te), ligands and solvents used for the synthesis of CdX QDs in organic solvents.

Peng and co-workers extensively investigated alternative and greener cadmium precursors for the colloidal synthesis of CdX QDs.[81−83] A typical example is their work of 2001 where they explored safer, cheaper, and more accessible synthetic routes to CdSe while maintaining high optical quality.[82] Their goal was to replace the hazardous and expensive reagents used in conventional organometallic syntheses, with more benign and practical alternatives.

The authors investigated more than ten different solvent and ligand systems, using combinations of fatty acids, amines, phosphine oxides (both technical-grade and pure TOPO), and phosphonic acids, often mixed in varying ratios. As cadmium sources, they tested cadmium acetate ($Cd(OAc)_2$), cadmium oxide (CdO), and cadmium carbonate ($CdCO_3$), while selenium was supplied as trioctylphosphine selenide (TOPSe), prepared by dissolving elemental selenium in trioctylphosphine.

https://doi.org/10.1021/jacsau.5c01449
JACS Au XXXX, XXX, XXX−XXX

Reactions were conducted under inert atmosphere using hot-injection procedures at temperatures between 250 and 360 °C, followed by controlled growth to tune the nanocrystal size. The resulting CdSe exhibited narrow size distributions and tunable diameters (1.5−25 nm). Importantly, $Cd(OAc)_2$ was identified among the most versatile precursors, and that fatty acids served as effective ligands and solvents for promoting uniform growth. In contrast, precursors containing strong-acid anions or thiolates were found to degrade optical quality, likely due to defect formation.

Other works then described the preparation also of CdS, CdSe and CdTe from CdO, $Cd(OAc)_2$, and $CdCO_3$.[80−82,84] Currently, common cadmium precursors include $CdCl_2$ and $Cd(NO_3)_2$ as well as the already mentioned CdO, $Cd(OAc)_2$, and $CdCO_3$.[78,82,85−89] Although these salts and oxides are considerably safer and easier to handle than $Cd(Me)_2$, they are also less reactive, which complicates burst nucleation and reduces the reproducibility of forming small QDs. In contrast to $Cd(Me)_2$, which rapidly releases reactive Cd species due to weak Cd−C bonds, cadmium salts and oxides are more stable and form stronger interactions with coordinating ligands or anions. This stabilizing effect slows precursor decomposition, limiting the instantaneous availability of free Cd^{2+} and resulting in slower nucleation kinetics and lower reproducibility. In general, the strength of the Cd−ligand interaction plays a decisive role in reaction kinetics and particle size distribution: stronger bonds favor gradual, diffusion-controlled growth and monodispersity, whereas weaker or more labile bonds lead to faster, less controlled growth and broader size distributions.[90]

Chalcogen precursors have been introduced through several strategies to provide X^{2-} species in organic solvents. Early approaches employed silylated chalcogenides such as $(TMS)_2S$, $(TMS)_2Se$, and $(BDMS)_2Te$.[2] However, the high reactivity and poor controllability of bis(trimethylsilyl)-based compounds led to a shift toward phosphine-mediated methods, where elemental chalcogens are reduced in situ by organo-soluble phosphines such as trioctylphosphine (TOP) or tributylphosphine (TBP).[82,84,87,89,91−99] For instance, CdTe QDs capped with stearate groups have been prepared from cadmium stearate and TOPTe in *N*-oleylmorpholine at 280 °C.[100] The obtained nanocrystals showed good stability, high crystallinity, narrow size distribution, and clear size-dependent optical properties. In a work by Cao et al., the use of TBPSe or Se powder as chalcogen precursors produced CdSe QDs of spherical or tetrahedral shape, respectively.[89]

Elemental sulfur or selenium can also be directly used as chalcogen sources in organic solvents.[84,88,101,102] To become reactive, S and Se must be thermally activated by heating in nonreductive solvents such as ODE above their melting points (115 °C for sulfur, 221 °C for selenium), where they undergo dismutation or chain fragmentation. The high melting point of Te (450 °C), however, makes elemental Te impractical for QDs synthesis. A notable phosphine-free route for CdSe nanocrystals that relies on elemental selenium dispersed in ODE was reported by Peng et al.[103] In this method, finely powdered Se is suspended in ODE, which upon heating provides a highly reactive yet "green" precursor. This approach avoids toxic TOPSe while maintaining excellent control over nucleation and growth. The Se-ODE precursor owes its reactivity to the thermal fragmentation of selenium rings and chains into short-chain species stabilized in the solvent. Spectroscopic studies confirmed this transformation, which makes Se-ODE an effective selenium source for CdSe QDs.[104]

Gaseous precursors such as H_2S are also sometimes used, particularly for shelling CdSe or CdTe with CdS or ZnS, though they are less suitable for core synthesis because of slow mass transfer during nucleation.[99,105] Direct H_2S gas is more often employed in aqueous or biomimetic syntheses rather than in hot-injection, organic-solvent protocols (see Section 2.2). Reports of CdX cores prepared directly with gaseous H_2S in organic solvents are rare due to the hazardous nature of H_2S and the difficulties of handling it at high temperature.

Another option, mainly explored in solvothermal syntheses, is the use of cadmium−chalcogen complexes such as cadmium xanthates.[106,107] For example, Efrima et al. reported the reaction of cadmium salts with alkyl xanthates to yield stable cadmium−xanthate complexes that incorporate both Cd and S moieties. Upon thermal decomposition in alkylamine solvents (e.g., oleylamine), these precursors release cadmium and sulfide in a controlled fashion, enabling the growth of high-quality, monodisperse CdS QDs. This single-source strategy eliminates the need for separate Cd and S reagents, simplifies the reaction scheme, and offers size control through the choice of xanthate ligand, solvent, and temperature.[107]

Ligands play a crucial role in stabilizing CdX nanocrystals, requiring functional groups capable of binding to the nanoparticle surface along with nonpolar moieties to ensure solubility in organic media. Amphiphilic molecules are typically used (e.g., fatty acids, hexylphosphonic acid, HDA).[85,86,97,103,105,106,108] In practice, QDs surfaces are passivated by a mixture of species, including not only intentionally added ligands but also precursor byproducts. Early generation precursors such as $Cd(Me)_2$ or silylated chalcogenides tend to produce volatile byproducts, while later-generation systems leave behind nonvolatile cadmium carboxylates or phosphonates that remain coordinated at the surface. Phosphine-based chalcogen sources can oxidize after delivering the chalcogen atom to generate L-type ligands, whose binding efficiency depends on steric factors such as the Tolman cone angle.[109] The final ligand shell composition has profound effects on both the photoluminescence and crystalline structure of the nanocrystals.[110]

Despite its long-established foundations, the organic-phase synthesis of Cd-chalcogenide QDs remains an active and rapidly evolving research area, with ongoing advances in precursor chemistry, ligand design, and reaction engineering continually refining material quality and synthetic control.[111−116] In Table S1, a summary of the organic solvent-based methods for the synthesis of CdX QDs is reported. The type of metal and chalcogen source, ligands and solvents are stated together with maximum reaction temperature, size of the dots and PLQY.

2.2. Water-Based Synthesis

The aqueous synthesis of CdX QDs dates back to the early 1980s, when CdS precipitation was first achieved on colloidal silica, which acted as both stabilizer and support.[117] Although these initial attempts did not produce nanocrystals small enough to be associated with quantum confinement, subsequent work relying on water-soluble copolymers such as styrene/maleic acid and sodium polyphosphate enabled the observation of pronounced blue shifts relative to bulk CdS.[30,118] In the 1990s, the introduction of diverse precursors and stabilizers expanded the scope and improved size distribution control, paving the way for more advanced aqueous protocols.

A distinctive feature of aqueous CdX QD synthesis, compared to organic routes, is the central role of pH control. Most aqueous strategies rely on thiol-containing ligands (e.g., TGA, MPA, TGL) to simultaneously stabilize Cd^{2+} in solution and passivate the nanocrystal surface.[119−121] The degree of thiol deprotonation, and thus the strength of Cd−thiol coordination, is highly pH-dependent, making alkaline adjustment a critical parameter. The Cd−thiol complexes used as precursors are generally stable and reactive only in a moderately alkaline environment, and most protocols therefore adjust the solution to pH ≈ 8−11 using NaOH. By contrast, when buffer systems are employed instead of NaOH, the restricted buffering range and competitive ligand interactions often result in reduced PLQY and broadened optical features.[122,123] Importantly, the selected pH must strike a balance between ensuring deprotonation of stabilizing ligands for efficient surface binding, enhancing precursor reactivity, and limiting side reactions.[30]

In Figure 4, the structures of typical ligands, cadmium and chalcogen precursors used for the aqueous preparation of CdX QDs are reported.

The availability and the preparation of water-soluble chalcogen precursors represent the most challenging aspects of aqueous synthesis. Sulfur sources are commercially available in diverse forms, including Na_2S, which provides highly reactive sulfide ions, and thiourea (TU), which offers lower reactivity and thus greater control over crystal growth.[124] Thiol/thiolate ligands, commonly used to stabilize cadmium precursors, can under thermal or annealing conditions partially decompose or convert to polysulfide/H_2S species.[125] Those sulfur-containing decomposition products may be incorporated into the particle, promoting local sulfide formation, improved crystallinity, and surface passivation; examples include aqueous CdTe/CdS formation via thiol decomposition and reports of thiolate-driven CdS shelling in hot syntheses.[126−128] In addition to thiol-mediated sulfur, several studies have demonstrated the use of H_2S as a direct sulfur source for CdS core formation. For instance, Ozdemir et al. report a bioinspired chemical cycle that generates H_2S in situ, which reacts with Cd^{2+} in aqueous solution to nucleate and grow size-tunable CdS QD cores (Figure 5).[129] Similarly, bacterial production of volatile sulfur compounds, notably H_2S, supplies S^{2-} for extracellular and intracellular formation of CdS nanocrystal cores.[130] Musić and co-workers described a classical method in which H_2S gas is bubbled into an aqueous $Cd(OAc)_2$ solution at room temperature, yielding nanosized CdS core particles.[131]

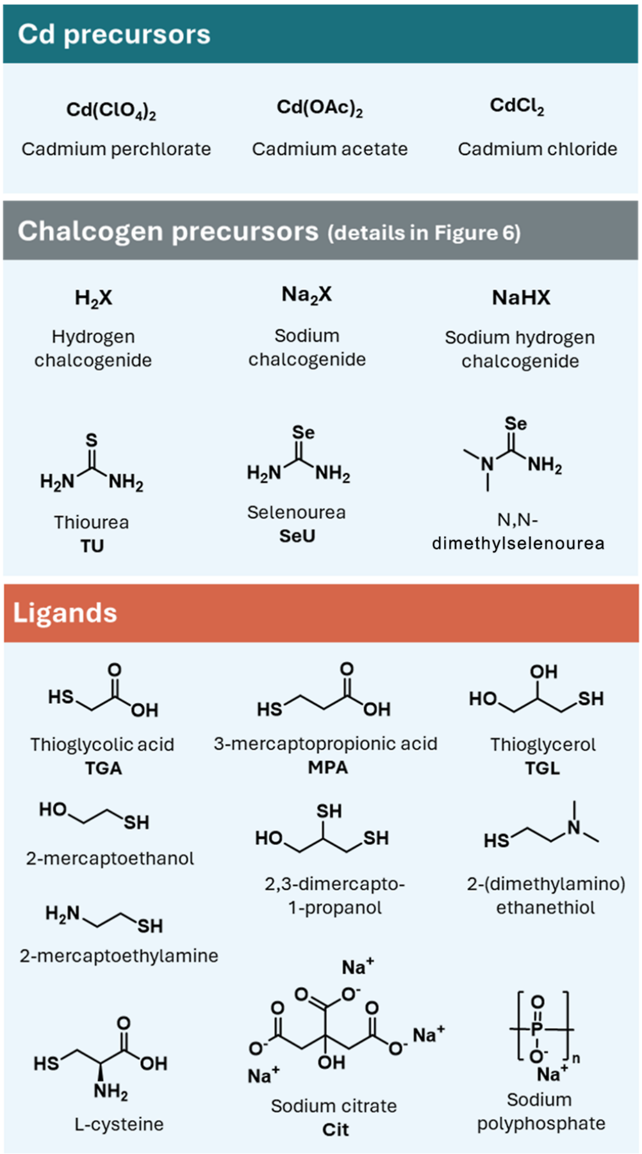


Figure 4. Structures of typical Cd precursors, chalcogen precursors (X = S, Se, Te) and ligands used for the aqueous synthesis of CdX QDs.

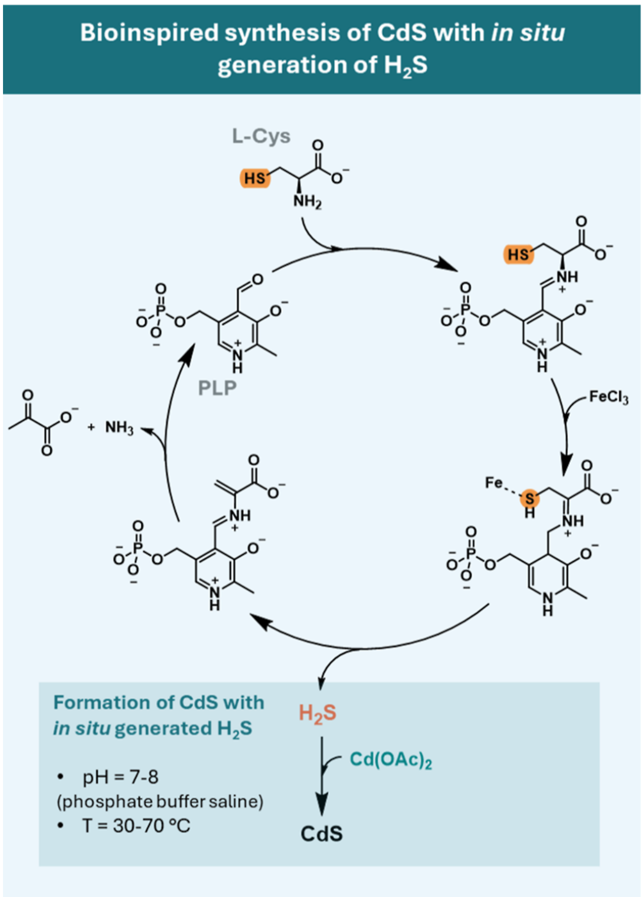


Figure 5. In situ generation of H_2S using pyridoxal 5′-phosphate (PLP) and L-cysteine (L-Cys) for the formation of CdS in water. Adapted from ref 129.

Commercial selenium precursors for aqueous CdSe synthesis are more limited than sulfur sources and are most commonly selenourea (SeU) or *N*,*N*-dimethylselenourea, both of which are water-soluble and thermally/chemically labile to produce Se^{2-}

under alkaline or heated conditions.[132−135] For example, Pan et al. used SeU in a two-phase (toluene/water) autoclave route to prepare OA-capped CdSe cores, reporting PLQYs up to 35%.[136] SeU-type precursors are relatively slow to decompose, which can limit rapid nucleation compared to reactive organic-phase precursors such as TOPSe. In addition to organoselenium sources, a significant number of aqueous CdSe syntheses rely on inorganic selenium precursors. Sodium selenide (Na_2Se) and sodium hydrogen selenide (NaHSe) can be generated in situ by reducing elemental Se with $NaBH_4$ under alkaline conditions, providing a highly reactive Se^{2-} source (Figure 6).[136−138]

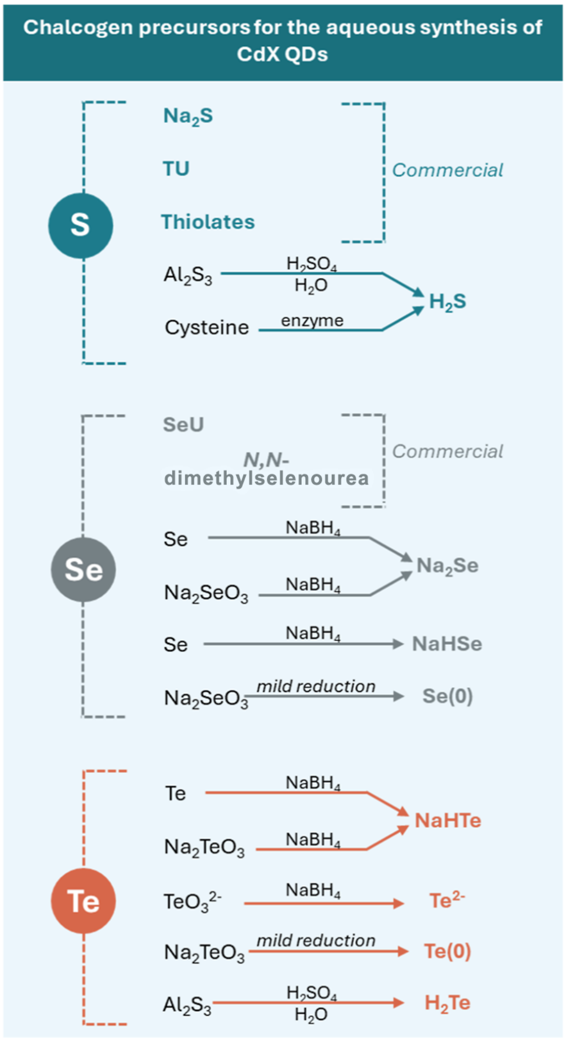


Figure 6. Overview of the main chalcogen precursors for aqueous synthesis of CdX QDs. Both commercial and in situ generated precursors are reported.

Sodium selenosulfate (Na_2SeSO_3), prepared by dissolving Se in sodium sulfite solution, has also been widely used as a safer and more controllable Se^{2-} donor.[136,139] Se(IV) salts (selenite/selenate) can also be reduced to Se^0 or Se^{2-} and be exploited in aqueous syntheses and biogenic routes.[140−142] Mild reducing agents, like ascorbic acid, can also be used in substitution to $NaBH_4$, to produce reactive Se species.[142] These inorganic routes avoid organic phosphines, but typically require strict pH control and stabilizing thiols to suppress uncontrolled precipitation and to obtain luminescent, monodisperse CdSe nanocrystals.

Tellurium precursors are not commercially available, so CdTe synthesis requires in situ generation of reactive Te species (Figure 6). Typically, Te^{2-} is produced by reduction of Te^0 or Te(IV) salts, such as Na_2TeO_3 or K_2TeO_3, with $NaBH_4$ under alkaline conditions to produce sodium hydrogen telluride (NaHTe), a reactive telluride ion source.[143] This method has been employed in various studies to synthesize CdTe.[144,145] For instance, Zuo et al. prepared NaHTe from Te powder and $NaBH_4$ and used it as a precursor to prepare water-soluble multicolored fluorescent CdTe QDs, achieving high PLQY.[146] Recently ammonia has also been reported as an effective reducing agent to obtain CdTe using Na_2TeO_3 as the chalcogen precursor.[147,148]

Direct use of H_2Te gas is rare due to its extreme toxicity and poor solubility; when employed, it is typically generated in situ or bubbled through basic cadmium solutions to form soluble telluride salts.[149−151] These strategies allow controlled Te delivery in aqueous media, enabling nucleation and growth of CdTe while avoiding unstable, preisolated Te^{2-} compounds. Figure 6 reports the most common commercial chalcogen precursors together with the synthetic strategies to prepare them in situ.

A general consideration in selecting chalcogen sources is the balance between precursor reactivity and reaction temperature: highly reactive species may be oxidized by water at elevated temperatures, becoming ineffective for CdX formation (Figure 7).[47,62,152]

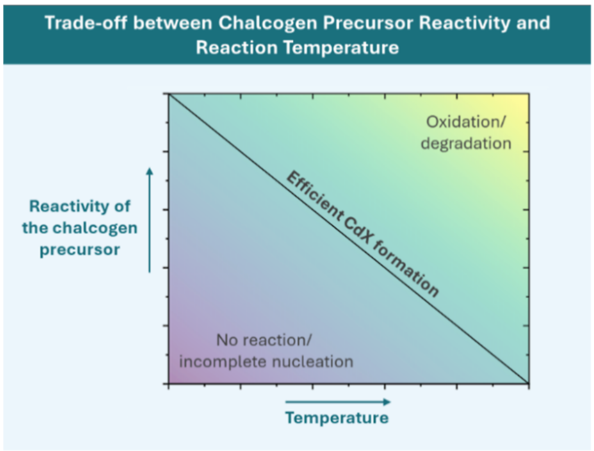


Figure 7. Trade-off between chalcogen precursor reactivity and reaction temperature in aqueous CdX QD synthesis. Highly reactive precursors require lower temperatures to prevent oxidation, while less reactive ones need higher temperatures for efficient nucleation. The optimal region represents balanced conditions for controlled CdX formation.

As mentioned earlier, the synthesis of CdX QDs in aqueous media typically requires basic conditions. Under these circumstances, insoluble $Cd(OH)_2$ readily precipitates, and ligands play a crucial role in mitigating this challenge. To stabilize the reaction, strongly binding, water-soluble ligands are needed, with anionic X-type ligands (e.g., thiolates, phosphates, or carboxylates) being the most commonly employed.[43,153,154] The binding strength of surface ligands, indeed, strongly influence nucleation and growth kinetics of QDs (Figure 8).[21,39,155,156]

In a notable study, Weller and co-workers systematically investigated thiol-capped CdTe QDs and demonstrated that each ligand exerts a distinct influence on PLQY, surface charge,

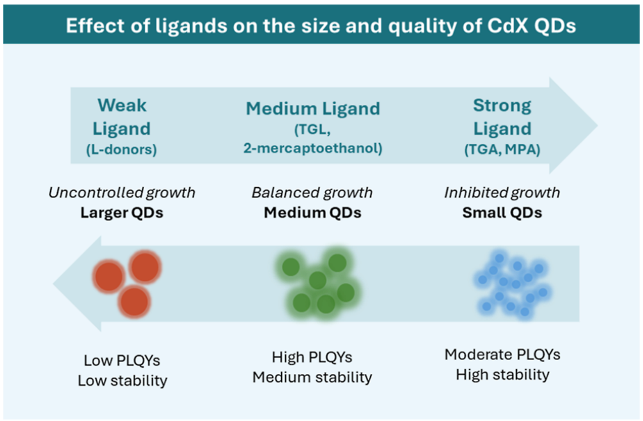


Figure 8. Correlation between the choice of the ligands, the size and the quality of the obtained CdX QDs.

and colloidal stability.[151] Common examples of such ligands include TGA,[157] TGL,[158] MPA,[159,160] and 2-mercaptoethanol,[161] as well as hydrophilic polymers such as sodium polyphosphate or poly(vinyl alcohol), which provide additional steric stabilization.[162,163] Importantly, the ligands used during aqueous synthesis often remain as the final biocompatible surface ligands, eliminating the need for postsynthetic ligand exchange in biorelated applications.[164]

Neutral donors (L-type) such as alcohols, amines, and phosphines can also coordinate to Cd^{2+}; however, they provide weaker stabilization and are generally insufficient to prevent $Cd(OH)_2$ precipitation.[164] Recently also biomass derived ligands/stabilizers, such as castor oil, have been proved efficient for the preparation of CdTe QDs.[165] Finally, cadmium counteranions (e.g., acetate, chloride) themselves act as surface ligands and influence both nucleation and growth kinetics.

Generally, the aqueous synthesis of CdX involves:

1) preparing a Cd-ligand solution at proper pH;
2) introducing the chalcogen source (Na_2X, NaHX, or H_2X);
3) aging the reaction mixture under reflux at ∼100 °C (lower temperatures are possible with highly reactive precursors, higher temperatures have also been employed using autoclaves).

Ligands interact with metal ions both before and after QDs formation, making their affinity crucial for size control. Strong ligands suppress growth, while weak ligands lead to uncontrolled growth (Figure 8).[150]

Although early aqueous CdX syntheses generally produce smaller core sizes than organic methods, which in turn limits PLQY, optimized aqueous protocols (careful ligand choice, alloying, core/shell growth or postsynthetic passivation) have raised ensemble PLQYs up to ∼50−80%.[38,40−42] Aqueous conditions, indeed, impose extra constraints (hydrolysis, $Cd(OH)_2$ formation, stronger surface trap formation in polar media) and commonly rely on short, anionic ligands (thiols, phosphonates, carboxylates) that are essential for colloidal stability but can be less effective at eliminating surface traps than the careful ligand engineering possible in organic syntheses. These factors make it harder to reach organic-phase near-unity PLQYs (≈ 90−98%) in strictly aqueous syntheses.[166,167]

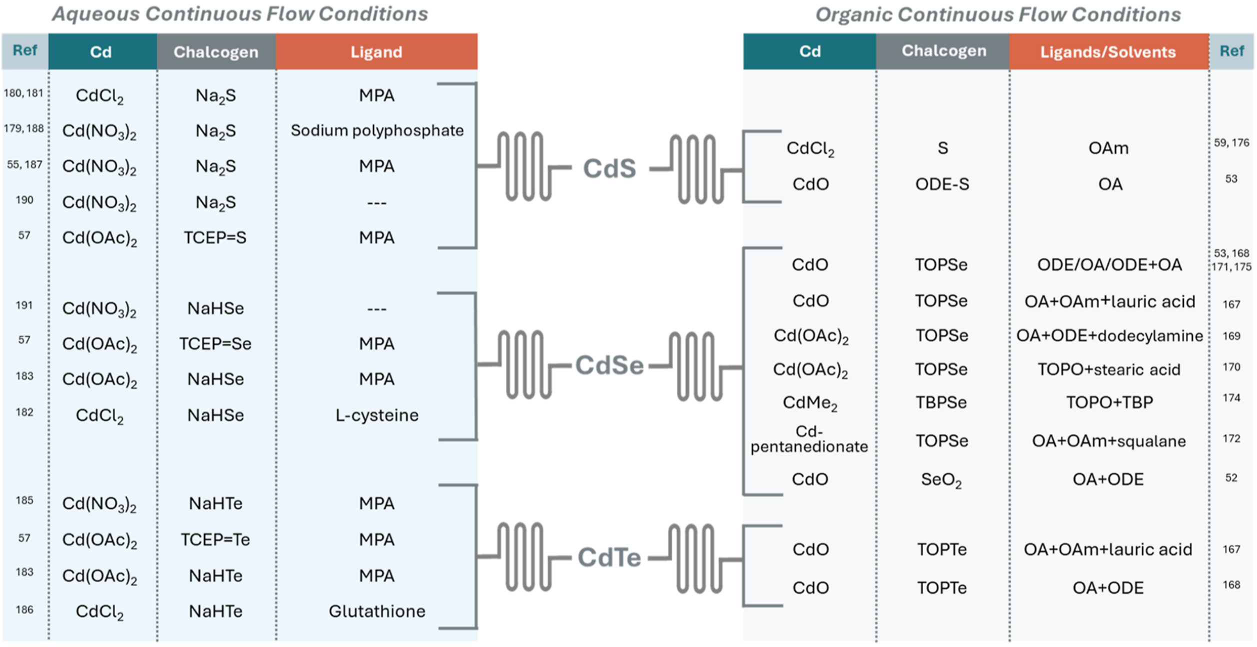
However, in one recent example, Wang, Shen and co-workers developed a one-step aqueous synthesis to obtain CdTe/CdSe QDs with PLQY up to 80.5%.[38] In their methodology, the simultaneous addition of Te and Se sources passivates the defects of CdTe while suppressing the overgrowth of CdSe shell, obtaining core−shell structure with small size and high PLQY.

Another work reported the influence of the nature of thiol-type capping ligands on the optical properties of CdTe synthesized in aqueous media.[41] The comparison of MPA, TGA, TGL, and glutathione revealed that the PLQY, along with other properties, strongly depend on the type of surface ligand. The obtained PLQY ranged from 38% to 73% depending on the chosen thiol and the reaction time.

In Table S2 an overview of the aqueous methods for the synthesis of CdX QDs is reported. The type of ligand, metal and chalcogen source are shown together with the pH, maximum reaction temperature, size of the dots and PLQY.

Table 1. Comparison of Batch Aqueous and Organic Solvent-Based Synthesis of CdX QDs

aspect	aqueous synthesis	organic solvent synthesis
solvent	water at controlled pH (7−12)	high-boiling organic solvents
Cd precursors	readily available hydrated salts. Risk of $Cd(OH)_2$ precipitation; mitigated by thiolate complexation	organometallic or pretreated cadmium complexes. Often require custom preparation for compatibility
chalcogen precursors	**S:** Na_2S, thiourea, thiolates, H_2S (commercial) **Se:** Selenoureas (commercial) or in situ generated Se^{2-} sources **Te:** none available, require in situ generation	-TOPX or TBPX; - elemental S or Se; -H_2S; -silylated chalcogenides; -Cd-chalcogen complexes
Ligands	common examples: TGA, MPA, mercaptoethanol, mercaptoethylamine, hydrophilic polymers (sodium polyphosphate, PVA). Cd counteranions also act like ligands	hydrophobic, longchain ligands: phosphines, thiols, amines, carboxylates
reaction conditions	- normally reflux at ∼100 °C; - lower T with highly reactive precursors; - higher T using autoclaves	hot-injection at high temperature (200−350 °C)
particle size	typically small cores due to slow precursor reactivity	larger, more tunable sizes with better monodispersity
PLQY	generally <80%. Improvements with core−shell	can reach >90% with optimized core−shell structures
Pros	- water is safe, cheap, biocompatible; - directly employs commercial Cd salts; - suitable for biomedical applications	- high-quality QDS - better control over size, shape, and PLQY; - widely used for display/lighting applications
cons	- lower PLQY, smaller sizes, slower growth kinetics - requires pH and precursor solubility control	- toxic and sensitive reagents; - less biocompatible; - postsynthetic ligand exchange for water solubility



Aqueous Continuous Flow Conditions

Ref	Cd	Chalcogen	Ligand
180, 181	$CdCl_2$	Na_2S	MPA
179, 188	$Cd(NO_3)_2$	Na_2S	Sodium polyphosphate
55, 187	$Cd(NO_3)_2$	Na_2S	MPA
190	$Cd(NO_3)_2$	Na_2S	---
57	$Cd(OAc)_2$	TCEP=S	MPA
191	$Cd(NO_3)_2$	NaHSe	---
57	$Cd(OAc)_2$	TCEP=Se	MPA
183	$Cd(OAc)_2$	NaHSe	MPA
182	$CdCl_2$	NaHSe	L-cysteine
185	$Cd(NO_3)_2$	NaHTe	MPA
57	$Cd(OAc)_2$	TCEP=Te	MPA
183	$Cd(OAc)_2$	NaHTe	MPA
186	$CdCl_2$	NaHTe	Glutathione

Organic Continuous Flow Conditions

Cd	Chalcogen	Ligands/Solvents	Ref
$CdCl_2$	S	OAm	59, 176
CdO	ODE-S	OA	53
CdO	TOPSe	ODE/OA/ODE+OA	53, 168 171, 175
CdO	TOPSe	OA+OAm+lauric acid	167
$Cd(OAc)_2$	TOPSe	OA+ODE+dodecylamine	169
$Cd(OAc)_2$	TOPSe	TOPO+stearic acid	170
$CdMe_2$	TBPSe	TOPO+TBP	174
Cd-pentanedionate	TOPSe	OA+OAm+squalane	172
CdO	SeO_2	OA+ODE	52
CdO	TOPTe	OA+OAm+lauric acid	167
CdO	TOPTe	OA+ODE	168

Figure 9. Literature protocols to access CdX with flow processes. For each chalcogen (S, Se, Te), the precursors and ligands are summarized according to the reaction medium (organic/aqueous).

While aqueous synthesis of CdX QDs still lags behind organic routes in terms of PLQY and overall optical performance, it offers clear advantages in other aspects. The use of water as solvent facilitates scalability, reduces costs, and eliminates the need for high-boiling, often hazardous organic media. Moreover, aqueous protocols align better with current sustainability goals and regulatory frameworks, particularly within the EU, where directives increasingly emphasize hazard reduction, safer chemical alternatives, and waste minimization.[3] These aspects make aqueous synthesis a promising pathway for greener and more compliant large-scale QDs production, even if further optimization is required to match the photophysical properties achieved in organic systems. A comparison of the preparation of CdX QDs in organic solvents and in water is reported in Table 1.

Building on these considerations, an important next step is to assess not only the choice of solvent, but also the synthetic strategy itself. In particular, the comparison between batch and continuous-flow approaches in aqueous media provides critical insight into how scalability and reproducibility can be further advanced. These aspects are discussed in the following section.

3. AQUEOUS CONTINUOUS FLOW SYNTHESIS OF CDX QDS

The continuous-flow synthesis of CdX QDs has attracted growing attention to improve synthetic control and achieve scalable production. Compared with conventional batch methods, flow reactors offer superior reproducibility through well-defined mixing, precise temperature management, and tunable residence times, which allow more uniform nucleation and growth.[52,168] This typically results in narrower size distributions, higher reproducibility, and the possibility of in-line monitoring, making flow chemistry an attractive alternative for QDs production.[3,55,68,169−173] Early studies focused mainly on nonaqueous syntheses in high-boiling coordinating solvents, which provide good control but limit biocompatibility and scalability in green contexts.

Among nanosized semiconductors, type II−VI QDs, and more specifically CdX QDs, have been extensively studied.[174] Their hot-injection synthesis is particularly amenable to translation into flow conditions, as rapid thermal exchange enables sharper temperature gradients than those achievable with batch methods. Furthermore, the synthesis of CdX QDs involves the use of harmful reagents: microfluidics is employed to reduce the risks by limiting the amount of reagent reacting at a given moment. Additionally, the reagents are usually pumped from a closed container, preventing the operator from exposure.

CdSe QDs have been among the first to be synthesized using microfluidics demonstrating the advantages brought by the technique such as the preparation of monodisperse nanocrystals with narrow emission spectra and higher PLQY.[68,175] In a recent paper CdS QDs were continuously synthesized using an impinging jet mixer: the setup was able to deliver monodisperse 2.7 nm nanocrystals at a production rate of more than 5 g/min.[64]

Various types of chalcogen sources have been transposed into microfluidics, such as TOPX,[2,58,176−182] TBPX,[183,184] or those chelated by the solvent itself (such as octadecene[58]). Similarly, the cadmium precursors followed the same trend as observed in batch: early syntheses were carried out using $Cd(Me)_2$.[184] Subsequently, the precursors evolved toward less toxic compounds, prepared ex situ (e.g., $Cd(OAm)_2$ from $CdCl_2$ and OAm or $Cd(OA)_2$ from CdO and OA).[57,185,186]

These organic-phase systems established the general principle that flow chemistry can deliver reproducible, scalable, and tailorable nanocrystals. However, the reliance on toxic and pyrophoric reagents as well as nonbiocompatible solvents has motivated the development of greener, aqueous alternatives.

Aqueous synthesis offers several advantages, such as biocompatibility, no additional ligand exchange steps, and lower reaction temperatures. However, aqueous protocols often lead to broader size distribution and lower quantum yield.[187,188] Moreover, the relatively limited number of reports using aqueous protocols suggests that they are more cumbersome compared to their organic counterparts.

One of the challenges in synthesizing QDs in water lies in the preparation of a suitable reduced chalcogen source, which is essential for initiating the transfer to the cadmium precursor. Most reported protocols involve an ex situ preparation of the chalcogenide source in batch, which could potentially lead to its decomposition. These protocols typically rely on the reduction of native chalcogens with ionic reductants such as $NaBH_4$ to give air-sensitive ionic chalcogenides such as Na_2S,[189−191] NaHSe,[192,193] or NaHTe.[193,194] Their decomposition prevents a seamless scale-up that continuous flow aims to offer.

Figure 9 report examples of the various precursors used in the aqueous and organic protocols to obtain CdX in continuous flow. Reports on the aqueous preparation of QDs in flow often lack photoluminescence data, suggesting that the resulting optical properties are poorer or, at best, comparable to those obtained in batch.[171] Nevertheless, the advantages offered by water continue to push researchers to develop suitable continuous-flow aqueous protocols for preparing CdX. Furthermore, the introduction of a BPR downstream facilitates high-pressure syntheses, including hydrothermal conditions, within microfluidic platforms.

Two main technological approaches for the continuous aqueous preparation of CdX can be distinguished: droplet-based microfluidics and homogeneous micro/mesofluidic reactors, with more recent extensions into hydrodynamic cavitation (HC) systems.

Several studies have demonstrated the use of droplets as confined microreactors to achieve controlled and reproducible synthesis. Yan and co-workers reported a continuous chemical aerosol flow method for the fabrication of CdTe/CdS/ZnS core−shell−shell nanocrystals.[195] In this integrated process, an ultrasonic nebulizer coupled to a quartz tube furnace (200−300 °C, under nitrogen flow) generated CdTe/CdS intermediates, which were subsequently overcoated with ZnS in a secondary low-temperature (∼80 °C) setup. The resulting particles displayed narrow photoluminescence features tunable between 525 and 567 nm and a PLQY exceeding 45%, with production rates approaching 0.1 g h^{-1}.

Some years later, another study further demonstrated the versatility of droplet reactors, using picoliter droplets as individual reaction vessels.[196] To form the droplets, mineral oil was used as the continuous phase and an aqueous solution of the Cd and Te precursors. By fine-tuning local temperatures by as little as 1−2 °C, they were able to produce multicolor, water-soluble CdTe QDs within approximately 1 min, highlighting the ultrafast and precise control offered by droplet microfluidics. In addition to ultrafast color-varying syntheses, droplet-based microfluidic platform capable of multistep nanoparticle synthesis on millisecond time scales has also been reported.[190] Aqueous reagents are introduced as plugs in an immiscible carrier fluid, mixed via winding microchannels, and then sequentially merged with further reactive streams within the same droplet. They used this scheme to generate colloidal CdS and CdS/CdSe core−shell nanoparticles, maintaining the reaction confined to droplets to avoid aggregation on channel walls. The fine temporal control and reagent merging provide tighter control over nucleation and shell growth, improving uniformity and reproducibility in QDs size and structure. This concept was later simplified using a water−oil digital droplet reactor (Figure 10).[60] This approach, relying on aqueous precursors such as cadmium nitrate and MPA, enabled CdS synthesis under ambient conditions. Enhanced mixing in a helical droplet mixer produced highly uniform nanoparticles (3.05 nm ± 6.3%), confirming the reproducibility and mild reaction conditions achievable with droplet microfluidics.

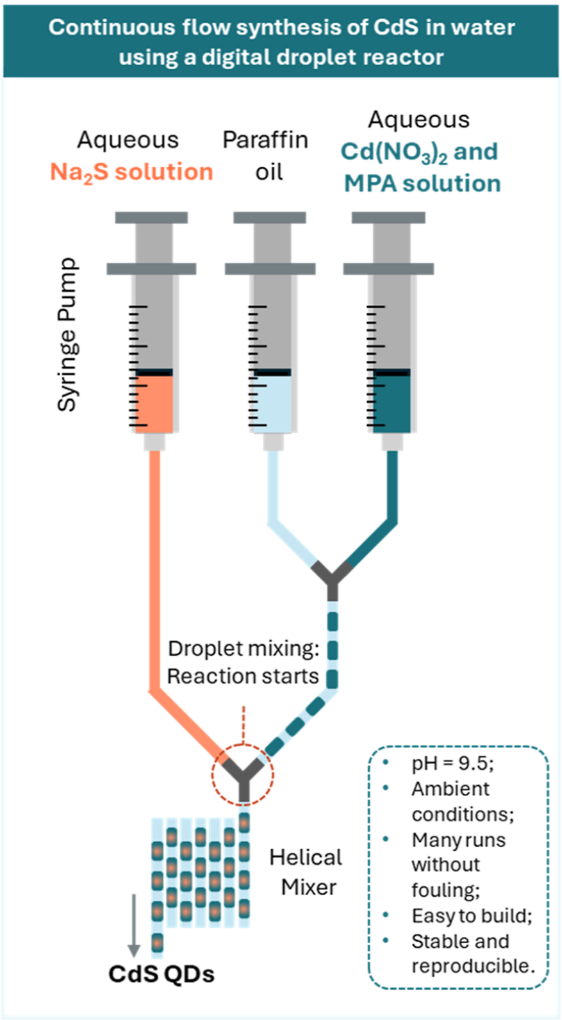


Figure 10. Digital water−oil droplet-based continuous reactor for the aqueous production of CdS QDs. Adapted from ref 60.

In parallel, several studies have investigated continuous homogeneous micro- and mesofluidic reactors for aqueous CdX QDs. In a recent work from Monbaliu and co-workers, tris(2-carboxyethyl)phosphine chalcogenides (TCEP = X) have been introduced as innovative chalcogenide transfer agents for the continuous preparation of CdS, CdSe, and CdTe QDs in water (Figure 11).[62] The microfluidic process was then implemented in a commercial mesofluidic reactor capable of flow rates up to 80 mL min^{-1}, with real-time monitoring by Raman and in-line ^{31}P NMR spectroscopy and optimization via design of experiments. This work represents a notable step toward scalable, biocompatible production under continuous flow.

In a 2022 study, a microjet reactor was also used to prepare $Cd_{1-x}Zn_xS$ and CdS/ZnS core/shell QDs in water in a continuous manner.[197] Due to the short mixing times compared to nucleation in the microjet reactor, supersaturation is reached everywhere at once and all nuclei were formed synchronously from homogeneous solution, resulting in a narrow particle size distribution. The resulting QDs were stable, monodisperse and crystalline.

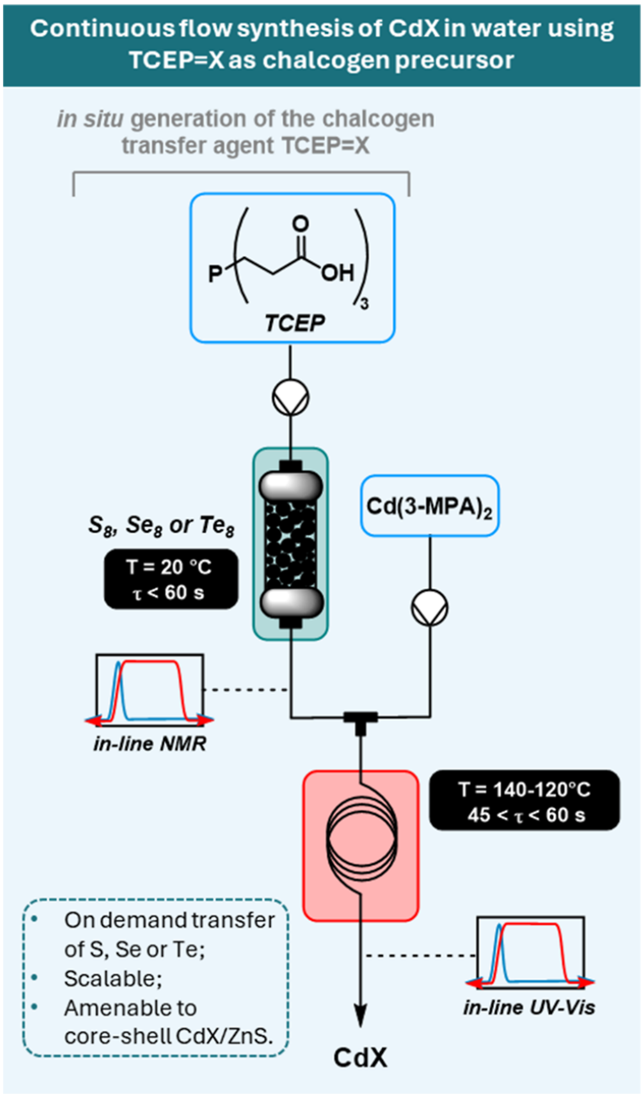


Figure 11. Concatenated continuous flow setup for the production of tris(2-carboxyethyl)phosphine chalcogenides (TCEP = X) and its use as a chalcogen precursor to prepare CdX in water. X = S, Se, Te. Adapted from ref 62.

The preparation of CdX, in particular CdS, has been explored also with oscillatory flow mixing in serpentine microchannels as a mean to overcome clogging in conventional microreactors.[198] Using oscillatory forward−reverse pumping, enhanced advection and mixing in larger channels was achieved, validated by computational fluid dynamics and by experiments. QDs with a smaller and more uniform size in respect to those obtained by laminar flow alone were observed, underscoring the benefits of oscillatory flow for reproducibility and size control.

Another type of microreactor was recently used by Bodas et al. for the synthesis of CdTe QDs in water.[199] The nanocrystals were produced in a custom polydimethylsiloxane microreactor, using mathematically derived process parameters to optimize conditions with >95% accuracy. The resulting QDs exhibited narrow emission (540−550 nm, FWHM ≈ 40 nm), high PLQY (∼61.5%), and good photostability.

Earlier contributions reported the use of a continuous flow micromixer to prepare aqueous CdS[189] and educational modules have also demonstrated the accessibility of these technologies, bringing microreactor-based aqueous CdX synthesis into teaching laboratories.[193]

More recently, HC has emerged as a powerful continuous method for aqueous nanomaterial production. In this approach, rapid pressure drops in Venturi-type reactors generate microbubbles that collapse to release localized energy, driving nucleation and growth. Qi and co-workers reported the preparation of CdS QDs using an HC reactor optimized at 12 h cycle time, 3.0 bar inlet pressure, and a 2.0 mm throat.[200] The resulting nanocrystals were blue-emitting with narrow size distribution, large Stokes shift, and high PLQY. In 2025 this method was extended to CdSe QDs, achieving highly stable particles as small as 1.83 nm, with an 87 nm Stokes shift and long fluorescence lifetime (1255 ns) (Figure 12).[201] These studies underline the scalability, low energy demand, and reproducibility of HC-based systems for continuous aqueous QDs production.

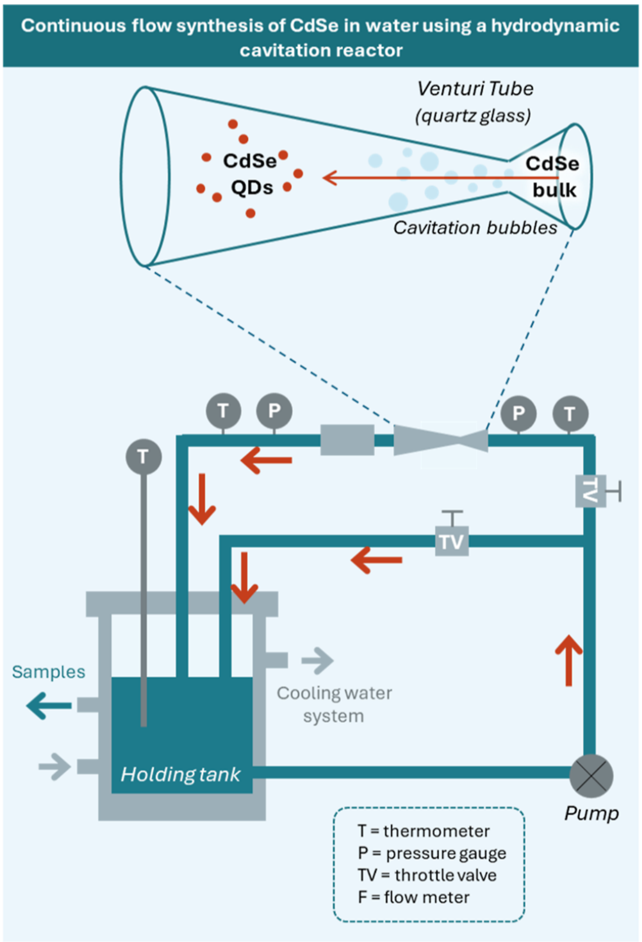


Figure 12. Structure diagram of HC reactor and Venturi tube for the aqueous continuous production of CdSe. Adapted from ref 201.

Taken together, these works illustrate the versatility of continuous-flow technologies for the aqueous synthesis of CdX QDs. Droplet microfluidics offers ultrafast, highly controlled reactions ideal for fine-tuning emission, while micro/mesofluidic reactors enable process intensification, monitoring, and scalability. Hydrodynamic cavitation adds an emerging dimension, combining continuous operation with straightforward scale-up. Collectively, these strategies merge the environmentally friendly conditions of aqueous synthesis with

Table 2. Recap of the Aqueous Continuous Synthesis of CdX QDs[a]

entry	core	reactor type	T (°C)	size (nm)	PLQY (%)	procedure details	ref
1	CdTe/CdS/ZnS	chemical aerosol flow	200−300	2.5	<45	flow rate = 1.5 mL/min	195
2	CdTe	picoliter droplet microreactor	81.5−91	1.4−2.6	n.a	flow rates: water = 10 μL/h oil = 30 μL/h residence time = 66s	196
3	CdS and CdS/CdSe	droplet (plug) microreactor	r.t	n.a	n.a	reaction time = 5 ms − 1 min	190
4	CdS	water−oil digital droplet reactor	r.t.-230	3.05	n.a	residence time = 9−45 min flow rate = 220−1000 μL/min	60
5	CdX & CdSe/ZnS	micro and mesofluidic flow reactor	120−200	3.31−4.0	<51	residence time = 45−60 s	62
6	CdS	micromixer chip	r.t	3.2−12	n.a	flow rate = 10−300 μL/min	189
7	$Cd_{1-x}Zn_xS$ and CdS/ZnS	microjet reactor	30−90	1−3	n.a	flow rate = 40 g/min	197
8	CdTe	polydimethylsiloxane microreactor	90−200	5−15	61.5	flow rate = 21−500 μL/min	199
9	CdS	oscillatory microreactor (serpentine microchannel)	n.a	11.3	n.a	particle residence time = 0.42−1.66 s flow rate = 125−501 mL/min	198
10	CdS	hydrodynamic cavitation reactor	60	1.38−1.50	<47.1	cycle time = 6−12 h	200
11	CdSe	hydrodynamic cavitation reactor	r.t.-160	1.83	n.a	flow rate = 29.25 m/s	201

[a] The type of reactor used and some synthetic details are reported together with reaction temperature range, size of the dots and PLQY. n.a. = not available.

the engineering strengths of flow chemistry, marking a clear improvement over conventional batch approaches.

Continuous aqueous strategies, indeed, offer precise control of precursor addition, mixing, and growth kinetics in real time, producing colloidally stable, luminescent QDs with higher reproducibility and reduced need for postsynthetic processing. Table 2 reports some examples of aqueous continuous flow synthesis of CdX with details on the used setup and on the obtained nanocrystals.

Other types of QDs, such as InP QDs, carbon dots, or ternary QDs (e.g., $CuInS_2$ or $AgInS_2$), have also been successfully synthesized and applied under aqueous continuous-flow conditions.[202−209]

For example, $CuInS_2$ QDs have been produced using a microwave-assisted continuous setup, where rapid and homogeneous heating enabled the formation of high-quality luminescent nanocrystals under fully water-based conditions.[208] Similarly, $AgInS_2$ and $AgInS_2$/ZnS QDs with PLQYs up to 83% have been synthesized using a fully aqueous flow apparatus.[209] Continuous hydrothermal platforms have also been employed for the preparation of carbon quantum dots, where efficient flow-based carbonization generated bright, water-dispersible nanodots subsequently applied for metal-ion sensing.[207] Although many InP QDs syntheses still rely on organic-phase precursors, continuous approaches have significantly improved nucleation−growth separation, size distribution, and optical performance, underscoring the broader trend that continuous processing, whether aqueous or organic, enhances the uniformity and scalability of cadmium-free QDs.[203,205]

These examples further demonstrate that flow chemistry in water can achieve scalable production while minimizing the use of toxic solvents and reagents. Insights and methodologies developed for one type of QDs are often transferable to other systems, highlighting the broader potential of aqueous flow approaches for environmentally friendly nanomaterial synthesis.

4. CONCLUSIONS, OPPORTUNITIES AND FUTURE DIRECTIONS

Aqueous continuous-flow synthesis of CdX QDs represents a crucial step toward the sustainable and scalable production of these nanomaterials. While traditional batch routes in organic solvents have delivered high-quality QDs, their reliance on toxic reagents, limited reproducibility, and challenges in scaling up constrain translation beyond the academic laboratory. In contrast, water-based continuous-flow platforms combine environmental compatibility with intrinsic process advantages such as modularity, reproducibility, and in-line monitoring. This makes them uniquely suited to bridge the gap between academic discovery and industrial production, positioning aqueous QDs as the next Frontier for sustainable nanomaterials in optoelectronics, photonics, and biomedicine.

Future opportunities for aqueous continuous-flow synthesis of chalcogenide QDs lie at the intersection of technical refinement, industrial translation, and digital automation. On the technical side, one of the most pressing challenges is the identification of ligands that can maintain long-term colloidal stability in water. While earlier droplet-based and homogeneous microfluidic studies demonstrated reproducible CdS, CdSe, and CdTe QDs with narrow emission and high PLQYs,[62,189,195,196] instability over extended operation remains a critical bottleneck. Developing multifunctional ligand shells, capable of both stabilizing surfaces and preventing hydrolytic degradation, would help close this gap. Another technical need is the integration of antifouling coatings within micro- and mesofluidic channels. For example, Bhargava and co-workers noted reactor fouling as a concern in their digital droplet reactor for the synthesis of CdS and CdSe.[60] To mitigate the problem the devices were flushed with paraffin oil after runs so they could be reused without fouling. Clogging clearly remains one of the biggest obstacles to the scale-up of the continuous production of QDs, particularly when nucleation is rapid and particle loading increases.[198,210,211] Tailored surface chemistries, whether polymeric or inorganic, could mitigate nanoparticle deposition, extend reactor lifetimes, and reduce downtime. In parallel, in-line optical monitoring methods such as real-time fluorescence and absorption spectroscopy would enable unprecedented

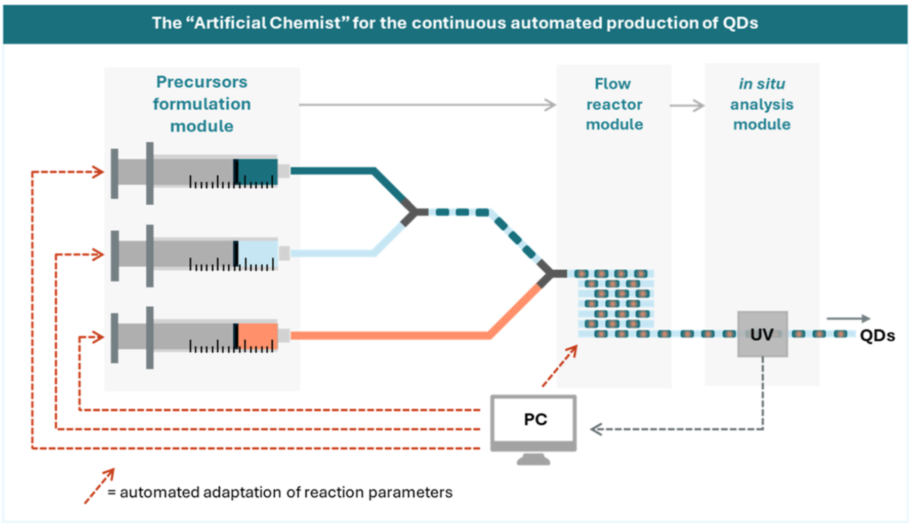


Figure 13. Diagram of the modular smart fluidic microprocessor designed for autonomous exploration and optimization of colloidal QD synthesis routes. Adapted from ref 213.

control over nucleation and growth. Coupling synthesis with real-time PL or Raman diagnostics would provide the missing link for adaptive control.[62]

From an industrial perspective, aqueous continuous-flow technologies hold clear advantages. Pharmaceutical and biotechnology sectors already operate under water-based, sterile, and modular process environments, making integration of aqueous QDs synthesis both natural and scalable. Compared to traditional batch processes in toxic organic solvents, aqueous platforms promise easier regulatory approval and alignment with existing good manufacturing practice frameworks. The work of Monbaliu and colleagues on mesofluidic protocol to obtain CdX in water, illustrates how industrially relevant reactors can achieve controlled, high-throughput production with in-line analytical validation.[62] As the demand for biocompatible luminescent probes grows, particularly for imaging in biological tissues, the convergence between water-based chemistry and clinical manufacturing workflows will make aqueous QDs uniquely positioned for translational applications.

A third and rapidly emerging direction involves automation through artificial intelligence (AI) and machine learning (ML). These approaches take advantage of modular and reconfigurable flow platforms that integrate precursor delivery, controlled reaction conditions, and real-time diagnostics, enabling high-throughput experiments with immediate feedback on QDs properties.[212]

Within this area, Abolhasani and colleagues have carried out extensive work on automated synthesis of multiple classes of QDs, ranging from Cd-based to lead halide perovskites. Their efforts make use of autonomous flow reactors that allow synthetic parameters to be tuned on the fly through AI-guided decision-making, resulting in reproducible protocols and improved material quality. In particular, they introduced closed-loop systems such as the "Artificial Chemist," specifically developed to accelerate materials discovery by continuously adjusting reaction conditions based on real-time optical signals and predictive modeling (Figure 13).[213] One notable application was an automated microfluidic platform for biphasic CdSe QDs synthesis and ligand exchange, which improved control over segmented flow and minimized particle adhesion to channel walls.[214]

More recently, the same group developed "AlphaFlow", a reinforcement learning-based self-driving platform built from modular fluidic units that can autonomously navigate complex multistep synthetic routes.[215] Using CdSe/CdS core−shell QDs as a model, AlphaFlow was able to independently identify optimal reagent sequences, producing nanocrystals with enhanced optical performance even without predefined chemical order. Further advances include a modular microfluidic reactor with AI-driven optimization for lead halide perovskites, capable of simultaneously controlling up to ten parameters to accelerate synthesis of ten distinct QDs types.[216] In addition, the "Smart Dope" platform combined digital twin simulations with closed-loop experimentation to streamline the synthesis of multication-doped lead halide perovskites, enabling both rapid optimization of existing protocols and on-demand discovery of novel reaction pathways.[217]

Beyond these examples, some reviews and perspectives highlight the broader promise of AI/ML and automation in colloidal nanomaterials. Munyebvu and co-workers stress that the vast multidimensional parameter spaces typical of QDs syntheses demand data-driven workflows; they propose modular flow platforms with in situ diagnostics to build standardized, rich data sets for reproducibility and accelerated optimization.[218] Bayesian optimization, surrogate modeling, and reinforcement learning are also being presented as effective tools to map optical signals to structural and functional properties of QDs.[219] The importance of robust data curation, model validation, and transferability across laboratories is also highlighted in the context of nanomaterials in general, emphasizing how continuous flow reactors with integrated sensing can accelerate process development, minimize fouling, and improve scalability.[220−222] At the same time, more targeted studies, such as the automated production of CdSe but also perovskite and PbS QDs, illustrate how computational and engineering strategies can provide precise control over nucleation, growth, and passivation in flow.[223−226] Also carbon QDs have been synthesized with similar strategies using ML to predict photoluminescence behavior and optimize synthetic conditions.[227] More generally, future directions point toward the convergence of high-throughput experimentation, closed-loop control, and robotics as the foundation for reproducible nanomaterial discovery.[228,229]

In the case of aqueous chalcogenide QDs, AI- and ML-driven methods are still rarely explored, even though these systems are particularly well suited for such approaches. Water-based synthesis involves a complex interplay of parameters, including pH, ligand choice, residence time, mixing rate, and temperature, that create a multidimensional space where automated optimization could be especially powerful. Closed-loop systems that integrate in-line PL or absorption readouts with reinforcement learning or predictive models, could autonomously tune conditions to yield optimal size, surface passivation, and optical properties of QDs. These arguments align closely with recent discussions of autonomous discovery pipelines, where flow chemistry is described as a natural enabler of data intensification and scalable optimization.[222,230]

In conclusion, aqueous continuous-flow synthesis of chalcogenide QDs not only enables environmentally benign processing but also provides a pathway toward reproducible, scalable, and industrially relevant nanomaterials. Technical advances in ligands, antifouling strategies, and in-line monitoring will lay the foundation, while integration with AI and ML promises to transform optimization into a closed-loop, autonomous process (Figure 14). By uniting sustainability with automation and scalability, aqueous continuous-flow approaches could redefine QDs manufacturing, bringing high-performance materials from the academic laboratory into industrial production and real-world applications.

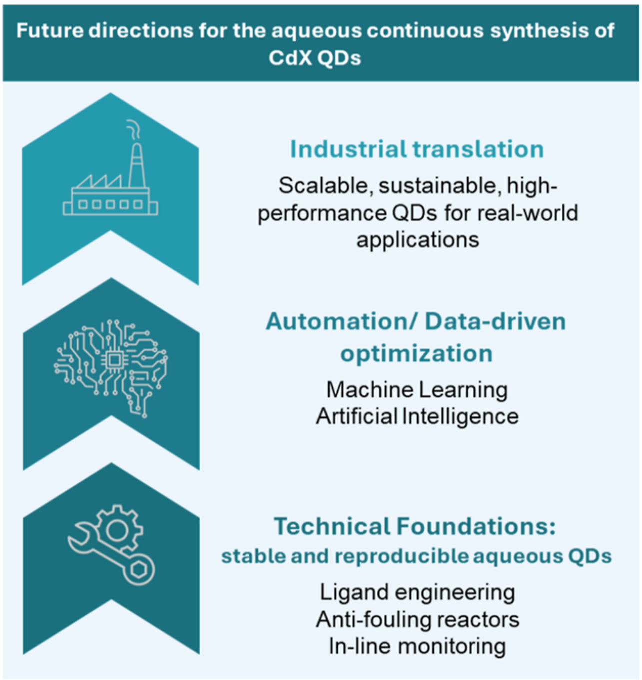


Figure 14. Perspectives for the continuous aqueous synthesis of CdX QDs. Technical advances in ligands, reactor coatings, and in-line monitoring establish the foundation; AI/ML integration enables closed-loop optimization; together these elements enable reproducible, scalable, and sustainable production suitable for industrial translation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacsau.5c01449.

Tables with an overview of the batch protocols to obtain cadmium chalcogenides quantum dots in organic solvents and in water (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Jean-Christophe M. Monbaliu − *Center for Integrated Technology and Organic Synthesis (CiTOS), MolSys Research Unit, University of Liège, Liège (Sart Tilman) B-4000, Belgium; WEL Research Institute, Wavre B-1300, Belgium;* orcid.org/0000-0001-6916-8846; Email: jc.monbaliu@uliege.be

Authors

Carlotta Campalani − *Center for Integrated Technology and Organic Synthesis (CiTOS), MolSys Research Unit, University of Liège, Liège (Sart Tilman) B-4000, Belgium*
Guillaume Petit − *Center for Integrated Technology and Organic Synthesis (CiTOS), MolSys Research Unit, University of Liège, Liège (Sart Tilman) B-4000, Belgium*

Complete contact information is available at:
https://pubs.acs.org/10.1021/jacsau.5c01449

Author Contributions

All authors have given approval to the final version of the manuscript. CRediT: **Carlotta Campalani** conceptualization, writing - original draft; **Guillaume Petit** writing - review & editing; **Jean-Christophe M Monbaliu** conceptualization, project administration, supervision, writing - review & editing.

Notes

The authors declare no competing financial interest.

■ ABBREVIATIONS

AI, artificial intelligence
BPR, back pressure regulator
CdX, cadmium chalcogenides
Cit, sodium citrate
FWHM, full width at half-maximum
HC, hydrodynamic cavitation
HDA, hexadecylamine
MA, mercaptoethylamine
ML, machine learning
MPA, mercaptopropionic acid
MR, nuclear magnetic resonance
OA, oleic acid
OAM, oleylamine
ODE, octadecene
PL, photoluminescence
PLQY, photoluminescence quantum yield
QDs, quantum dots
SeU, selenourea
TBP, tributylphosphine
TBPX, tributylphoshine chalcogenide
TCEP, tris(2-carboxyethyl)phosphine
TCEPX, tris(2-carboxyethyl)phosphine chalcogenide
TGA, thioglycolic acid

TGL, thioglycerol
TOP, trioctylphosphine
TOPO, trioctylphosphine oxide
TOPX, trioctylamine chalcogenide
TU, thiourea
UV−vis, ultraviolet−visible

REFERENCES

(1) Brus, L. E. A Simple Model for the Ionization Potential, Electron Affinity, and Aqueous Redox Potentials of Small Semiconductor Crystallites. *J. Chem. Phys.* **1983**, *79* (11), 5566−5571.

(2) Murray, C. B.; Norris, D. J.; Bawendi, M. G. Synthesis and Characterization of Nearly Monodisperse CdE (E = Sulfur, Selenium, Tellurium) Semiconductor Nanocrystallites. *J. Am. Chem. Soc.* **1993**, *115* (19), 8706−8715.

(3) Campalani, C.; Monbaliu, J.-C. M. Towards Sustainable Quantum Dots: Regulatory Framework, Toxicity and Emerging Strategies. *Mater. Sci. Eng. R Rep.* **2025**, *163*, 100940.

(4) Yu, Y.; Ma, T.; Huang, H. Semiconducting Quantum Dots for Energy Conversion and Storage. *Adv. Funct. Mater.* **2023**, *33* (16), 2213770.

(5) Brus, L. Electronic Wave Functions in Semiconductor Clusters: Experiment and Theory. *J. Phys. Chem.* **1986**, *90* (12), 2555−2560.

(6) Brus, L. E. Electron−Electron and Electron-hole Interactions in Small Semiconductor Crystallites: The Size Dependence of the Lowest Excited Electronic State. *J. Chem. Phys.* **1984**, *80* (9), 4403−4409.

(7) Sun, P.; Xing, Z.; Li, Z.; Zhou, W. Recent Advances in Quantum Dots Photocatalysts. *Chem. Eng. J.* **2023**, *458*, 141399.

(8) Hamadamin, A.; Benazzi, V.; Campalani, C.; Quattri, L.; Ravelli, D.; Hussain, F.; Perosa, A.; Selva, M.; Protti, S. Nitrogen-Doped Carbon Dots as Biobased Catalysts for Visible Light Driven 1,2-Functionalization of Olefins through an Atom Transfer Radical Addition Process. *ChemCatChem* **2023**, *15* (17), No. e202300708.

(9) Campalani, C.; Bragato, N.; Morandini, A.; Selva, M.; Fiorani, G.; Perosa, A. Carbon Dots as Green Photocatalysts for Atom Transfer Radical Polymerization of Methacrylates. *Catal. Today* **2023**, *418*, 114039.

(10) Zhang, J.; Bifulco, A.; Amato, P.; Imparato, C.; Qi, K. Copper Indium Sulfide Quantum Dots in Photocatalysis. *J. Colloid Interface Sci.* **2023**, *638*, 193−219.

(11) Liu, Y.; Yang, G.; Hui, Y.; Ranaweera, S.; Zhao, C.-X. Microfluidic Nanoparticles for Drug Delivery. *Small* **2022**, *18* (36), 2106580.

(12) Sobhanan, J.; Rival, J. V.; Anas, A.; Sidharth Shibu, E.; Takano, Y.; Biju, V. Luminescent Quantum Dots: Synthesis, Optical Properties, Bioimaging and Toxicity. *Adv. Drug Delivery Rev.* **2023**, *197*, 114830.

(13) Liu, S.; Li, M.-Y.; Xiong, K.; Gao, J.; Lan, X.; Zhang, D.; Gao, L.; Zhang, J.; Tang, J. Efficient Quantum Dot Infrared Solar Cells with Enhanced Low-Energy Photon Conversion via Optical Engineering. *Nano Res.* **2023**, *16* (2), 2392−2398.

(14) Campalani, C.; Causin, V.; Selva, M.; Perosa, A. Fish-Waste-Derived Gelatin and Carbon Dots for Biobased UV-Blocking Films. *ACS Appl. Mater. Interfaces* **2022**, *14* (30), 35148−35156.

(15) Shin, D.; Park, Y.; Jeong, H.; Tran, H.-C. V.; Jang, E.; Jeong, S. Exploring the Potential of Colloidal Quantum Dots for Near-Infrared to Short-Wavelength Infrared Applications. *Adv. Energy Mater.* **2025**, *15* (2), 2304550.

(16) Zhang, J.; Zhang, S.; Zhang, Y.; Al-Hartomy, O. A.; Wageh, S.; Al-Sehemi, A. G.; Hao, Y.; Gao, L.; Wang, H.; Zhang, H. Colloidal Quantum Dots: Synthesis, Composition, Structure, and Emerging Optoelectronic Applications. *Laser Photonics Rev.* **2023**, *17* (3), 2200551.

(17) Spanhel, L.; Haase, M.; Weller, H.; Henglein, A. Photochemistry of Colloidal Semiconductors. 20. Surface Modification and Stability of Strong Luminescing CdS Particles. *J. Am. Chem. Soc.* **1987**, *109* (19), 5649−5655.

(18) Henglein, A. Small-Particle Research: Physicochemical Properties of Extremely Small Colloidal Metal and Semiconductor Particles. *Chem. Rev.* **1989**, *89* (8), 1861−1873.

(19) Zhao, X. K.; Baral, S.; Rolandi, R.; Fendler, J. H. Semiconductor Particles in Bilayer Lipid Membranes. Formation, Characterization, and Photoelectrochemistry. *J. Am. Chem. Soc.* **1988**, *110* (4), 1012−1024.

(20) Meyer, M.; Wallberg, C.; Kurihara, K.; Fendler, J. H. Photosensitized Charge Separation and Hydrogen Production in Reversed Micelle Entrapped Platinized Colloidal Cadmium Sulphide. *J. Chem. Soc. Chem. Commun.* **1984**, *2*, 90−91.

(21) Jing, L.; Kershaw, S. V.; Li, Y.; Huang, X.; Li, Y.; Rogach, A. L.; Gao, M. Aqueous Based Semiconductor Nanocrystals. *Chem. Rev.* **2016**, *116* (18), 10623−10730.

(22) Sanjayan, C. G.; Jyothi, M. S.; Sakar, M.; Balakrishna, R. G. Multidentate Ligand Approach for Conjugation of Perovskite Quantum Dots to Biomolecules. *J. Colloid Interface Sci.* **2021**, *603*, 758−770.

(23) Mansur, H. S.; González, J. C.; Mansur, A. A. P. Biomolecule-Quantum Dot Systems for Bioconjugation Applications. *Colloids Surf., B* **2011**, *84* (2), 360−368.

(24) Kundu, S.; Ghosh, M.; Sarkar, N. State of the Art and Perspectives on the Biofunctionalization of Fluorescent Metal Nanoclusters and Carbon Quantum Dots for Targeted Imaging and Drug Delivery. *Langmuir* **2021**, *37* (31), 9281−9301.

(25) Mondal, A.; Pandit, S.; Sahoo, J.; Subramaniam, Y.; De, M. Post-Functionalization of Sulfur Quantum Dots and Their Aggregation-Dependent Antibacterial Activity. *Nanoscale* **2023**, *15* (46), 18624−18638.

(26) Li, G.; Zheng, J.; Li, J.; Kang, J.; Jin, X.; Guo, A.; Chen, Z.; Fei, X.; Wang, K.; Liu, H.; Zhao, H.; Liu, W.; Yang, G. Chiral Quantum Dots for Bioapplications. *J. Mater. Chem. C* **2024**, *12* (29), 10825−10836.

(27) Deng, Z.; Samanta, A.; Nangreave, J.; Yan, H.; Liu, Y. Robust DNA-Functionalized Core/Shell Quantum Dots with Fluorescent Emission Spanning from UV−Vis to Near-IR and Compatible with DNA-Directed Self-Assembly. *J. Am. Chem. Soc.* **2012**, *134* (42), 17424−17427.

(28) Tikhomirov, G.; Hoogland, S.; Lee, P. E.; Fischer, A.; Sargent, E. H.; Kelley, S. O. DNA-Based Programming of Quantum Dot Valency, Self-Assembly and Luminescence. *Nat. Nanotechnol.* **2011**, *6* (8), 485−490.

(29) Reiss, P.; Protière, M.; Li, L. Core/Shell Semiconductor Nanocrystals. *Small* **2009**, *5* (2), 154−168.

(30) Vossmeyer, T.; Katsikas, L.; Giersig, M.; Popovic, I. G.; Diesner, K.; Chemseddine, A.; Eychmueller, A.; Weller, H. CdS Nanoclusters: Synthesis, Characterization, Size Dependent Oscillator Strength, Temperature Shift of the Excitonic Transition Energy, and Reversible Absorbance Shift. *J. Phys. Chem.* **1994**, *98* (31), 7665−7673.

(31) Vossmeyer, T.; Reck, G.; Katsikas, L.; Haupt, E. T. K.; Schulz, B.; Weller, H. A. Double-Diamond Superlattice" Built Up of $Cd_{17}S_4(SCH_2CH_2OH)_{26}$ Clusters. *Science* **1995**, *267* (5203), 1476−1479.

(32) Zhu, X.; Chass, G. A.; Kwek, L.-C.; Rogach, A. L.; Su, H. Excitonic Character in Optical Properties of Tetrahedral CdX (X = S, Se, Te) Clusters. *J. Phys. Chem. C* **2015**, *119* (52), 29171−29177.

(33) Resch, U.; Weller, H.; Henglein, A. Photochemistry and Radiation Chemistry of Colloidal Semiconductors. 33. Chemical Changes and Fluorescence in CdTe and ZnTe. *Langmuir* **1989**, *5* (4), 1015−1020.

(34) Rajh, T.; Micic, O. I.; Nozik, A. J. Synthesis and Characterization of Surface-Modified Colloidal Cadmium Telluride Quantum Dots. *J. Phys. Chem.* **1993**, *97* (46), 11999−12003.

(35) Rogach, A. L.; Katsikas, L.; Kornowski, A.; Su, D.; Eychmüller, A.; Weller, H. Synthesis and Characterization of Thiol-Stabilized CdTe Nanocrystals. *Ber. Bunsenges. Phys. Chem.* **1996**, *100* (11), 1772−1778.

(36) Gao, M.; Kirstein, S.; Möhwald, H.; Rogach, A. L.; Kornowski, A.; Eychmüller, A.; Weller, H. Strongly Photoluminescent CdTe Nanocrystals by Proper Surface Modification. *J. Phys. Chem. B* **1998**, *102* (43), 8360−8363.

(37) Zhang, H.; Zhou, Z.; Yang, B.; Gao, M. The Influence of Carboxyl Groups on the Photoluminescence of Mercaptocarboxylic

https://doi.org/10.1021/jacsau.5c01449

Acid-Stabilized CdTe Nanoparticles. *J. Phys. Chem. B* **2003**, *107* (1), 8−13.

(38) Du, D.; Wang, L.; Ding, D.; Guo, Y.; Xu, J.; Qiao, F.; Wang, H.; Shen, W. One-Step Synthesis of Aqueous CdTe/CdSe Composite QDs toward Efficiency Enhancement of Solar Cell. *Chem. Eng. J.* **2023**, *461*, 142040.

(39) Shavel, A.; Gaponik, N.; Eychmüller, A. Factors Governing the Quality of Aqueous CdTe Nanocrystals: Calculations and Experiment. *J. Phys. Chem. B* **2006**, *110* (39), 19280−19284.

(40) Lau, P. C.; Norwood, R. A.; Mansuripur, M.; Peyghambarian, N. An Effective and Simple Oxygen Nanosensor Made from MPA-Capped Water Soluble CdTe Nanocrystals. *Nanotechnology* **2012**, *24*, 015501.

(41) Silva, F. O.; Carvalho, M. S.; Mendonça, R.; Macedo, W. A.; Balzuweit, K.; Reiss, P.; Schiavon, M. A. Effect of Surface Ligands on the Optical Properties of Aqueous Soluble CdTe Quantum Dots. *Nanoscale Res. Lett.* **2012**, *7* (1), 536.

(42) Huang, X.; Li, N.; Kim, K.-H.; Chang, Q.; Leng, M.; Wang, J.; Cheng, C.; Ao, Z. Enhancing Luminescence Efficiency of CdSe Quantum Dots through the Amine-Assisted Z-Type Ligand. *Cell Rep. Phys. Sci.* **2024**, *5* (11), 102268.

(43) Guo, J.; Yang, W.; Wang, C. Systematic Study of the Photoluminescence Dependence of Thiol-Capped CdTe Nanocrystals on the Reaction Conditions. *J. Phys. Chem. B* **2005**, *109* (37), 17467−17473.

(44) Zhang, H.; Wang, L.; Xiong, H.; Hu, L.; Yang, B.; Li, W. Hydrothermal Synthesis for High-Quality CdTe Nanocrystals. *Adv. Mater.* **2003**, *15* (20), 1712−1715.

(45) He, Y.; Sai, L.-M.; Lu, H.-T.; Hu, M.; Lai, W.-Y.; Fan, Q.-L.; Wang, L.-H.; Huang, W. Microwave-Assisted Synthesis of Water-Dispersed CdTe Nanocrystals with High Luminescent Efficiency and Narrow Size Distribution. *Chem. Mater.* **2007**, *19* (3), 359−365.

(46) Li, L.; Qian, H.; Ren, J. Rapid Synthesis of Highly Luminescent CdTe Nanocrystals in the Aqueous Phase by Microwave Irradiation with Controllable Temperature. *Chem. Commun.* **2005**, No. 4, 528−530.

(47) Deng, D.-W.; Yu, J.-S.; Pan, Y. Water-Soluble CdSe and CdSe/CdS Nanocrystals: A Greener Synthetic Route. *J. Colloid Interface Sci.* **2006**, *299* (1), 225−232.

(48) Samanta, A.; Deng, Z.; Liu, Y. Aqueous Synthesis of Glutathione-Capped CdTe/CdS/ZnS and CdTe/CdSe/ZnS Core/Shell/Shell Nanocrystal Heterostructures. *Langmuir* **2012**, *28* (21), 8205−8215.

(49) Chen, J.; Xiao, A.; Zhang, Z.; Yu, Y.; Yan, Z. The Synthesis and Modification of CdTe/CdS Core Shell Quantum Dots. *Spectrochim. Acta, Part A* **2015**, *151*, 506−509.

(50) Peng, H.; Zhang, L.; Soeller, C.; Travas-Sejdic, J. Preparation of Water-Soluble CdTe/CdS Core/Shell Quantum Dots with Enhanced Photostability. *J. Lumin.* **2007**, *127* (2), 721−726.

(51) Ma, Y.; Li, Y.; Zhong, X. Facile Synthesis of High-Quality CdTe/CdS Core/Shell Quantum Dots in Aqueous Phase by Using Dual Capping Ligands. *RSC Adv.* **2014**, *4* (85), 45473−45480.

(52) Bianchi, P.; Petit, G.; Monbaliu, J.-C. M. Scalable and Robust Photochemical Flow Process towards Small Spherical Gold Nanoparticles. *React. Chem. Eng.* **2020**, *5* (7), 1224−1236.

(53) Bartolomei, B.; Dosso, J.; Prato, M. New Trends in Nonconventional Carbon Dot Synthesis. *Trends Chem.* **2021**, *3* (11), 943−953.

(54) Lin, L.; Yin, Y.; Starostin, S. A.; Xu, H.; Li, C.; Wu, K.; He, C.; Hessel, V. Microfluidic Fabrication of Fluorescent Nanomaterials: A Review. *Chem. Eng. J.* **2021**, *425*, 131511.

(55) Guidi, M.; Seeberger, P. H.; Gilmore, K. How to Approach Flow Chemistry. *Chem. Soc. Rev.* **2020**, *49* (24), 8910−8932.

(56) Guidelli, E. J.; Lignos, I.; Yoo, J. J.; Lusardi, M.; Bawendi, M. G.; Baffa, O.; Jensen, K. F. Mechanistic Insights and Controlled Synthesis of Radioluminescent ZnSe Quantum Dots Using a Microfluidic Reactor. *Chem. Mater.* **2018**, *30* (23), 8562−8570.

(57) Mirhosseini Moghaddam, M.; Baghbanzadeh, M.; Sadeghpour, A.; Glatter, O.; Kappe, C. O. Continuous-Flow Synthesis of CdSe Quantum Dots: A Size-Tunable and Scalable Approach. *Chem. − Eur. J.* **2013**, *19* (35), 11629−11636.

(58) Naughton, M. S.; Kumar, V.; Bonita, Y.; Deshpande, K.; Kenis, P. J. A. High Temperature Continuous Flow Synthesis of CdSe/CdS/ZnS, CdS/ZnS, and CdSeS/ZnS Nanocrystals. *Nanoscale* **2015**, *7* (38), 15895−15903.

(59) Bianchi, P.; Monbaliu, J.-C. M. New Opportunities for Organic Synthesis with Superheated Flow Chemistry. *Acc. Chem. Res.* **2024**, *57* (15), 2207−2218.

(60) Richard, C.; McGee, R.; Goenka, A.; Mukherjee, P.; Bhargava, R. On-Demand Milifluidic Synthesis of Quantum Dots in Digital Droplet Reactors. *Ind. Eng. Chem. Res.* **2020**, *59* (9), 3730−3735.

(61) Li, Y.; Li, Y.; Li, X.; Hou, T.; Qiao, C.; Tai, Y.; Gu, X.; Zhao, D.; Sang, L.; Zhang, J. Microreactor Platform for Continuous Synthesis of Electronic Doped Quantum Dots. *Nano Res.* **2022**, *15* (10), 9647−9653.

(62) Petit, G.; Malherbe, C.; Bianchi, P.; Monbaliu, J.-C. M. An Innovative Chalcogenide Transfer Agent for Improved Aqueous Quantum Dot Synthesis. *Chem. Sci.* **2024**, *15* (33), 13148−13159.

(63) Machut, P.; Antonini, A. K.; Rivaux, C.; Gromova, M.; Kaur, H.; Ling, W. L.; Mugny, G.; Reiss, P. Continuous Flow Synthesis of PbS/CdS Quantum Dots Using Substituted Thioureas. *Nano Res.* **2024**, *17* (12), 10677−10684.

(64) Kim, S.; Kim, S.; Oh, H.; Choi, W. I.; Lim, J.-M. Large-Scale Continuous Synthesis of CdS Quantum Dots Using an Impinging Jet Mixer. *Colloids Surf., A* **2024**, *703*, 135202.

(65) Muzyka, C.; Renson, S.; Grignard, B.; Detrembleur, C.; Monbaliu, J.-C. M. Intensified Continuous Flow Process for the Scalable Production of Bio-Based Glycerol Carbonate. *Angew. Chem., Int. Ed.* **2024**, *63* (10), No. e202319060.

(66) Hellwig, H.; Bovy, L.; Van Hecke, K.; Vlaar, C. P.; Romañach, R. J.; Noor-E-Alam, M.; Myerson, A. S.; Stelzer, T.; Monbaliu, J.-C. M. Continuous Flow Synthesis of Nitrofuran Pharmaceuticals Using Acetyl Nitrate. *Angew. Chem., Int. Ed.* **2025**, *64* (25), No. e202501660.

(67) Bianchi, P.; Monbaliu, J.-C. M. Revisiting the Paradigm of Reaction Optimization in Flow with a Priori Computational Reaction Intelligence. *Angew. Chem., Int. Ed.* **2024**, *63* (5), No. e202311526.

(68) Cheng, Y.; Ling, S. D.; Geng, Y.; Wang, Y.; Xu, J. Microfluidic Synthesis of Quantum Dots and Their Applications in Bio-Sensing and Bio-Imaging. *Nanoscale Adv.* **2021**, *3* (8), 2180−2195.

(69) Xiang, X.; Wang, L.; Zhang, J.; Cheng, B.; Yu, J.; Macyk, W. Cadmium Chalcogenide (CdS, CdSe, CdTe) Quantum Dots for Solar-to-Fuel Conversion. *Adv. Photonics Res.* **2022**, *3* (11), 2200065.

(70) Williams, J. V.; Adams, C. N.; Kotov, N. A.; Savage, P. E. Hydrothermal Synthesis of CdSe Nanoparticles. *Ind. Eng. Chem. Res.* **2007**, *46* (13), 4358−4362.

(71) Wang, J.; Zhai, J.; Han, S. Non-Injection One-Pot Preparation Strategy for Multiple Families of Magic-Sized CdTe Quantum Dots with Bright Bandgap Photoemission. *Chem. Eng. J.* **2013**, *215−216*, 23−28.

(72) Moghaddam, M. M.; Baghbanzadeh, M.; Keilbach, A.; Kappe, C. O. Microwave-Assisted Synthesis of CdSe Quantum Dots: Can the Electromagnetic Field Influence the Formation and Quality of the Resulting Nanocrystals? *Nanoscale* **2012**, *4* (23), 7435−7442.

(73) Singh, R. K.; Kumar, R.; Singh, D. P.; Savu, R.; Moshkalev, S. A. Progress in Microwave-Assisted Synthesis of Quantum Dots (Graphene/Carbon/Semiconducting) for Bioapplications: A Review. *Mater. Today Chem.* **2019**, *12*, 282−314.

(74) Wuister, S. F.; de Mello Donegá, C.; Meijerink, A. Influence of Thiol Capping on the Exciton Luminescence and Decay Kinetics of CdTe and CdSe Quantum Dots. *J. Phys. Chem. B* **2004**, *108* (45), 17393−17397.

(75) Owen, J. S.; Park, J.; Trudeau, P.-E.; Alivisatos, A. P. Reaction Chemistry and Ligand Exchange at Cadmium−Selenide Nanocrystal Surfaces. *J. Am. Chem. Soc.* **2008**, *130* (37), 12279−12281.

(76) Shen, Y.; Gee, M. Y.; Tan, R.; Pellechia, P. J.; Greytak, A. B. Purification of Quantum Dots by Gel Permeation Chromatography and the Effect of Excess Ligands on Shell Growth and Ligand Exchange. *Chem. Mater.* **2013**, *25* (14), 2838−2848.

(77) Shen, Y.; Roberge, A.; Tan, R.; Gee, M. Y.; Gary, D. C.; Huang, Y.; Blom, D. A.; Benicewicz, B. C.; Cossairt, B. M.; Greytak, A. B. Gel

Permeation Chromatography as a Multifunctional Processor for Nanocrystal Purification and On-Column Ligand Exchange Chemistry. *Chem. Sci.* **2016**, *7* (9), 5671−5679.

(78) Li, J.; Zheng, H.; Zheng, Z.; Rong, H.; Zeng, Z.; Zeng, H. Synthesis of CdSe and CdSe/ZnS Quantum Dots with Tunable Crystal Structure and Photoluminescent Properties. *Nanomaterials* **2022**, *12* (17), 2969.

(79) Danek, M.; Jensen, K. F.; Murray, C. B.; Bawendi, M. G. Synthesis of Luminescent Thin-Film CdSe/ZnSe Quantum Dot Composites Using CdSe Quantum Dots Passivated with an Overlayer of ZnSe. *Chem. Mater.* **1996**, *8* (1), 173−180.

(80) Qu, L.; Peng, X. Control of Photoluminescence Properties of CdSe Nanocrystals in Growth. *J. Am. Chem. Soc.* **2002**, *124* (9), 2049−2055.

(81) Peng, Z. A.; Peng, X. Formation of High-Quality CdTe, CdSe, and CdS Nanocrystals Using CdO as Precursor. *J. Am. Chem. Soc.* **2001**, *123* (1), 183−184.

(82) Qu, L.; Peng, Z. A.; Peng, X. Alternative Routes toward High Quality CdSe Nanocrystals. *Nano Lett.* **2001**, *1* (6), 333−337.

(83) Biju, V.; Itoh, T.; Anas, A.; Sujith, A.; Ishikawa, M. Semiconductor Quantum Dots and Metal Nanoparticles: Syntheses, Optical Properties, and Biological Applications. *Anal. Bioanal. Chem.* **2008**, *391* (7), 2469−2495.

(84) Yu, W. W.; Peng, X. Formation of High-Quality CdS and Other II−VI Semiconductor Nanocrystals in Noncoordinating Solvents: Tunable Reactivity of Monomers. *Angew. Chem., Int. Ed.* **2002**, *41* (13), 2368−2371.

(85) Widness, J. K.; Enny, D. G.; McFarlane-Connelly, K. S.; Miedenbauer, M. T.; Krauss, T. D.; Weix, D. J. CdS Quantum Dots as Potent Photoreductants for Organic Chemistry Enabled by Auger Processes. *J. Am. Chem. Soc.* **2022**, *144* (27), 12229−12246.

(86) Kiczor, A.; Mergo, P. Synthesis of CdSe Quantum Dots in Two Solvents of Different Boiling Points for Polymer Optical Fiber Technology. *Materials* **2024**, *17* (1), 227.

(87) He, R.; Gu, H. Synthesis and Characterization of Mondispersed CdSe Nanocrystals at Lower Temperature. *Colloids Surf., A* **2006**, *272* (1), 111−116.

(88) Joo, J.; Na, H. B.; Yu, T.; Yu, J. H.; Kim, Y. W.; Wu, F.; Zhang, J. Z.; Hyeon, T. Generalized and Facile Synthesis of Semiconducting Metal Sulfide Nanocrystals. *J. Am. Chem. Soc.* **2003**, *125* (36), 11100−11105.

(89) Yang, Y. A.; Wu, H.; Williams, K. R.; Cao, Y. C. Synthesis of CdSe and CdTe Nanocrystals without Precursor Injection. *Angew. Chem., Int. Ed.* **2005**, *44* (41), 6712−6715.

(90) Heuer-Jungemann, A.; Feliu, N.; Bakaimi, I.; Hamaly, M.; Alkilany, A.; Chakraborty, I.; Masood, A.; Casula, M. F.; Kostopoulou, A.; Oh, E.; Susumu, K.; Stewart, M. H.; Medintz, I. L.; Stratakis, E.; Parak, W. J.; Kanaras, A. G. The Role of Ligands in the Chemical Synthesis and Applications of Inorganic Nanoparticles. *Chem. Rev.* **2019**, *119* (8), 4819−4880.

(91) Bullen, C. R.; Mulvaney, P. Nucleation and Growth Kinetics of CdSe Nanocrystals in Octadecene. *Nano Lett.* **2004**, *4* (12), 2303−2307.

(92) Wu, D.; Kordesch, M. E.; Van Patten, P. G. A New Class of Capping Ligands for CdSe Nanocrystal Synthesis. *Chem. Mater.* **2005**, *17* (25), 6436−6441.

(93) van Embden, J.; Mulvaney, P. Nucleation and Growth of CdSe Nanocrystals in a Binary Ligand System. *Langmuir* **2005**, *21* (22), 10226−10233.

(94) Dabbousi, B. O.; Rodriguez-Viejo, J.; Mikulec, F. V.; Heine, J. R.; Mattoussi, H.; Ober, R.; Jensen, K. F.; Bawendi, M. G. (CdSe)ZnS Core−Shell Quantum Dots: Synthesis and Characterization of a Size Series of Highly Luminescent Nanocrystallites. *J. Phys. Chem. B* **1997**, *101* (46), 9463−9475.

(95) Asokan, S.; Krueger, K. M.; Alkhawaldeh, A.; Carreon, A. R.; Mu, Z.; Colvin, V. L.; Mantzaris, N. V.; Wong, M. S. The Use of Heat Transfer Fluids in the Synthesis of High-Quality CdSe Quantum Dots, Core/Shell Quantum Dots, and Quantum Rods. *Nanotechnology* **2005**, *16* (10), 2000.

(96) Talapin, D. V.; Rogach, A. L.; Kornowski, A.; Haase, M.; Weller, H. Highly Luminescent Monodisperse CdSe and CdSe/ZnS Nanocrystals Synthesized in a Hexadecylamine−Trioctylphosphine Oxide−Trioctylphospine Mixture. *Nano Lett.* **2001**, *1* (4), 207−211.

(97) Bailey, R. E.; Nie, S. Alloyed Semiconductor Quantum Dots: Tuning the Optical Properties without Changing the Particle Size. *J. Am. Chem. Soc.* **2003**, *125* (23), 7100−7106.

(98) Talapin, D. V.; Haubold, S.; Rogach, A. L.; Kornowski, A.; Haase, M.; Weller, H. A Novel Organometallic Synthesis of Highly Luminescent CdTe Nanocrystals. *J. Phys. Chem. B* **2001**, *105* (12), 2260−2263.

(99) Talapin, D. V.; Mekis, I.; Götzinger, S.; Kornowski, A.; Benson, O.; Weller, H. CdSe/CdS/ZnS and CdSe/ZnSe/ZnS Core−Shell−Shell Nanocrystals. *J. Phys. Chem. B* **2004**, *108* (49), 18826−18831.

(100) Liu, X.; Jiang, Y.; Wang, C.; Li, S.; Lan, X.; Chen, Y.; Zhong, H. Synthesis and Spectrum Stability of High Quality CdTe Quantum Dots Capped with Stearate Groups in N-Oleoylmorpholine Solvent. *J. Cryst. Growth* **2010**, *312* (19), 2656−2660.

(101) Li, Z.; Ji, Y.; Xie, R.; Grisham, S. Y.; Peng, X. Correlation of CdS Nanocrystal Formation with Elemental Sulfur Activation and Its Implication in Synthetic Development. *J. Am. Chem. Soc.* **2011**, *133* (43), 17248−17256.

(102) Cao, Y. C.; Wang, J. One-Pot Synthesis of High-Quality Zinc-Blende CdS Nanocrystals. *J. Am. Chem. Soc.* **2004**, *126* (44), 14336−14337.

(103) Pu, C.; Zhou, J.; Lai, R.; Niu, Y.; Nan, W.; Peng, X. Highly Reactive, Flexible yet Green Se Precursor for Metal Selenide Nanocrystals: Se-Octadecene Suspension (Se-SUS). *Nano Res.* **2013**, *6* (9), 652−670.

(104) Bullen, C.; van Embden, J.; Jasieniak, J.; Cosgriff, J. E.; Mulder, R. J.; Rizzardo, E.; Gu, M.; Raston, C. L. High Activity Phosphine-Free Selenium Precursor Solution for Semiconductor Nanocrystal Growth. *Chem. Mater.* **2010**, *22* (14), 4135−4143.

(105) Mekis, I.; Talapin, D. V.; Kornowski, A.; Haase, M.; Weller, H. One-Pot Synthesis of Highly Luminescent CdSe/CdS Core−Shell Nanocrystals via Organometallic and "Greener" Chemical Approaches. *J. Phys. Chem. B* **2003**, *107* (30), 7454−7462.

(106) Pradhan, N.; Efrima, S. Single-Precursor, One-Pot Versatile Synthesis under near Ambient Conditions of Tunable, Single and Dual Band Fluorescing Metal Sulfide Nanoparticles. *J. Am. Chem. Soc.* **2003**, *125* (8), 2050−2051.

(107) Pradhan, N.; Katz, B.; Efrima, S. Synthesis of High-Quality Metal Sulfide Nanoparticles from Alkyl Xanthate Single Precursors in Alkylamine Solvents. *J. Phys. Chem. B* **2003**, *107* (50), 13843−13854.

(108) He, R.; You, X.; Tian, H.; Gao, F.; Cui, D.; Gu, H. Synthesis and Characterization of Monodisperse CdSe Quantum Dots in Different Organic Solvents. *Front. Chem. China* **2006**, *1* (4), 378−383.

(109) De Roo, J. The Surface Chemistry of Colloidal Nanocrystals Capped by Organic Ligands. *Chem. Mater.* **2023**, *35* (10), 3781−3792.

(110) Mohamed, M. B.; Tonti, D.; Al-Salman, A.; Chemseddine, A.; Chergui, M. Synthesis of High Quality Zinc Blende CdSe Nanocrystals. *J. Phys. Chem. B* **2005**, *109* (21), 10533−10537.

(111) Dou, F. Y.; Nishiwaki, E.; Larson, H.; Homer, M. K.; Zion, T.; Nguyen, H. A.; Cossairt, B. M. Pathways of CdS Quantum Dot Degradation during Photocatalysis: Implications for Enhancing Stability and Efficiency for Organic Synthesis. *ACS Appl. Nano Mater.* **2024**, *7* (13), 15781−15785.

(112) Souza Junior, J. B.; Mouriño, B.; Gehlen, M. H.; Moraes, D. A.; Bettini, J.; Varanda, L. C. Acid Selenites as New Selenium Precursor for CdSe Quantum Dot Synthesis. *Heliyon* **2024**, *10* (1), No. e23837.

(113) Chang, K.-P.; Yeh, Y.-C.; Wu, C.-J.; Yen, C.-C.; Wuu, D.-S. Improved Characteristics of CdSe/CdS/ZnS Core-Shell Quantum Dots Using an Oleylamine-Modified Process. *Nanomaterials* **2022**, *12* (6), 909.

(114) Xu, R. H. J.; Keating, L. P.; Vikram, A.; Shim, M.; Kenis, P. J. A. Understanding Hot Injection Quantum Dot Synthesis Outcomes Using Automated High-Throughput Experiment Platforms and Machine Learning. *Chem. Mater.* **2024**, *36* (3), 1513−1525.

(115) Jin, G.; Zeng, Y.; Liu, X.; Wang, Q.; Wei, J.; Liu, F.; Li, H. Synthesis and Optical Properties of CdSeTe/CdZnS/ZnS Core/Shell Nanorods. *Nanomaterials* **2024**, *14* (11), 989.

(116) Sun, X.; Wang, S.; Wang, Z.; Shen, Q.; Chen, X.; Chen, Z.; Luan, C.; Yu, K. Lower-Temperature Nucleation and Growth of Colloidal CdTe Quantum Dots Enabled by Prenucleation Clusters with Cd−Te Bond Conservation. *J. Am. Chem. Soc.* **2024**, *146* (22), 15587−15595.

(117) Henglein, A. Photo-Degradation and Fluorescence of Colloidal-Cadmium Sulfide in Aqueous Solution. *Ber. Bunsenges. Phys. Chem.* **1982**, *86* (4), 301−305.

(118) Rossetti, R.; Nakahara, S.; Brus, L. E. Quantum Size Effects in the Redox Potentials, Resonance Raman Spectra, and Electronic Spectra of CdS Crystallites in Aqueous Solution. *J. Chem. Phys.* **1983**, *79* (2), 1086−1088.

(119) Singh, A.; Tripathi, V. S.; Neogy, S.; Rath, M. C. Facile and Green Synthesis of 1-Thioglycerol Capped CdSe Quantum Dots in Aqueous Solution. *Mater. Chem. Phys.* **2018**, *214*, 320−329.

(120) Sharma, S.; Yadav, P.; Chowdhury, P. Thioglycolic Acid Capped CdSe/ZnS Quantum Dot as Fluorescent Sensor for the Detection of Water-Soluble Hazardous Heavy Metal Ions. *Appl. Phys. A: Mater. Sci. Process.* **2024**, *130* (5), 326.

(121) Luan, W.; Yang, H.; Wan, Z.; Yuan, B.; Yu, X.; Tu, S. Mercaptopropionic Acid Capped CdSe/ZnS Quantum Dots as Fluorescence Probe for Lead(II). *J. Nanoparticle Res.* **2012**, *14* (3), 762.

(122) Chaudhry, M.; Lim, D.-K.; Qamar, R.; Bhatti, A. S. The Adverse Role of Excess Negative Ions in Reducing the Photoluminescence from Water Soluble MAA−CdSe/ZnS Quantum Dots in Various Phosphate Buffers. *Phys. Chem. Chem. Phys.* **2018**, *20* (46), 29446−29451.

(123) Boldt, K.; Bruns, O. T.; Gaponik, N.; Eychmüller, A. Comparative Examination of the Stability of Semiconductor Quantum Dots in Various Biochemical Buffers. *J. Phys. Chem. B* **2006**, *110* (5), 1959−1963.

(124) Aboulaich, A.; Billaud, D.; Abyan, M.; Balan, L.; Gaumet, J.-J.; Medjadhi, G.; Ghanbaja, J.; Schneider, R. One-Pot Noninjection Route to CdS Quantum Dots via Hydrothermal Synthesis. *ACS Appl. Mater. Interfaces* **2012**, *4* (5), 2561−2569.

(125) Mauritz, V.; Crisp, R. W. Unravelling the Intricacies of Solvents and Sulfur Sources in Colloidal Synthesis of Metal Sulfide Semiconductor Nanocrystals. *J. Mater. Chem. C* **2024**, *12* (30), 11319−11334.

(126) Pu, C.; Peng, X. To Battle Surface Traps on CdSe/CdS Core/Shell Nanocrystals: Shell Isolation versus Surface Treatment. *J. Am. Chem. Soc.* **2016**, *138* (26), 8134−8142.

(127) Vale, B. R. C.; Mourão, R. S.; Bettini, J.; Sousa, J. C. L.; Ferrari, J. L.; Reiss, P.; Aldakov, D.; Schiavon, M. A. Ligand Induced Switching of the Band Alignment in Aqueous Synthesized CdTe/CdS Core/Shell Nanocrystals. *Sci. Rep.* **2019**, *9* (1), 8332.

(128) Archer, P. I.; Santangelo, S. A.; Gamelin, D. R. Inorganic Cluster Syntheses of TM2+-Doped Quantum Dots (CdSe, CdS, CdSe/CdS): Physical Property Dependence on Dopant Locale. *J. Am. Chem. Soc.* **2007**, *129* (31), 9808−9818.

(129) Ozdemir, N. K.; Cline, J. P.; Wu, T.-H.; Spangler, L. C.; McIntosh, S.; Kiely, C. J.; Snyder, M. A. Bioinspired, Non-Enzymatic, Aqueous Synthesis of Size-Tunable CdS Quantum Dots for Sustainable Optoelectronic Applications. *ACS Appl. Nano Mater.* **2023**, *6* (9), 7668−7678.

(130) Gallardo-Benavente, C.; Carrion, O.; Todd, J. D.; Pieretti, J. C.; Seabra, A. B.; Durán, N.; Rubilar, O.; Pérez-Donoso, J. M.; Quiroz, A. Biosynthesis of CdS Quantum Dots Mediated by Volatile Sulfur Compounds Released by Antarctic Pseudomonas Fragi. *Front. Microbiol.* **2019**, *10*, 1866.

(131) Ristić, M.; Popović, S.; Ivanda, M.; Musić, S. A. Simple Route in the Synthesis of CdS Nanoparticles. *Mater. Lett.* **2013**, *109*, 179−181.

(132) Williams, J. V.; Kotov, N. A.; Savage, P. E. A Rapid Hot-Injection Method for the Improved Hydrothermal Synthesis of CdSe Nanoparticles. *Ind. Eng. Chem. Res.* **2009**, *48* (9), 4316−4321.

(133) Khan, Z. M. S. H.; Khan, H.; Zulfequar, M. CdSe Quantum Dots Using Selenourea as Selenium Source in Polymer Matrix. *J. Mater. Sci. Mater. Electron.* **2017**, *28* (19), 14638−14645.

(134) Lin, Y.-W.; Liu, C.-W.; Chang, H.-T. Synthesis and Properties of Water-Soluble Core−Shell−Shell Silica−CdSe/CdS−Silica Nanoparticles. *J. Nanosci. Nanotechnol.* **2006**, *6* (4), 1092−1100.

(135) Jalilehvand, F.; Amini, Z.; Parmar, K. Cadmium(II) Complex Formation with Selenourea and Thiourea in Solution: An XAS and ^{113}Cd NMR Study. *Inorg. Chem.* **2012**, *51* (20), 10619−10630.

(136) Pan, D.; Wang, Q.; Jiang, S.; Ji, X.; An, L. Low-Temperature Synthesis of Oil-Soluble CdSe, CdS, and CdSe/CdS Core−Shell Nanocrystals by Using Various Water-Soluble Anion Precursors. *J. Phys. Chem. C* **2007**, *111* (15), 5661−5666.

(137) Rogach, A. L.; Kornowski, A.; Gao, M.; Eychmüller, A.; Weller, H. Synthesis and Characterization of a Size Series of Extremely Small Thiol-Stabilized CdSe Nanocrystals. *J. Phys. Chem. B* **1999**, *103* (16), 3065−3069.

(138) Shin, N. H.; Lim, Y. J.; Kim, C.; Kim, Y. E.; Jeong, Y. R.; Cho, H.; Park, M.-S.; Lee, S. H. An Efficient Method for Selective Syntheses of Sodium Selenide and Dialkyl Selenides. *Molecules* **2022**, *27* (16), 5224.

(139) Raevskaya, A. E.; Stroyuk, A. L.; Kuchmiy, S. Y. Preparation of Colloidal CdSe and CdS/CdSe Nanoparticles from Sodium Selenosulfate in Aqueous Polymers Solutions. *J. Colloid Interface Sci.* **2006**, *302* (1), 133−141.

(140) Riskowski, R. A.; Nemeth, R. S.; Borgognoni, K.; Ackerson, C. J. Enzyme-Catalyzed in Situ Synthesis of Temporally and Spatially Distinct CdSe Quantum Dots in Biological Backgrounds. *J. Phys. Chem. C* **2019**, *123* (44), 27187−27195.

(141) Wang, R.; Xu, X.; Wang, Y.; Zhou, L.; Li, B. Synthesis of Color-Tunable CdSe Nanocrystals via a Green Synthetic Method. *IEEE Photonics Technol. Lett.* **2014**, *26* (12), 1196−1198.

(142) Wang, Y.; Yu, M.; Yang, K.; Lu, J.; Chen, L. Simple Synthesis of Luminescent CdSe Quantum Dots from Ascorbic Acid and Selenium Dioxide. *Luminescence* **2015**, *30* (8), 1375−1379.

(143) Kini, S.; Kulkarni, S. D.; Ganiga, V.; Nagarakshit, T. K.; Chidangil, S. Dual Functionalized, Stable and Water Dispersible CdTe Quantum Dots: Facile, One-Pot Aqueous Synthesis, Optical Tuning and Energy Transfer Applications. *Mater. Res. Bull.* **2019**, *110*, 57−66.

(144) Yang, W.; Li, W.; Dou, H.; Sun, K. Hydrothermal Synthesis for High-Quality CdTe Quantum Dots Capped by Cysteamine. *Mater. Lett.* **2008**, *62* (17), 2564−2566.

(145) Li, M.; Ge, Y.; Chen, Q.; Xu, S.; Wang, N.; Zhang, X. Hydrothermal Synthesis of Highly Luminescent CdTe Quantum Dots by Adjusting Precursors' Concentration and Their Conjunction with BSA as Biological Fluorescent Probes. *Talanta* **2007**, *72* (1), 89−94.

(146) Liu, J.; Shi, Z.; Yu, Y.; Yang, R.; Zuo, S. Water-Soluble Multicolored Fluorescent CdTe Quantum Dots: Synthesis and Application for Fingerprint Developing. *J. Colloid Interface Sci.* **2010**, *342* (2), 278−282.

(147) Ta, V.-T.; Nguyen, D.-K.; Nguyen, X.-B.; Nguyen, P.-N.; Nguyen, S.-H.; Mai, X.-D. Cost-Effective, Hydride-Free Aqueous Synthesis of CdTe Quantum Dots Enabled by Using Ammonia as the Reducing Agent. *J. Cryst. Growth* **2025**, *661*, 128182.

(148) Song, J. H.; Nguyen, T.-P.; Nguyen, D.-K.; Nguyen, X.-B.; Nguyen, P.-N.; Nguyen, S.-H.; Mai, V.-T.; Pham, P.-U.; Vu Thi, H.-Y.; Dung, M.-X. Hydrothermal Synthesis of CdTe Quantum Dots Using Ammonia as a Reducing Agent. *HPU2 J. Sci. Nat. Sci. Technol.* **2024**, *3* (2), 3−9.

(149) Dremliuzhenko, K.; Kulchytskyi, B.; Korbutyak, D.; Kosinov, O.; Isaieva, O.; Mazur, N.; Trishchuk, L. Colloidal Synthesis and Optical Properties of Ultra-Small CdTe Quantum Dots. *Phys. Chem. Solid State* **2024**, *25* (4), 838−845.

(150) Talapin, D. V.; Rogach, A. L.; Shevchenko, E. V.; Kornowski, A.; Haase, M.; Weller, H. Dynamic Distribution of Growth Rates within the Ensembles of Colloidal II−VI and III−V Semiconductor Nanocrystals as a Factor Governing Their Photoluminescence Efficiency. *J. Am. Chem. Soc.* **2002**, *124* (20), 5782−5790.

(151) Gaponik, N.; Talapin, D. V.; Rogach, A. L.; Hoppe, K.; Shevchenko, E. V.; Kornowski, A.; Eychmüller, A.; Weller, H. Thiol-

Capping of CdTe Nanocrystals: An Alternative to Organometallic Synthetic Routes. *J. Phys. Chem. B* **2002**, *106* (29), 7177−7185.

(152) Rempel, A. A.; Ovchinnikov, O. V.; Weinstein, I. A.; Rempel, S. V.; Kuznetsova, Y. V.; Naumov, A. V.; Smirnov, M. S.; Eremchev, I. Y.; Vokhmintsev, A. S.; Savchenko, S. S. Quantum Dots: Modern Methods of Synthesis and Optical Properties. *Russ. Chem. Rev.* **2024**, *93*, RCR5114.

(153) Zhou, J.; Liu, Y.; Tang, J.; Tang, W. Surface Ligands Engineering of Semiconductor Quantum Dots for Chemosensory and Biological Applications. *Mater. Today* **2017**, *20* (7), 360−376.

(154) De Roo, J.; Huang, Z.; Schuster, N. J.; Hamachi, L. S.; Congreve, D. N.; Xu, Z.; Xia, P.; Fishman, D. A.; Lian, T.; Owen, J. S.; Tang, M. L. Anthracene Diphosphate Ligands for CdSe Quantum Dots; Molecular Design for Efficient Upconversion. *Chem. Mater.* **2020**, *32* (4), 1461−1466.

(155) Rogach, A. L.; Franzl, T.; Klar, T. A.; Feldmann, J.; Gaponik, N.; Lesnyak, V.; Shavel, A.; Eychmüller, A.; Rakovich, Y. P.; Donegan, J. F. Aqueous Synthesis of Thiol-Capped CdTe Nanocrystals: State-of-the-Art. *J. Phys. Chem. C* **2007**, *111* (40), 14628−14637.

(156) Zou, L.; Gu, Z.; Zhang, N.; Zhang, Y.; Fang, Z.; Zhu, W.; Zhong, X. Ultrafast Synthesis of Highly Luminescent Green- to near Infrared-Emitting CdTe Nanocrystals in Aqueous Phase. *J. Mater. Chem.* **2008**, *18* (24), 2807−2815.

(157) Salas-Vázquez, E.; López-Moreno, M. L.; Bailón-Ruiz, S. J. Synthesis of CdS and TGA-Capped CdS Quantum Dots from Different Cd Precursors. *MRS Adv.* **2022**, *7* (10), 235−238.

(158) Ben Brahim, N.; Poggi, M.; Lambry, J.-C.; Bel Haj Mohamed, N.; Ben Chaâbane, R.; Negrerie, M. Density of Grafted Chains in Thioglycerol-Capped CdS Quantum Dots Determines Their Interaction with Aluminum(III) in Water. *Inorg. Chem.* **2018**, *57* (9), 4979−4988.

(159) Huang, Y.; Zhuang, Z.; Xue, X.; Zheng, J.; Lin, Z. Growth Kinetics Study Revealing the Role of the MPA Capping Ligand on Adjusting the Growth Modes and PL Properties of CdTe QDs. *CrystEngComm* **2014**, *16* (8), 1547−1552.

(160) Bel Haj Mohamed, N.; Ben Brahim, N.; Mrad, R.; Haouari, M.; Ben Chaâbane, R.; Negrerie, M. Use of MPA-Capped CdS Quantum Dots for Sensitive Detection and Quantification of Co^{2+} Ions in Aqueous Solution. *Anal. Chim. Acta* **2018**, *1028*, 50−58.

(161) Mahmoud, W. E.; Al-Amri, A. M.; Yaghmour, S. J. Low Temperature Synthesis of CdSe Capped 2-Mercaptoethanol Quantum Dots. *Opt. Mater.* **2012**, *34* (7), 1082−1086.

(162) Ferrer, J. C.; Salinas-Castillo, A.; Alonso, J. L.; Fernández de Ávila, S.; Mallavia, R. Synthesis and Characterization of CdS Nanocrystals Stabilized in Polyvinyl Alcohol−Sodium Polyphosphate. *Mater. Lett.* **2009**, *63* (6), 638−640.

(163) Mansur, H. S.; Mansur, A. A. P. CdSe Quantum Dots Stabilized by Carboxylic-Functionalized PVA: Synthesis and UV−Vis Spectroscopy Characterization. *Mater. Chem. Phys.* **2011**, *125* (3), 709−717.

(164) Zhang, Y.; Clapp, A. Overview of Stabilizing Ligands for Biocompatible Quantum Dot Nanocrystals. *Sensors* **2011**, *11* (12), 11036−11055.

(165) Kyobe, J. W.; Khan, M. D.; Kinunda, G.; Mubofu, E. B.; Revaprasadu, N. Synthesis of CdTe Quantum Dots Capped with Castor Oil Using a Hot Injection Solution Method. *Mater. Sci. Semicond. Process.* **2020**, *106*, 104780.

(166) Greytak, A. B.; Allen, P. M.; Liu, W.; Zhao, J.; Young, E. R.; Popović, Z.; Walker, B. J.; Nocera, D. G.; Bawendi, M. G. Alternating Layer Addition Approach to CdSe/CdS Core/Shell Quantum Dots with near-Unity Quantum Yield and High on-Time Fractions. *Chem. Sci.* **2012**, *3* (6), 2028−2034.

(167) Page, R. C.; Espinobarro-Velazquez, D.; Leontiadou, M. A.; Smith, C.; Lewis, E. A.; Haigh, S. J.; Li, C.; Radtke, H.; Pengpad, A.; Bondino, F.; Magnano, E.; Pis, I.; Flavell, W. R.; O'Brien, P.; Binks, D. J. Near-Unity Quantum Yields from Chloride Treated CdTe Colloidal Quantum Dots. *Small* **2015**, *11* (13), 1548−1554.

(168) Pan, L.-J.; Tu, J.-W.; Ma, H.-T.; Yang, Y.-J.; Tian, Z.-Q.; Pang, D.-W.; Zhang, Z.-L. Controllable Synthesis of Nanocrystals in Droplet Reactors. *Lab Chip* **2018**, *18* (1), 41−56.

(169) Skrabalak, S. E.; Brutchey, R. L. Going with the Flow: Continuous Flow Routes to Colloidal Nanoparticles. *Chem. Mater.* **2016**, *28* (4), 1003−1005.

(170) Wojnicki, M.; Hessel, V. Quantum Materials Made in Microfluidics - Critical Review and Perspective. *Chem. Eng. J.* **2022**, *438*, 135616.

(171) Kubendhiran, S.; Bao, Z.; Dave, K.; Liu, R.-S. Microfluidic Synthesis of Semiconducting Colloidal Quantum Dots and Their Applications. *ACS Appl. Nano Mater.* **2019**, *2* (4), 1773−1790.

(172) Li, S.; Hsiao, J. C.; Howes, P. D.; deMello, A. J. Microfluidic Tools for the Synthesis of Bespoke Quantum Dots. In *Nanotechnology and Microfluidics*; Xingyu, J.; Chunli, B.; Minghua, L., Eds.; Wiley, 2020, pp 109−148.

(173) Li, G.-X.; Li, Q.; Cheng, R.; Chen, S. Synthesis of Quantum Dots Based on Microfluidic Technology. *Curr. Opin. Chem. Eng.* **2020**, *29*, 34−41.

(174) Pu, Y.; Cai, F.; Wang, D.; Wang, J.-X.; Chen, J.-F. Colloidal Synthesis of Semiconductor Quantum Dots toward Large-Scale Production: A Review. *Ind. Eng. Chem. Res.* **2018**, *57* (6), 1790−1802.

(175) Sarbaland, F. B.; Kobayashi, M.; Tanaka, D.; Fujita, R.; Furuya, M. Redefining Quantum Dot Synthesis with Additive-Manufactured Microfluidics—A Review. *J.* **2025**, *8* (2), 18.

(176) Yen, B. K. H.; Stott, N. E.; Jensen, K. F.; Bawendi, M. G. A Continuous-Flow Microcapillary Reactor for the Preparation of a Size Series of CdSe Nanocrystals. *Adv. Mater.* **2003**, *15* (21), 1858−1862.

(177) Kikkeri, R.; Laurino, P.; Odedra, A.; Seeberger, P. H. Synthesis of Carbohydrate-Functionalized Quantum Dots in Microreactors. *Angew. Chem., Int. Ed.* **2010**, *49* (11), 2054−2057.

(178) Abolhasani, M.; Coley, C. W.; Xie, L.; Chen, O.; Bawendi, M. G.; Jensen, K. F. Oscillatory Microprocessor for Growth and in Situ Characterization of Semiconductor Nanocrystals. *Chem. Mater.* **2015**, *27* (17), 6131−6138.

(179) Toyota, A.; Nakamura, H.; Ozono, H.; Yamashita, K.; Uehara, M.; Maeda, H. Combinatorial Synthesis of CdSe Nanoparticles Using Microreactors. *J. Phys. Chem. C* **2010**, *114* (17), 7527−7534.

(180) Nakamura, H.; Tashiro, A.; Yamaguchi, Y.; Miyazaki, M.; Watari, T.; Shimizu, H.; Maeda, H. Application of a Microfluidic Reaction System for CdSe Nanocrystal Preparation: Their Growth Kinetics and Photoluminescence Analysis. *Lab Chip* **2004**, *4* (3), 237−240.

(181) Krishnadasan, S.; Brown, R. J. C.; deMello, A. J.; deMello, J. C. Intelligent Routes to the Controlled Synthesis of Nanoparticles. *Lab Chip* **2007**, *7* (11), 1434−1441.

(182) Yen, B. K. H.; Günther, A.; Schmidt, M. A.; Jensen, K. F.; Bawendi, M. G. A Microfabricated Gas−Liquid Segmented Flow Reactor for High-Temperature Synthesis: The Case of CdSe Quantum Dots. *Angew. Chem., Int. Ed.* **2005**, *44* (34), 5447−5451.

(183) Chan, E. M.; Mathies, R. A.; Alivisatos, A. P. Size-Controlled Growth of CdSe Nanocrystals in Microfluidic Reactors. *Nano Lett.* **2003**, *3* (2), 199−201.

(184) Kawa, M.; Morii, H.; Ioku, A.; Saita, S.; Okuyama, K. Large-Scale Production of CdSe Nanocrystal by a Continuous Flow Reactor. *J. Nanoparticle Res.* **2003**, *5* (1), 81−85.

(185) Cheng, R.; Ma, K.; Ye, H.-G.; Ling, L.; Wu, G.; Wang, C.-F.; Chen, S. Magnetothermal Microfluidic-Directed Synthesis of Quantum Dots. *J. Mater. Chem. C* **2020**, *8* (19), 6358−6363.

(186) Hong, L.; Cheung, T.-L.; Rao, N.; Ouyang, Q.; Wang, Y.; Zeng, S.; Yang, C.; Cuong, D.; Chong, P. H. J.; Liu, L.; Law, W.-C.; Yong, K.-T. Millifluidic Synthesis of Cadmium Sulfide Nanoparticles and Their Application in Bioimaging. *RSC Adv.* **2017**, *7* (58), 36819−36832.

(187) Nightingale, A. M.; de Mello, J. C. Microscale Synthesis of Quantum Dots. *J. Mater. Chem.* **2010**, *20* (39), 8454−8463.

(188) de Oliveira, A. R. M.; Piovan, L.; Simonelli, F.; Barison, A.; de Fatima C Santos, M.; de Mello, M. B. M. A ^{77}Se NMR Study of Elemental Selenium Reduction Using NaBH4. *J. Organomet. Chem.* **2016**, *806*, 54−59.

(189) Edel, J. B.; Fortt, R.; deMello, J. C.; deMello, A. J. Microfluidic Routes to the Controlled Production of Nanoparticles. *Chem. Commun.* **2002**, *10*, 1136−1137.

(190) Shestopalov, I.; Tice, J. D.; Ismagilov, R. F. Multi-Step Synthesis of Nanoparticles Performed on Millisecond Time Scale in a Microfluidic Droplet-Based System. *Lab Chip* **2004**, *4* (4), 316−321.

(191) Dai, J.; Yang, X.; Hamon, M.; Kong, L. Particle Size Controlled Synthesis of CdS Nanoparticles on a Microfluidic Chip. *Chem. Eng. J.* **2015**, *280*, 385−390.

(192) Mbwahnche, R. C.; Matyushkin, L. B.; Ryzhov, O. A.; Aleksandrova, O. A.; Moshnikov, V. A. Segmented Flow Reactor for Synthesis of Quantum Dot Nanocrystals and Plasmonic Nanoparticles. *J. Phys. Conf. Ser.* **2016**, *741*, 012026.

(193) Emmanuel, N.; Emonds-Alt, G.; Lismont, M.; Eppe, G.; Monbaliu, J.-C. M. Exploring the Fundamentals of Microreactor Technology with Multidisciplinary Lab Experiments Combining the Synthesis and Characterization of Inorganic Nanoparticles. *J. Chem. Educ.* **2017**, *94* (6), 775−780.

(194) Das, D.; Dutta, R. K. Structure-Optical Property Correlation in CdTe/CdS Core-Shell Quantum Dots and Their Effects on Cu2+ Sensing Mechanisms. *J. Photochem. Photobiol. Chem.* **2020**, *400*, 112709.

(195) Yan, C.; Tang, F.; Li, L.; Li, H.; Huang, X.; Chen, D.; Meng, X.; Ren, J. Synthesis of Aqueous CdTe/CdS/ZnS Core/Shell/Shell Quantum Dots by a Chemical Aerosol Flow Method. *Nanoscale Res. Lett.* **2010**, *5* (1), 189.

(196) Yao, S.; Shu, Y.; Yang, Y.-J.; Yu, X.; Pang, D.-W.; Zhang, Z.-L. Picoliter Droplets Developed as Microreactors for Ultrafast Synthesis of Multi-Color Water-Soluble CdTe Quantum Dots. *Chem. Commun.* **2013**, *49* (64), 7114−7116.

(197) Hiemer, J.; Stöwe, K. Continuous Flow Synthesis of Cd1-xZnxS and CdS/ZnS Core/Shell Semiconductor Nanoparticles by MicroJet Reactor Technology. *ChemistryOpen* **2022**, *11* (12), No. e202200232.

(198) Palanisamy, B.; Su, Y.-W.; Garrison, A.; Paul, B.; Chang, C. Cadmium Sulfide Nanoparticle Synthesis Using Oscillatory Flow Mixing. In *ASME 2011 International Manufacturing Science and Engineering Conference*; ASME, 2011, pp 591−598.

(199) Pandey, S.; Mukherjee, D.; Kshirsagar, P.; Patra, C.; Bodas, D. Multiplexed Bio-Imaging Using Cadmium Telluride Quantum Dots Synthesized by Mathematically Derived Process Parameters in a Continuous Flow Active Microreactor. *Mater. Today Bio* **2021**, *11*, 100123.

(200) Qi, X.; Hu, Y.; Chen, Y.; Zhang, J.; Fang, D.; Wang, J.; Fang, D.; Jin, T. Preparation of Water-Soluble Cadmium Sulfide Quantum Dots with Narrow Small-Size Distribution by Controlling Hydrodynamic Cavitation Device Parameters. *Powder Technol.* **2024**, *440*, 119755.

(201) Zhang, J.; Qi, X.; Jin, T.; Fang, D.; Li, Y.; Zhou, Z.; Wu, H.; Wang, J.; Fang, D. Hydrodynamic Cavitation Synthesis of Water-Soluble CdSe Quantum Dots: Effect of Venturi Tube Parameters on Size Distribution and Fluorescence Properties, with Application in Fe^{3+} Detection. *Anal. Chim. Acta* **2025**, *1348*, 343828.

(202) Campalani, C.; Rigo, D. Continuous Flow Synthesis and Applications of Carbon Dots: A Mini-Review. *Sustain* **2023**, *1*, 100001.

(203) Epps, R. W.; Delgado-Licona, F.; Yang, H.; Kim, T.; Volk, A. A.; Han, S.; Jun, S.; Abolhasani, M. Accelerated Multi-Stage Synthesis of Indium Phosphide Quantum Dots in Modular Flow Reactors. *Adv. Mater. Technol.* **2023**, *8* (4), 2201845.

(204) Campalani, C.; Petit, G.; Monbaliu, J.-C. M.; Selva, M.; Perosa, A. Continuous Flow Photooxidative Degradation of Azo Dyes with Biomass-Derived Carbon Dots. *ChemPhotoChem* **2023**, *7* (5), No. e202200234.

(205) Okamoto, A.; Toda, S.; Hirakawa, M.; Bai, H.; Tanaka, M.; Seino, S.; Nakagawa, T.; Murakami, H. Narrowing of the Particle Size Distribution of InP Quantum Dots for Green Light Emission by Synthesis in Micro-Flow Reactor. *ChemistrySelect* **2022**, *7* (6), No. e202104215.

(206) Chen, Y.; Shen, A.; Guo, J.; Zhu, L.; Li, G.; Qin, Y.; Qu, X.; Wang, C.-F.; Chen, S. Continuous Productions of Highly Fluorescent Carbon Dots and Enriched Polymer Nanofibers via Microfluidic Techniques. *Chem. Eng. J.* **2023**, *471*, 144444.

(207) Baragau, I.-A.; Power, N. P.; Morgan, D. J.; Lobo, R. A.; Roberts, C. S.; Titirici, M.-M.; Middelkoop, V.; Diaz, A.; Dunn, S.; Kellici, S. Efficient Continuous Hydrothermal Flow Synthesis of Carbon Quantum Dots from a Targeted Biomass Precursor for On−Off Metal Ions Nanosensing. *ACS Sustain. Chem. Eng.* **2021**, *9* (6), 2559−2569.

(208) Chen, L.; Ding, Z.; Ye, H.-G.; Wang, C.-F.; Chen, S. Rapid Continuous Aqueous Production of Copper Indium Sulfide Quantum Dots via a Microwave-Assisted Microfluidic Technique. *Nanoscale* **2024**, *16* (42), 19911−19917.

(209) Rivaux, C.; Akdas, T.; Yadav, R.; El-Dahshan, O.; Moodelly, D.; Ling, W. L.; Aldakov, D.; Reiss, P. Continuous Flow Aqueous Synthesis of Highly Luminescent $AgInS_2$ and $AgInS_2$/ZnS Quantum Dots. *J. Phys. Chem. C* **2022**, *126* (48), 20524−20534.

(210) Phillips, T. W.; Lignos, I. G.; Maceiczyk, R. M.; deMello, A. J.; deMello, J. C. Nanocrystal Synthesis in Microfluidic Reactors: Where Next? *Lab Chip* **2014**, *14* (17), 3172−3180.

(211) Besenhard, M. O.; Pal, S.; Gkogkos, G.; Gavriilidis, A. Non-Fouling Flow Reactors for Nanomaterial Synthesis. *React. Chem. Eng.* **2023**, *8* (5), 955−977.

(212) Abdel-Latif, K.; Bateni, F.; Crouse, S.; Abolhasani, M. Flow Synthesis of Metal Halide Perovskite Quantum Dots: From Rapid Parameter Space Mapping to AI-Guided Modular Manufacturing. *Matter* **2020**, *3* (4), 1053−1086.

(213) Epps, R. W.; Bowen, M. S.; Volk, A. A.; Abdel-Latif, K.; Han, S.; Reyes, K. G.; Amassian, A.; Abolhasani, M. Artificial Chemist: An Autonomous Quantum Dot Synthesis Bot. *Adv. Mater.* **2020**, *32* (30), 2001626.

(214) Volk, A. A.; Epps, R. W.; Yonemoto, D.; Castellano, F. N.; Abolhasani, M. Continuous Biphasic Chemical Processes in a Four-Phase Segmented Flow Reactor. *React. Chem. Eng.* **2021**, *6* (8), 1367−1375.

(215) Volk, A. A.; Epps, R. W.; Yonemoto, D. T.; Masters, B. S.; Castellano, F. N.; Reyes, K. G.; Abolhasani, M. AlphaFlow Autonomous Discovery and Optimization of Multi-Step Chemistry Using a Self-Driven Fluidic Lab Guided by Reinforcement Learning. *Nat. Commun.* **2023**, *14* (1), 1403.

(216) Abdel-Latif, K.; Epps, R. W.; Bateni, F.; Han, S.; Reyes, K. G.; Abolhasani, M. Self-Driven Multistep Quantum Dot Synthesis Enabled by Autonomous Robotic Experimentation in Flow. *Adv. Intell. Syst.* **2021**, *3* (2), 2000245.

(217) Bateni, F.; Sadeghi, S.; Orouji, N.; Bennett, J. A.; Punati, V. S.; Stark, C.; Wang, J.; Rosko, M. C.; Chen, O.; Castellano, F. N.; Reyes, K. G.; Abolhasani, M. Smart Dope: A Self-Driving Fluidic Lab for Accelerated Development of Doped Perovskite Quantum Dots. *Adv. Energy Mater.* **2024**, *14* (1), 2302303.

(218) Munyebvu, N.; Lane, E.; Grisan, E.; Howes, P. D. Accelerating Colloidal Quantum Dot Innovation with Algorithms and Automation. *Mater. Adv.* **2022**, *3* (18), 6950−6967.

(219) Lv, H.; Chen, X. Intelligent Control of Nanoparticle Synthesis through Machine Learning. *Nanoscale* **2022**, *14* (18), 6688−6708.

(220) Frigerio, C.; Ribeiro, D. S. M.; Rodrigues, S. S. M.; Abreu, V. L. R. G.; Barbosa, J. A. C.; Prior, J. A. V.; Marques, K. L.; Santos, J. L. M. Application of Quantum Dots as Analytical Tools in Automated Chemical Analysis: A Review. *Anal. Chim. Acta* **2012**, *735*, 9−22.

(221) Breen, C. P.; Nambiar, A. M. K.; Jamison, T. F.; Jensen, K. F. Ready, Set, Flow! Automated Continuous Synthesis and Optimization. *Trends Chem.* **2021**, *3* (5), 373−386.

(222) Mukhin, N.; Jha, P.; Abolhasani, M. The Role of Flow Chemistry in Self-Driving Labs. *Matter* **2025**, *8* (7), 102205.

(223) Sitapure, N.; Epps, R.; Abolhasani, M.; Kwon, J. S.-I. Multiscale Modeling and Optimal Operation of Millifluidic Synthesis of Perovskite Quantum Dots: Towards Size-Controlled Continuous Manufacturing. *Chem. Eng. J.* **2021**, *413*, 127905.

(224) Salaheldin, A. M.; Walter, J.; Herre, P.; Levchuk, I.; Jabbari, Y.; Kolle, J. M.; Brabec, C. J.; Peukert, W.; Segets, D. Automated Synthesis of Quantum Dot Nanocrystals by Hot Injection: Mixing Induced Self-Focusing. *Chem. Eng. J.* **2017**, *320*, 232−243.

(225) Pan, J.; El-Ballouli, A. O.; Rollny, L.; Voznyy, O.; Burlakov, V. M.; Goriely, A.; Sargent, E. H.; Bakr, O. M. Automated Synthesis of

Photovoltaic-Quality Colloidal Quantum Dots Using Separate Nucleation and Growth Stages. *ACS Nano* **2013**, *7* (11), 10158−10166.

(226) Nguyen, T. T. H.; Bui, H. K.; Im, J. Y.; Seo, T. S. Cognitively Driven Autonomous Flow Chemistry for Producing On-Demand Perovskite Quantum Dots Via Advanced Closed-Loop Feedback Control. *Small Methods* **2025**, *9* (1), 2400094.

(227) Duman, A. N.; Jalilov, A. S. Machine Learning for Carbon Dot Synthesis and Applications. *Mater. Adv.* **2024**, *5* (18), 7097−7112.

(228) Peng, J.; Muhammad, R.; Wang, S.-L.; Zhong, H.-Z. How Machine Learning Accelerates the Development of Quantum Dots?†. *Chin. J. Chem.* **2021**, *39* (1), 181−188.

(229) Epps, R. W.; Abolhasani, M. Modern Nanoscience: Convergence of AI, Robotics, and Colloidal Synthesis. *Appl. Phys. Rev.* **2021**, *8* (4), 041316.

(230) Delgado-Licona, F.; Alsaiari, A.; Dickerson, H.; Klem, P.; Ghorai, A.; Canty, R. B.; Bennett, J. A.; Jha, P.; Mukhin, N.; Li, J.; López-Guajardo, E. A.; Sadeghi, S.; Bateni, F.; Abolhasani, M. Flow-Driven Data Intensification to Accelerate Autonomous Inorganic Materials Discovery. *Nat. Chem. Eng.* **2025**, *2* (7), 436−446.

https://doi.org/10.1021/jacsau.5c01449